Future Energy Horizons of the Pacific Coast

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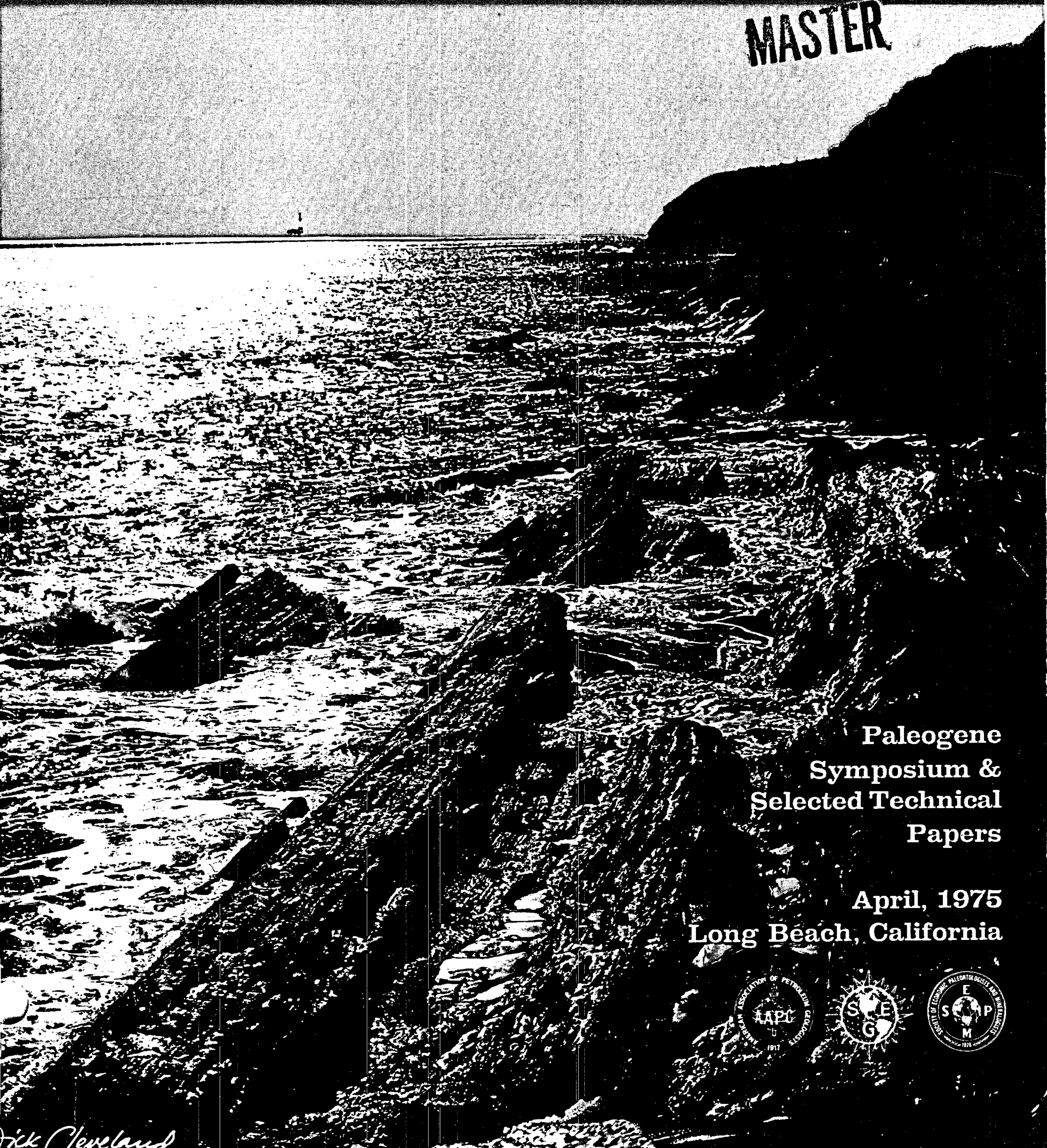

Paleogene Symposium & Selected Technical Papers

April, 1975
Long Beach, California

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PALEOGENE SYMPOSIUM
&
SELECTED TECHNICAL PAPERS

CONFERENCE ON
FUTURE ENERGY HORIZONS OF THE PACIFIC COAST

EDITORS

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ANNUAL MEETING — PACIFIC SECTIONS

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LONG BEACH, CALIFORNIA
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Conference on Future Energy Horizons
of the Pacific Coast

Paleogene Symposium and other Selected
Technical Papers

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INTRODUCTION

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Director, U.S. Geological Survey, Reston, Virginia

The theme of this conference, "Energy Horizons on the Pacific Coast," appropriately encompasses the full spectrum of problems which must be dealt with to provide adequate, reliable supplies of energy to a region which has heretofore been notable for its heavy dependence upon oil and gas. New sources of oil and gas must indeed be found, and recovery from known deposits enhanced, using every available tool of geology, paleontology, geophysics, and production technology.

Beyond the traditional fuels, however, the Pacific Coast region must increasingly look to other sources of energy for the satisfaction of its requirements: the rich and largely unutilized resources of coal, heavy crude oil, oil shale, and geothermal energy.

The authors of the papers presented here have responded imaginatively to the invitation to contribute to the advancement of geological exploration and development of all energy resources in the Pacific region. All of us recognize the magnitude of the challenge in Pacific energy development and the authors here show that the challenge can be taken on with confidence!

STRATIGRAPHIC RELATIONSHIP OF THE MIDDLE EOCENE KELLOGG AND SIDNEY FLAT SHALES OF NORTHERN CALIFORNIA

Alvin A. Almgren and Kristin McDougall
Union Oil of California
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ABSTRACT

The Kellogg shale and the Sidney Flat shale are planktonic-rich units that are exposed on Mt. Diablo in Contra Costa County, California. Although the planktonic foraminiferal faunas are the same, and no distinct differences exist in the diatom assemblages, the two shales have been considered stratigraphically separate units in the literature.

Evidence is presented which indicates that the Kellogg shale and the Sidney Flat shale represent separate exposures of the same stratigraphic unit. This correlation is based on published diatom and foraminiferal data, planktonic foraminiferal data concerning the underlying Nortonville shale, and supporting regional subsurface data.

INTRODUCTION

The Kellogg shale and the Sidney Flat shale are fossiliferous units that are exposed on Mt. Diablo in Contra Costa County, California (see Figure 1). Although published data have indicated that the planktonic foraminiferal faunas are the same, and that no distinct differences exist in the diatom assemblages, the two shales have been considered stratigraphically separate units.

Evidence is presented herein that indicates that the Kellogg shale and the Sidney Flat shale represent separate exposures of the same stratigraphic unit. This correlation is based on published diatom and foraminiferal data, and supporting regional subsurface data.

STRATIGRAPHY

On the north side of Mt. Diablo in Township 1 North, Range 1 East, MDBM, approximately 6000 feet of Middle Eocene sediments are exposed in an apparently continuous marine cycle of deposition (Figure 2). This cycle of deposition began with the marine Domengine sandstone transgression which covered most of the southern Sacramento Valley.

Following this transgression and a rapid subsidence of the basin, the deposition of 500 feet of Nortonville shale occurred probably under deep bathyal conditions in the Mt. Diablo area. Deposition in this deep western trough continued with the Markley Formation. The lower member of the Markley Formation is predominantly a sandstone which attains a thickness of about 3000 feet in the western Mt. Diablo area, but thins

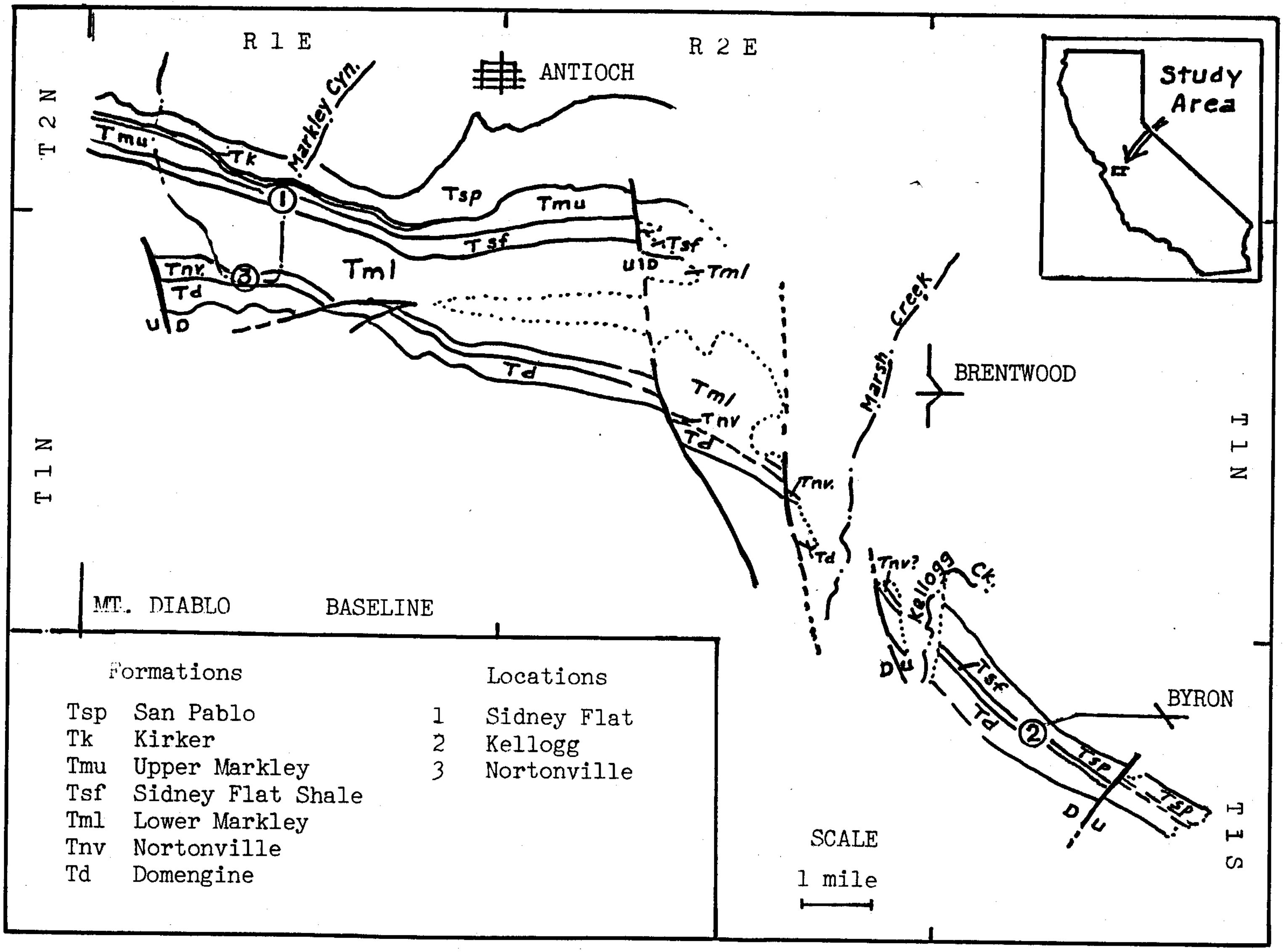

FIGURE 1 SIMPLIFIED GEOLOGIC MAP, NORTH AND EAST OF MT. DIABLO, MODIFIED AFTER CLARK AND CAMPBELL, 1942

rapidly to the east. The middle member of the Markley Formation, the Sidney Flat shale conformably overlies the lower Markley sand in the west, but to the east the authors believe it onlaps the older sediments overlying the Nortonville shales and Domengine sandstone. In the eastern part of Mt. Diablo, near Byron, the Sidney Flat shale has been described as the Kellogg shale (Clark and Campbell, 1942).

Conformably overlying the Sidney shale on the north side of Mt. Diablo is the upper Markley sandstone, about 700 feet thick, which is overlain by the Oligocene, Kirker Formation. To the east, the Kellogg shale is unconformably overlain by the Upper Miocene, San Pablo Formation.

LITHOLOGY

The type localities of the Sidney Flat shale and Kellogg shale are on the north side of Mt. Diablo about eleven miles apart (Figure 1), but the exposures are discontinuous in the vicinity of Marsh Creek making their stratigraphic relationship based on field mapping uncertain.

The middle member of the Markley Formation exposed at Sidney Flat in Markley Canyon, Township 2 North, Range 1 East, MDBM, is the type locality of the Sidney Flat shale (Clark and Campbell, 1942). Here (Figure 1, ①) the white diatomaceous shale member is about 700 feet in thickness and is conformable between the upper and lower Markley sandstone units.

The Kellogg shale consists of light gray to buff colored, diatomaceous shale that crops out in a belt of (discontinuous) restricted exposures in the hills due west of the town of Byron, cutting diagonally across Township 1 South, Range 3 East, MDBM (Clark and Campbell, 1942, p. 6). It is best exposed in a road cut about one and one-half miles west of the town of Byron (Figure 1, ②) where it has a thickness of about 120 feet. Here the Kellogg shale overlies the Domengine sandstone with apparent conformity. Solari and McFadden (in Clark and Campbell, 1942, p. 6) with the aid of auger borings claimed to have traced the Kellogg shale to the northwest where they interpreted it to be overlain by the basal sands of the Markley Formation. They also considered it to be stratigraphically equivalent to the type Nortonville shale which is overlain by the basal sands of the Markley Formation and underlain by the Domengine sandstone.

The authors do not agree with this interpretation and consider the "basal sands of the Markley Formation" of Solari and McFadden to be instead the basal sands of the upper Markley sandstone member. The authors have not, however, done any additional augering to support this interpretation.

The Nortonville Formation is lithologically unlike the Sidney Flat shale and the Kellogg shale, as it consists dominantly of chocolate brown mudstone. In the type area at Nortonville (Figure 1, ③) it is about 500 feet thick and is conformable with the underlying Domengine sandstone and the overlying lower Markley sandstone.

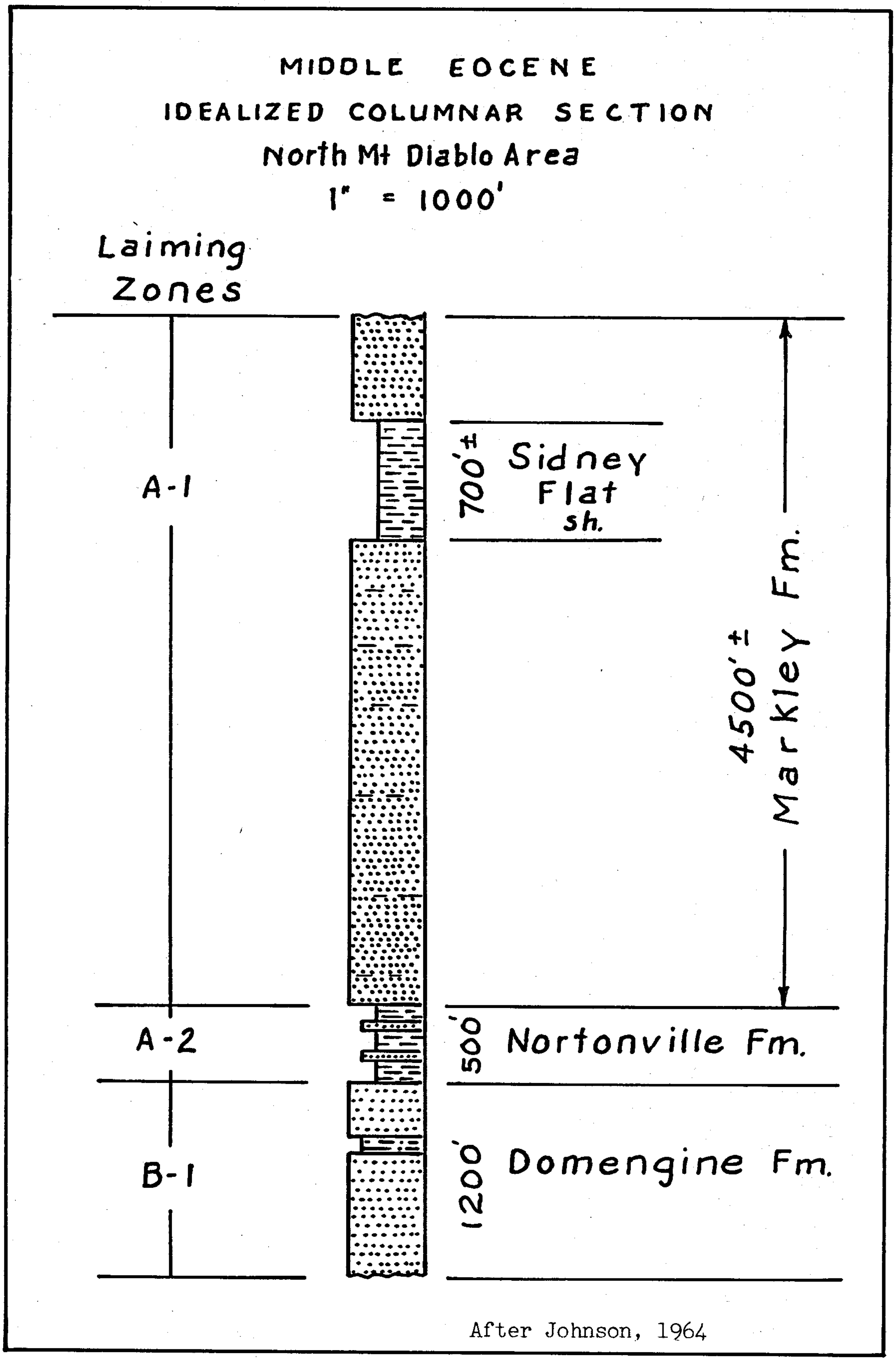
MIDDLE EOCENE
IDEALIZED COLUMNAR SECTION
North Mt Diablo Area
1" = 1000'
Laiming Zones
A-1
A-2
B-1
700'± Sidney Flat sh.
4500'± Markley Fm.
500' Nortonville Fm.
1200' Domengine Fm.
After Johnson, 1964

FIGURE 2

MICROFOSSIL ASSEMBLAGES

Sidney Flat and Kellogg Shales

Taro Kanya (1957) and Ronald Roy Schmidt (1970) have described and compared microfossil assemblages of the Kellogg shale and the Sidney Flat shale and pointed out that they are essentially the same.

The benthonic foraminiferal assemblages of the Sidney Flat shale and the Kellogg shale have been listed by several workers. Some of the more common and characteristic benthonic foraminifera present in these shales, listed by various authors, are shown on accompanying checklist (Figure 3).

Taro Kanaya (1957, p. 40) pointed out that the foraminiferal assemblages of the Kellogg shale and the Sidney Flat shale are "not particularly different," except for the presence of *Amphimorphina jenkensi* in the latter shale unit. Laiming (1939, p. 543) assigned the diatomaceous shale of the Markley Formation, the Sidney Flat shale, to his A-1 zone which he defined as being characterized by the common and restricted occurrence of *Amphimorphina jenkensi* associated with *Planularia markleyana*, *Valvulineria tumeyensis*, and *Robulus welchi*.

Ronald Roy Schmidt (1970, p. 75) listed a number of species of planktonic foraminifera from the Kellogg shale and The Sidney Flat shale, shown on Figure 4. In comparing the foraminifera of the Sidney Flat shale and the Kellogg shale, Schmidt (1970, p. 73) stated: "There is little benthic and no planktonic foraminiferal fauna change to indicate an age difference between the Kellogg shale and the Sidney Flat shale." Schmidt assigned both of these shales to the *Truncoratatoides rotundimarginatus* planktonic foraminiferal zone and to the *Chiphragmalithus quadratus* nannoplankton zone (p. 73).

Taro Kanaya (1957) made a detailed study of the diatoms of the Kellogg and Sidney Flat shales in which he described thirty-nine species and made a comparison of the assemblages of the two units.

Kanaya concluded that "the assemblages from the two stratigraphic units should be considered as one fossil flora which lived during the late Eocene time in the geographic area where the Kellogg and "Sidney" sediments accumulated."

The radiolarian assemblages of the subject shale units were interpreted by Clark and Campbell (1942) to be markedly different and were considered to represent distinct faunal zones. A total of 127 species were described with only thirty-one being common to both formations; forty-three species were restrcited to the Sidney Flat shale and fifty-three to the Kellogg shale. Schmidt (1970) suggests that much of this variance may be an artifact resulting from excessive splitting of taxa.

Nannoplankton from a limited number of samples indicate that the assemblages from all three formations fall within the *Chiphragmalithus quadratus* zone of Hay, et al (1967), which corresponds to Sullivan's (1965) faunizone IV. The most common species present include

SELECTED BENTHONIC FORAMINIFERA MIDDLE EOCENE MT. DIABLO

RELATIVE ABUNDANCES

A ABUNDANT R RARE
C COMMON P REPORTED
F FEW

	Nortonville		Sidney Flat		Kellogg	
SPECIES	CAS 16749	FULMER	CHURCH	FULMER	CLARK & CAMPBELL	FULMER
Amphimorphina ignota	R					
Asterigerina crassaformis	R					
Anomalina garzaensis	R					
Bolivina aragonensis	R					
Cibicides martinezensis	R					
Pleurostomella nuttalli	R					
Pullenia eocenica	R					
Textularia mississippiensis	R					
Trifarina cf. T. advena	R					
Vaginulinopsis asperuliformis	F	C				
Anomalina crassisepta		A				
Anomalina judas		C				
Bulimina corrugata		A				
Cibicides spiropunctatus		A				
Eponides mexicana		C				
Eponides umbonata	R	C				
Gyroidina orbicularis var. planata	R	C				
Lenticulina inornatus		A				
Uvigerina churchi		C				
Vaginulinopsis vacavillensis	R	A				
Lenticulina welchi		C		C		
Bulimina microcostata			P	C	P	
Nodogenerina bradyi			P		P	
Planularia markleyana			P	C	P	
Amphimorphina jenkinsi			P	A		
Valvulineria tumeyensis		R	P	C	P	C

FIGURE 3

SELECTED PLANKTONIC FORAMINIFERA
MIDDLE EOCENE
MT. DIABLO

RELATIVE ABUNDANCES

A ABUNDANT   R RARE
C COMMON   P REPORTED
F FEW

PLANKTONIC SPECIES	Nortonville		Sidney Flat		Kellogg	
	CAS 16749	FULMER	FULMER	SCHMIDT	FULMER	SCHMIDT
Globorotalia aragonensis	R					
Globorotalia naussi	R					
Globorotalia nitida		A				
Globorotalia crassata var. densa		R				
Globigerina cf. cretacea		R				
Globigerina cf. danvillensis		R				
Globigerina cf. decepta		F				
Globigerina triloculinoides	R	A	R		R	
Pseudohastigerina micra	R	F	A	C	A	C
Truncorotaloides aspensis				C		C
Subbotina yeguaensis						C
Clavigerinella eocenica				R		R
Truncorotaloides densus				R		R
Globigerina index						R

FIGURE 4

Chiasmolithus grandis, Chiasmolithus gigas, Reticulofenestra umbilica, Reticulofenestra coenura, Braarudosphaera bigelowi, Transversopontis pulcheroides, and *Discoaster elegans*. With additional studies, it may be possible to divide this zone into subzones.

Nortonville Shale

The foraminiferal assemblage of the Nortonville shale is very different from that of the Sidney Flat shale and the Kellogg shale. It is characterized by the restricted occurrence of *Bulimina corrugata, Uvigerina churchi, Uvigerina garzaensis, Gyroidina orbicularis var. planata,* and many other species restricted to the A-1 zone of Laiming (1940) or the *Bulimina corrugata* zone of the lower Narizian stage of Mallory (1969, p. 72). Charles V. Fulmer (1964) published a detailed checklist of foraminifera that demonstrates the very different assemblages of the Sidney Flat and Kellogg shales and the Nortonville shale. Selected species from Fulmer's checklist are shown on Figure 3.

A sample, C.A.S. 16749 from the basalmost part of the type Nortonville, furnished to the authors by C. C. Church, contains a diverse assemblage of benthonic and planktonic foraminifers that correlates with the type Canoas which immediately overlies the Domengine Formation in the Coalinga area. Some of the more characteristic benthonic foraminifers present in sample C.A.S. 16749 are shown in the checklists, Figure 3 and Figure 4. This assemblage of foraminifers, which includes the planktonic species *Morozovella aragonensis*, is Ulatisian in age, within the *Amphimorphina californica* zone of Mallory.

SUBSURFACE MIDDLE EOCENE STRATIGRAPHY, SO. SACRAMENTO VALLEY

As mentioned earlier, the continuous sequence of Middle Eocene strata, as exposed on the north slope of Mt. Diablo, is also present in the subsurface north of Mt. Diablo and extending over much of the southern Sacramento Valley. Figure 5 shows the location of a section of wells in reference to the Mt. Diablo outcrop section. This section of wells (Figure 6) shows that the lower Markley sandstone thins to the east and in the eastern part of the Valley it is absent with the Sidney Flat shale equivalent resting on the Nortonville. The absence of the lower Markley sandstone to the east is probably due to nondeposition, rather than unconformity.

The scope of this paper does not permit detailed listing of foraminiferal and nannoplankton data for the wells shown in Figure 6. However, a brief summary of foraminiferal data from the wells shown in the cross section and projected from nearby wells is given below to support the interpretation shown which is the subsurface equivalent of the section exposed on Mt. Diablo.

As in the outcrop section, the subsurface equivalent of the Sidney Flat shale is characterized by the presence of *Amphimorphina jenkinsi, Valvulineria tumeyensis, Globigerinella micra,* and abundant nonpyritized radiolaria. The foraminifera are generally sparse in occurrence in the eastern part of the basin.

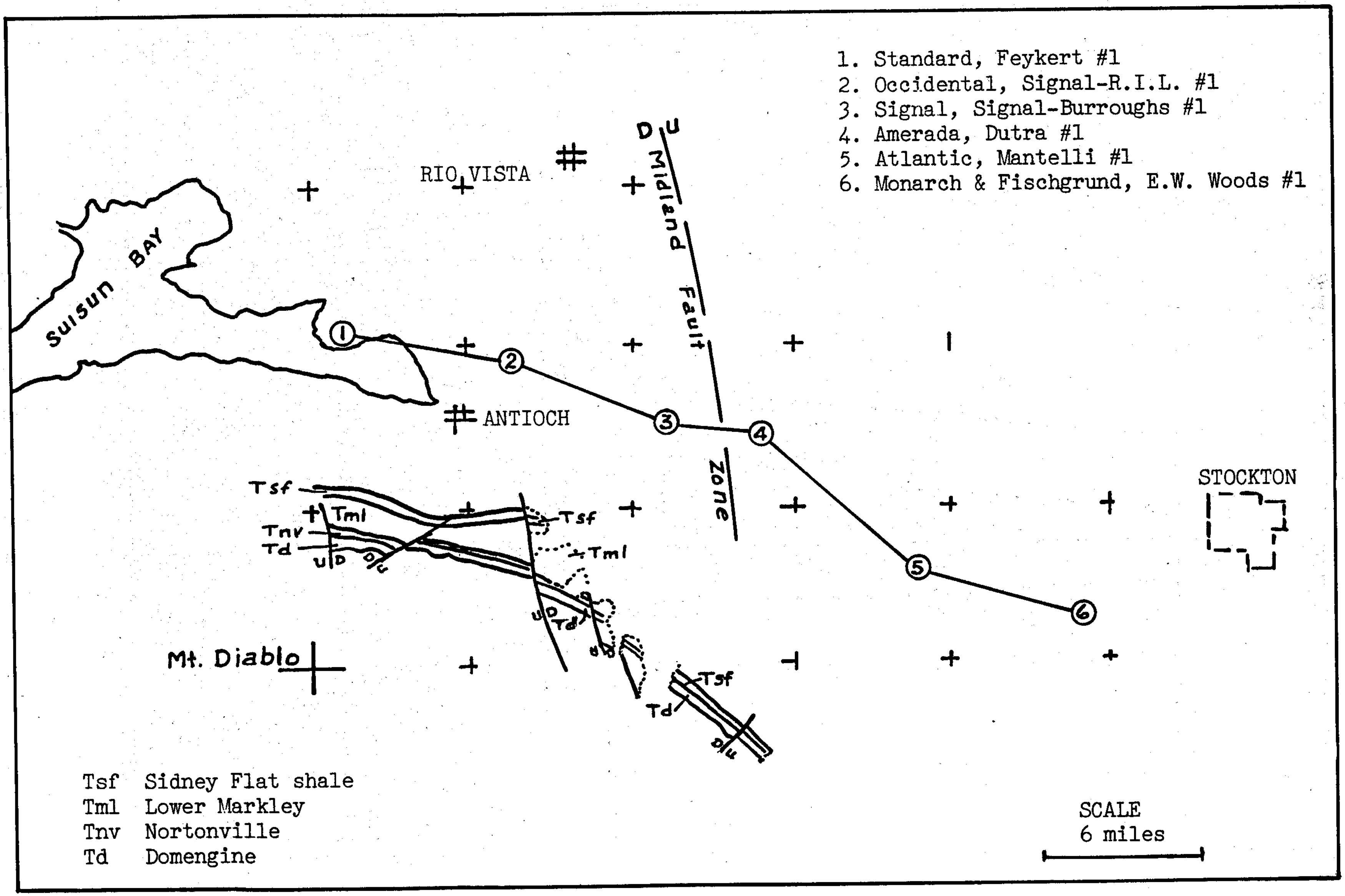

FIGURE 5 LOCATION OF WELLS IN THE SUBSURFACE CROSS SECTION

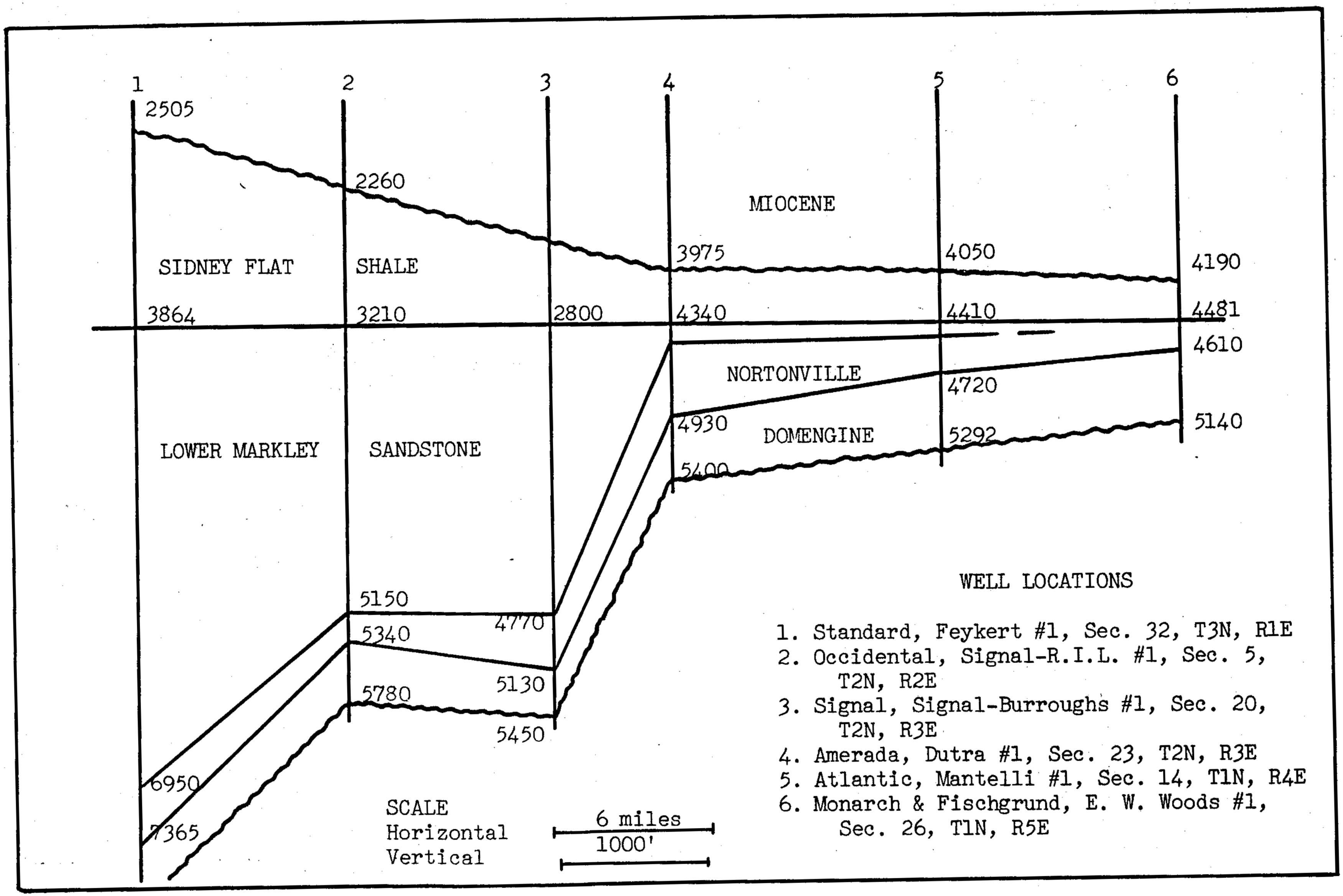

FIGURE 6 SUBSURFACE STRATIGRAPHIC SECTION OF MIDDLE EOCENE STRATA

The subsurface equivalent of the Nortonville shale is characterized by common pyritized radiolaria and the restricted occurrence of *Bulimina corrugata, Bulimina sculptilis,* and *Valvulineria thomasi.* This subsurface stratigraphic relationship of the Sidney Flat shale and the Nortonville shale is the same as that as interpreted by the authors for the surface exposures of these units on Mt. Diablo.

SUMMARY

As cited in this paper, previously published benthonic and planktonic foraminiferal data, foraminiferal occurrences observed by the authors, and published diatom data all indicate the equivalency of the microfossil assemblages of the Sidney Flat shale and the Kellogg shale. They are Eocene A-1 zone of Laiming or upper Narizian *Amphimorphina jenkinsi* zone of Mallory in age. The microfossil assemblage of the older Nortonville shale is distinctly different and is Eocene A-2 zone, lower Narizian/upper Ulatisian in age. (See Figure 7.)

The overlap of the Sidney Flat shale over the lower Markley sandstone and, in part, the Nortonville shale, as demonstrated in the subsurface, is supporting evidence for the interpretation of the stratigraphic relationship of these units as exposed in the outcrop.

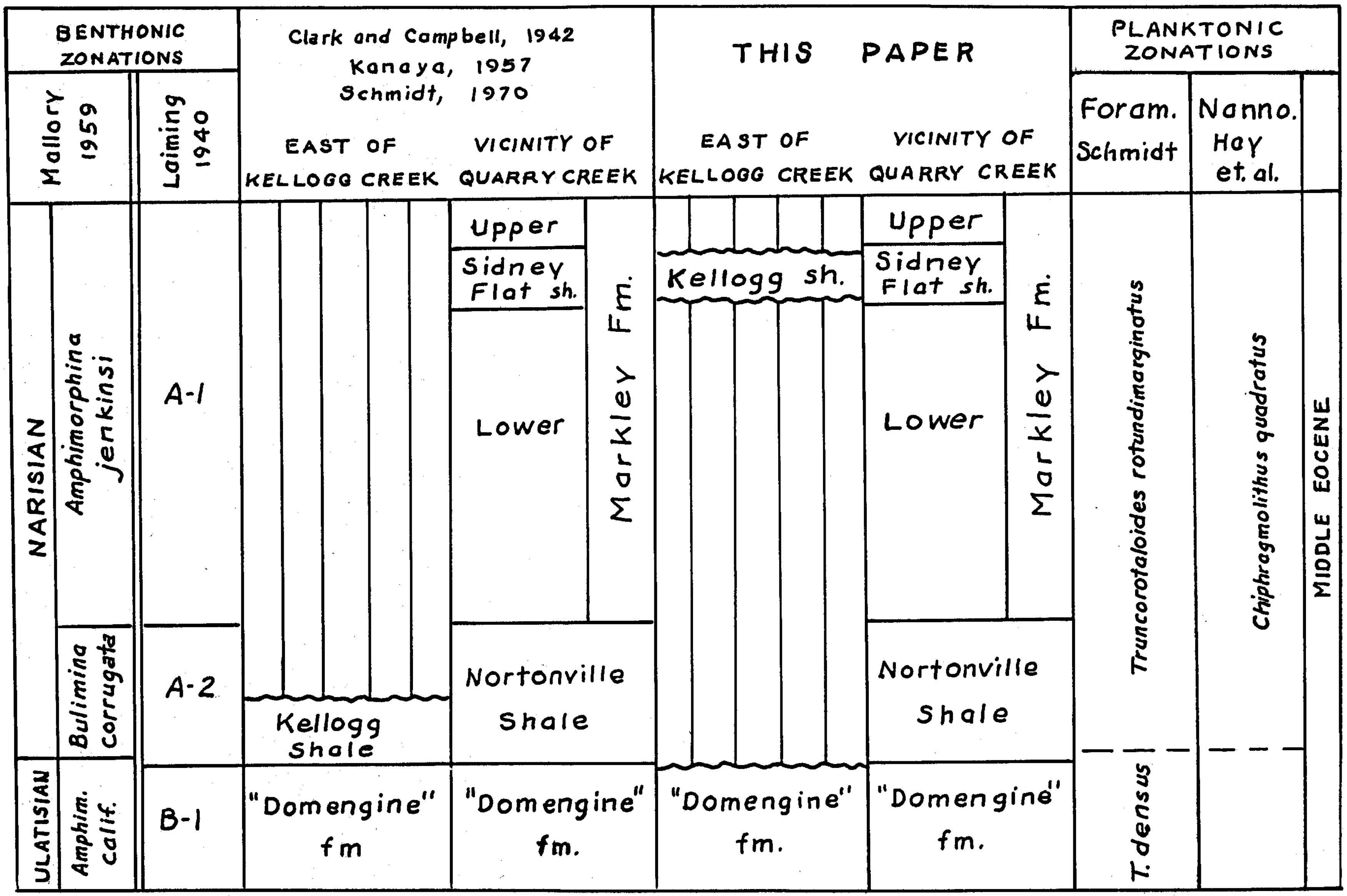
BENTHONIC ZONATIONS
Mallory 1959
Laiming 1940
Clark and Campbell, 1942
Kanaya, 1957
Schmidt, 1970
EAST OF KELLOGG CREEK
VICINITY OF QUARRY CREEK
THIS PAPER
EAST OF KELLOGG CREEK
VICINITY OF QUARRY CREEK
PLANKTONIC ZONATIONS
Foram. Schmidt
Nanno. Hay et. al.
NARISIAN
Amphimorphina jenkinsi
A-1
Upper
Sidney Flat sh.
Lower
Markley Fm.
Kellogg sh.
Upper
Sidney Flat sh.
Lower
Markley Fm.
Truncorotaloides rotundimarginatus
Chiphragmolithus quadratus
MIDDLE EOCENE
Bulimina corrugata
A-2
Kellogg Shale
Nortonville Shale
Nortonville Shale
ULATISIAN
Amphim. calif.
B-1
"Domengine" fm
"Domengine" fm.
"Domengine" fm.
"Domengine" fm.
T. densus

FIGURE 7

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MOLLUSCAN BIOSTRATIGRAPHY OF THE LINCOLN CREEK FORMATION, SOUTHWEST WASHINGTON

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The Tertiary rocks of southwestern Washington represent a unique, well preserved succession of nearly continuous upper Eocene to lower Miocene deposition. This report presents qualitative biostratigraphic documentation of the latest Eocene through Oligocene molluscan sequence within the Lincoln Creek Formation and defines molluscan stages and concurrent range zones. The zones and stages defined in this report are considered to augment or replace Durham's (1944) zones and replace Weaver and others (1944) "Stages" as applied to the Pacific Northwest late Eocene through Oligocene formations (Fig. 1).

PREVIOUS STUDIES

The framework for provincial age determinations and correlations of marine Tertiary strata of the Pacific Northwest has followed three main historical thrusts. The initial framework was established in California by Arnold (1906) (Fig. 2) and later extended to the Pacific Northwest by Arnold and Hannibal (1913). Arnold defined "formations" which were, in effect, biostratigraphic units characterized by distinctive invertebrate assemblages. The inherent time-stratigraphic nature of these "formations" has been demonstrated by their effectiveness in interbasinal correlations. These units were redefined and modified by subsequent workers (Weaver, 1912, 1916a, 1916c, 1937; Clark, 1918, 1929, 1930) who variously termed them "faunas," "formations," or "horizons."

The second phase of molluscan biostratigraphic investigations involved defining "zones" [e.g., Weaver's (1916a, 1916c) "*Turritella porterensis*" and "*Molopophorus lincolnensis* zones" and Van Winkles (1918) "*Barbatia merriami* zone"]. These "zones" were little more than a euphemism for local, richly fossiliferous beds and are more appropriately referred to as zonules (Fenton and Fenton, 1928).

The third phase of research involved the detailing of the stratigraphic occurrence of molluscan taxa within essentially continuous stratigraphic intervals. Such data allowed for the refinement and definition of provincial, molluscan biostratigraphic sequences. A series of Oligocene zones defined by Durham (1944) in northwestern Washington became the basis for a sequence of three stages (Keasey, "Lincoln," "Blakeley") erected by Weaver and others (1944). These stages have become part of the molluscan biostratigraphic standard for the Pacific West Coast.

NECESSITY OF A NEW BIOCHRONOLOGY

Three problems inherent in the present Pacific West Coast molluscan biochronologies require the development of a new biostratigraphic and time-stratigraphic system for Oregon and Washington.

The first problem concerns the provincialism of Pacific West Coast molluscan faunas. The traditional molluscan stages of Weaver and others (1944) were erected under the presumption that the Tertiary molluscan faunas of the southern Californian and northern Oregon-Washington areas constituted a single faunal province and that a single set of "stages" and "zones" could be utilized throughout the entire area. Correlations between California, Oregon, and Washington can be easily accomplished with molluscan assemblages of middle and early late Eocene age which do occupy a single faunal province. However, latest Eocene to Recent faunas show intensified provincialism and inherently greater difficulty in correlation. The relationship between the "Blakeley" and "Vaqueros Stages" of Weaver and others (1944) is a case in point. Originally defined as successive time-stratigraphic entities, the "Blakeley Stage" fauna of Washington is now recognized as a temperate biofacies in part coeval with the tropical to subtropical biofacies fauna of the "Vaqueros Stage" of California (Addicott, 1967, 1968, 1972). Therefore, the Tertiary molluscan fauna of Oregon and Washington is most appropriately treated as belonging to a biogeographic province distinct from that of the more southern faunas of California.

A second problem with the stages of Weaver and others (1944), is the unfortunate nomenclatural confusion that has resulted from using primarily lithostratigraphic terms in a time-stratigraphic context. For example, the "Lincoln Stage" of Weaver and others (1944) is early and middle Oligocene in age, whereas the Lincoln Formation, which served as the type for the "Lincoln Stage," has subsequently been shown to encompass late Eocene through Oligocene strata. Similar nomenclatural problems also exist for both the Keasey and "Blakeley."

And third, two of Durham's (1944) zones lack superpositional control and well defined stratotypes. Therefore, a need exists for the establishment of a well defined and superpositionally controlled sequence of biostratigraphic and time-stratigraphic molluscan units applicable to the biogeographic province of Oregon and Washington.

CURRENT STUDY

The Lincoln Creek Formation (Beikman and others, 1967) of southwestern Washington (Figs. 1 and 3) was chosen as the stratigraphic base for this study as it affords some of the best exposed and most fossiliferous sections in the Pacific Northwest. The formation is, in many sections, conformable with underlying and overlying sediments and lacks structural complexity. It is thus ideal for use as the type for a provincial molluscan biostratigraphic and chronostratigraphic sequence. Rau (1958, 1966) has defined the benthonic foraminiferal zones for western Washington within many of the same sections as studied for this report, permitting a close correlation of both biochronologies.

Field work involved the sampling of fifteen sections as well as several significant isolated localities within the Lincoln Creek Formation. Sampling was carried out during 1971 and 1972, with fossils collected from 200 localities (Fig. 4). The faunal assemblages collected include 258 taxa, 226 being mollusks. Twenty-three new taxa were recognized. A more extensive treatment of the stratigraphy and paleontology, including paleoecology, systematics, new species descriptions, check lists, plates, locality data, and maps, is available in Armentrout (1973b, unpublished University of Washington thesis--available through University Microfilms, Ann Arbor, Michigan). The types and stratigraphic collections are on deposit at the Thomas Burke Memorial Washington State Museum, University of Washington, Seattle, Washington. A comparison of type material of this study and that of Weaver (1942), Durham (1944), and Hickman (1969), permits a synthesis of biostratigraphic data from the four reports.

BIOSTRATIGRAPHY

Based upon the local range and total range of taxa, the sequence of late Eocene to late Oligocene Lincoln Creek Formation strata is subdivided into five concurrent range zones and two stages with informal definition of overlying and underlying units for superpositional control. Previously proposed names are retained when a redefinition without substantive alteration of the original definition would suffice. Species used for the zone names are either restricted to that zone or are characteristic of the zone. Correlations of the stages and zones with Pacific Coast biostratigraphic and lithostratigraphic units are given in Figures 5-7. The time-scale utilized in this report for correlation of the European and Pacific West Coast series is that of Berggren (1972) modified by the work of Kleinpell and Weaver (1963), Rau (1966), Addicott (1972), Bandy (1972), and Lipps and Kalisky (1972). The resulting correlations are shown on Figure 5 as well as on the other correlation charts of this report. New species utilized in definitions of zones are described in Armentrout (1973b).

UNNAMED LATE EOCENE ZONULE

An Unnamed Late Eocene Zonule is tentatively defined for subjacent control of the stratigraphically lowest, formally defined zone of this report. It possibly is indicative of a zonal entity but extensive studies on the distribution, ecology, and taxonomy of related faunas would be required before erection of a formal biostratigraphic unit.

The reference section for the Unnamed Late Eocene Zonule is within the Cowlitz Formation along Olequah Creek between Vader and Winlock, Washington, where more than 2,300 feet of poorly exposed siltstone and sandy siltstone occur along the creek banks (Figs. 3 and

4). The section has been studied in detail by Weaver (1916b) and Henricksen (1956). Henricksen (1956) interpreted the contact between the Cowlitz Formation and the overlying Lincoln Creek Formation to be unconformable along Olequah Creek. The stratigraphically highest fossil locality of the Unnamed Late Eocene Zonule occurs at the Big Bend of the Cowlitz River 1.5 miles east of Vader. The locality (UW loc. 1) has an abundant and varied fauna, well described and illustrated in Weaver (1942).

Taxa making their highest occurrence in the Unnamed Late Eocene Zonule are:

GASTROPODS

Acrilla berthiaumei
Cerithiopsis washingtoniana
Conus cowlitzensis
Conus vaderensis
Crepidula dickersoni
Cymathium cowlitzensis
Cymathium etheringtoni
Cymathium washingtonianum
Echinophoria tri-tuberculata
Ectinochilus elongata
Ectinochilus washingtonensis
Molopophorus bretzi
Murex cowlitzensis
Murex packardi
Olequahia washingtoniana
Perse washingtonensis
Polinices hornii
Polinices weaveri
Priscofusus willisi
Turritella uvasana olequahensis
Turritella uvasana stewarti

PELECYPODS

Callista williamsoni
Gari cowlitzensis
Loxocardium olequahensis
Nuculana cowlitzensis
Ostrea idriaensis
Pitar eocenica
Venericardia hornii clarki

Taxa typical of but not restricted to the Unnamed Late Eocene Zonule are:

GASTROPODS

Exilia dickersoni
Ficopsis cowlitzensis
Siphonalia sopenahensis
Turricula cowlitzensis

PELECYPODS

Acila decisa
Pitar californiana

SCAPHOPOD

Dentalium stramineum

These latter species occur in sediments interbedded with the overlying basal sandstones of the Lincoln Creek Formation in the Chehalis-Centralia area (Snavely and others, 1958, p. 52), and may in part be transitional to the Bathybembix columbiana Zone, which overlies the Unnamed Late Eocene Zonule.

The lowest collection from Lincoln Creek strata along Olequah Creek (UW loc. 291) contains a fauna assignable to the Echinophoria dalli Zone which occurs stratigraphically above the Bathybembix columbiana Zone. The absence of Bathybembix columbiana Zone assemblages may be due to failure to sample, as the interval between the highest Unnamed Late Eocene Zonule locality along Olequah Creek is about 400 feet stratigraphically below the lowest Echinophoria dalli Zone faunal locality; or the Bathybembix columbiana Zone interval may be represented by the unconformity between the Cowlitz and Lincoln Creek Formations. In Oregon, the type section of the Bathybembix columbiana Zone along Rock Creek (Durham, 1944) overlies, with probable conformity, strata of the "Cowlitz" Formation which contains a fauna (Warren and Norbisrath, 1946) assignable to the Unnamed Late Eocene Zonule.

The molluscan assemblage of the Unnamed Late Eocene Zonule is also known in Washington from the Cowlitz Formation along Coal Creek in Lewis County (Weaver, 1916b), from the Skookumchuck Formation (Snavely and others, 1958), and from rocks assigned to the Puget Group south of Seattle (McWilliams, 1971).

Age of the Unnamed Late Eocene Zonule

Correlations have been made between the molluscan assemblages of the Unnamed Late Eocene Zonule and the "Tejon Stage" of California (Weaver and others, 1944) by Arnold and Hannibal (1913), Dickerson (1917), Weaver (1916b, 1937, 1942), and others (Figs. 2 and 5). The "Tejon Stage" is assigned to the provincial early late Eocene (Durham 1954, Addicott 1972, 1973).

The foraminiferal assemblage associated with the mollusca at the type locality of the Unnamed Late Eocene Zonule has been assigned to the A-1 Zone of Laiming (1940) by Henricksen (1956) and Rau (1958), and to the Bulimina schencki - Plectofrondicularia cf. P. jenkinsi Zone of Rau (1958). These Zones are correlatives of the upper Narizian Stage Amphimorphina jenkinsi Zone of Mallory (1959), assigned to the provincially early late Eocene (Kleinpell and Weaver, 1963) (Fig. 5).

GALVINIAN STAGE

The Galvinian Stage, named for Galvin, Washington, near where strata of this age are widely distributed, is subdivided into three zones. Type sections are designated in those areas with the best molluscan assemblages and superpositional control:

Upper   Echinophoria fax Zone

Porter Bluff Section, Lincoln Creek Formation, Washington

Middle Echinophoria dalli Zone

Pe Ell-Doty Section, Lincoln Creek Formation, Washington

Lower Bathybembix columbiana Zone

Rock Creek Section, Keasey Formation, Oregon; reference section defined in the Willapa River Section, Lincoln Creek Formation.

The lower boundary of the Galvinian Stage is conformable in some sections, unconformable in others. These relationships reflect the transgressive character of the basal Lincoln Creek Formation (Armentrout, 1973a). In the western part of the basin, deposition was uninterrupted with Cowlitz Formation strata grading upward into the Lincoln Creek Formation. Here strata correlated with the Unnamed Late Eocene Zonule are conformably overlain by a sequence of strata containing the successively younger Bathybembix columbiana and Echinophoria dalli Zonal assemblages. Eastward in the basin the transgressing basal Lincoln Creek Formation was not deposited until Echinophoria dalli Zone time and this Zone unconformably overlies differentially preserved portions of the Unnamed Late Eocene Zonule strata or older units. Within the Galvinian Stage the zonal boundaries occur in gradational sedimentary sequences (Fig. 4).

BATHYBEMBIX COLUMBIANA ZONE

The lowest zone of the Galvinian Stage is the Bathybembix columbiana Zone. Its type is in the basal member of the Keasey Formation along Rock Creek in Columbia County, Oregon (Warren and others, 1945, Locs. 38, 39, 30, 26, 23, 21, 22). Rocks of the type Bathybembix columbiana Zone are dominantly siltstone with interbeds of claystone and some glauconitic layers. Strata of this Zone overlie with apparent conformity siltstones and micaceous sandstones of the Cowlitz Formation and grade upward into tuffaceous siltstones of the overlying Echinophoria dalli Zone. A reference section is proposed in the Willapa River Section where the lower 250 feet of the Lincoln Creek Formation are assigned to the Bathybembix columbiana Zone (Loc. WR-2) (Figs. 3 and 4).

The Zone is characterized by the lowest occurrence of:

GASTROPODS

Conus
n. sp. Armentrout
Exilia lincolnensis
Scaphander stewarti
Turricula washingtonensis
Phanerolepida cf. P. oregonensis

PELECYPODS

Callista pittsburgensis
Nemocardium weaveri
Nucula hannibali
Solemya dalli
Thyasira bisecta
Yoldia chehalisensis
Yoldia oregona

SCAPHOPOD

Dentalium porterensis

and by the restricted occurrrence of:

GASTROPODS

Bathybembix columbiana
Bathybembix A n. sp. Armentrout
Conus n. sp.
Epitonium keaseyense
Margarites n. sp.

PELECYPODS

Acila nehalemensis
Solemya willapaensis

In Washington, the molluscan assemblages of the Bathybembix columbiana Zone are known from the basal sandstones of the Lincoln Creek Formation in the Willapa (Loc. WR-2) and Canyon River Sections (Loc. CR-1 to CR-4), as well as from the Centralia-Chehalis area (Figs. 3 and 4). In this latter area, Vokes (in Snavely and others, 1958) recognized two faunas; one occurring in sandstone and closely related to the faunule of the underlying Unnamed Late Eocene Zonule, with the following species in common:

GASTROPODS

Exilia dickersoni
Ficopsis cowlitzensis
Siphonalia sopenahensis
Turricula cowlitzensis

PELECYPODS

Acila decisa
Pitar californiana

SCAPHOPOD

Dentalium porterensis

The second of Vokes' faunas occurs in siltstone slightly higher in the basal Lincoln Creek Formation than the above sandstone fauna. It contains such diagnostic post Unnamed Late Eocene Zonule taxa as:

GASTROPODS

Exilia lincolnensis
Gemmula bentsonae
Scaphander stewarti

PELECYPODS

Acila nehalemensis
Pitar clarki

Acila nehalemensis is restricted to the Bathybembix columbiana Zone; thus, Loc. M-26 of Snavely and others (1958) is referable to the Bathybembix columbiana Zone age. Other siltstone faunas of the basal sandstone of the Lincoln Creek Formation in the Centralia-Chehalis area (Loc. M18, M22, M23) are more closely allied to faunas of the overlying Echinophoria dalli Zone.

Nomenclature of the *Bathybembix columbiana* Zone

As both the type section and the time interval of the *Bathybembix columbiana* Zone are the same as that of the "*Turcicula columbiana* Zone" of Durham (1944), the same zonal species is retained with the generic name modified to current usage (*Turcicula* = *Bathybembix*) (Fig. 5). Durham tentatively proposed his "*Turcicula columbiana* Zone" as the fauna of that interval was poorly known. Reports by Warren and others (1945, 1946), Snavely and others (1958), and Armentrout (1973b) provide sufficient documentation for its formal definition.

Age of the *Bathybembix columbiana* Zone

The strata encompassed by the *Bathybembix columbiana* Zone were used to define the "Keasey Stage" of Weaver and others (1944) which overlies the "Tejon Stage" of the same authors (Figs.2 and 5). This overlying relationship results in a correlation of the *Bathybembix columbiana* Zone with the Refugian Stage of Schenck and Kleinpell (1936) more commonly used for benthonic foraminiferal biochronologies. However, as pointed out by Addicott (1972, 1973) the Refugian Stage was defined on both Foraminifera and Mollusca and has been used with both in California where it represents the provincial latest Eocene and earliest Oligocene.

Correlations of the Foraminifera from the same stratigraphic interval as the *Bathybembix columbiana* Zone molluscan assemblage suggests lower Refugian age, specifically the *Sigmomorphina schencki* Zone of Rau (1958) (Figs. 4 and 5). This Zone is correlated by Rau (1958) with Laiming's (1940) R-Zone, and with at least part of the lower Refugian *Uvigerina cocoaensis* Zone of Kleinpell and Weaver (1963), both California zones. These correlations result in an age assignment for the *Bathybembix columbiana* Zone of late Eocene according to current provincial usage of European series names in California (Kleinpell and Weaver, 1963; Addicott, 1972, 1973).

ECHINOPHORIA DALLI ZONE

The middle zone of the Galvinian Stage is the *Echinophoria dalli* Zone. The type section is the lower 1100 feet of the Lincoln Creek Formation along the Chehalis River between Pe Ell and Doty, Washington (Loc. PD-1 to PD-8) (Figs. 3 and 4). In the Pe Ell-Doty Section, the Lincoln Creek Formation overlies, with unconformity, sandstones of the Skookumchuck Formation, which are a lithologic and biostratigraphic correlative of the Cowlitz Formation and Unnamed Late Eocene Zonule. Strata of the *Bathybembix columbiana* Zone have not been recognized in the Pe Ell-Doty section and may be represented by the unconformity. Gradationally overlying the *Echinophoria dalli* Zone are strata of the superjacent *Echinophoria fax* Zone. The rocks of the *Echinophoria dalli* Zone in the type section are medium-to coarse-grained, glauconitic sandstones which grade upward to tuffaceous, medium-grained sandstones.

The Zone is characterized by the lowest occurrence of:

GASTROPODS	PELECYPODS
Acteon chehalisensis	Acila shumardi
Bruclarkia columbianum	Myadesma dalli
Molopophorus gabbi	Nuculana washingtonensis
Neverita nomlandi	Ostrea lincolnensis
Olequahia lorenzana	Pitar clarki
Polinices washingtonensis	Pitar dalli
Priscofusus chehalisensis	Tellina townsendensis
Siphonalia washingtonensis	Thracia condoni

and by the restricted occurrence of:

GASTROPODS	PELECYPODS
Acteon parvum	Arca merriami
Acmaea oakvillensis	Barbatia reinharti
Bruclarkia n. sp. Armentrout	Cyclocardia hannibali
Echinophoria dalli	Diplodontia griesensis
Gyrineum jeffersonensis	Lima bella
Molopophorus dalli	Lima oregonensis
Molopophorus effingeri	Lima oakvillensis
Molopophorus stephensoni	Mytilus buwaldana
Odostomia griesensis	Ostrea griesensis
Perse pittsburgensis	Posterius gabbi
	Spisula packardi

The Zone is further characterized by the last occurrence of:

PELECYPODS

Nemocardium weaveri
Yoldia oregona

The Echinophoria dalli Zone fauna occurs within the Lincoln Creek Formation in the Pe Ell-Doty Section (Loc. PD-1 to PD-8), in the Porter Bluff Section (Loc. PB-1 and PB-2), at the Oakville Basalt Quarry and Gries Ranch localities, and in the Middle Fork of the Satsop River Section (Loc. MF-1 to MF-3) (Figs. 3 and 4). In Oregon, strata of the Echinophoria dalli Zone occur above strata of the Bathybembix columbiana Zone in the Keasey and Pittsburg Bluff Formations (Warren and others, 1945, Loc. 55, 101, and 113, in the Keasey Formation; Loc. 6, 13, 15, 27, 29, 52, 57, 58, 59, 62, 115, 116, 117, and 124 in the Pittsburg Bluff Formation).

Nomenclature of the Echinophoria dalli Zone

The molluscan assemblage of the Echinophoria dalli Zone represents the same time span as the Molopophorus stephensoni and Molopophorus gabbi Zones of Durham (1944) (Fig. 5). The faunal assemblages used by Durham to separate his two Zones unquestionably occur in his type sections in the Quimper Sandstone near Hadlock, Washington. However, the Zones are not recognized as distinctly separate entities elsewhere, as elements of each occur together in areas of Oregon (Warren and others, 1945), and in Washington outside Durham's type sections. In the basal sandstone of the Lincoln Creek Formation, Pe Ell-Doty Section, the Echinophoria dalli Zone fauna of localities PD-4 to PD-6 includes the species Molopophorus stephensoni and forms very similar to M. gabbi (M. nodosa of Armentrout, 1973b). There is a gradation from M. stephensoni toward and including the more nodose forms close to, but not conspecific with, M. gabbi. As these species, suggestive of Durham's two Zones, occur within the same collecting horizons it is probable that Durham's Zones represent biofacies of the Echinophoria dalli Zone.

The Echinophoria dalli Zone also includes strata previously assigned to the "Barbatia merriami Zone" of Van Winkle (1918) (Fig. 2) typed at the Porter Creek and Oakville Basalt Quarry localities near the towns of Porter and Oakville, Washington, respectively (Figs. 3 and 4). Van Winkle considered the Gries Ranch fauna to be a correlative of the "Barbatia merriami Zone," a relationship substantiated by this report (Figs. 3 and 4).

Age of the Echinophoria dalli Zone

Strata of the Echinophoria dalli Zone include the previously defined Molopophorus stephensoni and Molopophorus gabbi Zones of Durham (1944). These molluscan zones were used by Weaver and others (1944) to define the lower part of the "Lincoln Stage" of the West Coast molluscan chronology (Fig. 5). The "Lincoln Stage" was originally considered early Oligocene in age.

The Echinophoria dalli Zone and the underlying Bathybembix columbiana Zone both contain foraminiferal assemblages assignable to the Sigmomorphina schencki Zone of Rau (1958). As such, the molluscan zones are considered to be coeval with the lower and upper parts of the Sigmomorphina schencki Zone respectively, a relationship demonstrated by stratigraphic position of all three within the same sections. The S. schencki zone is correlated with the lower Refugian Uvigerina cocoaensis Zone of California (Rau, 1966). The latter California Zone is considered latest Eocene in age (Kleinpell and Weaver, 1963; Rau, 1966; Addicott, 1972, 1973). The above correlation suggests that the Echinophoria dalli Zone is latest Eocene in age.

ECHINOPHORIA FAX ZONE

The youngest zone of the Galvinian Stage is the Echinophoria fax Zone. The type section is within the Porter Bluff Section of the Lincoln Creek Formation, from 200 to 1,600 feet above the basalts at the base of the section (Loc. PB-3 to PB-27) (Figs. 3 and 4). The rocks are typically massive, tuffaceous siltstone and sandstone with concretionary beds throughout. Strata of the type Echinophoria fax Zone overlie and are gradational with strata of the Echinophoria dalli Zone, and underlie and are conformable with strata of the overlying Echinophoria rex Zone.

The Zone is characterized by the lowest occurrence of:

GASTROPODS

Bathybembix washingtoniana
Liracassis
  n. sp. Armentrout
Musashia
  n. sp. Armentrout
Turris kincaidi

PELECYPODS

Limopsis carmanahensis
Macoma twinensis
Nemocardium lorenzanum
Venericardia castor
Yoldia tenuissima

SCAPHOPOD

Dentalium n. sp. Armentrout

and by the restricted occurrence of:

GASTROPODS

Acrilla lincolnensis
Aforia campbelli
Aforia packardi
Echinophoria fax
Molopophorus lincolnensis
Neptunea cf. N. landesi
Olequahia lincolnensis
Perse lincolnensis
Scaphander washingtonensis
Suavodrillia thurstonensis
Suavodrillia worchesteri
Turris dickersoni
Turritella porterensis

PELECYPODS

Glycymeris chehalisensis

SCAPHOPOD

Cadulus durhami

The Zone is further characterized by the last occurrence of:

GASTROPODS

Conus
  n. sp. Armentrout
Exilia lincolnensis
Bruclarkia columbianum
Priscofusus chehalisensis
Siphonalia washingtonensis
Turricula washingtonensis

PELECYPODS

Acila shumardi
Cyclocardia hannibali
Ostrea lincolnensis
Pitar clarki
Pitar dalli
Tellina lincolnensis

The molluscan assemblage characteristic of this Zone is best developed in the Lincoln Creek Formation at the type section at Porter Bluffs (Loc. PB-3 to PB-27) and in the lower 250 feet of the Galvin Section (Loc. GS-1 to GS-8). It is less well developed in the Lincoln Creek Formation in the Pe Ell-Doty Section (Loc. PD-9 to PD-11), Middle Fork of the Satsop River Section (Loc. MF-4 to MF-7), Canyon River Section (Loc. CR-6 to CR-11), Little River Section (Loc. LR-2 and LR-3), West Fork of the Satsop River Section (Loc. WF-4), and the Willapa River Section (Loc. WR-3).

Nomenclature of the *Echinophoria fax* Zone

The *Echinophoria fax* Zone encompasses both the *Turritella olympicensis* and *Turritella porterensis* Zones of Durham (1944) (Fig. 5). Durham described the *Turritella olympicensis* Zone as having a poorly preserved and poorly known fauna, recognized only in the upper part of one section of the Quimper Sandstone. Re-collection of the type section by this author failed to add to the number of taxa listed. The fauna of Durham's type *Turritella porterensis* Zone at Porter Bluff was found to extend several hundred feet down-section from its previously recognized occurrence to a point where it overlies strata of the *Echinophoria dalli* Zone. The writer believes that the *Turritella olympicensis* Zone and the *T. porterensis* Zone are local ecological variants within the regionally recognizable *Echinophoria fax* Zone.

Age of the *Echinophoria fax* Zone

The *Echinophoria fax* Zone strata contain foraminiferal faunas of the *Cassidulina galvinensis* Zone of Rau (1966) (Figs. 4 and 5). This Zone is correlated by Rau (1966) with the upper Refugian Stage *Uvigerina vicksburgensis* Zone defined in the type area of the Refugian Stage in California by Kleinpell and Weaver (1963). The upper part of the Refugian Stage is considered to be lower Oligocene in the current provincial West Coast chronology (Kleinpell and Weaver, 1963; Addicott, 1972, 1973); therefore the *Echinophoria fax* Zone is regarded as lower Oligocene.

MATLOCKIAN STAGE

The younger Matlockian Stage, named for Matlock, Washington, near where strata of this age are widely distributed, is subdivided into two zones, both typed in this report in the Canyon River Section of the Lincoln Creek Formation. The Zones are:

Upper: *Echinophoria apta* Zone

Lower: *Echinophoria rex* Zone

The lower boundary of the Matlockian Stage is within a sequence of strata continuous with that of the underlying Galvinian Stage. The upper boundary of the Matlockian Stage is conformable with Unnamed Superjacent Stage strata or unconformably overlain by the Montesano Formation where strata of the Unnamed Superjacent Stage are missing.

ECHINOPHORIA REX ZONE

Strata of the lower part of the Matlockian Stage are assigned to the *Echinophoria rex* Zone. The reference section proposed in this report is in strata of the Lincoln Creek Formation in the Canyon River Section (Figs. 3 and 4). Here the strata consist of dominantly massive siltstone beds with interbedded, fine-grained, silty sandstone from 3,450 to 6,130 feet above the base of the Formation (Loc. CR-12 to CR-26). The reference section of the *Echinophoria rex* Zone is conformable above and below with the strata containing the overlying and underlying zones.

The *Echinophoria rex* Zone is characterized by the lowest occurrence of:

GASTROPODS

- Aforia wardi
- Amauropsis blakelyensis
- Argobuccinum goodspeedi
- Bathybembix B n. sp. Armentrout
- Marginella shepardae
- Priscofusus hannibali
- Scaphander gordoni
- Suavodrillia hertleini

PELECYPODS

- Acila gettysburgensis
- Acila nelsoni
- Anadara devincta
- Cochlodesma bainbridgensis
- Lima twinensis
- Macoma lorenzanum
- Macoma vancouverensis
- Modiolus restorationensis
- Serripes n. sp. Armentrout
- Yoldia clallamensis

and is further defined by the restricted occurrence of:

GASTROPODS

- Ancestrolepis landesi
- Oxystele dornii
- Perse teglandae
- Priscofusus foxi
- Priscofusus stewarti
- Solariella kincaidi
- Turritella blakeleyensis

PELECYPODS

- Callista n. sp. Armentrout

Species making their last appearance in this Zone are:

GASTROPODS

- Pseudoperissolax (?) trophonoides

PELECYPODS

- Chlamys grunskyi
- Nuculana hannibali
- Nuculana washingtonensis

Within the Lincoln Creek Formation the Echinophoria rex Zone assemblage is developed in the Canyon River Section (Loc. CR-12 to CR-26), Middle Fork of the Satsop River Section (Loc. MF-11 to MF-14), West Fork of the Satsop River Section (Loc. WF-5 to WF-12), Willapa River Section (Loc. WR-4 to WR-6), Galvin Section (Loc. GS-9 to GS-10), Porter Bluff Section (Loc. PB-28 to PB-29, and Pe Ell-Doty Section (Loc. PD-12 to PD-13).

Nomenclature of the *Echinophoria rex* Zone

The *Echinophoria rex* Zone of this report is the time equivalent of Durham's (1944) Zone of the same name (Fig. 5). The type section, however, has been augmented by definition of a reference section in the Canyon River Section in addition to Durham's type in the Blakeley Formation at Restoration Point on Bainbridge Island near Seattle, Washington. Strata in the Canyon River Section includes faunas of both the underlying and overlying zones whereas the section at Restoration Point lacks assemblages of either of the bounding zones.

Age of the *Echinophoria rex* Zone

Durham's (1944) *Echinophoria rex* Zone was used as a lower zone of the type "Blakeley Stage" by Weaver and others (1944), who considered the "Blakeley Stage" to be lower upper Refugian; it was originally interpreted as of Zemorrian age by Durham.

Foraminiferal faunas occurring with the molluscan assemblage of the *Echinophoria rex* Zone are of the lower Zone of the Zemorrian Stage of Rau (1966) which he correlates with the *Uvigerina gallowayi* Zone of California. General correlation of faunal assemblages and superposition of strata of the *Echinophoria rex* Zone suggests an age assignment of middle Oligocene in context of the provincial West Coast chronology (Kleinpell and Weaver, 1963; Addicott, 1972, 1973).

ECHINOPHORIA APTA ZONE

The upper zone of the Matlockian Stage is the *Echinophoria apta* Zone. The reference section of this report is in the Canyon River Section of the Lincoln Creek Formation (Figs. 3 and 4). Strata of the type section are dominantly tuffaceous siltstone and fine-grained sandstone between 6,130 and 8,875 feet above the base of the measured section, and occur conformably above strata of the underlying *Echinophoria rex* Zone and conformably below strata of the overlying *Liracassis petrosa* zone (Loc. CR-27 to CR-52).

The *Echinophoria apta* Zone is characterized by the lowest occurrence of:

PELECYPOD

Pitar oregonensis

and by the restricted occurrence of:

GASTROPODS

Bathybembix C
n. sp. Armentrout
Echinophoria apta

and by the last occurrence of the following taxa:

GASTROPODS

Aforia wardi
Amauropsis blakeleyensis
Argobuccinum goodspeedi
Bathybembix B
n. sp. Armentrout
Liracassis
n. sp. Armentrout
Marginella shepardae
Musashia
n. sp. Armentrout
Musashia weaveri
Natica teglandae
Natica weaveri
Scaphander gordoni
Suavodrillia hertleini

PELECYPODS

Acila nelsoni
Cochlodesma bainbridgensis
Lima twinensis
Limopsis carmanahensis
Modiolus restorationensis
Myadesma dalli
Nemocardium lorenzanum
Serripes
n. sp. Armentrout
Solemya dalli
Solena lincolnensis
Tellina townsendensis
Thyasira bisecta
Venericardia castor
Yoldia clallamensis

SCAPHOPODS

Dentalium porterensis
Dentalium
n. sp. Armentrout

Faunas of the Echinophoria apta Zone occur in the Lincoln Creek Formation in the Canyon River Section (Loc. CR-27 to CR-52), Middle Fork of the Satsop River Section (Loc. MF-15 to MF-35), West Fork of the Satsop River Section (Loc. WF-13 to WF-27), Willapa River Section (Loc. WR-7), and Galvin Section (Loc. GS-11 to GS-13).

Nomenclature of the Echinophoria apta Zone

The Echinophoria apta Zone of this report is the time equivalent of the zone of the same name erected by Durham in 1944 (Fig. 5). The definition of the Echinophoria apta Zone of this report differs from that of Durham in a reference section being proposed within the Canyon River Section of the Lincoln Creek Formation where excellent stratigraphic and faunal control is available. The original type section is in the Twin River Formation in the 2,500 feet of section between one and one-eighth miles east of Twin Rivers westerly to the vicinity of Pysht, Washington (Durham, 1944, p. 113). Exposures there are discontinous, structurally complex, and lack well-defined superpositional faunal control.

Age of the *Echinophoria apta* Zone

Weaver and others (1944) utilized the *Echinophoria apta* Zone of Durham (1944) as the upper zone of the "Blakeley Stage" which was considered to be of late Oligocene and early Miocene age. Addicott (1967) suggested that the "Blakeley Stage" was in part contemporaneous with the "Vaqueros Stage" of California and was thus of latest Oligocene and perhaps earliest Miocene age in the context of the provincial West Coast chronostratigraphic nomenclature.

The foraminiferal assemblages of the *Echinophoria apta* Zone are assigned to the upper Zemorrian zone of Rau (1966) and correlated with upper Zemorrian age strata of California. These strata in both California and Washington are overlain by foraminiferal assemblages of Saucesian Stage age. Currently, the Zemorrian-Saucesian boundary is taken as the provincial Oligocene-Miocene boundary (Rau, 1966; Bandy, 1972; Lamb and Hickernell, 1972; Lipps and Kalisky, 1972). Thus strata of the *Echinophoria apta* Zone are of latest Oligocene age.

One occurrence of Saucesian Stage Foraminifera has been reported from the strata of "Blakeley Stage" age in Washington. That report, by Rau (1951, 1958), involved the occurrence of Rau's (1958) *Epistominella parva* Zone in the upper part of the Lincoln Creek Formation of the Willapa River Section of southwestern Washington. Subsequent detailed mapping by Wagner (1967) along the Willapa River has shown that the section is repeated by faulting and that the strata of the *Epistominella parva* Zone belong in the overlying Astoria (?) Formation (Beikman and others, 1967). Strata of the *Echinophoria apta* Zone occur no higher than upper Zemorrian and thus are of late Oligocene age only.

UNNAMED SUPERJACENT STAGE

Rocks of the Unnamed Superjacent Stage overlie with conformity (in most areas) the strata of the Matlockian Stage. One zone is informally defined encompassing the entire fauna of the Astoria (?) Formation occurring within the area of this study. A formal zone and perhaps additional younger zones may be definable upon completion of detailed studies of the regional character of the Astoria (?) Formation and its correlatives.

Weaver (1937, p. 173) considered the lower Miocene of Oregon and Washington to be largely absent, with the middle Miocene Clallam and Astoria (?) Formations unconformably overlying the older Oligocene "Blakeley" age rocks. Correlation of the molluscan faunas of these stratigraphic intervals resulted in the Oligocene strata being considered of "Blakeley Age," the Astoria (?) and Clallam Formations of "Temblor" age (Weaver and others, 1944) and the intervening "Vaqueros Stage" time, in Oregon and Washington, represented as a hiatus marked by the pre-Astoria (?)-Clallam unconformity. Subsequent work however, (Snavely and others, 1958; Pease and Hoover, 1957, Rau, 1958, 1966, 1967; Gower, 1960; Beikman and others, 1967; Addicott, 1967), has shown that the above unconformity does not exist in most cases, but that the

Astoria (?) Formation of southwestern Washington conformably overlies the Lincoln Creek Formation in the Willapa River and Canyon River Sections, and that the Clallam Formation of northwestern Washington conformably overlies the Twin River Formation. Thus, in Washington, strata containing the molluscan assemblage of the Echinophoria apta Zone are overlain in most places conformably by strata of the superjacent Liracassis petrosa zone of the Unnamed Superjacent Stage.

In Oregon, strata of the Astoria Formation, a correlative of, but not necessarily the same as the Astoria (?) Formation of Washington (see Snavely and others, 1958, p. 54), overlie the Nye Mudstone with angular discordance. The Nye Mudstone is Saucesian in age (W.W. Rau, personal communication, 1975) and contains a molluscan fauna (Vokes and others, 1949) closely related to the faunule of the Liracassis petrosa zone. Subjacent to, and in part interfingering with, the Nye Mudstone is the Yaquina Formation. The molluscan fauna of the Yaquina Formation (Vokes and others, 1949) has strong affinities with the fauna of the Echinophoria apta Zone. Yaquina Formation Foraminifera are considered Zemorrian in age (Rau, 1966). Thus, deposition across the Zemorrian-Saucesian boundary was continuous in the Yaquina Bay area of Oregon, the post-Nye, pre-Astoria unconformity occurring during middle Saucesian time. Strata containing the Echinophoria apta Zone assemblage and those of the overlying Liracassis petrosa zone are, in most cases, conformable.

The upper boundary of the Astoria (?) Formation is an unconformity of at least intra-regional extent. Rocks of the Astoria (?), Astoria and other age equivalent units are, in most cases, overlain with marked unconformity by the Montesano Formation, by basalt flows generally correlated with the Columbia River (Basalt) Group (both of middle to late Miocene age), or younger units. This post Unnamed Superjacent Stage erosion removed varying thicknesses of the Astoria (?) Formation, and part of uppermost Lincoln Creek Formation. In the Canyon River Section only the lower 300 feet of the Astoria (?) Formation is present. Further west in the Wynoochee River Valley an estimated thickness of nearly 3,500 feet of Astoria (?) Formation is preserved (Rau, 1967). Here Rau (1967, p. 23) recognized and informally named three foraminiferal zones; Siphogenerina kleinpelli zone, Baggina washingtonensis zone, and Rotalia becki zone. These zones are assignable to the Saucesian, Relizian, and possibly Luisian Stages, thus representing a much greater period of time than the Astoria (?) Formation in the Canyon River Section where only foraminifers of Saucesian age are known. On the Middle and West Forks of the Satsop River the Astoria (?) Formation has been completely removed and the Lincoln Creek Formation is unconformably overlain by the Montesano Formation (Figs. 4).

LIRACASSIS PETROSA ZONE

One zone, the Liracassis petrosa zone, is informally defined within the Unnamed Superjacent Stage for superpositional control at the upper boundary of the Echinophoria apta Zone. It is typed in the

Canyon River Section within the micaceous sandstone and siltstone of the Astoria (?) Formation. The section is 300 feet thick (Loc. CR-53 to CR-58) conformably overlying siltstone of the Lincoln Creek Formation and underlying with marked angular discordance the conglomeratic sandstone of the Montesano Formation (Figs. 3 and 4).

The *Liracassis petrosa* zone is characterized by the lowest occurrence of:

GASTROPODS

Crepidula praerupta

PELECYPODS

Chione ensifera
Vertipecten sp.
Katherinella angustifrons
Solen conradi
Spisula albaria

by the restricted occurrence of:

GASTROPODS

Amphissa decepta
Bruclarkia oregonensis
"Cancellaria" wynoochensis
Cylichnina petrosa
Cylichnina temblorensis
Epitonium clallamensis
Hinia ? lincolnensis
Liracassis petrosa
Musashia indurata
Natica oregonensis
Priscofusus medialis
Searlesia ? carlsoni
Turritella oregonensis

PELECYPODS

Acila conradi
Cyclocardia subtenta
Litorhadia astoriana
Macoma albaria
Mytilus watersi
Nucula nuculana
Nuculana chehalisensis
Nuculana ochsneri elmana

and the last occurrence of:

GASTROPODS

Fiscus modesta

PELECYPODS

Acila gettysburgensis
Crenella porterensis Lucinoma
hannibali Macoma arctata
Portlandia chehalisensis
Thracia trapezoides

The above taxa are well defined in Moore (1963).

The *Liracassis petrosa* zone occurs in strata assignable to the Astoria (?) Formation, overlying strata of the Lincoln Creek Formation, in the Canyon River Section as mentioned, the Pe Ell-Doty Section (Loc. PD-14), the Willapa River Section (Loc. WR-8), and the Galvin Section (Loc. GS-14).

Nomenclature of the Liracassis petrosa zone

The first reference to strata coeval with the Liracassis petrosa zone in a biostratigraphic context was by Weaver (1916a). He referred the fauna of this stratigraphic interval to the "Arca montereyana Zone" of the "Wahkiakum Horizon" typed in Wahkiakum County, Washington, along the Alockaman River about twelve miles north of the town of Cathlamet (Weaver, 1912, 1916a, 1916c). These strata would today be included within the Astoria (?) Formation.

Etherington (1931) recognized three faunal "zones" in the Astoria (?) Formation strata along the south side of the Chehalis River and arranged them as follows:

Upper	"Nuculana chehalisensis Zone"
Middle	"Arca devincta Zone"
Lower	"Arca devincta montereyana Zone"

The faunal assemblages characteristic of these "zones" were recognized as facies-faunas (Etherington, 1931; Weaver, 1937) and as such are not concurrent range zones. The faunas given by Etherington as characteristic of each "zone" are all present in the Canyon River Section fauna, and this fauna, the Liracassis petrosa zone assemblage, is considered to encompass the entire time span of Astoria (?) Formation deposition in southwestern Washington and includes each of Etherington's "zones" as biofacies.

As Weaver's "Arca montereyana Zone" was never defined precisely, a new name, Liracassis petrosa zone, is here informally proposed, typed in the Canyon River Section with good superpositional control and including both sandstone and siltstone facies.

Age of the Liracassis petrosa zone

The molluscan faunas of the Astoria, Astoria (?), and Clallam Formations of Oregon and Washington have long been correlated with the Temblor Formation of California and considered middle Miocene in age. With the recognition of the partial equivalency of the "Vaqueros" and "Blakeley" stages of California and Washington respectively, the "Temblor Stage", superjacent to the "Vaqueros," is considered to be late early and middle Miocene in age (Fig. 5).

Foraminiferal correlations of the microfaunas associated with the molluscan assemblage of the Liracassis petrosa zone in the type section indicate a Saucesian age. The Saucesian Stage in California is considered to be early and middle Miocene in age (Kleinpell and Weaver, 1963). Elsewhere in Washington (Rau, 1967) and Oregon (Moore, 1963), strata assignable to the Liracassis petrosa zone include foraminiferal faunas considered correlatives of Saucesian, Relizian, and Luisian Stages. These stages, and thus the Liracassis petrosa zone, encompass earliest Miocene to middle Miocene time.

UNNAMED LATE MIOCENE ZONULE

The fauna of the Montesano Formation in the West Fork of the Satsop River Section was studied and possibly is indicative of an Unnamed Late Miocene Zonule. The Montesano Formation unconformably overlies the Astoria Formation in the Canyon River Section (Fig. 4-3), and unconformably overlies the Lincoln Creek Formation in the West and Middle Forks of the Satsop River Sections (Figs. 4-1 and 4-4). Detailed regional studies of the late Miocene of Washington and the associated faunas must be undertaken before formal zones and stages may be defined. Sediments in the area studied, representative of the late Miocene, are dominantly coarse-grained, cross-bedded, brownish gray sandstones with channel deposits of pebbly sandstones and conglomerates.

The faunal assemblage of the Zonule is based upon collections by the author and review of checklists compiled by Weaver (1916a, 1916c). Species characteristic of the Unnamed Late Miocene Zonule and making their last appearance within the Zonule are:

GASTROPODS

Crepidula praerupta

PELECYPODS

Chione ensifera
Katherinella angustifrons
Pitar oregonensis

Taxa restricted to the Zonule include:

PELECYPODS

Chione securis
Solen conradi

Making their first appearance are the species:

GASTROPOD

Thais precursor

PELECYPODS

Acila empirensis
Anadara trilineata

Several species not restricted to this Zonule but characteristic of it are:

PELECYPODS

Cerastoderma corbis
Panopea abrupta
Spisula albaria

Molluscan assemblages of the Unnamed Late Miocene Zonule occur in southwestern Washington within the Montesano Formation. Collections for this report were made in the West Fork of the Satsop River Section (Loc. WF-28 to WF-30).

Nomenclature of the Unnamed Late Miocene Zonule

Strata of the upper Miocene of Washington yield faunas referred to as the "*Yoldia strigata* Zone" by Weaver (1916a). Weaver did not cite a type section or locality but the faunal assemblage was definitely from the Montesano Formation of the Chehalis River Valley. To date, no definitive study of the molluscan fauna of this age has been made and the zonule introduced is done so in only the most tentative manner for superpositional control on the upper boundary of the *Echinophoria apta* Zone.

Age of the Unnamed Late Miocene Zonule

Weaver (1912) assigned an upper Miocene age to the Montesano Formation based on the mollusca which he considered correlative with a late Miocene San Pablo Formation megafauna of California. Foraminifera of the Montesano Formation, from siltstone units well to the west of the area studied in this report, have suggested correlation with the Mohnian and Delmontian Stages of California indicating an upper Miocene age (Fowler, 1965; Rau, 1967, 1970).

DISCUSSION

The molluscan biochronology proposed in this report is defined by objective stratotypes and documented by assemblages on file at the Burke Museum at the University of Washington. The zones and stages are proposed as an improvement on previous biostratigraphic and time-stratigraphic frameworks applied to the marine late Eocene and Oligocene strata of Oregon and Washington. This is done with full awareness that the proposed sequence of zones and stages represent a progress report, and that additional research is certain to bring about refinement.

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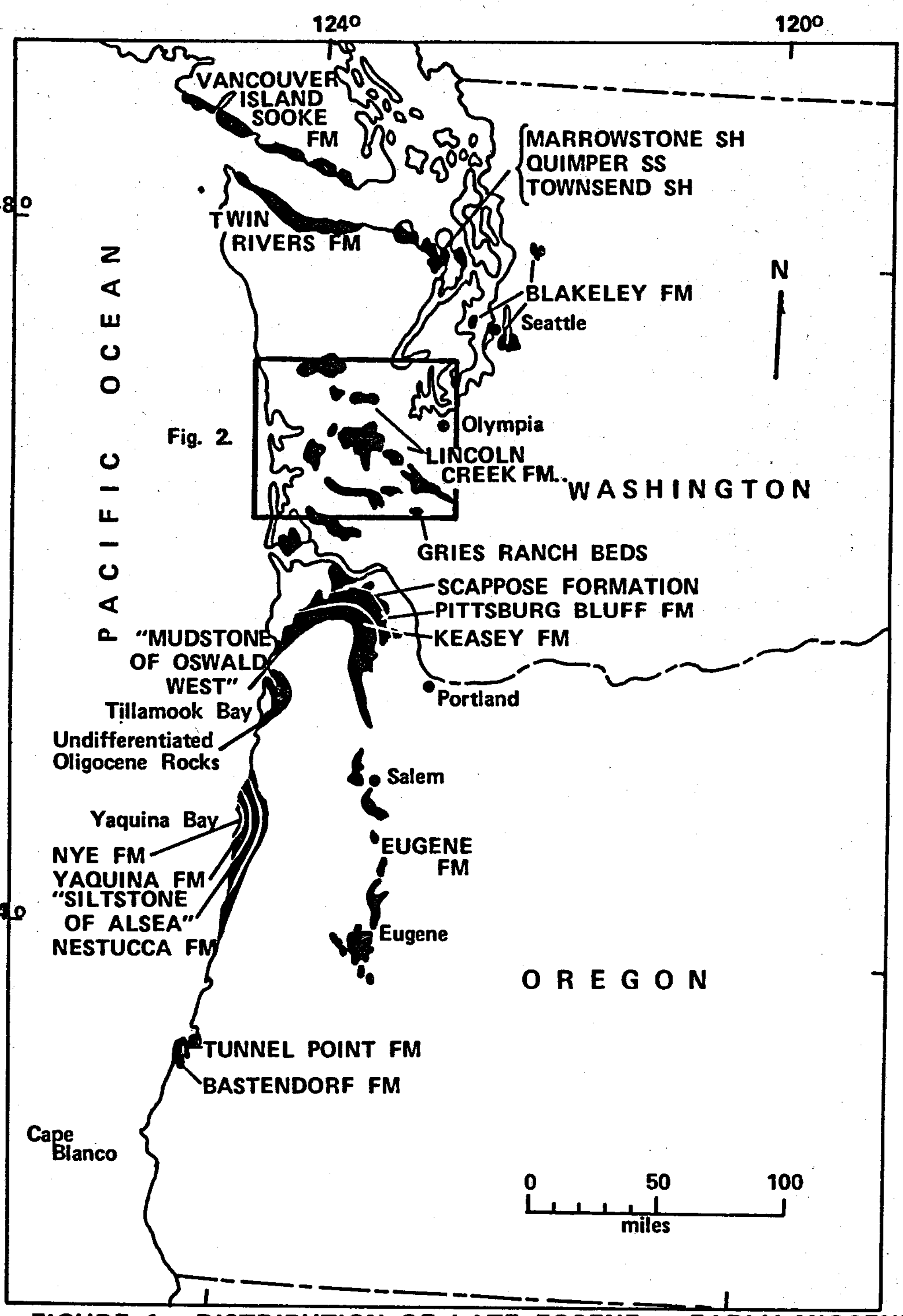


FIGURE 1. DISTRIBUTION OF LATE EOCENE – EARLY MIOCENE FORMATIONS IN WASHINGTON AND OREGON. MODIFIED FROM HICKMAN (1969).

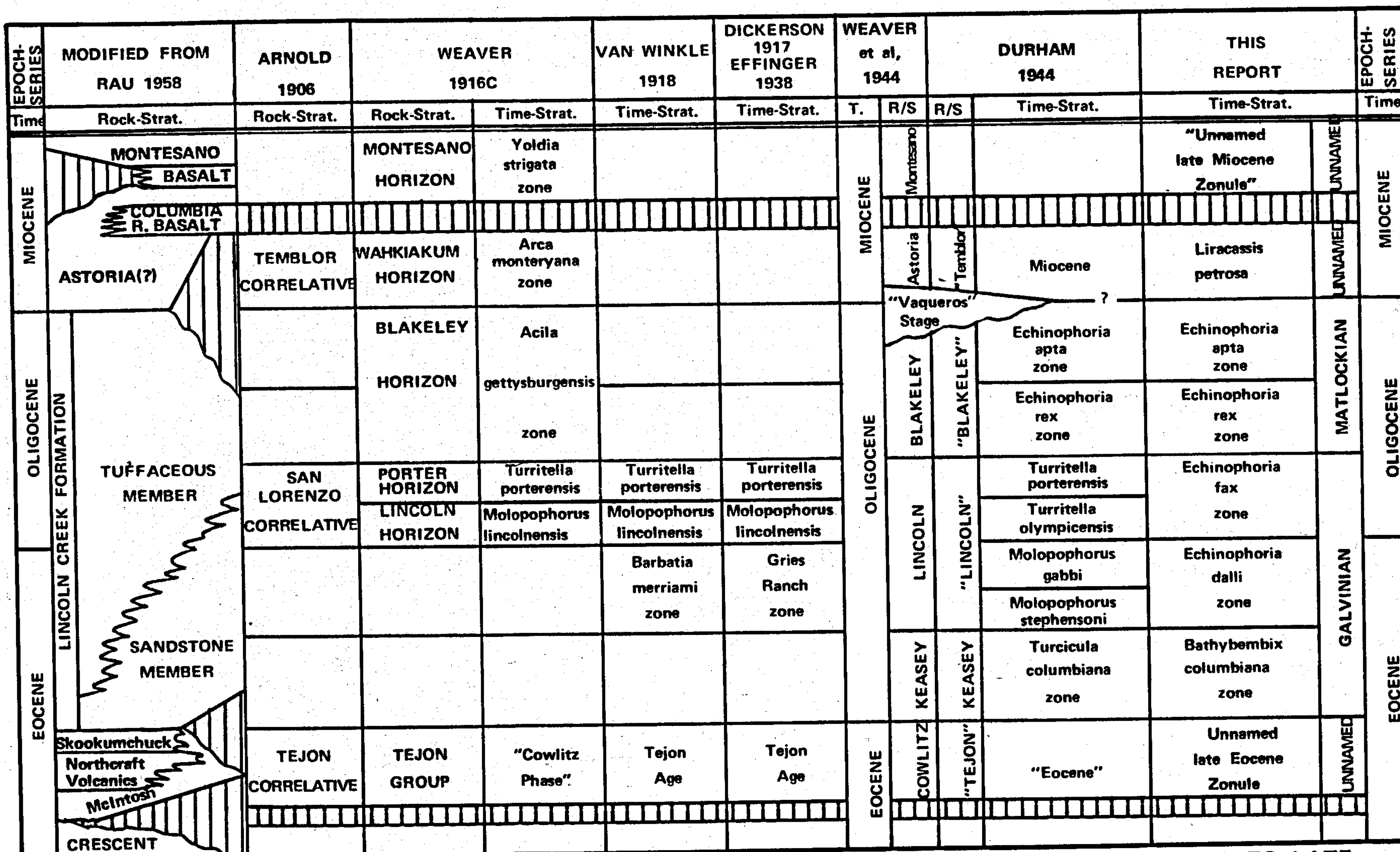


FIGURE 2. SELECTED ROCK–STRATIGRAPHIC AND TIME–STRATIGRAPHIC NOMENCLATURE APPLIED TO LATE EOCENE TO LATE MIOCENE UNITS IN SOUTHWESTERN WASHINGTON.

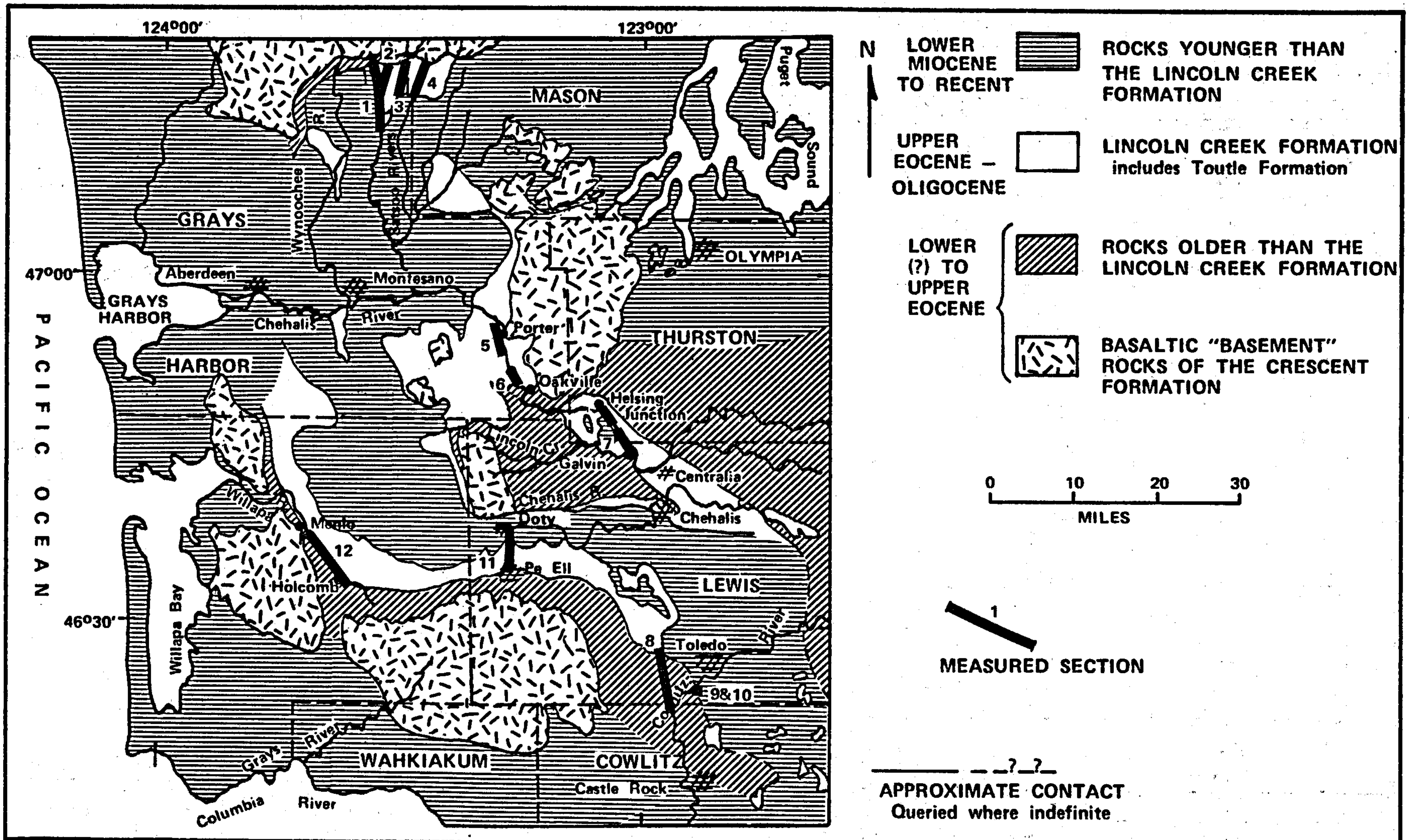
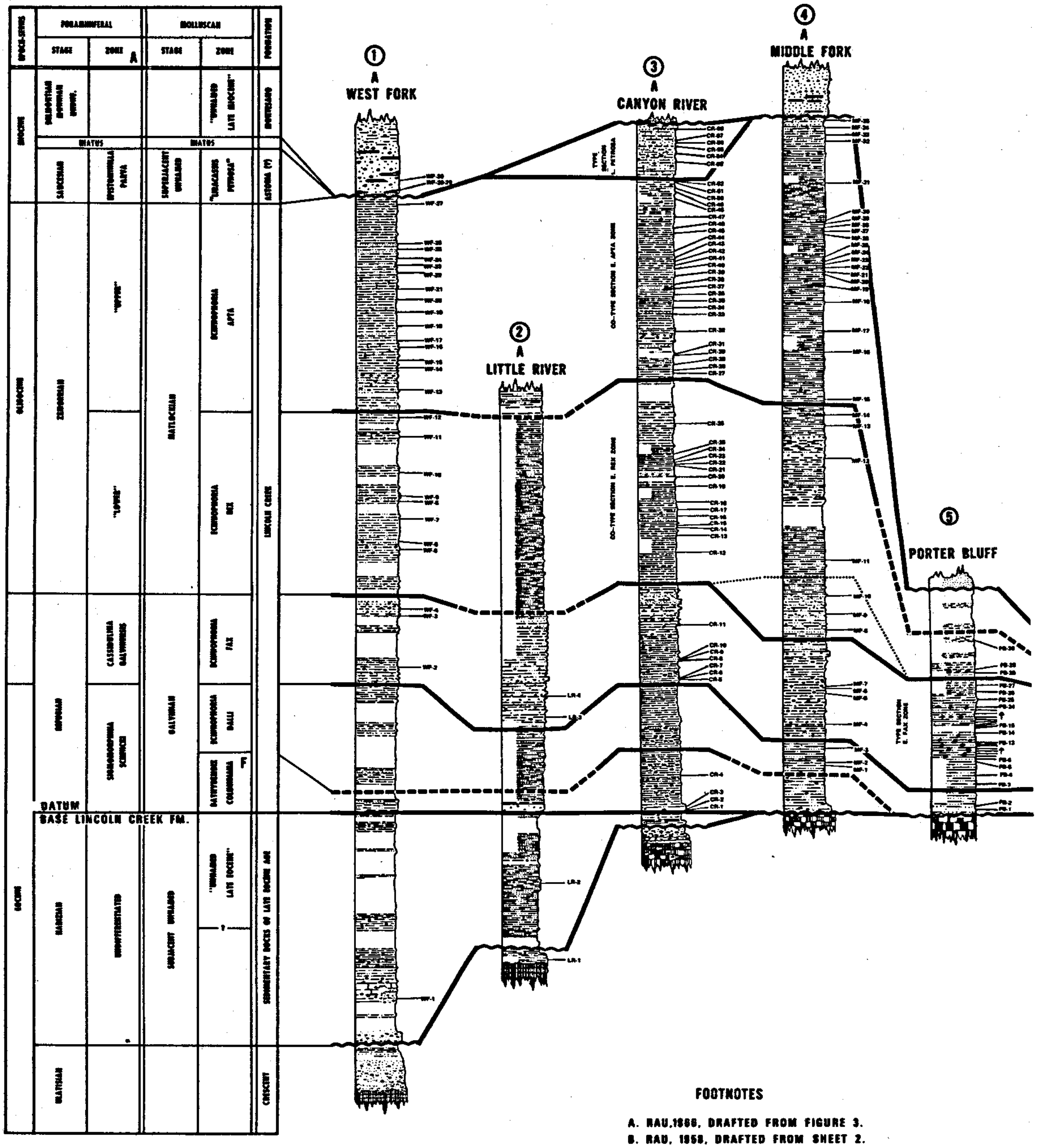


FIGURE 3. GEOLOGIC MAP OF AREA OF OUTCROP AND LOCATION OF MEASURED SECTIONS OF THE LINCOLN CREEK FORMATION IN THE GRAYS HARBOR AREA. GEOLOGY FROM PEASE AND HOOVER (1957); SNAVELY, BROWN, ROBERTS, AND RAU (1958); HUNTTING, BENNETT, LIVINGSTONE, AND MOEN (1961); GOWER AND PEASE (1965); AND H.C. WAGNER (1967). FIGURE REPRODUCED FROM BEIKMAN, RAU, AND WAGNER (1967).



FOOTNOTES

A. RAU, 1966, DRAFTED FROM FIGURE 3.
B. RAU, 1958, DRAFTED FROM SHEET 2.
C. PEASE & HOOVER, 1956, MEASURED FROM GEOLOGIC MAP.
D. HENRIKSEN, 1956, DRAFTED FROM PLATE 2.
E. ROBERTS, 1958, COMPILED FROM MEASURED SECTIONS.
F. TYPE SECTION ALONG ROCK CREEK, COLUMBIA COUNTY, OREGON, IN THE KEASEY FORMATION.

FIGURE 4. CORRELATION OF SECTIONS

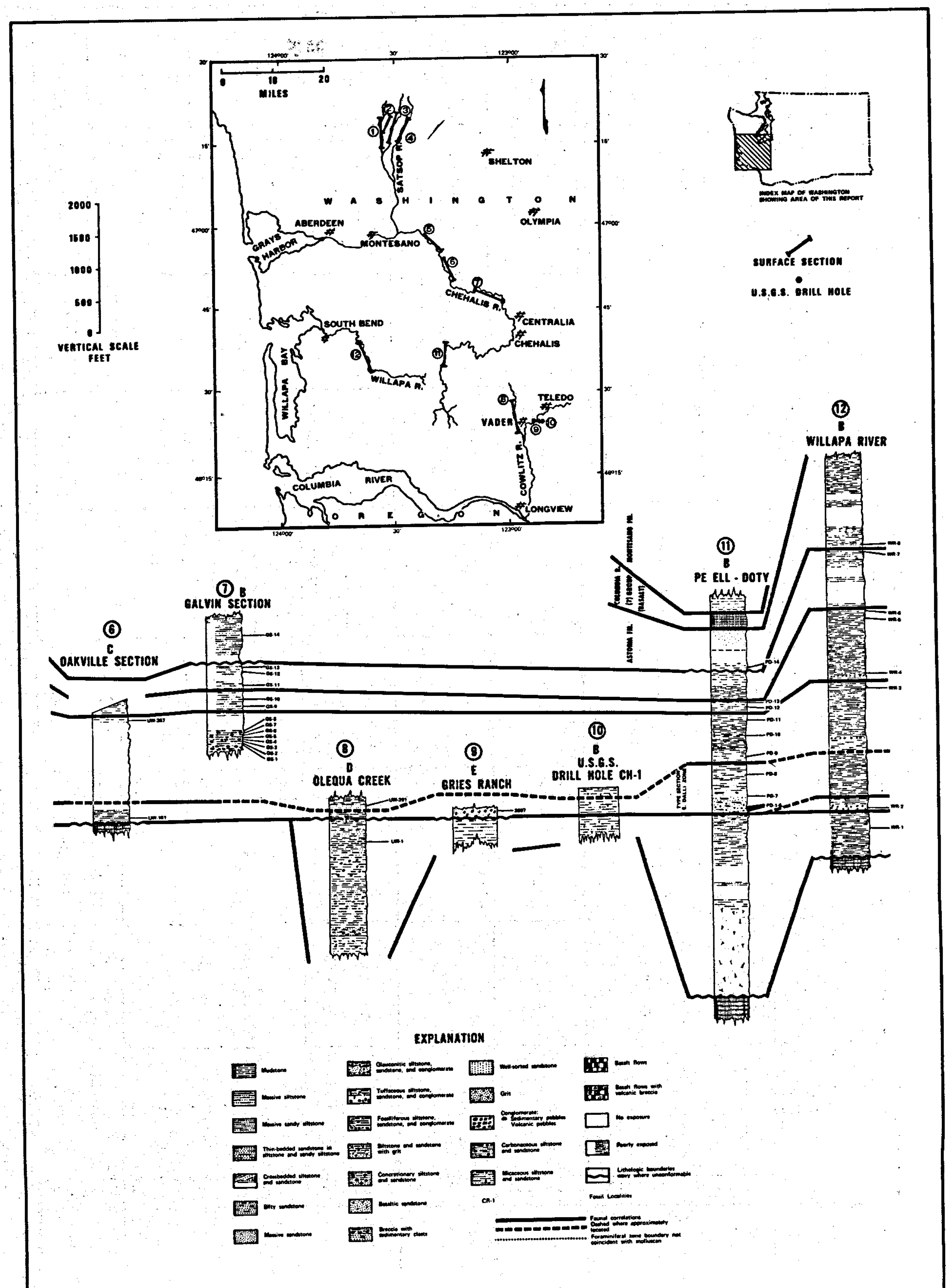


FIGURE 4. CORRELATION OF SECTIONS

EPOCH SERIES	KLEINPELL AND WEAVER 1963 — CALIFORNIAN FORAMINIFERAL — STAGES	KLEINPELL AND WEAVER 1963 — CALIFORNIAN FORAMINIFERAL — ZONES	RAU 1966 — WASHINGTON FORAMINIFERAL — ZONES	THIS REPORT — OREGON–WASHINGTON MOLLUSCAN — STAGES	THIS REPORT — OREGON–WASHINGTON MOLLUSCAN — ZONES	DURHAM 1944 — NW WASHINGTON MOLLUSCAN — ZONES	WEAVER, et al 1944 — WEST COAST MOLLUSCAN — STAGES	ADDICOTT 1972 — CALIFORNIAN MOLLUSCAN — STAGES	KLEINPELL AND WEAVER 1963 — CALIFORNIAN MOLLUSCAN — ZONES
MIOCENE	SAUCESIAN	UPPER: Uvigerinella obesa		SUPERJACENT UNNAMED	Liracassis petrosa	Miocene	"TEMBLOR"	"TEMBLOR"	Teilzone of Turritella ocoyana; Bruclarkia ("Agasoma") barkeriana zone
		LOWER: Plectofrondicularia miocenica, Siphogenerina transversa	Epistominella parva						Teilzone of Turritella inezana altacorona; Vaqueros-Temblor "Transitional zone" of Loel & Corey
OLIGOCENE	ZEMORRIAN	UPPER: Uvigerinella sparsicostata	"Upper"	MATLOCKIAN	UPPER: Echinophoria apta	Echinophoria apta	"VAQUEROS"	"VAQUEROS"	Teilzone of turritella inezana inezana
		LOWER: Uvigerina gallowayi	"Lower"		LOWER: Echinophoria rex	Echinophoria rex	"BLAKELEY"	UNNAMED ? ?	Teilzone of Turritella inezana sespensis ?; ? Bruclarkia ("Agasoma") gravida zone
OLIGOCENE / EOCENE	REFUGIAN	UPPER: Uvigerina vicksburgensis	Cassidulina galvinensis	GALVINIAN	UPPER: Echinophoria fax	Turritella porterensis; Turritella olympicensis	"LINCOLN"	REFUGIAN	Teilzone of Turritella variata variata; Turritella variata lorenzana zone; Yoldia tenuissima subzone
EOCENE		LOWER: Uvigerina cocoaensis	Sigmomorphina schencki		MIDDLE: Echinophoria dalli	Molopophorus gabbi; Molopophorus stephensoni			
					LOWER: Bathybembix columbiana	"Turcicula columbiana"	KEASEY		Crassortella collina subzone
	NARIZIAN	UPPER: Amphimorphina jenkinsi	Bulimina schencki-Plectofrondicularia cf. p. jenkinsi	SUBJACENT UNNAMED	UPPER: Unnamed late Eocene		"TEJON"	"TEJON"	Turritella schencki delaguerrae zone

FIGURE 5 CORRELATION OF PACIFIC COAST NORTH AMERICA PROVINCIAL MARINE–INVERTEBRATE CHRONOLOGIES (EPOCH-SERIES BOUNDARIES ARE AS USED IN THIS REPORT).

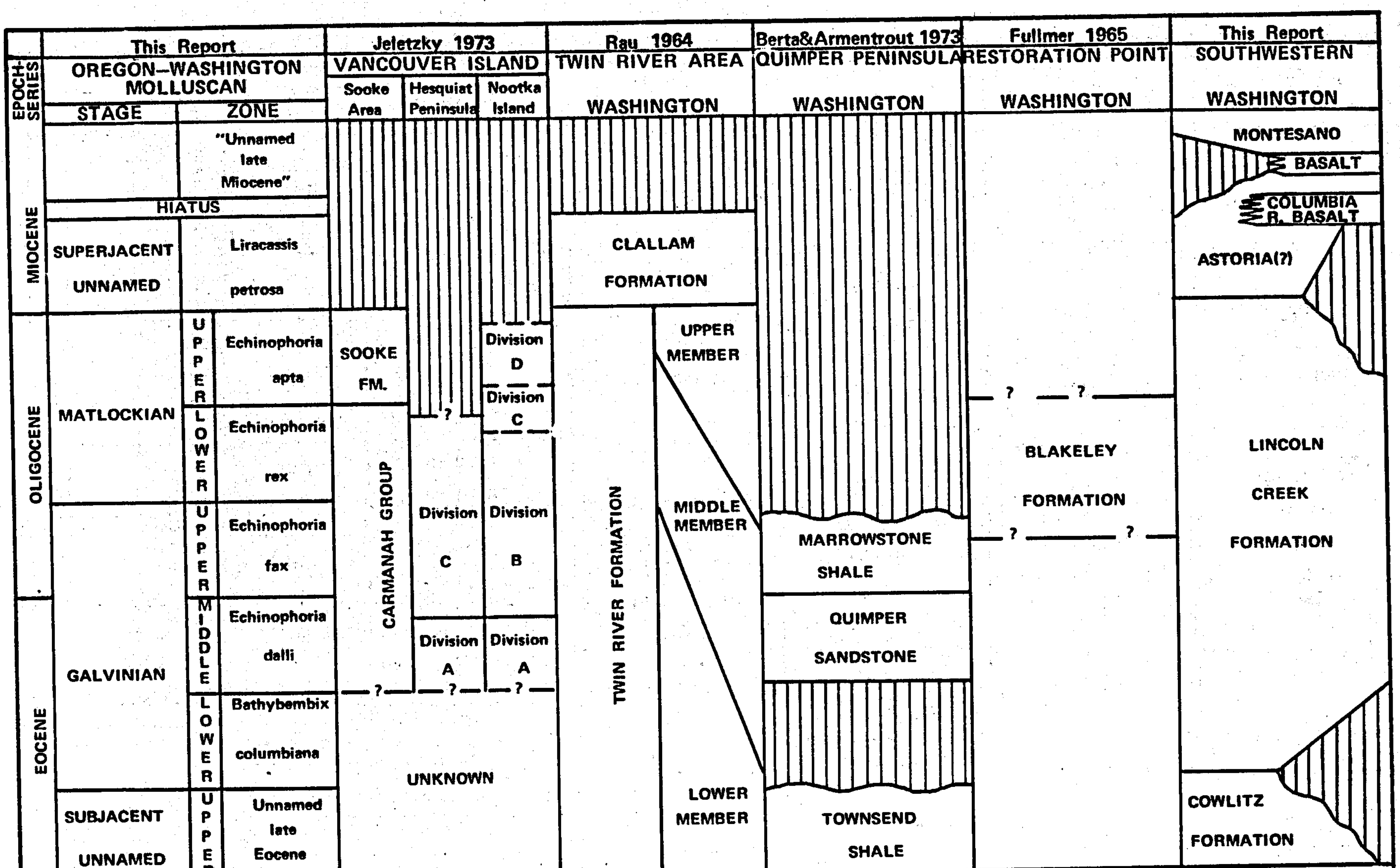


FIGURE 6. CORRELATION OF SOME LATE EOCENE, OLIGOCENE AND EARLY MIOCENE FORMATIONS IN WASHINGTON AND BRITISH COLUMBIA.

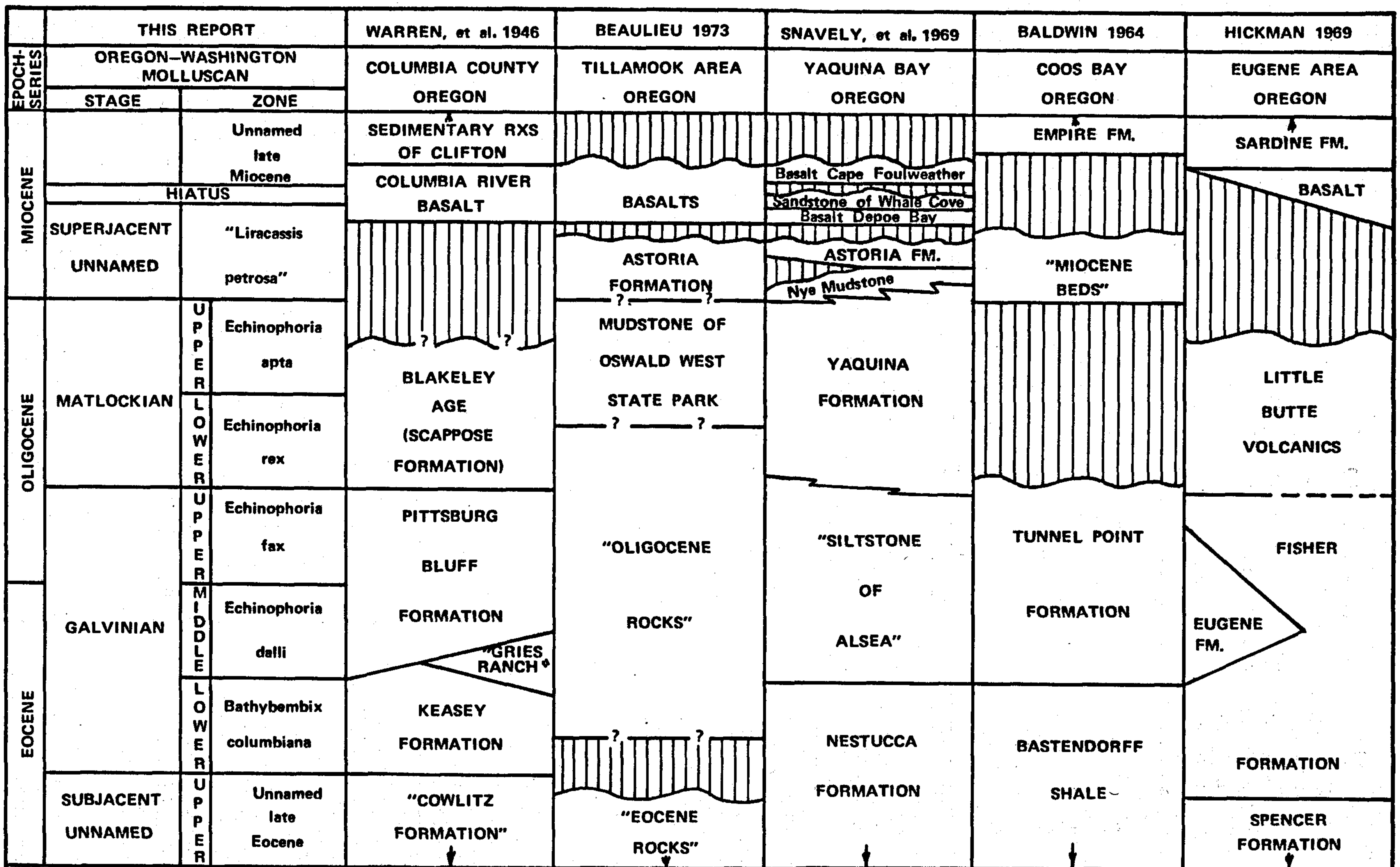


FIGURE 7. CORRELATION OF SOME LATE EOCENE, OLIGOCENE AND EARLY MIOCENE FORMATIONS OF OREGON.

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Revision of the Eocene Stratigraphy of Southwestern Oregon

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Introduction

The formations of southwestern Oregon are mostly of sedimentary and volcanic rocks deposited in a basin located along a mobile belt marginal to the continent. The basin bordered the Klamath Mountains on the south and extended northward through western Oregon and Washington. The eastern margin lies beneath the western Cascades. The region was tectonically active during the early Cenozoic and there were several invasions of the sea of successively decreasing extent.

The southern end of the Paleogene basin is underlain by thick Triassic, Jurassic, and Cretaceous sedimentary and volcanic units intruded by diorite and granodiorite bodies and overthrust by serpentinite and schist. Repeated uplift of this area has contributed much of the sediment that filled the Paleogene basin of southwestern Oregon. The pre-Tertiary formations are not differentiated on the geologic map (Figure 1).

Paleogene deposits of southwestern Oregon are in a rugged area of relief up to 4,000 feet dissected by numerous streams. Regional rainfalls reach 100 inches near the crest of the Coast Range but are on the order of 35 inches at Roseburg. Vegetation is dense but access is facilitated by a network of public roads and private logging roads.

Previous Work

Diller (1898, 1899, 1901) named the well known Cenozic units: Umpqua, Tyee, and Coaledo. Schenck (1927) named the late Eocene Fisher and Bastendorff Formations. Turner (1938) described fossils of the Eocene units and named the late Eocene Spencer Formation. Baldwin (1965) noted a threefold division of the Umpqua Formation and divided it into three new units (1974), the Roseburg, Lookingglass, and Flournoy Formations and their members. He restricted the extent of the Tyee Formation (Figure 1). The Elkton Formation was first designated as an upper member of the Tyee Formation (Baldwin, 1961) and the Bateman Formation was proposed for the sandstone overlying the Elkton in the heart of the Coast Range. Wells (1956) proposed the name Colestin Formation for volcanic rocks and sediments in the Medford area and this unit has been extended northward by Peck and others (1964) to include rocks mapped as the Fisher Formation. Volcanic rock along the coast at Heceta Head were designated the Yachats Basalt by Snavely and MacLeod (1974). The geology of Coos County was mapped by Baldwin (1973) with a geological report by Baldwin and Beaulieu (1973), and the geology of the Paleogene formations of southwestern Oregon was described by Baldwin (1974). These later articles give a more extensive list of previous workers.

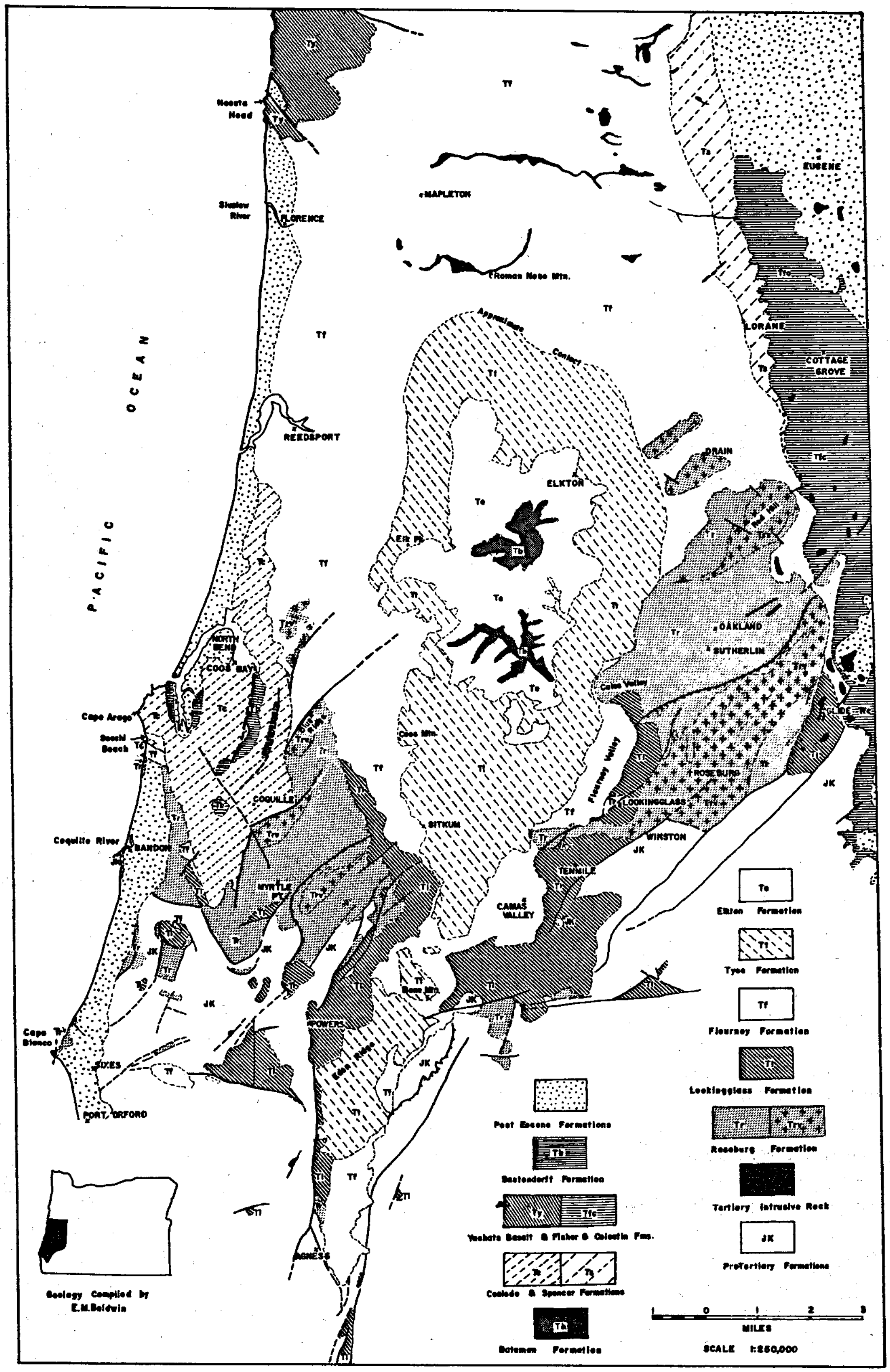

Figure 1. Geologic map of the Eocene formations of southwestern Oregon

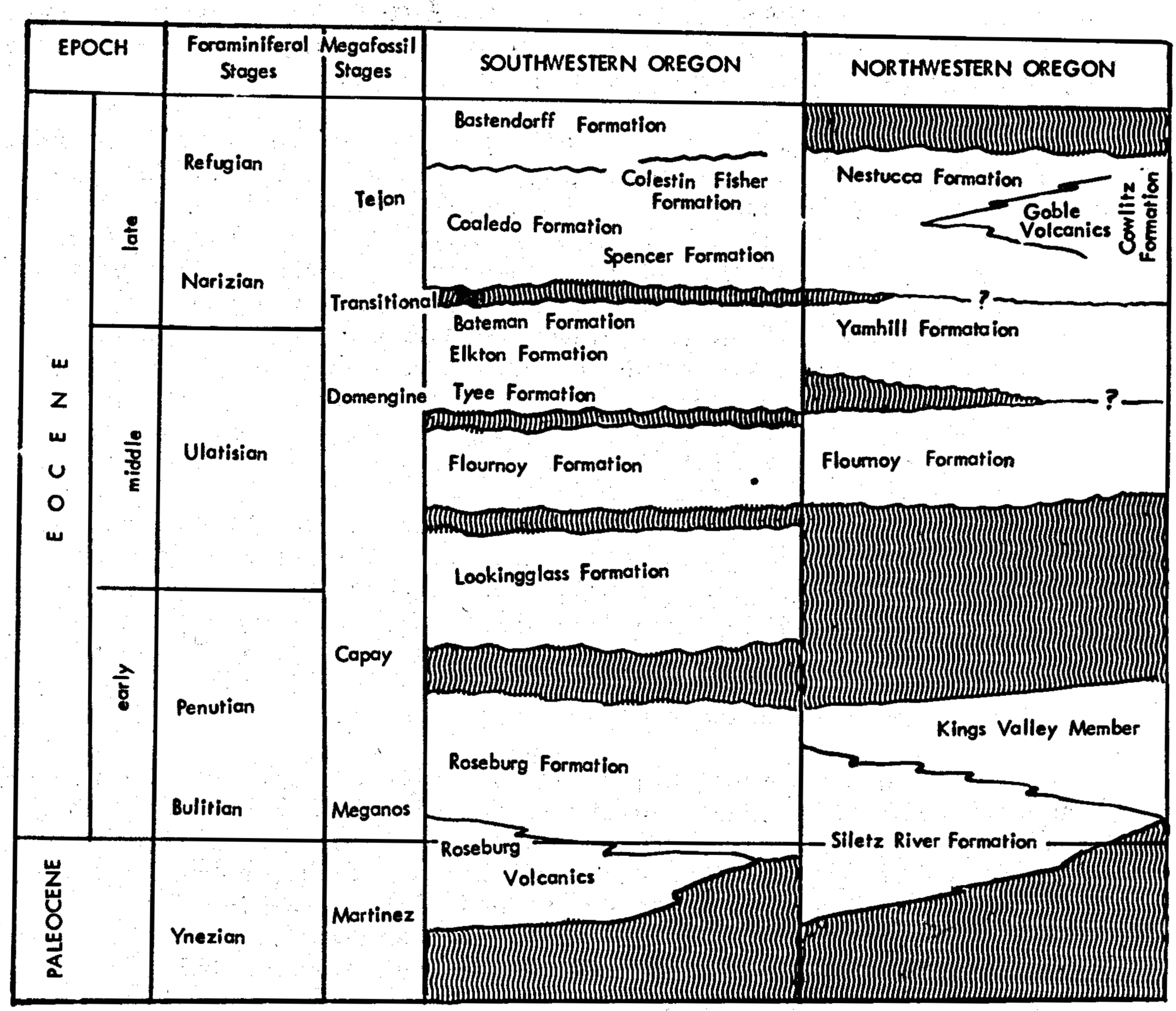

Figure 2. Correlation chart of lower Cenozoic formations.

Stratigraphy

Roseburg Formation. The Roseburg Formation of Baldwin (1974) encompasses the volcanic rock and intercalated sedimentary beds in the lower part of the Umpqua Formation of Diller (1898). Its type section is exposed in the North Fork of the Umpqua River from the Frear Bridge, west of Glide, to the junction with the South Fork. Additional type section includes nearly 8,000 feet of strata exposed along U. S. Highway I-5 south of the Red Hill anticline. These two areas are separated by a thrust fault which may in places be high angle reverse. The base of the Roseburg Formation is usually faulted and not exposed. The Formation may be 12,000 to 15,000 feet thick. Another thick section of Roseburg crops out along Highway 42 between Coquille and Myrtle Point. Here, roughly 2,000 feet of basalt is overlain by nearly 8,000 feet of sedimentary rocks bounded at the top by the valley of the North Fork of the

Coquille River. Neither the top or the bottom of the Formation is exposed here and it is only along the south end of the Roseburg exposure in the West Branch of Cow Creek that the base is exposed.

The basalt appears to be restricted to the lower part of the Roseburg Formation. It is made up largely of pillow basalts and breccias which are exposed in anticlinal highs and along the southeast side of major faults. The basalt has been penetrated in deep wells in several other places indicating that it is even more widespread. Some of the largest exposures of volcanic rocks are along the North Fork of the Umpqua, in the Red Hill anticline, and in three parallel anticlines near Drain. In places along the North Fork of the Umpqua beds of conglomerate and sandstone are present. This section is either unusually thick or repeated by infolding or imbricated fault plates. The basalt has been described by Hoover (1963, p. D10-13).

The sedimentary section of the upper part of the Roseburg Formation contains graywacke turbidites which range from thin dark gray fine-grained sandstone and siltstone only a few inches thick to more massive coarse- to medium-grained sandstone and conglomerate several feet thick with minor amounts of silt. Blocks of blue schist and greenstone occur in wildflysch. These blocks probably slid into the basin from the nearby Late Jurassic Otter Point Formation.

Fossils are not abundant in the turbidite section but Thoms (1965) found Foraminifera he considered to be Penutian or lower Eocene. A Paleocene microfauna was found in interbeds within the basalt east of Myrtle Point (Baldwin 1965) and it is likely that extrusion started in the Paleocene and was succeeded by the sedimentary section which is largely early Eocene. Nannoplankton from three localities in the Roseburg strata were considered to be early Eocene by Bukry (Baldwin, 1974, p. 9). The basalts are considered equivalent to the Siletz River Volcanics (Snavely and Baldwin, 1948) and the sedimentary section at least in part is equivalent to the Kings Valley Siltstone Member of the Siletz River Volcanics (Figure 2).

Microfossils of the Roseburg sedimentary rocks as well as some of the overlying Lookingglass Formation contain a Penutian fauna (Thoms, 1965). Yet the Roseburg Formation has been severely folded and faulted prior to deposition of the Lookingglass. It is likely that rather abrupt movements of the oceanic plate against the continent telescoped the Roseburg Formation during subduction. The Colebrooke Schist was probably emplaced at this time. The deformation, uplift, and ensuing erosion all took place within the Penutian stage prior to advent of the Lookingglass sea.

<u>Lookingglass Formation</u>. The Lookingglass Formation was named and described by Baldwin (1974). Its name was derived from Lookingglass Valley, but its type section of nearly 5,000 feet is along Tenmile Creek between Bushnell Rock and Tenmile Butte near the community of Tenmile. It also crops out at Glide, at places in Cow Creek drainage, between Powers and Agness, in the Sixes River valley, and along Bear

Creek near Bandon. Small remnants are faulted against pre-Tertiary rock of the Klamath Mountains indicating that the Lookingglass sea at one time overstepped infaulted Roseburg onto the Klamaths. There is no evidence that the Lookingglass sea reached as far north as Eugene.

Basal Lookingglass is nearly always composed of massive conglomerate and coarse- to medium-grained sandstone. The conglomerate is exposed in Bushnell Rock along Tenmile Creek and this was named the Bushnell Rock Member by Baldwin (1974). Pebbles of chert, quartz, greenstone, sandstone, and some medium-grained intrusive rocks are present indicating a source in the Klamath Mountains to the south. The conglomerate thickens to the south against the Klamaths but thins or is absent along the North Fork of the Coquille River west of Sitkum.

The conglomerate grades rapidly upward into thin rhythmically bedded fine- to medium-grained graywacke sandstone and siltstone. This unit was designated the Tenmile Member and underlies Tenmile Valley. The Tenmile Member grades upward into pebbly sandstone and conglomerate unit. This latter unit capping Tenmile Butte and exposed along Olalla Creek is called the Olalla Creek Member (Baldwin, 1974). Both the Bushnell Rock and Olalla Creek Members thicken to the south as the Tenmile Member thins suggesting that the Lookingglass sea approached, then withdrew from the Klamaths at a time the Klamaths were actively rising, distributing coarse material at the top of the formation by an offlapping sea (Figure 3).

Microfossils are abundant in the Lookingglass Formation and they are considered to be Penutian and Ulatisian by Thoms (1965). The Glide megafauna contains many shallow water forms such as oysters, Venericardia and Turritella. Turner (1938) described it as transitional between faunas found in the Capay and Domengine Formations of the California Eocene. The terms Domengine, Capay and Tejon are also used as West Coast megafossil stages by Weaver and others (1944) and shown in their approximate position on Figure 2.

Flournoy Formation. The Flournoy Formation was described by Baldwin (1974) and its type section is in Flournoy Valley. Other sections are present along the Middle Fork of the Coquille River from a point near the east line of Sec. 14, T. 30 S., R. 10 W., westward to the mouth of Rock Creek near Remote and a nearly continuous section lies along yet another Rock Creek south of Bone Mountain. A thick section of graded sandstone beds, formerly mapped as Tyee and exposed along the tributaries of the Coos and Coquille Rivers, is now assigned to the Flournoy Formation. The beds that wrap around Roseburg from Yoncalla to the foothills of the Cascades and south to Lone Rock Bridge near Glide are also assigned to the Flournoy Formation. The writer now assigns all the beds formerly mapped as Burpee (Schenck, 1927) and later as Tyee (Voke, Norbisrath, and Snavely, 1949) to the Flournoy Formation. The Tyee probably does not reach the Siuslaw River (Figure 1).

The Flournoy Formation is divisible into two members. The basal pebbly sandstone and sandstone which makes up White Tail and Sugar Pine ridges along the southeast side of Flournoy Valley are included in the White Tail Member. The overlying siltstone and thin-bedded sandstone in Flournoy Valley and elsewhere are designated as the Camas Valley Member (Baldwin, 1974). On the west side of the basin the sandstone is much thicker and the siltstone is thinner and intermittently present owing to deformation and erosion prior to the advent of the Tyee sea. An infaulted section of siltstone at Sacchi Beach, south of Cape Arago, is assigned to the Camas Valley Member as is the siltstone at Lorane near Eugene. Both have been paleontologically correlated with the Elkton Formation but their stratigraphic position is more compatible with the Flournoy Formation.

The sandstone is rhythmically bedded and contains quartz, feldspar, and lithic fragments in a matrix of clay minerals and chloritic material. Mica flakes and plant fragments are present along the bedding planes. The beds are very similar to much of the Tyee and difficult to distinguish.

Microfossils are present which have been assigned to the Ulatisian Stage by Thoms (1965). A microfauna from Comstock, south of Cottage Grove, was assigned by Rau (Hoover, 1963, p. D28) to the middle Eocene B-1 Zone of Laiming. Megafossils found near Comstock by Turner (1938) were considered equivalent to the middle Eocene Domengine Formation of California. Many of the fossil localities formerly assigned to the Tyee are actually from the Flournoy Formation and this has been a source of confusion. There appears to be little lapsed time and the faunas changed little so that they would be difficult to distinguish anyway. The presence of pre-Tertiary rock along the coast as well as Roseburg strata as far north as Bandon suggest that the basin may have been partially enclosed on the west by a peninsula (Figure 3). Snavely and others (1964) measured flow structures which indicate that the source was to the south although some trends came from the west along that part of the basin south of Bandon.

<u>Tyee Formation</u>. The Tyee Formation was named by Diller (1898) for strata exposed in Tyee Mountain northwest of Roseburg and the section along the Umpqua River west of Coles Valley is generally considered the type section. Another section, which may be as much as 6,000 feet thick, lies along Oregon Highway 38 between a point 6 miles west of drain and Elkton (Baldwin, 1961; Hoover, 1963).

The Tyee Formation was extended from its type area into the Coos Bay area by Allen and Baldwin (1944) and into the central Coast Range by Vokes, Norbisrath, and Snavely (1949) during the early stages of detailed geologic mapping in the Coast Range. The similar strata of the Flournoy Formation evidently were mistaken for the Tyee.

The Tyee Formation has been considered in considerable detail by Snavely, Wagner and MacLeod (1964) and Lovell (1969). Baldwin (1973,

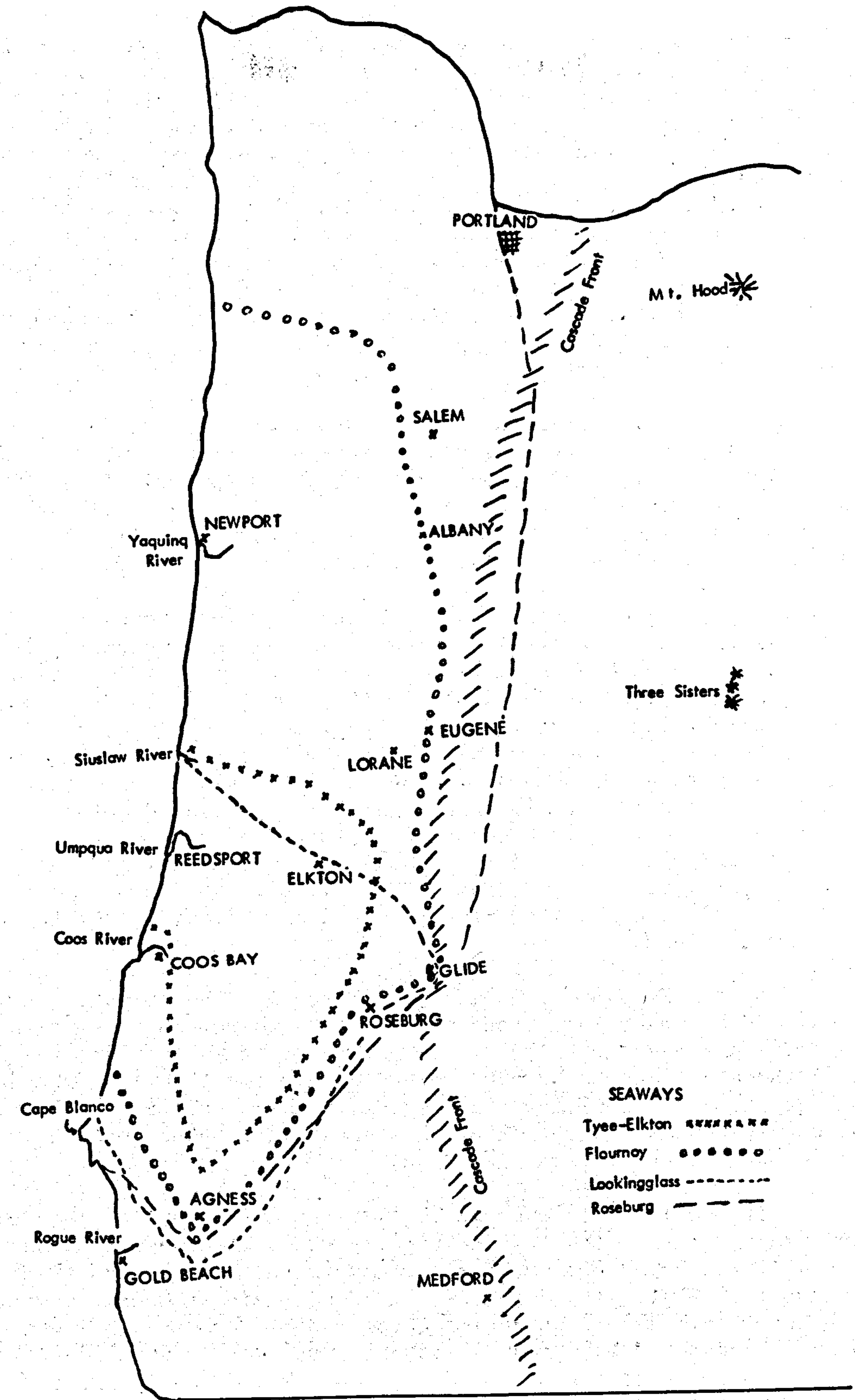

Figure 3. Approximate extent of Paleogene seaways.

1974) found that much of the sandstone near Coos Bay mapped as Tyee was Flournoy. In the Drain and Anlauf quadrangles, Hoover (1963) shows northwesterly trending strike ridges that are perpendicular to northeast trending anticlines flanked by Flournoy strata. Baldwin (1961) shows the Tyee striking eastward and plunging southward as it wraps around the Elkton basin. Although the northern contact between the Flournoy and Tyee has not been determined (Figure 1), structural trends and inferred differences in lithology indicate that the Tyee does not reach the Siuslaw River. It is easier to distinguish between the two formations to the south where the unconformity has been mapped. At the northern extent both units are rhythmically bedded sandstones with similar lithology and only a detailed study of the structure will reveal the unconformity.

Baldwin (1974) divided the Tyee along the eastern margin into three members, the lower Tyee Mountain Member which is about 2,500 feet thick, the silty Hubbard Creek Member which is approximately 400 feet thick, and the Baughman Member that is exposed at the Baughman Lookout and which underlies the center of the Coast Range syncline between Roseburg and Coos Bay. The latter unit is probably 2,500 feet thick.

The Tyee is a bluish-gray to medium gray, rhythmically bedded, micaceous lithic or feldspathic wacke with strained quartz, feldspar and lithic fragments in a matrix of clay minerals. It is firmly cemented and is characterized by abundant flakes of mica and plant fragments along bedding planes. At the south end the beds are commonly five feet or more in thickness, and show less rhythmic structure. The southern beds contain some conglomerate and coal and in places are crossbedded but to the north bedding is thinner, and the percentage of silt increases in the rhythmically bedded sandstone. The abundant quartz, some of it strained, and mica may indicate a source in the schist and uncovered granitic intrusives in the Klamath Mountains to the south. Snavely and others (1964) measured flow structures which indicated that the source was from the south.

The Tyee Formation unconformably overlies the Roseburg, Lookingglass, and Flournoy Formations and may lap against the pre-Tertiary overlooking the Rogue River. Pre-Tertiary rock as far north as Bandon and a thick section of Roseburg and Flournoy rocks in the Bandon to Coos Bay area may indicate that a positive area existed northward along the coast and that an uplift of that area contributed some sediments from eroded Flournoy and older beds.

Very few fossils occur in the Tyee Formation but a large megafauna is present at the top of the Tyee where it grades into the base of the Elkton Formation at Basket Point (Turner, 1938) and 1½ miles southwest of Elkton (Baldwin, 1961). The megafossils were correlated with the middle Eocene Domengine Formation by Turner. Corals and echinoids examined by Durham (Baldwin, 1961) were suggestive of relatively shallow water about 300 feet deep. Microfossils are scarce and most of the microfaunas previously referred to the Tyee probably come from the Flournoy Formation. Microfaunas in the underlying and overlying formations confine the Tyee Formation to the middle Eocene Ulatisian Stage of Mallory (1959).

Elkton Formation. The Elkton Formation occupies a basin south of Elkton, Oregon. It is made up of approximately 3,000 feet of siltstone with lenses of massive sandstone resembling the Tyee Formation in its lower part. The formations are conformable and gradational and Baldwin (1961) considered the Elkton a member of the Tyee. Thoms (1965), Bird (1967) and Lovell (1969) considered it a formation as does Baldwin (1973, 1974). At the time it was originally described the Lutsinger Creek Road exposure was considered to be the best section. Newer roads up Rader and Waggoner Creeks traverse better sections.

The Elkton Formation is thickest in the center and noticeably thins along the margin so that beneath Green Mountain to the south it is nearly pinched out. This thinning may be due to slight adjustment in the basin during deposition, or slight erosion of Elkton beds during a partial withdrawal of the sea. Any stratigraphic break, if present, appears to be minimal.

Beds of the Elkton Formation are dark gray siltstone with thin fine-grained sandstone. Lenses of thicker bedded sandstone, more common in the base of the formation, are very similar to the Tyee and were no doubt derived from the same general source to the south. The beds may be deposited in quiet water during a time of maximum onlap of the Tyee-Elkton seaway.

Microfossils are abundant and these were studied by Stewart (1957), Rau (Baldwin, 1961), and Bird (1967). The microfaunas are correlative with B-1 and B-1A Zones of Laiming (1940) which are comparable to the Ulatisian and perhaps lower Narizian Stages of Mallory (1959). Similar faunas are present in the Yamhill Formation of northwestern Oregon (Figure 2).

Beds at Sacchi Beach, west of Coos Bay, have been correlated with the Elkton Formation on the basis of fauna. These beds are overlain by the Coaledo Formation on both flanks of a small anticline. On the south the two formations are unconformable but on the north they are generally parallel and Dott (1966) argues for a gradational contact. If the Tyee is missing, as postulated, there would be a significant stratigraphic break here as usually occurs at the base of the Coaledo throughout the region.

McKeel (1972) found planktonic Foraminifera from Agate Beach, just south of Sacchi Beach, which are reported from the middle Eocene elsewhere. The Elkton Formation, beds at Sacchi Beach, and beds at Lorane are all argillaceous. It is likely that fossil assemblages from these beds are more indicative of facies than of equivalent age. Previous correlations of the Sacchi Beach have been largely on a faunal basis but the writer herein assigns both the Sacchi Beach and Lorane beds to the upper part of the Flournoy on the basis of stratigraphic position. The writer has found that microfossils have been useful in distinguishing between older and younger Eocene formations but are not diagnostic when dating formations that are not far apart in age. Deposition was probably faster than significant faunal changes. Benthonic Foraminifera make up most of the faunas used to date. Planktonic assemblages may help but to date not enough have been found to more closely pin ages of the Eocene formations.

The Elkton Formation is correlated with the Yamhill Formation of northwestern Oregon (Figure 2). The Yamhill has presented problems in correlation. Beds mapped formerly as Burpee and Tyee but now assigned to the Flournoy Formation were thought to grade upward into the Yamhill Formation. The Yamhill Formation (Baldwin and others, 1955) is exposed in the type section along Mill Creek, a tributary of the Yamhill River. As originally described, the formation--where it overlies the Siletz River Volcanics--contains about 500 feet of tuffaceous siltstone, and this lower siltstone is overlain by approximately 500 feet of predominantly greenish-gray sandstone which contains a meager fauna but whose Venericardia and Turritella have been correlated with faunas formerly called Tyee but could be equivalent to the Flournoy. Above the sandstone rests approximately 4,000 feet of micaceous thinbedded sandstone and siltstone which is generally thought of as typical Yamhill.

Stewart (Baldwin and others, 1955) shows that the fauna of the lower 1,000 feet is considerably different from that above. The writer now feels that the Yamhill should be restricted to the upper 4,000 feet and that the lower 1,000 feet from the volcanics to the top of the greenish-gray sandstone should be restudied and reassigned. Subsequent discussion of the Yamhill fauna will refer only to the upper thicker part which is younger than the Flournoy Formation and closer to that of the Elkton Formation.

Sills lie in the area between the Flournoy Formation and typical Yamhill beds. The writer has at times considered the Flournoy beds (mapped as Tyee, Baldwin, 1964) to grade upward and interfinger with the Yamhill. However, it seems that the juxtaposition of argillaceous beds is coincidental. A fauna collected from Flournoy beds at Black Rock beneath a thick sill was examined by Rau (Baldwin, 1964, p. 18) who stated that "Amphistegina californica Cushman and M. A. Hanna is present, together with other forms that suggest a middle to possible lower Eocene age". Downstream on the edge of Falls City and along Rickreall Creek near Dallas microfossils from beds the writer would place in the restricted Yamhill were assigned by Rau to the late Ulatisian to early Narizian or early late Eocene. The intervening sills appear to be discordant upon the Flournoy and generally parallel to the overlying Yamhill.

Bateman Formation. The Bateman Formation, named by Baldwin (1974) for Bateman Lookout, occupies the center of the southern Coast Range (Figure 1). The Elkton beds appear to grade upward into the massive crossbedded and current sorted Bateman sandstone although thinning of the Elkton along the margins suggests slight basin adjustment during deposition or local disconformities. The basal part of the Formation is well exposed along the Rader and Waggoner Creek roads and along Camp Creek where no break is detectable. Approximately 1,500 feet of shallow water beds are present. Baldwin (1961) questionably assigned the beds now mapped as Bateman to the Coaledo because of similar lithology and depositional environment.

The sandstone beds contain abundant quartz, mica, and lithic fragments not unlike the underlying Tyee sandstone but they lack the characteristic rhythmic bedding of the Tyee. The Bateman beds were probably deposited in prograding deltas during the offlap of the Tyee-Elkton sea and may share a common source. Coal beds indicate marshy conditions that accompanied sea withdrawal. Uplift and widespread erosion apparently took place before encroachment of the Coaledo and Spencer embayments.

Megafossils are rare but a late middle to early upper Eocene age is indicated by the stratigraphic position. The writer found Venericardia califia near the base of the Bateman Formation which is present in the Tyee Formation but not in the Coaledo. Brown (Baldwin, 1961) presented a floral list of plants associated with the coal-bearing strata near the top of the Bateman Formation which he considered to be no younger than late Eocene.

Microfossils are not abundant but Bird (written communication, June 20, 1967) reported finding Foraminifera in beds along the ridge east of Ivers Peak. The fauna indicated an upper Ulatisian age and deposition at shelf depths, probably between 200 and 600 feet.

Coaledo Formation. The Coaledo Formation, named by Diller (1901), is made up of 6,000 feet of shallow-water coal-bearing strata at the base and top with a middle member of more open water marine siltstone. The formation is confined to the Coos Bay area. Turner (1938) divided the formation into the lower, middle, and upper members and described the fauna. Allen and Baldwin (1944) studied the coal deposits and attempted to map the members throughout the field. Baldwin (1973) found that the middle Coaledo thinned along the eastern margin of the basin where it was difficult to determine position within the formation. However, throughout most of the field the threefold divisions could be mapped. Dott (1966) studied and illustrated the numerous primary structures of the Coaledo Formation, examined the composition, and postulated deposition on prograding deltas.

Coal was discovered in approximately 1855 and mining has continued intermittently since. Maximum production of nearly 115,000 tons in 1914 came mostly from the Beaver Hill bed of the upper Coaledo. The field was revived during World War II with production of approximately 35,000 tons mostly from the Southport mine. The coal is subbituminous and is rated at approximately 9,000 B.T.U. as received.

Later investigators were in search of oil and several wells were drilled. One by the Phillips Petroleum Co. along Davis Slough reached 6,900 feet. The well started near the top of the lower Coaledo and penetrated 2,300 feet before entering the Roseburg volcanic rocks without encountering intervening formations. This is not unusual since there is a pronounced regional unconformity at the base of the Coaledo and it rests on the Roseburg, Lookingglass, and Flournoy Formations at various places around the rim. The Coaledo is not known to be in contact with the Tyee Formation.

The Coaledo Formation is made up of light- to medium-gray current sorted sandstone with thin, dark gray beds of siltstone and mudstone commonly bearing carbonaceous material. In places, there are beds of pebbly sandstone and conglomerate. Pebbles of quartz perhaps derived from older formations, are common. Many of the pebbles and much of the material in the sandstone is however derived from volcanics. No doubt some of the Roseburg Volcanics were eroded to provide these pebbles but it is also likely that contemporaneous volcanism was taking place to the east in the older Cascades. Crossbedding, ripple marks, and slump structures are common.

Weaver (1945) believed that the "Arago beds", an earlier name that encompasses the Coaledo, were deposited in a gulf with a western barrier, with some sediments derived from the west. Snavely and Wagner (1963) show a slight western barrier in late Eocene times. Pre-Tertiary and older Eocene rocks are present along the coast as far north as Bandon. Coaledo strata unconformably lap against older formations within the center of Bandon but it is difficult to determine whether they are upon Roseburg or pre-Tertiary rock. The relationship calls for uplift and removal of a large amount of earlier Eocene rock from this part of the coast prior to and perhaps during the time of Coaledo deposition. It is possible that some of the sediments were contributed from the west as proposed by Weaver.

The Coaledo strata are overlain conformably by the Bastendorff Formation which in turn is conformable with the middle Oligocene Tunnel Point Formation. Significant deformation evidently followed the middle Oligocene at which time all three formations were steeply folded. Miocene strata present within South Slough syncline west of Coos Bay are apparently unconformable upon all three of the pre-Oligocene formations.

Megafossils are abundant in the lower and upper Coaledo members, and microfossils occur in the middle Coaledo and argillaceous part of the lower and upper members. Turner (1938) concluded that the Coaledo was late Eocene and generally equivalent to the Tejon Formation of California. The faunas of upper and lower Coaledo differ very little and thus may indicate rapid deposition. Weaver (1945) lists the fauna and correlates it with the Cowlitz Formation of Washington and the Tejon Formation of California. Microfaunas studied by Stewart (1957) fall in the A-1 Zone of Laiming (1940) and the Narizian Stage of Mallory (1959). The unit correlates with the Spencer, Nestucca, and

Cowlitz Formations of Western Oregon. All of these units were probably deposited at approximately the same time but it is not known whether the Spencer and Coaledo seaways were connected or whether the Coast Range had already created a barrier.

Bastendorff Formation. The Bastendorff Formation occupies the center of the Coos Bay coalfield and rests conformably upon the Coaledo Formation. It was named and described by Schenck (1927) and discussed by Allen and Baldwin (1944) and Baldwin and Beaulieu (1973). The formation is best exposed along Bastendorff Beach but also occurs infolded in narrow synclines along Isthmus Slough and at Sumner southeast of Coos Bay.

The Bastendorff beds are medium- to dark-gray siltstone and shale with very little sandstone. It weathers to a light buff color. Diller (1901) did not separate the Bastendorff from the Coaledo and referred to it as "diatomaceous shale". The Bastendorff Formation is nearly all argillaceous where found and if there were a coarser grained shoreline facies it is not known. The Bastendorff Formation was probably deposited in quiet water open to the ocean at a time when streams were not bringing much coarse material to the area.

Microfossils studied by Stewart (1957) indicated that although much of the Bastendorff was late Eocene the upper part was Refugian or early Oligocene. McKeel (1972) suggests that the entire Bastendorff may be late Eocene.

Intrusive Igneous Rocks. Intrusive bodies are shown on Figure 1 along the eastern and northern margin of the map. These occur as sills and dikes which now cap some of the mountains. The rocks are generally gabbroic although smaller bodies may be of basalt. The intrusive are not considered to be Eocene and in fact intrude rocks as young as middle Oligocene.

Post-Eocene Formations. Formations deposited after the Eocene are situated largely along the Coast at Coos Bay and Cape Blanco. They consist of the middle Oligocene Tunnel Point Formation, unnamed Miocene strata in South Slough near Coos Bay and Cape Blanco, the Pliocene Empire Formation of Coos Bay and Cape Blanco, Pleistocene terrace deposits, sand dunes, and Holocene alluvium, dunes and bay deposits. These have been described by Baldwin and Beaulieu (1973).

Tectonic History

The coastal margin of Oregon has been in a mobile belt at least as far back as the Mesozoic as shown by the arced pattern of the pre-Tertiary strata in the northern Klamath Mountains. They strike northward to the vicinity of Cape Blanco then turn northeastward into Eastern Oregon. Tectonic movements continued along the same general structural trends until the end of the lower Eocene with northeastern strikes through the center of the Coast Range paralleling the northern Klamaths. The final surge came rapidly during the Penutian stage as Roseburg volcanic and sedimentary rocks were closely folded and in some places thrust. This telescoping of oceanic deposits evidently added to the existing continent of that time. The Lookingglass deposits were deposited in an onlapping sea which overstepped the faulted and compressed Roseburg onto the Klamath pre-Tertiary. Coarse deposits both at base and top imply deposition at a time continued uplift was taking place along the Klamath margin. Most of the Lookingglass remnants are faulted against pre-Tertiary rocks, and some of these faults display throw in excess of 1,000 feet.

The Flournoy sea spread across both deformed Roseburg and Lookingglass as far as the western Cascades east of Glide and northward into northwestern Oregon. It withdrew without leaving coarser offlapping beds and is gently folded and broken by fewer faults than older formations. Structural trends tend to be more northerly than the northeasterly trends of the Roseburg Formation.

The Tyee, Elkton, and Bateman Formations occupy a central position in the southern Coast Range. The Tyee at the southern end occupies a simple shallow syncline which broadens toward the north. Deformation of the syncline is gentle and no steep dips or major faults are evident.

The Coaledo Formation was deposited in a rapidly subsiding basin near the coast at a time the Coast Range was relatively stable. Deposition of the Bastendorff and middle Oligocene Tunnel Point Formations continued without deformation. By late Oligocene compression caused steep dips commonly 60-70 degrees in the Coaledo, Bastendorff and Tunnel Point while the older beds in the central Coast Range remained relatively stable with much gentler dips. This may have been a period of minor movement of the oceanic plate against the continent.

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SEDIMENTARY FACIES AND TRACE FOSSILS IN THE EOCENE DELMAR FORMATION AND TORREY SANDSTONE, CALIFORNIA

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Introduction

Purpose and scope

The seacliffs at Solana Beach (Fig. 1) are formed from terrigenous sedimentary rocks of Middle Eocene age. The cliff face, swept clean by winds and waves, reveals an intricate pattern of sedimentary structures and trace fossils, affording an opportunity for detailed investigation of the clastic facies. The purpose of this study is to report those processes -- biologic and physical -- that contributed to the original character of the sediments, and thus to describe the depositional environments.

Methods

Eighteen stratigraphic sections in the Delmar Formation and Torrey Sandstone (Fig. 1 and 2) were measured at Solana Beach. Sediment textures, physical sedimentary structures, body fossils and trace fossils were described. Terminology relating to bed forms and types of stratification is after Reineck and Singh (1973), unless otherwise noted. Names assigned to the rocks follow the textural classification of Folk (1968), and are based on field observations and on textural analysis in the laboratory. Procedures are detailed in Boyer (1974, p. 153). Biogenic sedimentary structures were described both in outcrop and in impregnated slabs prepared in the lab (Boyer, 1974, p. 98,99).

Geologic Setting

Mesozoic and Early Tertiary history of the San Diego area

The San Diego coastal area is underlain by Cretaceous and Tertiary sedimentary strata that rest unconformably on an igneous and metamorphic basement of late Jurassic and Cretaceous age (Bushee and others, 1963; Fife and others, 1967). Basement rocks are the Santiago Peak Volcanics (Black Mountain Volcanis of Hanna, 1926, p. 199-204) and parts of the southern California batholith.

Pronounced uplift in middle and late Cretaceous time brought basement rocks to the surface, where they contributed debris westward to a belt of non-marine conglomerates and marine siltstones, sandstones, and conglomerates known collectively as the Rosario Group (Kennedy and Moore, 1971; Jones and Peterson, 1973). During latest Cretaceous and early Tertiary time a widespread erosion surface with several thousand feet of relief developed across the basement complex and the most landward deposits of the Rosario Group (Lusardi Formation) (Peterson and Abbott, 1973). Upon this surface were deposited Eocene fluviatile, marginal marine, and fully marine clastic strata that in the San Diego

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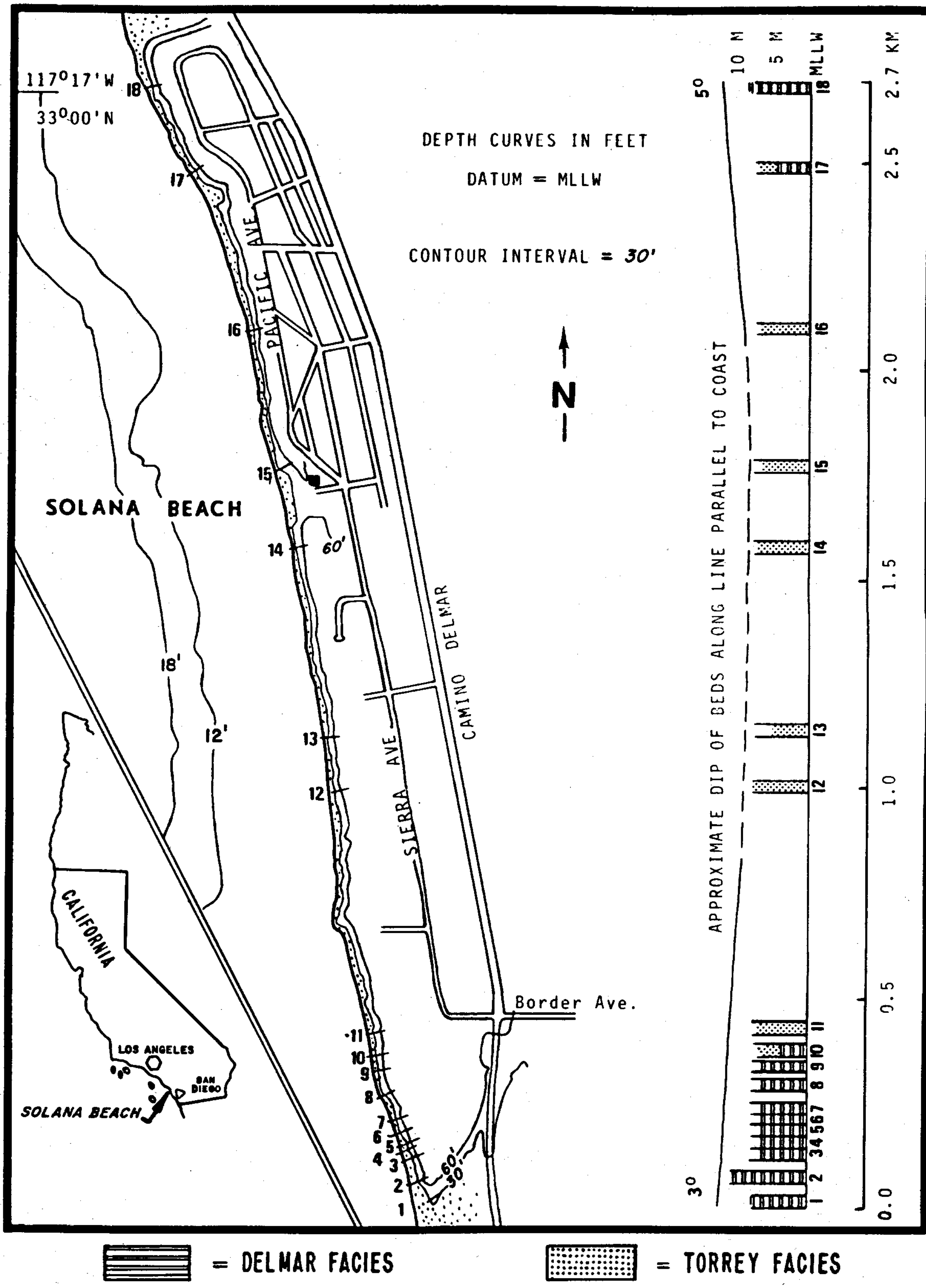
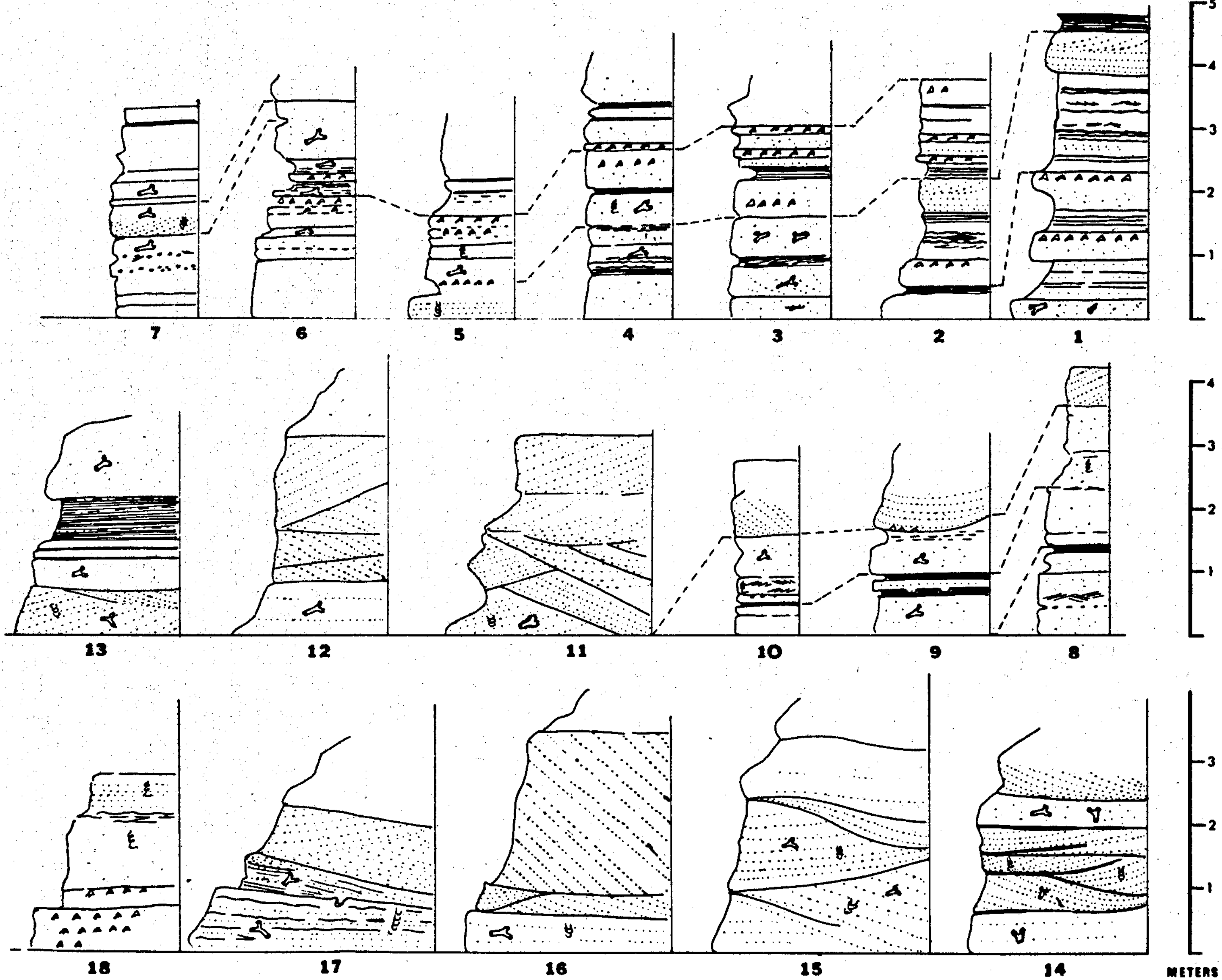


FIGURE 1. Locations of study area and of measured stratigraphic sections. Gross distribution of Delmar and Torrey facies are presented schematically at far right. Redrawn from U.S.G.S. topographic maps, including parts of 7 1/2' Del Mar and Encinitas quadrangles.

FIGURE 2. Graphic presentation of measured sections. For locations of sections refer to Fig. 1. Symbols are identical to those in Fig. 4.



area are approximately 700 m thick (Kennedy, 1973). The Eocene beds, including the formations investigated in this report, now crop out along the southern California coast.

Eocene rocks of the San Diego area, previous work and geologic history

The first geologic map of the San Diego area was made by Blake (1856) as part of a railroad survey. Since then, Ellis (1919), Clark (1926) and especially Hanna (1926, 1927) have contributed much to the geologic mapping of the region and to establishing formal stratigraphic nomenclature. Hanna defined the "Delmar Sand" and "Torrey Sand" as members of the La Jolla Formation, and assigned Delmar macrofossils to the Domengine molluscan stage (Middle Eocene) (Hanna, 1927).

Kennedy (1967) recently remapped the coastal area from Point Loma to Oceanside at a scale of 1:24,000, including the entire 7 1/2 minute Delmar quadrangle in which this study took place. Kennedy and Moore (1971) redefined stratigraphic nomenclature of the Cretaceous and Tertiary rocks and discussed their facies relationships; their analysis is summarized in Figure 3. Kennedy and Moore (1971) divided the Eocene strata into a Mid-Eocene La Jolla Group and Late Eocene Poway Group; these two groups include nine formations. The Delmar and Torrey members were raised to formational status and included in the La Jolla Group.

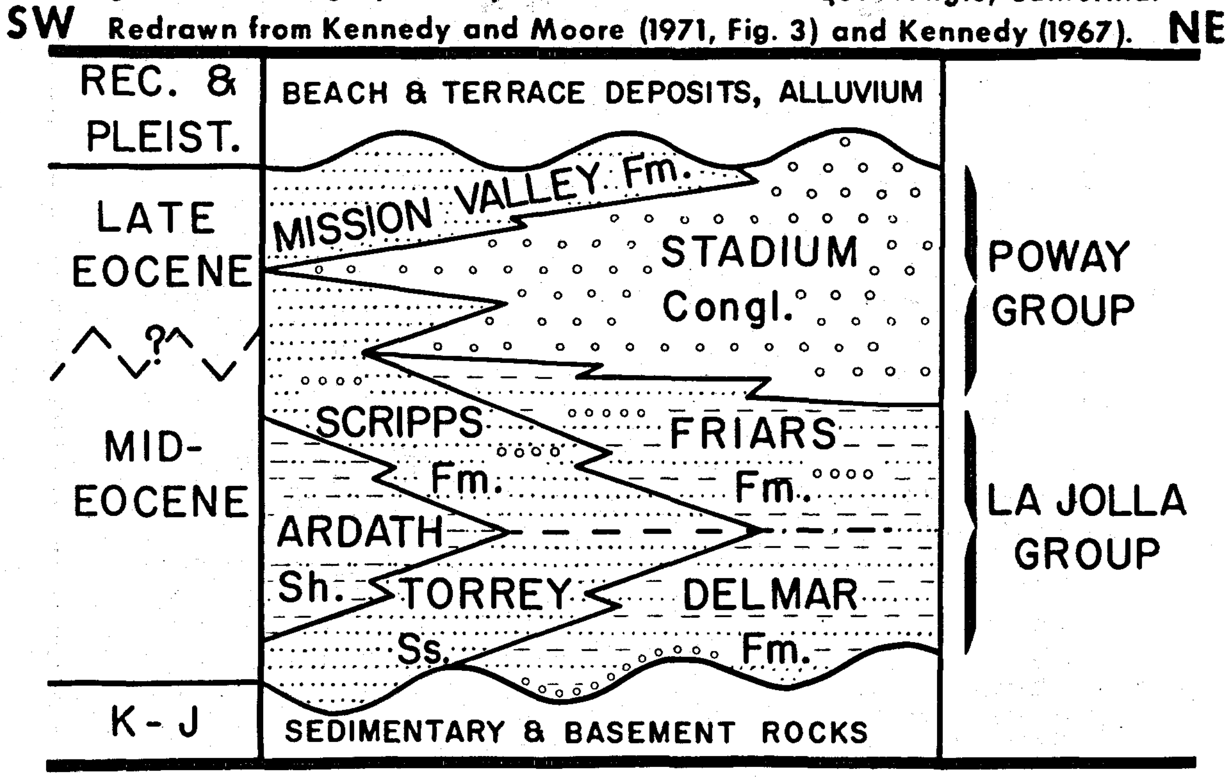
The Eocene formations record a series of interdigitations of marine and terrestrial deposits over a rather short lateral distance. The shelf and bathyal environments to the west are preserved now in the Ardath Shale of the San Diego coastal plain (Gibson, 1971; Kennedy and Moore, 1971; Steineck and others, 1972) and in some Middle Eocene units that outcrop on the channel islands of the continental borderland (Weaver, 1969; Howell and others, 1974; Yeats and others, 1974). The Ardath Shale contains coccoliths, planktonic and benthonic foraminifera and marine molluscs. Benthonic forams indicate water depths of 500-1500 m (upper middle bathyal) (Gibson, 1971), and coccolith zonation by Bukry and Kennedy (1969) suggests correlation with Lutetian strata in France (=Middle Eocene).

The Ardath interfingers with and transgresses over the Torrey Sandstone, which in turn interfingers with and transgresses over the Delmar (Fig. 3). Because both the Torrey and Delmar are correlative with part of the Ardath, they are considered to be Middle Eocene in age (Kennedy and Moore, 1971). The Delmar rests unconformably on basement rocks and interfingers eastward with non-marine deposits of the Friars Formation. The Friars contains terrestrial vertebrate fossils that according to Lillegraven (1973) belong to an "early Uintan North American land mammal age" (=Late Eocene).

The Delmar Formation and Torrey Sandstone

The Delmar Formation and Torrey Sandstone are time-transgressive units deposited in an interface zone between marine (Ardath) and terrestrial (Friars) environments. The Delmar is finer grained than the Torrey; it is characterized by a greater abundance of fossils and organic debris and by considerable biologic reworking. Delmar sediments are interpreted as deposits of a lagoon and associated tidal flats and tidal creeks (Kennedy and Moore, 1971; Boyer, 1974, p. 67-75).

Figure 3. Stratigraphic sequence in the Del Mar quadrangle, California. Redrawn from Kennedy and Moore (1971, Fig. 3) and Kennedy (1967).



The Torrey is coarser grained than the Delmar and its depositional features are dominantly those resulting from processes of physical sedimentation and reworking. Torrey sediments are interpreted to have been deposited in an offshore shoal or bar and in associated tidal deltas and channels (Kennedy and Moore, 1971; Boyer, 1974, p. 75-79). Torrey sands enclosed and then transgressed over Delmar sediments. Both formations are lens-shaped lithologic units that outcrop along the coast from 5-6 km north of Encinitas to Torrey Pines State Park, 20 km south. They are believed to extend southeastward in the subsurface and to have been eroded at their northwestward extent (Kennedy and Moore, 1971).

Delmar Formation The Delmar Formation is about 60 m thick (Hanna, 1926); about 15 m of nearly flat-lying Delmar strata are exposed at Solana Beach. The Delmar is highly variable laterally, so even in this relatively thin sequence diverse rock types and depositional features are displayed. A composite section (Fig. 4A) of the Delmar illustrates the rock types and sedimentary structures observed at Solana Beach outcrops.

The lower 9 m of the Delmar consists primarily of oyster beds, intensely bioturbated muddy sandstone, burrowed sandy mudstone, and interbedded silty sandstone, mudstone and clay-shale. The oyster beds are composed overwhelmingly of Ostrea idriaensis Gabb, but also contain a variety of other bivalve and gastropod shells in a sandy, calcite-cemented matrix. Muddy sandstones form 0.3-1.2 m thick beds that commonly are finer-grained upward and are capped by a layer of sandy mudstone. These beds contain scattered shells and molds of Ostrea and other molluscs. They also have abundant trace fossils, but in some beds distinct biogenic structures have been destroyed by intense and/or prolonged bioturbation. In contrast, interbedded silty sandstone, mudstone and clay-shale show relatively few trace fossils;

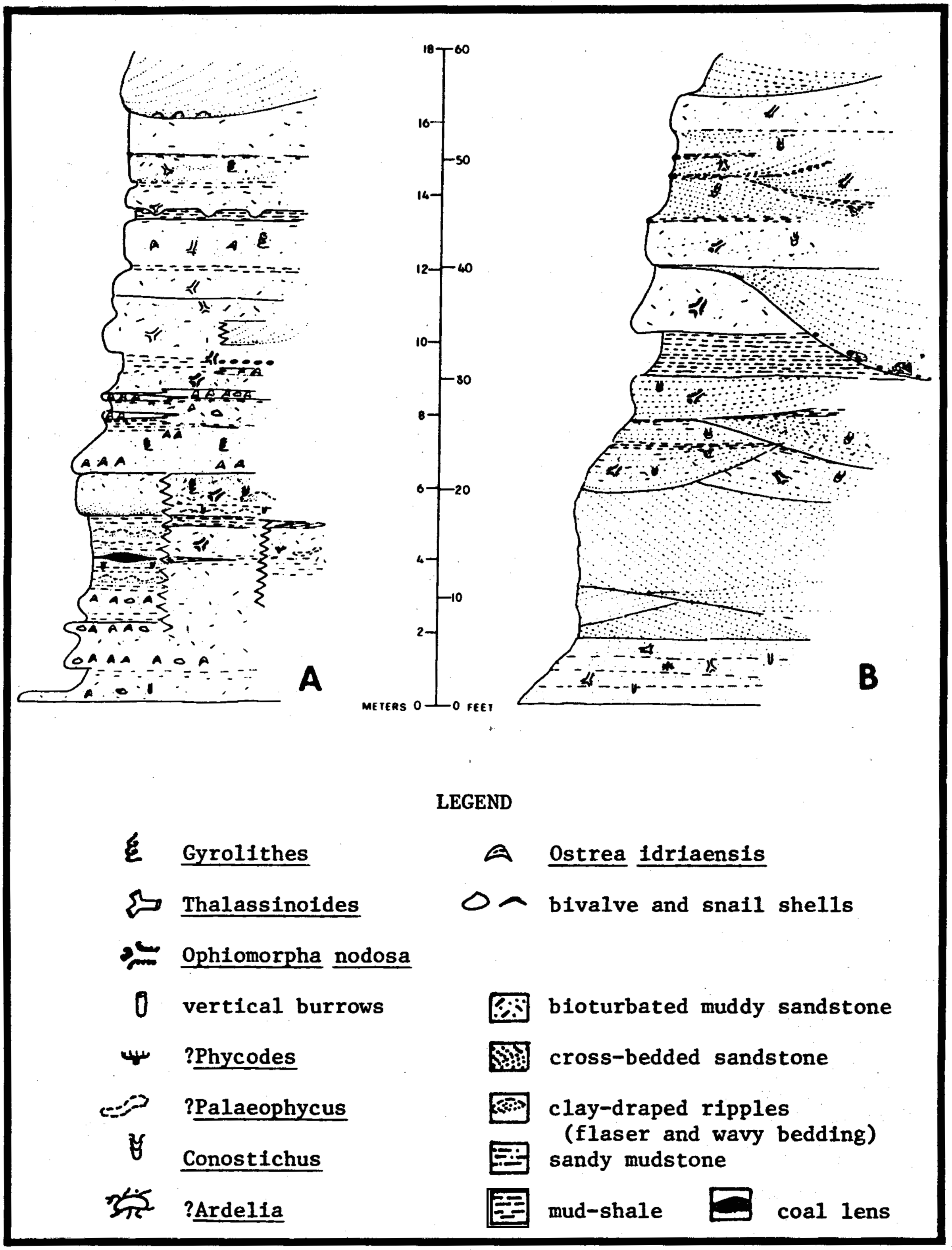


FIGURE 4. Generalized, composite stratigraphic sections of the Delmar Formation (A) and Torrey Sandstone (B) as they are exposed at Solana Beach

thus delicate planar and ripple lamination and flaser bedding are preserved. There is much carbonaceous material and even a small lens of coal in these beds.

The upper 6-7 m of the Delmar contains some scattered shell material but no biostromic oyster beds. The sediments are primarily muddy sandstones and sandy claystones; a vestige of medium-scale cross-bedding is preserved in some sandstone beds, but in general bioturbation is intense. A trough-shaped erosional surface marked by concave-downward pelecypod valves signals initiation of Torrey deposition.

Torrey Sandstone The Torrey Sandstone is at most 60 m thick (Kennedy and Moore, 1971); about 15 m of section are exposed at Solana Beach. A composite section (Fig. 4B) of the Torrey illustrates rock types and sedimentary structures observed in the Solana Beach outcrops. The Torrey is composed largely of broad, shallow troughs of cross-bedded muddy sandstone with mudstone lenses. Trace fossils are abundant, but overall bioturbation is not so intense that physical sedimentary structures are destroyed. There are some broad, 2-6 m deep channels in the Torrey that are filled with beds of slightly granular muddy sandstone that conform approximately to the channel shape. Burrows are rare in these beds.

Sediments

Sediments of the Delmar Formation and Torrey Sandstone are composed of clay-, silt-, sand- and some granule-sized grains. The sandstones are compositionally immature; they contain significant amounts of feldspars and lithic fragments. Many of the sandstones are texturally immature as well, containing 10-15 percent mud by weight.

Composition

The coarser-grained rocks of the Delmar and Torrey are subarkoses and arkoses, following the terminology of Folk (1968, p. 124) (Kennedy, 1973; Boyer, 1974, p. 28,55; J. W. Ericson, 1974, pers. commun.). The feldspars include orthoclase, plagioclase and a small amount of microcline. Biotite and muscovite compose up to 10-15 percent of the coarse fraction, and rock fragments from granitic, sedimentary (claystone and mudstone), silicic volcanic, and metamorphic rocks add another 1-6 percent. Minerals present in trace quantities include hematite, epidote, topaz, zircon, tourmaline, pyroxene, amphibole, and glauconite. According to Kennedy (1973), the clay-sized fraction consists of smectite and kaolinite. Carbonaceous material is present in most of the Delmar rocks: as fine debris in the sandy rocks, and, in the mudstones, as recognizable remains of grass and wood fragments that are concentrated along bedding planes. The Delmar also contains a small coal lens from which amber has been recovered (J. P. Kern, 1972, pers. commun.). The coal appears to be limited to a meter-wide pocket and may represent a tree trunk or large wood fragment.

Texture

Although the range of grain sizes is very similar for Delmar and Torrey sediments, the distribution of grain sizes is quite different in the two formations. The differences are of two types.

First, sand fractions of Torrey sediments are coarser and better sorted than those of the Delmar (Boyer, 1974, p. 154-156). The histograms in Figure 5 illustrate grain size distributions of some analyzed samples from the Delmar and Torrey. Three of four sand fractions from the Delmar exhibit a primary mode of fine sand (2.25-2.5Ø) and a secondary mode of medium sand (1.5-1.75Ø). In contrast, fine sand is a secondary mode or non-modal in all but one Torrey sample; medium sand (1.5-1.75Ø) is dominant, and very coarse sand and minor gravel are present in all samples. Sorting coefficients of Delmar sand fractions range from 0.83 to 1.09 (moderately to poorly sorted); sorting coefficients of all but one Torrey sand fraction are less than 8.3, as low as 0.7 (moderately well sorted to moderately sorted) (Folk, 1968, p. 46). The evidence discussed above indicates that Torrey sediments were subject to stronger and more persistent waves and currents than were sediments in Delmar environments.

The second major textural difference between Delmar and Torrey facies is that silt and clay are more abundant in the Delmar. Weight percent mud in Delmar sandstones ranges from 1.5 to 15.5 (see mud columns in Fig. 5), compared to mud contents of 7.6-12.8 percent in Torrey samples. Further, Delmar facies exhibit more and thicker beds of fine-grained sediment (Fig. 2). The reasons for these differences will be more obvious following a discussion (below) of the distribution of fines in general in the rocks at Solana Beach.

Sand- and mud-sized grains occur in very close association in both formations. There is mud interlaminated with sand in cross-bedded units, mud concentrated along ripple foresets (a type of flaser bedding), mud filling in ripple troughs and draping crests (flaser, wavy, and lenticular bedding using terminology of Reineck and Wunderlich, 1968), and mud in interstices between sand grains. There is evidence for several types of processes (listed below) that could contribute to the observed distribution of fine sediment.

(1) Silt and clay were deposited as fecal and other types of biogenic pellets. Probable fecal pellets have been recovered from mud-shale beds in the Delmar (Boyer, 1974, p. 23). Further, there are abundant body and trace fossils, in the Torrey and especially in the Delmar, that evidence an active faunal population that must have produced fecal pellets. A pellet would be hydrodynamically equivalent to a grain much larger than its constituent grains.

(2) Infauna introduced mud directly into coarser sediments by producing mud pellets and by mixing adjacent layers of sand and mud. Mud pellets that form burrow walls (Fig. 8B) or fill burrows are an example of this type of biologic mixing of coarse and fine sediments, as are the many churned, bioturbated layers.

(3) Much of the clay settled from suspension as floccules. Clay and silt have been observed together in single laminae of laminated mud beds. Since there is no evidence of biologic mixing, the clay and silt must have settled simultaneously -- the clay in floccules. Flocculation would have been aided by nuclei provided by abundant organic debris in the water column (van Straaten and Kuenen, 1958, p. 412).

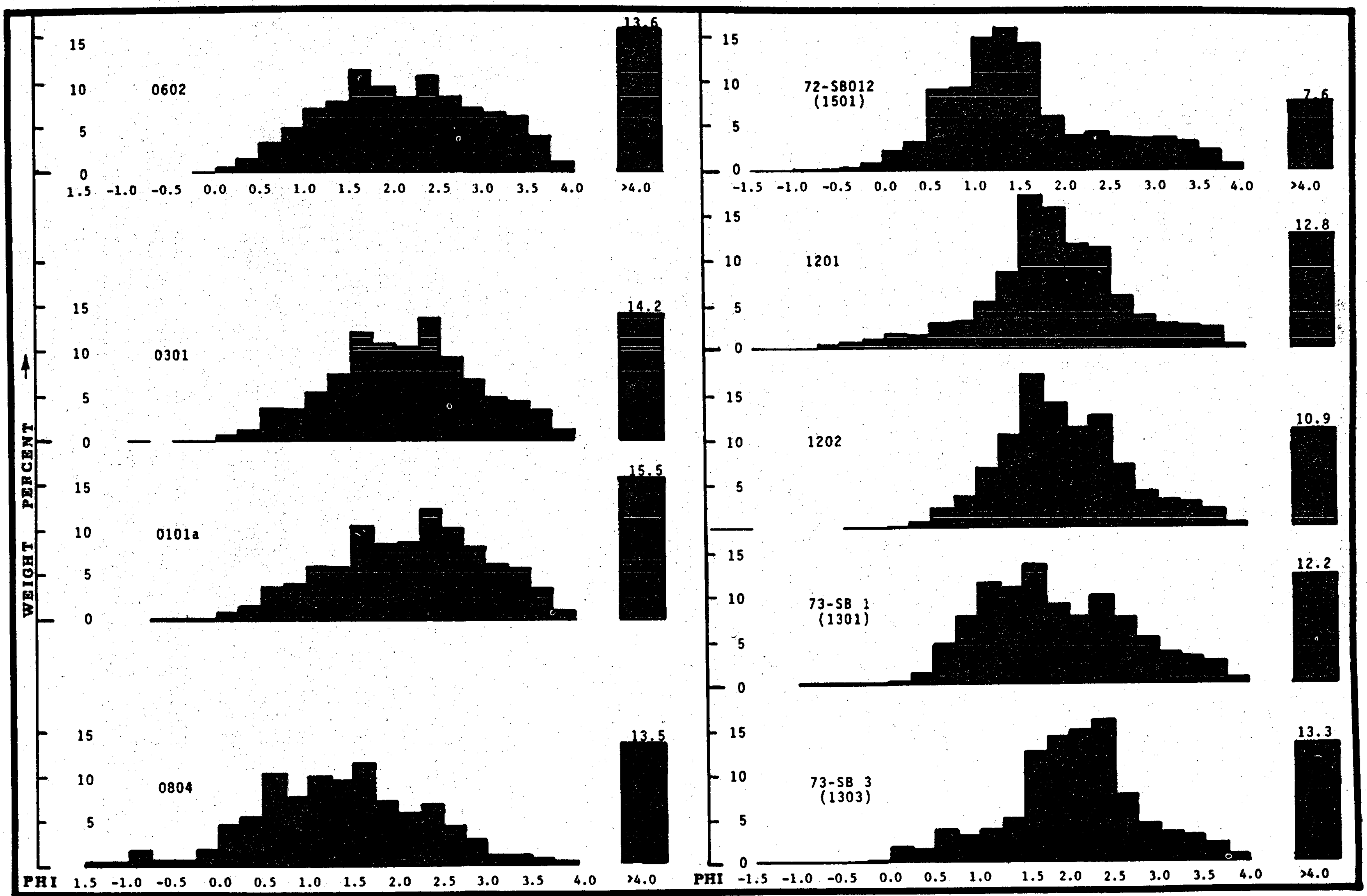


FIGURE 5 HISTOGRAMS SHOWING GRAIN-SIZE DISTRIBUTION OF SAND FRACTIONS OF SAMPLES FROM THE DELMAR FORMATION (LEFT) AND THE TORREY SANDSTONE (RIGHT). WEIGHT PERCENT MUD (SILT + CLAY) GIVEN IN COLUMNS TO RIGHT OF EACH HISTOGRAM.

The three processes discussed above were intensified in Delmar environments, because faunal densities were greater there (as indicated by more abundant body and trace fossils), and because there was more organic debris in the water (indicated by greater amounts of carbonaceous material preserved in the Delmar). Further, certain physical sedimentary structures in the Delmar (discussed elsewhere in this paper) suggest that fine sediment was concentrated shoreward by a variety of processes that are related to tidal cycles. These include fluctuations in energy levels caused by periods of tidal flow and slack, the "scour lag" and "settling lag" effects described by van Straaten and Kuenen (1958), and other processes that have been discussed by Postma (1961), Kuenen (1961, p. 492-495) and van Straaten (1965, p. 63-65).

Physical Sedimentary Structures

Some of the most striking and informative features in the Solana Beach outcrops are the physical sedimentary structures. In both Torrey and Delmar facies a variety of sedimentary structures occur that, along with evidence from trace and body fossils and from sediment textures, help to define the subfacies described in the latter part of this paper.

Physical sedimentary structures of the Delmar Formation

Physical sedimentary structures and bedding characteristics of the Delmar are more diverse and are on a smaller scale than those of the Torrey. The structures indicate sedimentary processes that commonly operate in tidally-influenced, protected, shoreline environments. There is evidence for frequent and radical fluctuations in physical energy levels, for both wave and current activity, for close juxtaposition in time and space of erosional and sedimentary events, and more generally, for heterogeneity of depositional processes in time and space. Specific structures are individually described and discussed below.

Interbedded sand and mud Interlaminated and interbedded sand and mud, and flaser, wavy and lenticular bedding are common bedding types, particularly in the lower part of the Delmar (Fig. 4A). The close association of mud and sand probably is a result of tidally-controlled deposition and biogenic pelletization. Sand is deposited from the traction load during tidal flow and ebb; mud settles from suspension during slack water (Reineck, 1960). The result is mud drapes that give rise to flaser, wavy, and lenticular bedding. Where fine sediment and organic debris have been reformed into pellets by organisms (Haven and Morales-Alamo, 1968; Pryor, 1972), the pellets can be deposited from the traction load, giving rise to mud laminae in foresets of rippled sand (Fig. 6A) and to mud interlaminated with sand in large-scale cross-bedded units (Fig. 7A).

Micrograded laminae A meter-thick, flaser-bedded sequence at section 1 (Fig. 2) exhibits four pairs of micrograded laminae (Fig. 6B). Each lamina grades upward from gray silt and fine sand to dark gray-green clay and is 2-4 mm thick. The laminae are persistent laterally for at least two meters (width of outcrop undisturbed by faults); the grains are well-segregated vertically acording to size. Probably the laminae were deposited from suspension in a very slow-

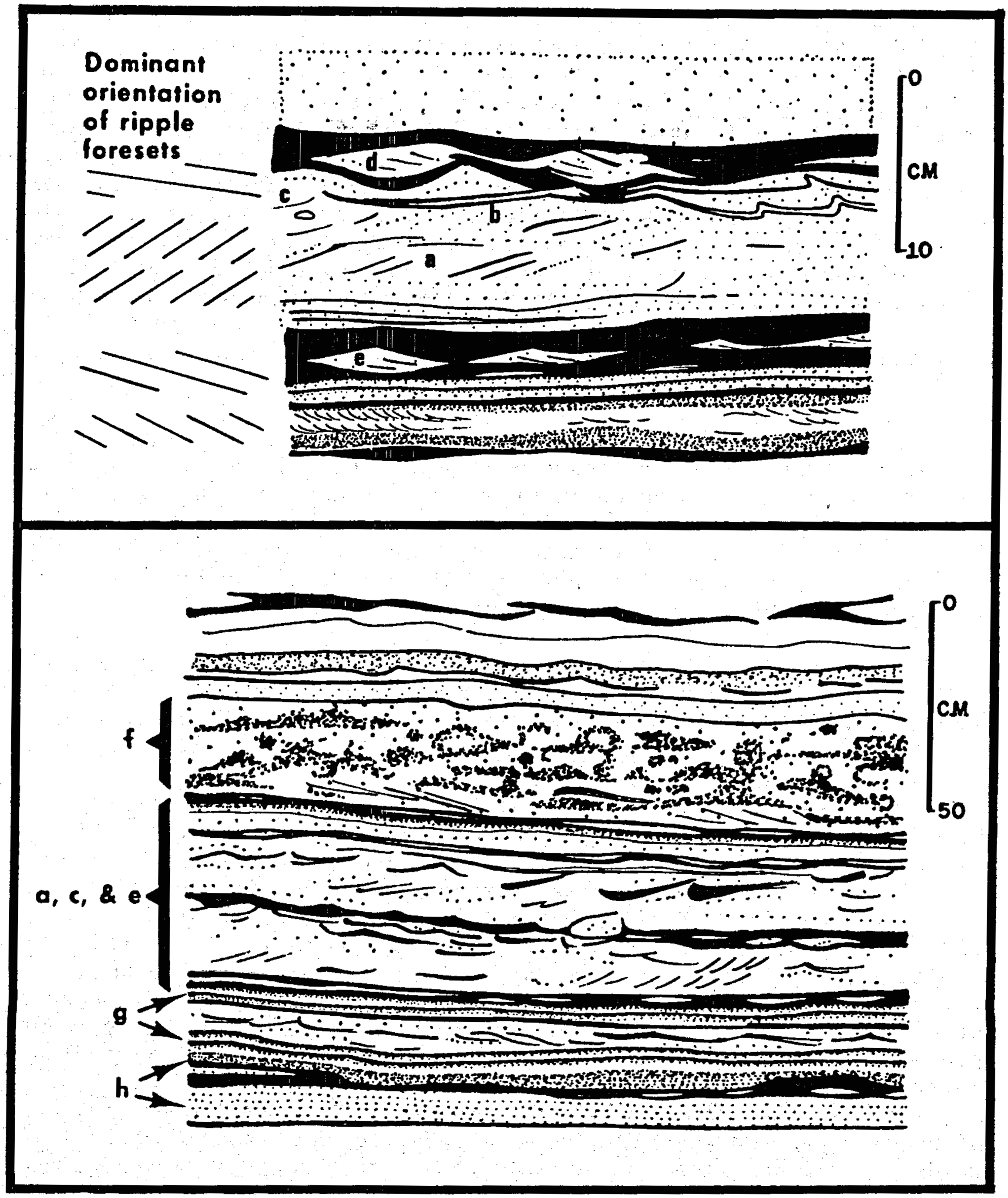


FIGURE 6. Physical sedimentary structures in the Delmar Formation, drawn from photographs of exposures normal to bedding. Legend: a = simple flaser bedding; b = bifurcated wavy bedding; c = wavy mud layer; d = lenticular bedding with connected lenses; e = lenticular bedding with single lenses; f = bioturbated mud layer (a biogenic structure); g = micrograded beds; h = laminated silty sandstone. Terminology after Reineck and Wunderlich (1968). Black = mudstone and clay-shale; dot pattern = muddy or silty sandstone and sandy siltstone.

moving or still body of water. The paired occurrences are quite striking and suggest deposition through tidal cycles.

Thicker mud beds The Delmar also contains relatively thick (greater than 5 cm) mud layers that exhibit millimeter laminae of pure clay-shale. Some of the mud layers are only a few meters wide; these may be plugs in abandoned, shallow channels. Other mud beds are more persistent laterally; these may have accumulated in areas of persistent high turbidity. Studies in Recent environments show that, if the concentrations of suspended sediment in water are sufficiently high, mud will be deposited at flow velocities that would normally keep such material in suspension (McCave, 1970; Oertel, 1973). This results in accumulations of thinly laminated muds that are associated with layers of much coarser sediment.

Laminated sand Planar laminated sands compose a small part of Delmar sediments; they are associated with interbedded sand and mud and with flaser bedding as shown in Figure 6B. Laminated sands are composed of fine and medium sand with some silt; beds are approximately 10 cm thick and grade upward into either interbedded sand/mud or rippled and cross-bedded sand. Some but not all laminated sand beds exhibit erosional contacts with underlying sediments.

These sands might have formed by swash and backwash (Reineck, 1963; Clifton, 1969), by currents in plane-bed phase of the upper flow regime (Simons and others, 1965, p. 36, 37), or by deposition from suspension clouds produced by channel currents or shoaling waves (Reineck, 1963).

Cross-stratification At least four types of cross-stratification have been observed in Delmar outcrops: (1) current ripple and (2) oscillation ripple cross-stratification, (3) medium scale trough cross-stratification, and (4) tabular sets of planar, inclined beds.

(1) and (2) Current and oscillation ripples associated with mud flasers (Fig. 6A) are composed of fine sand and silt. Oscillation ripples are formed by wave action; in Delmar strata they are much rarer than current ripples. Current ripples associated with larger scale cross-bedding are composed of muddy fine and medium sand. They occur above larger cross-sets and may represent waning currents or ripples superposed on megaripples.

(3) Trough cross-stratified sets are 15-20 cm thick and composed of muddy sand. One set clearly was deposited in a shallow channel 18 cm deep and 1.6 m wide. Other sets appear to be deposits of migrating, lunate megaripples.

(4) Tabular sets of planar, inclined beds occur at the base of 0.5-1.0 m thick units of muddy sandstone that grade upward to sandy mudstone. The lower bounding surface is planar to slightly irregular; inclined laminae dip 15-24 degrees and are discordant with the basal surface. These structures probably were formed by migration of straight-crested megaripples.

Sedimented shell beds Physically accumulated shell deposits in the Delmar Formation are preserved as decimeter-thick shell hashes and as thin stringers of Ostrea shells. The shell hashes observed are lenses about 10 cm thick and a meter or two long that are composed of whole and fragmented bivalve and gastropod shells other than Ostrea. Pelecypod valves occur in almost all orientations but exhibit a slight preference for concave upward positions. The shells are in a matrix of muddy sand that grades upward to sandy mudstone. The entire bed is about 20 cm thick and is intensely bioturbated. The absence of Ostrea and the broken shells suggest that the shell hashes were physically sorted and deposited. The shells perhaps were concentrated by storms (Howard and Reineck, 1972, p. 102), or they may be lag accumulations at the base of a shallow channel.

A more common shell deposit is thin stringers of large shells, chiefly Ostrea, that define the base of approximately meter-thick, intensely bioturbated, graded beds. The shells could be a lag deposit marking the base of a migrating channel; the entire channel-fill was then reworked by burrowing organisms. Alternatively, the shells might have been eroded from nearby oyster reefs by physical (wave) or biologic (burrowers) undercutting. Currents and waves then redistributed the shells and concentrated them slightly.

Bored claystone beds and mud-pebble beds Claystone clasts in Delmar sediments indicate exposure and erosion of cohesive claystone beds (Frey and Howard, 1969, p. 435). In fact, there is direct evidence for this process: a claystone bed that was bored by organisms is overlain by claystone clasts derived from it (Boyer, 1974, Plate 5). The claystone conformably overlies a muddy sandstone; its upper contact is very irregular but sharply defined. Cylindrical borings penetrate the bed from the top down and are filled with sediment from the overlying bed. The claystone bed probably was exhumed intertidally by waves, or by erosive currents in the inner sublittoral zone.

Physical sedimentary structures of the Torrey Sandstone

Physical sedimentary structures are on a considerably larger scale in the Torrey than in the Delmar. Exposed in the Solana Beach outcrops are large-scale trough cross-bedding, large channels, large-scale wedge sets of planar cross-bedding, and a minor amount of interbedded sandstone and mudstone with flaser bedding. Most of these structures formed by migration of channels, subaqueous dunes and megaripples[1], and by construction of sand lobes and bars into local depressions. There is no evidence in these outcrops for sand deposition in the wave swash zone of beaches or exposed bars. Rather, the Torrey structures are those characteristic of shoals and tidal deltas.

Trough cross-bedded sandstone A large part of the Torrey is composed of large-scale trough cross-bedded sandstone, illustrated in Figures 7A and 11-IV. The troughs are 5-30 m wide and 1-4 m deep; some of the sets are terminated by an erosional surface and/or a mud lens. Stratification has in most cases been disrupted but not destroyed by burrowers; apparently sedimentation rates were sufficiently rapid to

[1] As defined by Coleman (1969), dunes are distinguished from megaripples by size. Dunes are larger forms, with heights of 5-25 feet (1.5-7.5 m) and lengths of 140-1600 feet (42-480 m).

prevent complete destruction of bedding by infauna. These structures probably were formed by migration of subaqueous dunes and/or by infilling of channels (Reineck and Singh, 1973, p. 63, 92). Both of these processes result in deposition of curved, inclined beds in a trough-shaped scour, when viewed in section approximately normal to current flow. The mud lenses suggest that movement of bed forms was sporadic, and that mud accumulated in depressions and scours during times of less vigorous current and wave activity.

Large channels Four large channels (Fig. 7C) are exposed in the Solana Beach seacliffs; these channels are 2-6 m deep and up to 80 m wide (Fig. 11-IV). Very coarse sand, gravel, and some claystone clasts up to 30 cm across mark the base of the channels, which are filled with slightly granular muddy sandstone. Most of the internal structures are on the same size scale as the trough itself; the channels are filled in down-bowed beds that follow the shape of the scour surface. In one channel, megaripple cross-stratification is superposed on a larger-scale pattern of lateral channel fill.

All four channels are characterized by a unique lack of biogenic sedimentary structures that is especially striking because adjacent beds exhibit abundant trace fossils. This condition is in contrast to major tidal channels and inlets in Recent environments, which normally support an active infaunal population (Warme, 1971, p. 38, 39). The channels either were created by fresh-water flow and/or they were scoured and filled very rapidly, before burrowers were able to invade the substrate. Possibly the channels formed after periods of high rainfall. At this time brackish water would be flushed out of the lagoon, through the Torrey shoal. Scour and fill would occur quickly, perhaps in a few hours or days.

Planar cross-bedded sandstone Outcrops at section 10 of wedge-shaped sets of planar cross-bedded sandstone are shown in Figure 7B. The sediment (sample 1202, Fig. 5) is slightly granular muddy sandstone; the sand fraction is better sorted (σ_I = 0.7 or moderately well sorted) than any other sand collected from the Torrey or Delmar. Like the channels, these deposits have experienced little or no biogenic reworking.

The cross-bedded sets appear to have been generated either by migration of straight-crested subaqueous dunes or by sediment avalanching down the back of a bar or lobe of sand. The absence of trace fossils again suggests rapid deposition, perhaps related to storm activity. It is also possible that these beds are eolian in origin. However, it seems more likely that they were deposited subaqueously, because the sediments contain about 10 percent mud and because the sand is rather coarse, exhibiting a primary mode of medium (1.5-1.75ϕ) sand.

Interbedded sandstone and mudstone A thin sequence of interbedded sandstone and mudstone is exposed in the lower part of the Torrey, at section 17. The beds are flat-lying but are interrupted by low-angle erosion surfaces draped with mud. Trace fossils are abundant. The mud accumulated both in millimeter-laminae and in flasers.

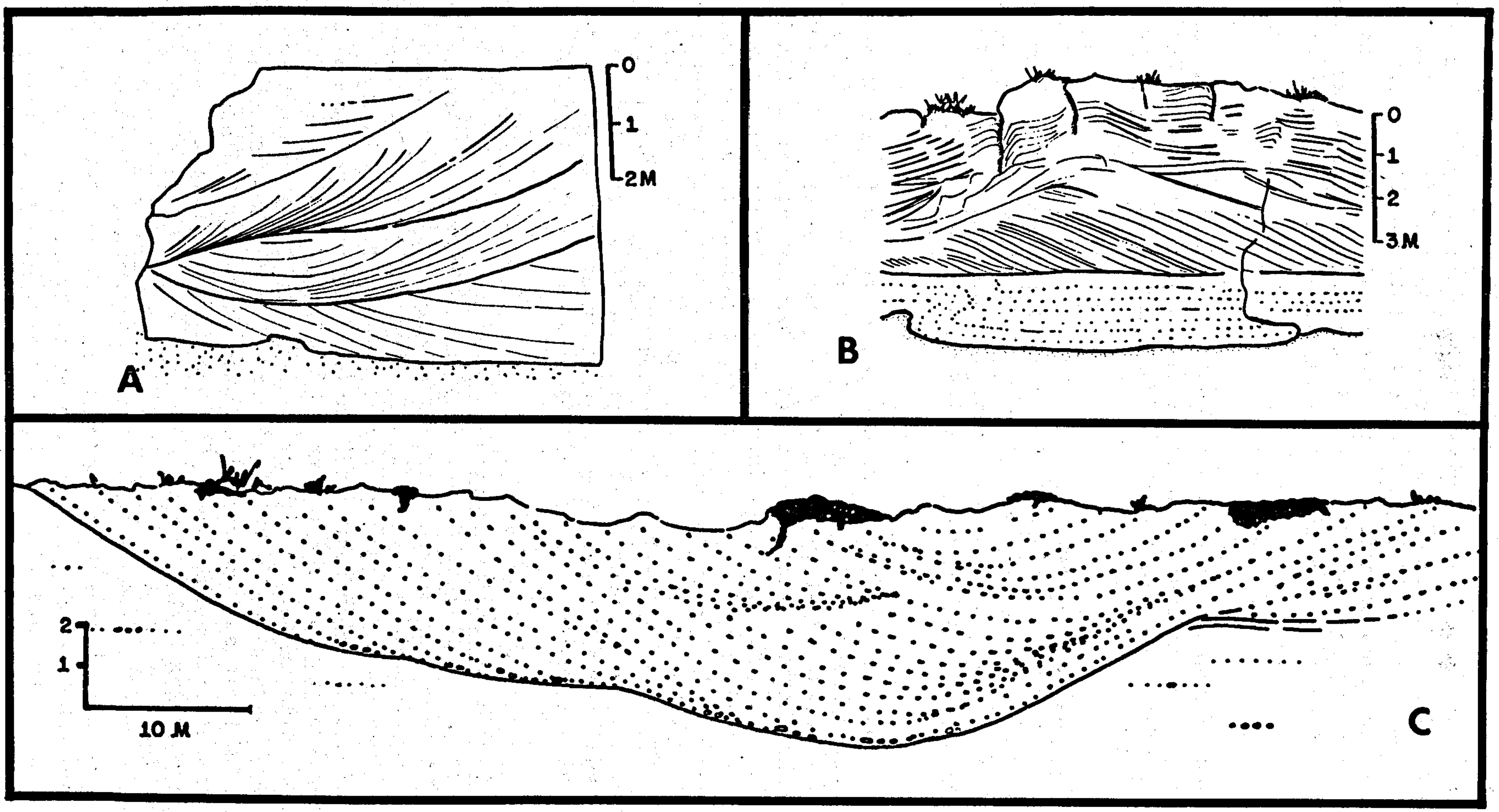


FIGURE 7. Physical sedimentary structures in the Torrey Sandstone. (A) View of cliff face near section 13. Large-scale trough cross-beds of slightly granular muddy sandstone are exposed in section oblique to current flow. (B) Cliff face at section 12. Wedge sets of planar cross-bedded sandstone rest conformably on horizontal beds of burrowed, muddy sandstone. (C) Large channel in section approximately normal to channel axis. The channel filled by lateral migration of the banks from left to right. Vertical exaggeration = 2X. A, B, and C drawn from photographs.

The interbedded sandstone and mustone beds were deposited by much weaker currents than those responsible for much of Torrey sedimentation. They are similar to Delmar deposits and appear to be transitional with them, as the oyster and flaser beds characteristic of Delmar facies crop out only a few tens of meters to the north, at section 18. Interbedded sandstones and mudstones probably accumulated in the intertidal zone, in tidal flats or in local depressions protected by shoals and bars.

Body Fossils

The Delmar Formation and Torrey Sandstone contain both microfossils and macrofossils. Macrofossils are particularly abundant in the Delmar, where the assemblage is characteristic of brackish water environments (see below).

Macrofossils in the Delmar Formation

The most diverse assemblage of molluscan fossils is preserved in cemented beds dominated by Ostrea idriaensis Gabb. The oyster beds are particularly interesting because they represent in situ oyster reefs; many of the oysters are preserved in living position with valves articulated.

Other mollusc species have been studied in the reefs, in sedimented shell beds, and as molds and casts in muddy sandstones. Hanna (1927) identified 16 species of Pelecypoda and 16 of Gastropoda; he correlated them with the Domengine molluscan stage (Mid-Eocene) defined by Clark (1926). Hanna (1927, p. 257) considered the assemblage to indicate "brackish water conditions". C. R. Givens (1973, pers. commun.) has recognized an additional four molluscs, two of them species misidentified by Hanna (see Boyer, 1974, Fig. 11). He did not, however, find either Turritella applinae or Turricula praeattenuata, two typically marine species common to Eocene units of the San Diego area that were deposited in sublittoral zones. Givens' environmental interpretation, in agreement with Hanna's, is that the Delmar fauna is "definitely brackish".

Macrofossils in the Torrey Sandstone

Macrofossils are present only rarely in the Torrey Sandstone. At Solana Beach mollusc shells were observed at one locality: ironstained outlines of a few, completely-leached pelecypod valves rest concave downward at the base of a large channel at section 9. The lack of body fossils is in part owing to poor preservation frequently encountered in coarse-grained, terrigenous rocks such as the Torrey Sandstone. Certainly trace fossils in the Torrey attest to an active fauna (see below). Ostrea shells, however, are exceptionally thick and resistent to leaching and abrasion, so their absence here indicates that they did not live in Torrey environments. Possibly the oysters could not survive the rigors of repeatedly shifting sands.

Microfossils

Palynomorphs recovered from mud-shale beds of the Delmar Formation and Torrey Sandstone include pollen, spores, hystrichospheres, and dinoflagellates. There are at least 44 genera of pollen and spores as well as several undescribed genera and species (Elsik and Boyer, in prep.). The age of the flora is Middle Eocene, based on angiosperm pollen type and diversity; it correlates well with Mid-Eocene assemblages from the Gulf and Pacific coasts (Elsik and Boyer, in prep.). Environmentally, the palynomorphs indicate a warm, humid climate, based on similarities to the Chalk Bluffs flora of northern California (Andrews, 1961, p. 200) and on the abundance of pollen of broadleaf trees and several tropical plant genera.

Other microfossils recovered from the Solana Beach outcrops include a single cast of an ostracode valve and some possible arenaceous foraminifera.

Trace Fossils

Animals living in the sediment or on the sediment surface have left their mark on almost every bed and lamination in the Solana Beach outcrops. The abundance of traces is particularly striking in the Delmar, where many beds have been so thoroughly churned by organisms that no discrete structures -- either physical or biogenic -- have been preserved. The physical environment in both Delmar and Torrey facies apparently was at all times hospitable to a diverse and plentiful infauna; variations in abundance of traces depended on faunal densities supported by each sub-environment, and on sedimentation rates and frequency and depth of physical reworking.

Trace fossils present in the Solana Beach outcrops are listed and described below. Each ichnologic name applies only to the lebenspur; it does not refer to the trace-making organism.

It is well known that similar traces are made by different organisms, and that a single organism can produce widely varying traces. As a result there is an unneccessary and confusing proliferation of names in ichnological literature. It is also generally true, however, that "trace fossils must be named to survive" (Osgood, 1970, p. 295). Therefore in this study a trace which does not fit readily into a previously described and named ichnogenus will wherever possible be assigned to the ichnogenus that most closely resembles it. Each description applies only to the trace fossil as it appears in Solana Beach outcrops and is not intended as a definition of the ichnogenus or ichnospecies. (For more detailed descriptions and illustrations, refer to Boyer, 1974, p. 100-152).

Trace fossils common to both Delmar and Torrey facies

Biogenic sedimentary structures that are characteristic of both formations are listed below in approximate order of decreasing abundance.

Ophiomorpha nodosa Lundgren 1891 - Figure 8A, B

Description: Cylindrical, branching burrow with smooth inner surface and nodose exterior. Burrow walls are constructed from a single layer of balls of mud and fine sand. The burrows divide in side- or Y-branches, usually at an angle of 90-120 degrees. *Ophiomorpha nodosa* (small form) are common trace fossils in bioturbated muddy sandstones and laminated sandstones of the Delmar. Inner diameters of burrows range from 0.8-2.0 cm; pelleted walls are 0.2-0.5 cm thick. Burrow orientations are chiefly horizontal. (Note: The pelleted burrow Ophiomorpha is continuous with a non-nodose, mud-walled burrow known as Thalassinoides Ehrenberg 1944; the two traces probably were constructed by the same organism and thus are considered together in this paper.) Ophiomorpha nodosa (large form) is abundant in trough cross-bedded sandstones of the Torrey. Inner diameters of burrows are 2.5-5.0 cm; walls are 0.5-1.5 cm thick. Burrow orientations are chiefly vertical.

Interpretation: Ophiomorpha is presently constructed by at least two species of the ghost shrimp Callianassa (Frey and Mayou, 1971; Hertweck, 1972, p. 136, 150-155); fossil Ophiomorpha probably also were built by decapod crustaceans, possibly of the genus Callianassa (Chamberlain and Baer, 1973). Although Ophiomorpha has been documented in deep water deposits (Kern and Warme, 1974), it is most characteristic of littoral and shallow neritic facies (Weimer and, Hoyt, 1964). In the Delmar and Torrey units, Ophiomorpha nodosa (large form) was built by a rather large crustacean that lived deep in shifting sands of the Torrey; the progenitor of Ophiomorpha nodosa (small form) was smaller and constructed less sturdy, shallower burrow systems in the protected Delmar lagoon.

Conostichus Lesquereux 1876 - Figure 8D

Description: Vertically-oriented locomotion trace in which successive strata are bowed down over a roughly circular area to form a cone of disturbed sediment. In axial section the distorted strata look like nested U's or V's. Conostichus is most abundant in cross-stratified sandstones of the Torrey, but is common in Delmar sandstones as well. The structures vary greatly in size, from 10 cm to several decimeters long and 5 to 15 cm wide.

Interpretation: Conostichus probably results from vertical migrations of infauna. Similar structures are known to be produced by burrowing anemones (Shinn, 1968; Schaefer, 1972, p. 289-290) and by certain lamellibranch bivalves (Reineck, 1958).

Vertical Burrow With Spreiten - Figure 8C

Description: Dwelling burrow and locomotion trace that is a vertical, rarely branching tube with curved, concave upward spreiten inside. Vertical burrows with spreiten are common traces in muddy sandstones and interbedded sandstone and mudstone of the Delmar and in cross-bedded Torrey sandstones. Burrows are up to 17-20 cm long and are 0.7-1.5 cm wide; the spreiten are at least 0.3 cm apart vertically.

Interpretation: Vertical burrows with spreiten can originate either (1) by physical meniscus-filling of an open burrow, or (2) as dwelling burrows of infauna such as anemones or bivalves. The spreiten form when the animal migrates upward and small amounts of sediment settle to the bottom of the tube (Schaefer, 1972, Fig. 165 and 223).

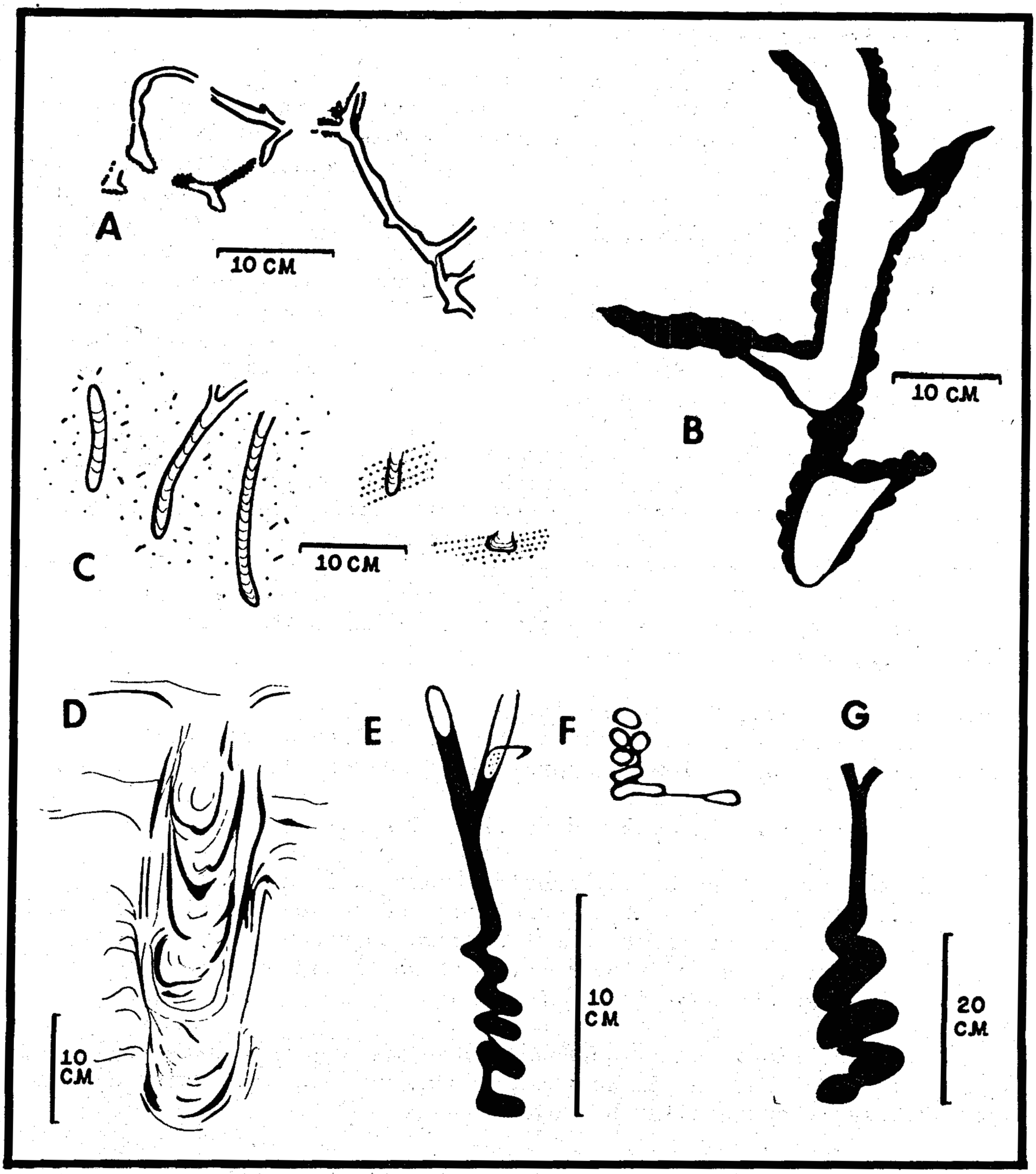


FIGURE 8. Trace fossils common to both the Delmar Formation and Torrey Sandstone. (A) Ophiomorpha nodosa (small form) grading into Thalassinoides in a burrow system exposed on a bedding plane in the Delmar. Note enlarged turnarounds at branchings. (B) O. nodosa (large form) in exposure perpendicular to bedding, Torrey Sandstone. Note size difference between specimens from Delmar (A) versus Torrey (B) facies. (C) Vertical burrows with spreiten in muddy sandstones of the Delmar and Torrey. (D) Conostichus in cross-bedded sandstone, Torrey Ss. (E) Gyrolithes in the Delmar. Note vertical upper access shafts. (F) Gyrolithes in the Delmar Fm. Note horizontal lower access shaft. (G) Gyrolithes in the Torrey Ss. Note difference in size from Delmar specimens (E,F). In drawings A,B,E,F, and G: black = mud.

Gyrolithes Saporta 1884 - Figure 8E-F

Description: Dwelling burrow that is loosely coiled and is oriented upright (coil axis vertical). The burrow shaft is roughly circular in cross-section and has a smooth mud wall. Some specimens exhibit a vertically-oriented, branching access shaft connecting to the upper end of the coiled shaft; a lower, horizontal access shaft also is present in a few Gyrolithes. Gyrolithes (small form, Fig. 8E, F) is a common lebensspur in bioturbated muddy sandstones of the Delmar. It exhibits 4-5 coils in a coiled section 4.0-13.0 cm long. Burrow walls are 0.1-1.5 cm thick; coil and shaft diameters are 2.0-3.5 cm and 0.5-1.3 cm, respectively. Gyrolithes (large form, Fig. 8G) is documented from a single specimen in cross-bedded Torrey sandstone; it is about 40 cm long and has a shaft diameter of 2-3 cm.

Interpretation: Like Ophiomorpha nodosa and Thalassinoides, Gyrolithes probably was constructed by a decapod crustacean. Although no direct connections between Gyrolithes and Ophiomorpha were observed in the Solana Beach outcrops, such connections have been noted by other workers (Kilpper, 1962; Keij, 1965; Kennedy, 1967; C. T. Siemers cited in Gernant, 1972). Further, in Solana Beach outcrops the two burrows are very similar in morphology, structure, size, and distribution (Boyer, 1974, p. 110, 114).

Trace fossils of the Delmar Formation

Lebensspuren that generally are restricted to Delmar facies are listed and described below in approximate order of decreasing abundance.

Small Horizontal and Vertical Burrows

Description: Sinuous, cylindrical burrows 1 cm or less in diameter that branch, cross-cut one another, and do not exhibit preferred orientations in the sediment. Most burrows in sandy sediments have mud walls; burrows in muddy sediments are not lined but are sand-filled. Burrows are most abundant in mudstone and very muddy sandstone.

Interpretation: Small burrows probably were created by vagile deposit feeders that dig in search of food, but also maintain the burrows briefly as dwelling burrows.

Dendritic Burrows - Figure 9E

Description: Mud-filled burrows that are oriented mainly normal to bedding and that branch upward in a dendritic pattern. Burrows are less than 5 mm in diameter but extend several decimeters vertically in the sediment. Dendritic burrows are common traces in bioturbated, muddy sandstones of the Delmar.

Interpretation: Polychaete worms are likely progenitors of these burrows. Somewhat similar burrow systems are constructed by modern polychaetes in the upper offshore of Sapelo Island, Georgia (Hertweck, 1972, p. 132, 133).

Vertical Movement Paths - Figure 9A

Description: Vertically-oriented columns or cones of churned sediment that are up to 60 cm long and 5.10 cm in diameter. The structures are well-defined burrows at their base, but become less distinct upward. Vertical movement paths are restricted to sequences of interbedded sandstone and mudstone.

Interpretation: Vertical movement paths probably were created during rapid, emergency ascents by animals in response to burial under freshly deposited sediment. The paths widen upward, suggesting that the upper layers of sediment were less compacted and more watery.

?Phycodes Richter 1850 - Figure 9B, C

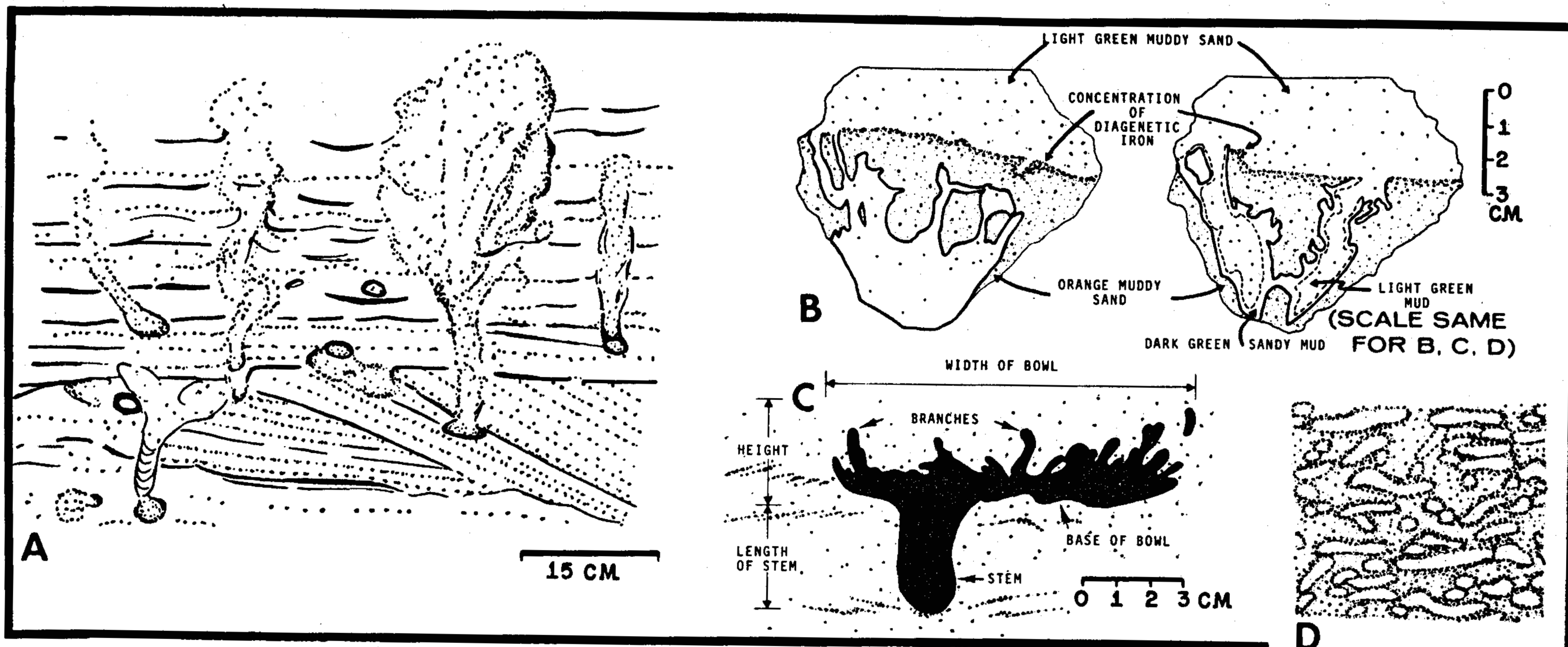
Description (For morphologic terminology refer to Fig. 9C): A bowl-shaped grouping of mud-filled tubes. The tubes are bundled together and are indistinguishable near the base and center of the bowl, but separate as they extend upward and outward with concave-upward curvature. Individuals range in shape from nearly circular to oblong, and are 6-15 cm wide; height of the trace averages 5-6 cm. Mud-filled branches are about 2 mm in diameter. A few specimens possess short, cylindrical stems about 2 cm in diameter and up to 5 cm long, extending downward from the base of the bowl.

Interpretation: These bowl-shaped structures were constructed endogenetically, probably by a deposit feeder. The organism might have been a burrowing brittle star that anchored itself in the sand and extended two or three arms to the surface to collect edibles (Boyer, 1974, p. 128, 129), much as the ophiuroid Hemipholus elongata behaves today (Hertweck, 1972, p. 138). Hemipholus lines the sediment around its arms with mud, so that various positions of the arms generate distinct burrows that converge downward. The Delmar Phycodes, on the other hand, could be the feeding burrow of a tentaculate detritus feeder such as an anemone; the branches would then represent positions of tentacles extended to the sediment surface. Alternatively, a deposit-feeding worm could have repeatedly burrowed up and out from a central area, stuffing each burrow (branch) with fecal material and mud as it returned to its point of origin.

?Palaeophycus Hall 1847 - Figure 9D

Description: Unlined, cylindrical burrows that are parallel or subparallel to bedding. The burrows do not branch, but wind back on themselves and interpenetrate so that they are quite dense. Burrows are nearly circular in cross-section and measure 0.4-0.5 cm in diameter. The infilling sediment is somewhat lighter colored than the matrix, and mica flakes are concentrated at burrow peripheries. Palaeophycus occurs in only one, meter-thick bed of micaceous muddy sandstone.

Interpretation: Palaeophycus was probably created by locally dense populations of small crustaceans, worms, or gastropods plowing through the sediment in search of food.



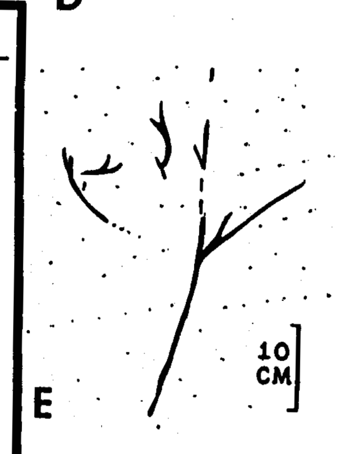


FIGURE 9. Trace fossils of the Delmar Fm. (A) Vertical movement paths in cross-bedded sandstone and flaser-bedded sand and mudstone. The organisms occupied the burrows at the base of each structure, but were forced to abandon them when buried too deeply by fresh sediment. The irregular, enlarged areas of the structures perhaps are caused by increased water content in upper layers of sediment, or by thixotropy induced by movements of the animal. (B) ?Phycodes in muddy sandstone. Right, an exposure normal to bedding; left, section cut parallel to exposure surface. Pure mud is concentrated in the inner part of the main branches; sandy mud is pushed to the perimeter. The branches extend upward to a surface of color change (orange to light green) that is parallel to bedding. (C) ?Phycodes viewed normal to bedding, illustrating morphologic terminology. Black = dark green mud and sandy mud. (D) ?Palaeophycus in fine, muddy sandstone. The interior of the burrows is lighter than the matrix sediment, and heavy minerals are concentrated at their periphery. (E) Burrow system in outcrop normal to bedding. Black = mud burrow fill.

Borings in Claystone

Description: Roughly cylindrical, non-branching tubes that penetrate downward from the eroded, irregular, upper surface of a claystone bed. The tubes are filled with sediment from an overlying bed. The tubes are 1.0-1.5 cm in diameter, extend downward up to 15 cm, and are densest near the upper surface of the claystone.

Interpretation: These tubes are borings, excavated by organisms when the clay was already stiff and cohesive. Such borings are presently made by some pelecypods in old marsh deposits exhumed intertidally at Sapelo Island, Georgia (Frey and Howard, 1969, p. 435).

Trace fossils of the Torrey Sandstone

Lebensspuren that generally are restricted to Torrey facies are listed below in order of decreasing abundance.

Surface Depressions - Figure 10B, C

Description: Roughly circular structure in which laminae have been pushed downward from a bedding plane or erosional surface. Surface depressions range in size from 5 cm wide and 12 cm deep to 20 cm wide and 30 cm deep.

Interpretation: Surface depressions are probably polygenetic. They could be resting traces made by organisms seeking temporary shelter in the sediment, or they could be shallow burrows of organisms that must maintain contact with the water-sediment interface. Similar traces are presently created by some burrowing crabs and cumacean crustaceans (Schaefer, 1972, p. 385-388, 392, 393).

Collapse Structure - Figure 10D

Description: Cone-in-cone structure in which vertical displacement of beds increases downward, and diameter of disturbed area decreases downward. Periphery of cone may exhibit small normal faults dipping towards the axis of the trace. Down-dropped laminae are continuous with surrounding stratification. Collapse structures are common in cross-bedded sandstones. They vary greatly in size, and can be up to 17 cm across and 50 cm deep. Large burrows are present beneath the tips of most collapse structures.

Interpretation: Collapse structures were created by sudden, downward displacement of sediment into an open burrow. Sediment immediately above the tube pours in, leaving steeply down-turned cutoff beds along the periphery and a disturbed, structureless zone immediately above the tube. Rapid collapse of superjacent laminae may be accommodated by small normal faults.

Fat, Mud-lined Burrows

Description: Simple, non-branching dwelling burrow with a mud wall that is smooth on the inside and rough and irregular on the exterior surface. The burrows penetrate obliquely downward up to

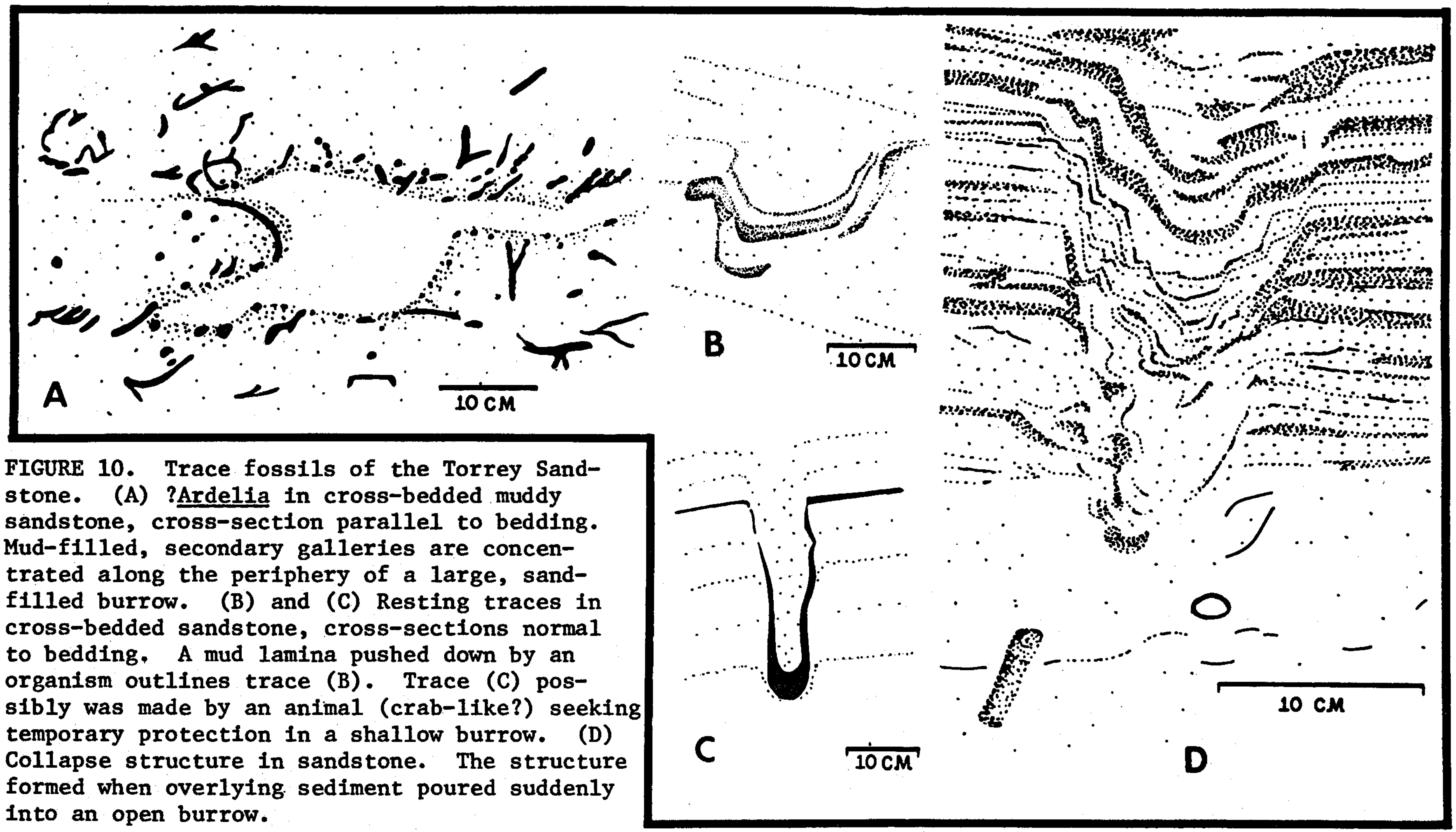


FIGURE 10. Trace fossils of the Torrey Sandstone. (A) ?<u>Ardelia</u> in cross-bedded muddy sandstone, cross-section parallel to bedding. Mud-filled, secondary galleries are concentrated along the periphery of a large, sand-filled burrow. (B) and (C) Resting traces in cross-bedded sandstone, cross-sections normal to bedding. A mud lamina pushed down by an organism outlines trace (B). Trace (C) possibly was made by an animal (crab-like?) seeking temporary protection in a shallow burrow. (D) Collapse structure in sandstone. The structure formed when overlying sediment poured suddenly into an open burrow.

18 cm; inner diameter is 4-5 cm and the mud wall is 1 cm thick.

Interpretation: Because of their size and mud walls, these burrows were most likely constructed by burrowing crustaceans. Somewhat similar (but unlined) burrows are constructed by some modern ghost and fiddler crabs (Frey and Howard, 1969, Pl. 3 and Fig. 4; Frey and Mayou, 1971, p. 58-65). The mantis shrimp Squilla also builds a large, obliquely-oriented burrow, usually lined with mud (Frey and Howard, 1969; Hertweck, 1972, p. 136).

?Ardelia Chamberlain and Baer 1973 - Figure 10A

Description: Small, branching, mud-filled burrows arising from larger burrows and covering them densely. The small tubes are 0.2-0.4 cm in diameter; they arise from a large shaft that is 2-4 cm wide and is probably continuous with Ophiomorpha. The tubes extend out several centimeters from the main shaft, and some branch in broad Y's.

Interpretation: Ardelia is probably the feeding burrow of a small, deposit-feeding animal that either lived commensally with the organism responsible for the main shaft or adopted its abandoned burrow.

Paleoecologic significant of trace fossils in the Delmar and Torrey

Contrasts between trace fossils of Delmar facies versus Torrey facies are particularly distinctive and emphasize the differences between the two formations. For example, traces of vertical or high angle movement (Conostichus, vertical burrows with spreiten) dominate the cross-bedded sands of the Torrey, whereas a variety of mud-filled or mud-lined feeding burrows characterizes Delmar sediments. Dwelling burrows such as Ophiomorpha nodosa, Thalassinoides and Gyrolithes are present in both formations, but are much larger and more stoutly-lined in the Torrey. Horizontal orientations of Ophiomorpha and Thalassinoides are more common in the Delmar, while vertical orientations predominate in the Torrey. Vertical burrows with spreiten exhibit contrasts in size between formations similar to that shown by Ophiomorpha and Gyrolithes. Relative abundances of trace fossils are also informative: several units in the Torrey contain few or no lebensspuren, while in the Delmar almost all beds exhibit some degree of biogenic reworking, often complete homogenization.

These observations indicate that the Delmar facies were characterized by lower current velocities and more stable, muddy substrates rich in organic matter. Therefore feeding burrows constructed by vagile and sessile animals mining the sediment for food are very common, and populations of infauna are denser, as predicted by Purdy (1964) based on studies of Recent animal/substrate relationships. In contrast, the Torrey lebensspuren suggest higher current velocities, unstable, shifting substrates, and less organic matter in the sediment. Therefore the burrowing fauna were dominated by vagile infauna, particularly suspension feeders. Crustacean burrows in the Torrey appear to have been constructed by large, strong species that lived deep in the sediment to avoid exposure by erosion. They built long, vertical burrows to the surface; therefore vertical orientations are common in the Torrey.

Description and Interpretation of Subfacies

The Delmar Formation and Torrey Sandstone are elongate sand bodies deposited approximately parallel to the Mid-Eocene shoreline trend. Delmar facies developed in a protected, shoreline environment such as an estuary, bay or lagoon; Torrey facies developed as parts of a shoal or bar separating the Delmar environments landward from an open sea to the southwest (Kennedy and Moore, 1971; Boyer, 1974). Within this general, paleoenvironmental setting were developed several subenvironments, each characterized by a distinctive suite of depositional processes. In Solana Beach outcrops of the Delmar Formation and Torrey Sandstone we have recognized five subenvironments (subfacies), based on sediments, sedimentary structures, body fossils and trace fossils. The subfacies are described below and interpreted in terms of depositional environments.

Subfacies of the Delmar Formation

I. Oyster beds - Figure 11-I

Description: The most distinctive and easily recognized subfacies are oyster beds that occur in the lower part of the Delmar Formation. These are 15-20 cm-thick, tabular beds of concentrated mollusc shells dominated by *Ostrea idriaensis* Gabb in living position. The beds are tightly cemented with calcite spar; they are quite hard and form prominent, broad ledges that jut out into the modern surf zone. Each bed persists no more than a few hundred meters along strike, thinning into a stringer of broken shells along its perimeter.

Oyster beds consistently develop atop surfaces of mudstone or very muddy sandstone, but there is little terrigenous sediment within shell beds. Muddy beds beneath oyster beds are almost structureless and probably have been thoroughly bioturbated. They exhibit a few sand-filled, cylindrical burrows approximately 1 cm in diameter.

Interpretation: The oyster beds are fossilized, in situ oyster reefs[1]. They grew in a protected, low energy, shallow-water environment -- such as a bay, lagoon, or estuary -- that experienced broad salinity fluctuations. This interpretation is based on several lines of evidence.

(1) Many *Ostrea* valves are preserved articulated and in living position.

(2) The associated molluscs either are characteristic of fresh to brackish-water environments or are euryhaline (C. R. Givens, 1973, pers. commun.).

(3) Oyster beds consistently rest conformably on surfaces of mudstone or very muddy sandstone. This relationship suggests biologic

[1]As defined by Stenzel (1971, p. N1041), oyster reefs are "natural accumulations of oyster shells, dead or alive, that rise above the general level of the substratum they are built on".

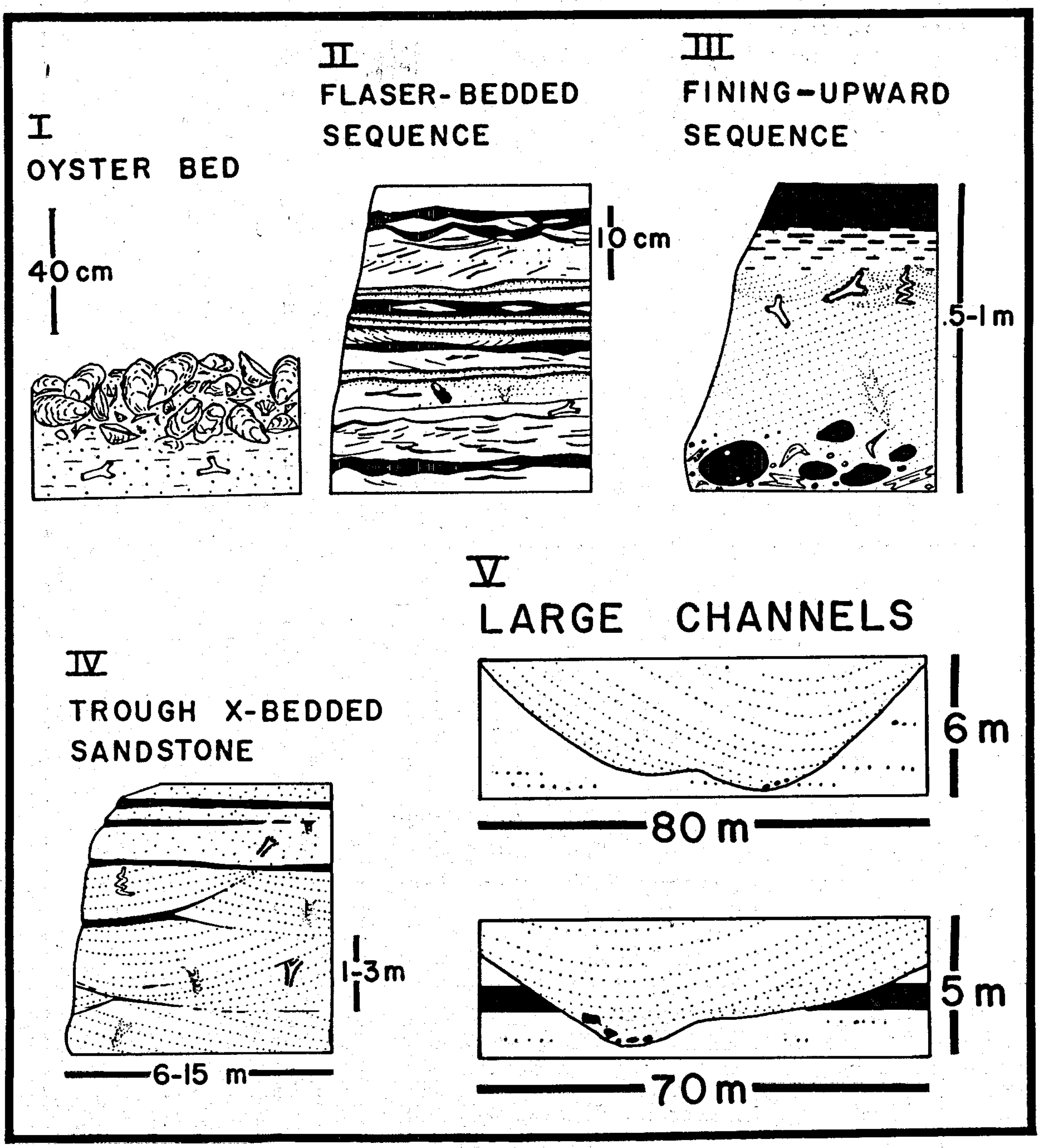


FIGURE 11. Schematic presentation of subfacies in the Delmar Fm. (I, II, III) and Torrey Ss. (IV, V) at Solana Beach outcrops. (I) The oyster beds are fossilized, in situ oyster reefs that thrived along the margins of the Delmar lagoon. (II) Flaser-bedded sequences formed on tidal flats bordering the lagoon. (III) Fining-upward sequences were deposited in tidal creeks of the lower tidal flats and in sublittoral tidal channels and ponds in deeper parts of the lagoon. (IV) Large-scale, trough cross-bedded sandstones are deposits of subaqueous dunes and major tidal channels on a tidal delta or interior side of an off-shore shoal or bar. (V) Large channels are short-lived channels generated by drainage of the lagoon after high run-off or spring tides.

SUB-FACIES	A: OYSTER BEDS	B: FLASER-BEDDED SEQUENCES	C: FINING-UPWARD SEQUENCES	D: LARGE-SCALE TROUGH CROSS-BEDDED SANDSTONE	E: LARGE CHANNELS
SEDIMENTS	Mollusc shells, sand, calcite cement. Oyster bed rests on substrate of very muddy sandstone.	Mudstone, clay-shale, and silty sandstone.	Muddy sandstone, sandy mudstone, mudstone with laminae of pure clay-shale.	Muddy sandstone and slightly granular muddy sandstone.	Slightly granular muddy sandstone.
PHYSICAL SEDIMENTARY STRUCTURES	None.	Interbedded sst. & mudst.; flaser, wavy and lenticular bedding; micrograded beds; current and oscillation ripples, small channels; erosional surfaces.	Tabular sets of med.-scale planar X-beds; med.-scale trough X-beds; current ripples; erosional surfaces; lag deposits; sedimented shell beds.	Large-scale trough X-bedding (5-20 wide and 20 m deep); erosional surfaces, mud lenses.	Trough-shapes scour surface, lag deposits, very large-scale trough X-beds (80 m wide and 6 m deep), medium-scale X-beds.
BODY FOSSILS	Gastropoda & Pelecypoda, mainly *Ostrea idriaensis* Gabb in living position.	Ostracod, fecal pellets, possible arenaceous forams, pollen and spores.	Pelecypoda and Gastropoda, including *Ostrea idriaensis* Gabb (not in living position).	A few pelecypod valves. In mud beds: pollen and spores, dinoflagellates, hystrichospheres.	None.
TRACE FOSSILS	Partial to complete bioturbate textures in strata on which beds develop.	Rare to abundant burrows. *O. nodosa* & *Thalassinoides* (s.f.), vertical burrows w/ spreiten, collapse structures, small vertical & horizontal burrows, vertical movement paths, *Gyrolithes* (s.f.), chewed-through mud beds.	Partial to complete bioturbate textures. *O. nodosa* & *Thalassinoides* (s.f.), *Gyrolithes* (s.f.), vertical burrows w/ spreiten, *Phycodes*, *Palaeophycus*, dendritic burrows, vertical movement paths, small vert. & horiz. burrows.	Rare to abundant burrows and partial bioturbate texture. *O. nodosa* & *Thalassinoides* (l.f.), *Conostichus*, *Gyrolithes* (l.f.), surface depressions, vertical burrows with spreiten, collapse structures.	Rare or no burrows. A very few *O. nodosa* and *Thalassinoides* (l.f.) and *Conostichus*.

TABLE 1. SUMMARY OF CHARACTERISTICS OF SUBFACIES.

selectivity for substrate and energy regime, rather than hydrodynamic concentration of shells.

(4) The beds are capped by sand. Apparently the oysters were able to sweep out most fine sediment, and succumbed only when smothered by a rapidly deposited, relatively thick sand unit.

(5) According to Stenzel (1971, p. N1041) only coastal, brackish-water species of modern oysters form reefs. With few exceptions, modern reefs grow most abundantly in bays and lagoons and along tidal channels of estuaries.

II. Flaser-bedded sequences - Figure 11-II

Description: Closely associated with the oyster reefs in the Delmar Formation are interbedded and interlaminated claystone, sandy mudstone, and muddy sandstone. These sequences are moderately bioturbated; they exhibit flaser, wavy and lenticular bedding, planar lamination, micro-graded beds, ripple cross-lamination, and some medium-scale trough cross-bedding. Abundant carbonized plant fragments are concentrated along bedding planes, and there is a small lens of coal.

Interpretation: Flaser-bedded sequences are tidal flat deposits of the littoral zone. This interpretation is based on the following observations:

(1) Flaser, wavy and lenticular bedding are common structures of tidal flat deposits.

(2) In the Delmar Formation, flaser, wavy and lenticular bedding are developed on both current and wave ripples, but current ripples predominate. This is in contrast to sublittoral zones of lagoons and bays, which display chiefly oscillation ripples, and to deeper (below wave base) environments offshore that exhibit only current ripples.

(3) Ripple cross-laminations indicate bidirectional current directions.

(4) Micro-graded beds occur in pairs, suggesting tidal control.

(5) Small channels are present in this subfacies.

(6) Percent bioturbation is quite variable, but a large proportion of these beds exhibit only rare burrows. This indicates locally rapid deposition and/or frequent physical reworking of the deposits. Such conditions can exist on tidal flats, in contrast to most offshore sublittoral environments, which usually are intensely bioturbated.

III. <u>Fining-upward sequences</u> - Figure 11-III

Description: Fining-upward sequences comprise a third subfacies recognized in the Delmar Formation. These sequences are more variable and less well-defined than subfacies A and B, because the beds have been intensely bioturbated and their physical origins obscured. We have included three types of deposits in this subfacies:

(1) Approximately 1.0 m-thick beds consisting of, from bottom to top, an erosional surface, a tabular set of medium-scale, planar cross-beds of muddy sandstone <u>or</u> medium-scale trough cross-beds of muddy sandstone, ± ripple cross-laminated muddy sandstone, and a cap of sandy mudstone and mudstone that may exhibit millimeter-laminae of clay-shale. Bioturbation increases upward, so that the sequence is "cross-stratified to burrowed" upward.

(2) 0.3-1.0 m-thick beds consisting of, from bottom to top, a stringer of Ostrea shells, bioturbated muddy sandstone, ±cap of sandy mudstone.

(3) Approximately meter-thick beds with a lag deposit of claystone clasts and wood fragments at the base, grading upward into muddy sandstone and sandy mudstone. Bioturbation increases upward.

Interpretation: Fining-upward sequences are polygenetic. They were deposited on the lower parts of tidal flats and on the sublittoral floor of the Delmar "lagoon". Some beds in this subfacies exhibit ghosts of interbedded sandstone and mudstone and flaser bedding, and are probably bioturbated equivalents of the tidal flat deposits described above (subfacies II). A majority of the beds, however, were deposited by migrating tidal channels. A lag deposit or erosional surface outlines the base of each channel; a cap of fine-grained sediment marks its passage.

Sediments accumulating in the channel probably were originally composed of interbedded sand and mud or of sand with biogenic mud pellets. The latter sediments were deposited as longitudinal beds (Reineck, 1958b) on point bars or as trough cross-beds of megaripples in the channel. Channels that were relatively stable were populated by burrowers at a very early stage; these deposits have been thoroughly bioturbated. Sediments deposited by rapidly migrating channels were later invaded by infauna from the surface; these are the "cross-stratified to burrowed" sequences.

Apparently these sediments were covered by water much of the time and physical reworking was sporadic, allowing burrowers to rework large volumes of sediment. This contrasts with conditions higher on the flats, where animal life was less abundant and/or physical reworking by tidal currents and storms was more frequent.

Subfacies of the Torrey Sandstone

IV. Large-scale trough cross-bedded sandstone - Figure 11-IV

Description: The Torrey Sandstone as exposed in Solana Beach seacliffs is composed mainly of coarse or slightly granular muddy sandstone in large-scale trough cross-beds. The troughs are 5-30 m wide and 1-4 m deep. Thin mud beds are also present that either follow the inclined bedding in the sand or rest on erosional surfaces. Stratification has been disrupted but not destroyed by burrowers; apparently sedimentation rates were sufficiently rapid to prevent complete destruction of bedding by infauna. The most abundant trace fossils in this subfacies are Ophiomorpha nodosa (large form) and Conostichus. A single Gyrolithes of very large size was observed.

Interpretation: Sediments in this subfacies were deposited in subaqueous sand dunes and in channels on a tidal delta or on the inshore side of a barrier bar of shoal. The physical and biogenic sedimentary structures indicate very strong waves and currents. Fluctuations in energy level were provided by the tidal cycle and accentuated by some shielding from wave action. Turbid waters from the protected (Delmar) environments shoreward contributed fine sediment that settled during periods of slack water in troughs protected by dunes and in depressions of abandoned channels.

Nordstrom and others (1965) have described beds in the Torrey Sandstone which they attribute to beach or eolian origins, indicating that the subfacies described here is indeed a part of a barrier bar. In the Solana Beach outcrops, however, there is no evidence of subaerial exposure of these sediments, either in a swash platform or as wind-blown dunes.

V. Large channels - Figure 11-V

Description: Large channels in the Torrey Sandstone comprise the fifth subfacies recognized in the Solana Beach outcrops. The channels are up to 80 m wide and 2-6 m deep; they are filled with slightly granular muddy sandstone. The base of each channel is a trough-shaped scour surface marked by lag deposits of coarse sediment and mudstone clasts. These beds exhibit little or no biogenic sedimentary structures.

Interpretation: The large channels were generated by temporary flushing of the Delmar lagoon after periods of high rainfall or after storms that piled up water along the coast. This interpretation is based on the following evidence:

(1) Trace fossils in the channels are rare or absent. This contrasts with active tidal channels in Recent nearshore environments; they usually support a healthy population of burrowers. Large channels in the Torrey either were created by fresh-water flow or were scoured and filled very quickly, before infauna had an opportunity to settle and to penetrate the sediment.

(2) Bidirectional currents are indicated by cross-beds in only one channel (Boyer, 1974, Pl. 12); the other three channels apparently were scoured and filled by unidirectional flow.

Conclusions

(1) The Delmar Formation and Torrey Sandstone are elongate sand bodies that were deposited in nearshore environments oriented parallel to the Mid-Eocene shoreline trend.

(2) The Delmar Formation, as exposed at Solana Beach, is composed of deposits of a shallow lagoon bounded on its landward side by tidal flats and oyster reefs in the intertidal (=littoral) zone, and on its seaward side by deposits of the Torrey Sandstone.

(3) The Torrey Sandstone, as exposed at Solana Beach, formed largely as subaqueous dunes and channels on an interior tidal delta or on the interior margin of a barrier bar or shoal. The Torrey sand body enclosed and separated the Delmar lagoon from an open ocean to the southwest.

(4) The presence of abundant biogenic structures in the Solana Beach outcrops is a reliable, easy-to-use indicator of marginal marine

to marine conditions.

(5) The abundant trace fossils *Ophiomorpha nodosa* and *Gyrolithes* appear to be good indicators of littoral and inner sublittoral environments in the formations studied; *Gyrolithes* is especially common in brackish environments of the Delmar lagoon.

(6) The size and wall thickness of both *Ophiomorpha nodosa* and *Gyrolithes* vary directly with the strength of waves and currents. In addition, vertical orientations of *Ophiomorpha*/*Thalassinoides* predominate in cross-bedded and planar laminated sandstones and are indicative of a shifting, unstable substrate and relatively high current velocities.

(7) Traces of vertical migrations of vagile infauna (such as *Conostichus* and the vertical movement paths described in this paper) are most abundant in the Torrey Sandstone. They indicate frequent, rapid erosion and sedimentation characteristic of littoral and inner sublittoral environments.

(8) Feeding burrows and traces left by vagile deposit feeders and sessile suspension feeders (?*Palaeophycus*, ?*Phycodes*, small horizontal and vertical burrows) are more common in muddy sediments of the Delmar Formation. These indicate lower current velocities and more abundant organic matter in the sediment relative to Torrey sands.

(9) Five major subfacies can be identified in the Solana Beach outcrops based on sediments, physical sedimentary structures, body fossils and trace fossils; they are as follows:

Delmar facies	I.	oyster beds = oyster reefs
	II.	flaser-bedded sequences = tidal flat deposits
	III.	fining-upward sequences = lower tidal flats and sublittoral tidal channels and ponds
Torrey facies	IV.	large-scale trough cross-bedded sandstone = subaqueous dunes and channels
	V.	large channels = temporary channels generated by drainage of the lagoon after high rainfall and/or storms

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GEOTHERMAL ENERGY ON THE PACIFIC COAST

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INTRODUCTION

The Geysers field north of San Francisco is the only geothermal field producing electricity in the United States. Gross generating capacity at The Geysers in December, 1974 was 412 megawatts (MW) which is sufficient electricity to supply the needs of a city of 400,000 people. Cerro Prieto field just south of Mexicali, Mexico is the only other geothermal field in the Americas that is currently generating electrical power. Gross generating capacity at Cerro Prieto in December, 1974 was 75 MW. Both fields are being further developed at the present time. The concentration of hot springs in the western United States indicates that geothermal energy may offer significant potential for generation of additional electrical power that can be utilized on the Pacific Coast.

NATURE OF GEOTHERMAL ENERGY

In order to assess the additional geothermal potential of the Pacific Coast, it is necessary to consider the nature of geothermal energy. What is it and how can it be used?

Geothermal energy is quite simply the natural heat of the earth. This heat is derived from radioactive decay within the earth and is conducted and convected to the surface where it is radiated into space (Figure 1). Normal flow of heat toward the surface is 1.5 microcalories per square centimeter per second, or 1.5 Heat Flow Units (HFU). This amount of heat flowing through ordinary rocks near the earth's surface results in geothermal gradients of 1°F to 2°F per 100 feet. This means a well would have to be drilled to a depth between 22,250 feet and 44,500 feet to encounter a temperature of 500°F (assuming an average ambient surface temperature of 55°F).

In areas of normal heat flow, the amount of heat per unit area is too small and the depth to commercial temperature is too great for the geothermal energy to be used for economical power generation. The heat flow must be upgraded, or concentrated, in some manner to suitable levels. On a worldwide basis, significant concentration of heat flow occurs where molten magma rises into shallower portions of the earth's crust, as along global plate boundaries which represent spreading ridges or subduction zones (Figure 2).

IMPORTANCE OF PERMEABILITY

Shallow magmas do not of themselves assure a commercial geothermal power development. With today's technology, commercial power cannot be developed from geothermal energy in impermeable rocks at any depth, regardless of temperature. Attempts to do so are currently underway, but it is not believed that these attempts will bear fruit in the near future.

If rocks above a magma have only horizontal permeability, heat transfer toward the surface will be by conduction alone and conductive heat transfer is quite inefficient. With technology available now, 500°F water can be withdrawn from rocks of sufficient horizontal permeability and used to generate commercial electrical power. However, if heat transfer is strictly conductive, 500°F water at an economical drilling depth of 5000 feet requires a convecting magma with a temperature of 1200°C at a depth of only 5 miles.

If rocks above a magma have vertical permeability, convective transfer of heat toward the surface is possible. Water of commercial temperature at great depths may be convected upward to shallow depths where it can be tapped and used to generate power. The close association of geothermal areas with faults suggests that faults or fault zones are the conduits, or vertical permeability, along which hot waters are convected toward the surface. With convection, there can be commercial development of power from geothermal energy even though the depth to the top of the magma is much greater than 5 miles. For example, if the top of a convecting magma with a temperature of 1200°C is at a depth of 10 miles, 500°F water will be encountered at about 11,000 feet in rocks having only horizontal permeability (conductive heat transfer). If a fault zone cutting across the rocks with horizontal permeability at 11,000 feet affords vertical permeability to the surface, 500°F water will be convected upward to about 1500 feet before it begins to cool. Therefore, wells to tap the resource can be drilled to 1500 feet rather than 11,000 feet.

Figure 3 illustrates the important role that permeability plays in conductive versus convective heat transfer above a concentrated source of heat. In each case, the top of the convecting, 1200°C magma is at a depth of 10 miles.

HOT WATER GEOTHERMAL SYSTEMS

Areas where hot water is convected upward along a fault zone are referred to as "hot water geothermal systems." If these systems are also associated with higher than normal heat flow, they have the potential for being developed to generate commercial electrical power. Figure 4 shows what is believed to represent a typical hot water geothermal system. The temperature profile plots temperature versus depth in the core of the system shown along the fault zone on the cross section.

In this model, the heat source is a convecting magma at an anomalously shallow depth in the earth's crust. Heat from the magma is conducted through impermeable rocks to the base of a succession of permeable sedimentary, igneous or metamorphic rocks. Heat conducted into the permeable rocks is stored in both the host rock and the fluids present in the host rock, creating a "hot spot."

If meteoric waters can circulate through the permeable rocks, these waters will absorb and redistribute to some degree the heat stored in the hot spot. Circulating waters are heated to a maximum temperature which is a function of the heat available and the rate of circulation. This maximum temperature is termed the "base temperature" of the system. Because of the hydrostatic head, water can remain in the liquid state at base temperatures approaching 700°F.

If a fault zone cutting across the hot spot offers sufficient vertical permeability, circulating meteoric waters, which are relatively less dense by virtue of being heated to base temperature, will be buoyantly convected up the fault zone. Initially, the rising water will cool to some extent on its way toward the surface because of conductive heat loss to cooler rocks. But once the overall system has reached thermal equilibrium, water at base temperature in the core of the system will not cool until it rises to that depth where hydrostatic pressure equals critical pressure for water of that temperature. At that depth boiling begins. As the water fraction continues to rise toward the surface, more and more steam is boiled off, or "flashed," and the water fraction cools progressively in conformance with the boiling point curve.

If the fault zone is open to the surface, the water fraction will cool to 212°F, or whatever the boiling temperature is at the surface altitude, and boiling springs will be found at the surface. However, if the rising water and flashed steam mix with cool, near-surface waters, the steam will be condensed and the hot water reduced in temperature. In this situation, warm springs or hot springs will be found at the surface instead of boiling springs.

However, it is believed that most hot water geothermal systems are sealed off below the surface. Hot water circulating through rocks will dissolve and take into solution silica and other minerals. In a convective hot water system, when these mineral-laden waters approach the surface and cool they become supersaturated with respect to silica and other minerals. The excess silica and other mineral content is precipitated in the fault zone, blocking further flow to the surface. Water and flashed steam then circulate laterally into permeable formations and mix with cool, near-surface waters. Steam is condensed and the hot water is further reduced in temperature, causing additional precipitation of silica and other minerals. In this manner, a horizontal "caprock" of silica and other minerals is created. Eventually the circuit may be completed to form a crude steady-state convection system.

HOT WATER GEOTHERMAL SYSTEMS WITH A DRY STEAM RESERVOIR

Water is the dominant phase in a typical hot water system. However, under certain conditions steam may accumulate to become the dominant phase overlying a water-dominated phase. The steam-dominated phase of a hot water system has been previously considered to be a separate type of geothermal system and has been referred to as a "vapor-dominated" or "dry steam" system. The exact nature of dry steam reservoirs is still open to considerable question but it appears likely that the so-called dry steam system is simply a special end-member product of a typical hot water system.

Figure 5 shows what is believed to best represent a hot water geothermal system that has a dry steam reservoir above the water-dominated phase. As before, the temperature profile plots temperature versus depth in the core of the system shown along the fault on the cross section.

Dry steam reservoirs are believed to occur when the country rock has very little permeability and regional recharge is not sufficient to maintain convective circulation throughout the original hot water system.

Fracture zones in rocks of low permeability tend to remain open and may serve initially as local recharge channels. However, as waters circulate through these fracture zones toward the system and become heated, minerals of inverse solubility, such as calcium carbonate and anhydrite, are precipitated and block further local recharge into the system. The silica caprock remaining from the original hot water system, the low permeability of the country rock and the sealing of local recharge channels combine to create an impermeable sheath around the system and this sheath serves to insulate the system from hydrostatic pressure. Flashed steam can then begin to accumulate in the upper part of the trap created by the sheath. As boil-off at the steam-water interface exceeds regional recharge, the interface drops and a steam-dominated reservoir accumulates above the water-dominated portion of the system. The steam-water interface continues to drop until a crude steady-state is achieved between boil-off and regional recharge.

The temperature profile shows that the temperature in a dry steam reservoir remains essentially the same throughout its vertical extent. No data are yet available concerning wells that have been drilled deep enough to penetrate the steam-water interface but it is believed that the temperature will be considerably higher in the liquid-dominated part of the system. Since the dry steam reservoir is insulated from hydrostatic pressure, reservoir pressure will be essentially that of a column of steam. Pressures are found to be around 500 psi in dry steam reservoirs to depths of 9000'.

Hot water geothermal systems having a dry steam reservoir at the top are believed to be relatively rare. It has been estimated that only one in twenty hot water systems discovered will have a dry steam reservoir above the water-dominated portion of the system. However, two of the relatively rare dry steam reservoirs account for nearly 75% of the electricity generated worldwide from geothermal energy.

OTHER TYPES OF GEOTHERMAL SYSTEMS

Although hot water systems are the only geothermal systems that are currently producing electrical power in the world, other types of geothermal systems shown in Figure 6 have also been considered for this purpose.

Geopressured systems are generally found in young sedimentary basins, such as the Gulf Coast, which are characterized by rapid subsidence and rapid sedimentary loading. In this environment, isolated sandstone reservoirs with abnormally high fluid pressures are found at depths of 10,000 to 15,000 feet or deeper. Water confined in the isolated reservoir cannot be expelled as loading and compaction progresses and part of the lithostatic load is transferred to the trapped water. Progressive thermal expansion of the confined water adds further to the excess fluid pressure. Research projects are underway to determine if geopressured systems can be economically exploited to produce power. However, it is not believed that geopressured geothermal systems will be generating significant power before 1985.

The Atomic Energy Commission has been investigating dry hot rock geothermal systems. These are systems in which high heat flow is confined to impermeable rocks. The impermeable rocks have to be fractured hydraulically or with explosives so that water introduced from the surface can be circulated through the hot rocks to "mine" heat for return to the surface. Two wells have been drilled within the last year to evaluate this technique. The results of these projects to date make it unlikely that dry hot rock geothermal systems will be generating significant power before 1985.

Normal gradient geothermal systems exist everywhere. If you drill deep enough, temperature sufficient for commercial power generation will be encountered. Because of the high costs of drilling and producing deep geothermal wells, it is unlikely that normal gradient systems will ever be utilized for power production.

POWER GENERATION CYCLES

Three methods of production and generation have been developed to produce electrical power from hot water systems.

Figure 7 shows how dry steam reservoirs are utilized to produce electricity. A well is drilled into the reservoir and the steam produced is piped directly to the turbo-generator. After expanding through the turbine, the steam is condensed and excess condensate is reinjected into the reservoir. This method is quite simple and relatively inexpensive. Unfortunately, dry steam reservoirs are expected to be quite rare.

Figure 8 shows how most hot water reservoirs are currently being exploited to produce power. A well is drilled into the reservoir and if the reservoir water is hot enough it will flow to the surface. On the way to the surface, pressure decreases and some percentage of the hot water flashes to steam (usually 20 to 25% by weight). At the surface, the mixture of hot water and steam is piped to a separator. The dry steam is drawn off and piped to a turbo-generator and condenser set just like that used in the previous dry steam reservoir example. Excess steam condensate and waste hot water are reinjected into the reservoir.

Figure 9 shows how hot water reservoirs of lower temperature can be utilized to generate electricity. A pump installed in the producing well delivers hot water under pressure to a heat exchanger. Pressure is maintained at a level sufficient to prevent flashing of steam and consequent cooling of the water. In the heat exchanger, heat is transferred from the hot water to freon or some other low boiling-point working fluid. The heat transferred vaporizes the freon and the freon vapor is expanded through the turbine. Downstream of the turbine, the freon vapor is condensed and returned again to the heat exchanger. The spent hot water is reinjected into the reservoir. No binary cycle heat exchange system is in commercial operation today. A small pilot plant of this type has been operating in Russia since 1967, using freon as the working fluid. It appears that a large percentage of the geothermal prospects in the United States will have reservoir temperatures that require binary cycle heat exchange to generate power. Therefore, early perfection of this method will have a significant impact on the development of geothermal power in the United States.

Unlike fossil fuels, geothermal energy cannot be transported great distances before consumption. Because of heat losses, it is impractical to pipe hot water or dry steam more than a mile or two. Therefore, geothermal power plants are constructed at the producing field in modules of 50 to 135 megawatt (MW) capacity, each in close proximity to the wells drilled to supply that module.

Geothermal power plants utilize steam-driven turbo-generators just like those used in conventional fossil fuel power plants. In contrast to conventional plants, however, geothermal power plants do not require boilers for generating steam to drive the turbines. The steam, or heat necessary to vaporize a working fluid, comes directly from the geothermal reservoir. Consequently, geothermal plants conserve that amount of fuel needed to fire the boilers in conventional plants generating an equal amount of power. Each megawatt hour (MWH) of electricity generated in a geothermal power plant conserves about

$1\frac{1}{2}$ barrels of fuel oil that would have otherwise been burned to generate the same MWH in the most efficient conventional fossil fuel plant. Each MW of geothermal capacity will thus conserve about 12,500 barrels of oil per year. Assuming geothermal plants displace existing conventional plants of average efficiency, each MW of geothermal capacity will conserve 15,000 barrels of oil per year.

OTHER USES OF GEOTHERMAL ENERGY

Geothermal energy offers a wide variety of potential uses other than electrical generation. Some of the more important potential uses are space heating and cooling, process or industrial heating, desalination and horticulture. Development of these uses will reduce demand for alternate fuels or energy sources accordingly. Over the near term however, economics of geothermal exploration and development will require that electrical generation remain the primary objective.

WORLDWIDE GENERATION

Figure 10 shows the location of geothermal power developments throughout the world. As of January 1, 1975, approximately 1150 MW of geothermal generating capacity were on line in the world. Note how closely power developments are associated with spreading ridges, subduction zones and major plate boundaries - areas of concentrated heat flow. The Pacific Coast is particularly well situated with respect to those features which serve to concentrate heat flow.

GEOTHERMAL POTENTIAL OF THE PACIFIC COAST

With this knowledge of the nature of geothermal energy and its utilization, it is possible to make some tentative estimates of the geothermal potential of the Pacific Coast.

Estimates of the future potential for geothermal power generation in the United States vary wildly. Recent Federal surveys estimate that geothermal generating capacity in the United States will be between 7000 and 15,000 MW by 1985 and between 150,000 and 190,000 MW by the year 2000. Estimates in the recent past have gone as high as 132,000 MW by 1985 and 395,000 MW by the year 2000. Assuming a realistic rate of exploration and discovery between now and 1980, it appears that something on the order of 5500 to 6000 MW of geothermal generating capacity could be on line in 1985. This level would conserve 75 to 90 million barrels of fuel oil that would otherwise be consumed in conventional fossil fuel power plants in 1985 to generate 6000 MW.

Although this represents a considerable savings of fuel oil, 6000 MW of geothermal power would amount to only $1\frac{1}{2}\%$ of the nation's electrical needs in 1985. Figure 11 makes it quite clear that by no stretch of the imagination can geothermal energy solve the nation's energy problems.

It is believed that most, if not all, of the geothermal power developed by 1985 will be in the western portion of the contiguous United States. Figure 12 is a map of the western portion of the contiguous United States which shows the location of hot springs. The Geysers and Cerro Prieto geothermal fields are also shown. It is obvious from this map that the entire western portion of the contiguous United States has geothermal potential. The Great Basin Area of California, Nevada, Oregon, Idaho and Utah is particularly attractive. Any geothermal power developed in the western Great Basin will likely be committed to the Pacific Coast market. The Imperial Valley of California and Mexico is another area that is very attractive because of its association with the East Pacific Rise spreading ridge and its proximity to the Los Angeles market.

Hopefully, geothermal energy can eventually generate 5% of the nation's electrical demand. In the western United States where most geothermal prospects are found, geothermal energy may ultimately generate perhaps 10% of local electrical needs. Although it might seem that this is an insignificant amount of power that does not justify the time or trouble to develop, Figure 13 shows the economic significance of a single geothermal field, The Geysers in California. This field was generating just over 400 MW in December of 1974 and projected expansion is expected to bring the total to around 2000 MW by 1985. If the 2000 MW goal is attained, some 25 to 30 million barrels of fuel oil will be conserved in 1985 that would have otherwise been required for a conventional 2000 MW fossil fuel plant. At the projected generating capacity and sales price for 1976, The Geysers will provide around $50,000,000 of gross revenue for the producers. Even if the sales price did not increase, 2000 MW at The Geysers in 1985 would provide some $120,000,000 of gross revenue for the producers. Over the anticipated 30 year field life, 2000 MW of capacity at The Geysers is equivalent to 750 to 900 million barrels of oil. This is obviously an economically significant project for natural resources producers.

The Geysers appears to be a very large reserve as geothermal fields go. It is a dry steam reservoir and dry steam reservoirs are expected to be relatively rare. There is only one other major dry steam reservoir producing and its capacity is about 400 MW. The more common hot water reservoirs do not appear to be as large, in terms of reserves, as dry steam reservoirs. The larger hot water fields are in the 200 MW range, but over a 30 year field life, 200 MW of capacity is equivalent to a 75 to 90 million barrel oil field.

All reported estimates of discovery rates, field sizes and generating capacity must be tempered by the realization that there are only a dozen or so geothermal fields generating power in the world today. The small number of producing fields and the lack of comprehensive drilling statistics preclude statistically accurate estimates of discovery rates, field sizes and generating capacity. The 1985 estimate of 5500 to 6000 MW on line in the United States is obviously subject to drastic revision in either direction. The estimate will prove to have been too high if constraints to exploration continue or become more strict, if the discovery rate is less than expected or if the fields discovered are smaller than expected. On the other hand, the estimate will prove to have been too low if exploration can move full speed ahead, if the discovery rate is higher than expected, if the fields discovered are larger than expected or if dry steam reservoirs are more common than expected.

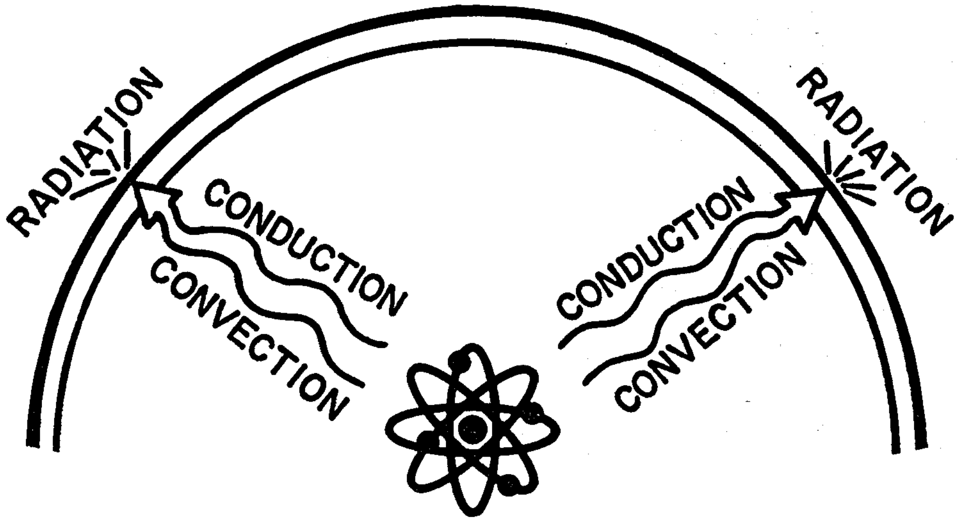
Even if 6000 MW on line by 1985 cannot make a dent in the nation's energy requirements, this capacity will certainly be significant in the areas where it is developed and will offer the opportunity for significant return to individual, privately-owned companies.

CONCLUSIONS

To conclude, geothermal energy is a unique resource that can be utilized to generate electrical power competitive in price with alternate sources and with less effect on the total environment. Each increment of geothermal energy developed will conserve an amount of alternate energy that would otherwise be needed for the same purpose. Although development of geothermal power is expected to be modest with respect to nationwide power requirements, this amount of power is expected to have a significant impact in the western United States. The development of geothermal energy is expected to have a particularly significant impact on the Pacific Coast because it is here that a zone of concentrated heat flow coincides with a growing, high-demand market for environmentally acceptable power.

GEOTHERMAL ENERGY

- NATURAL HEAT OF THE EARTH
- PRIMARY SOURCE IS RADIOACTIVE DECAY



NORMAL CONDITIONS

- HEAT FLOW = 1.5 μCAL / CM^2 - SEC.
- GRADIENT = 1° F. TO 2° F. PER 100'
- 500° F. = 22,250' TO 44,500'

Figure 1

CONCENTRATION OF HEAT FLOW

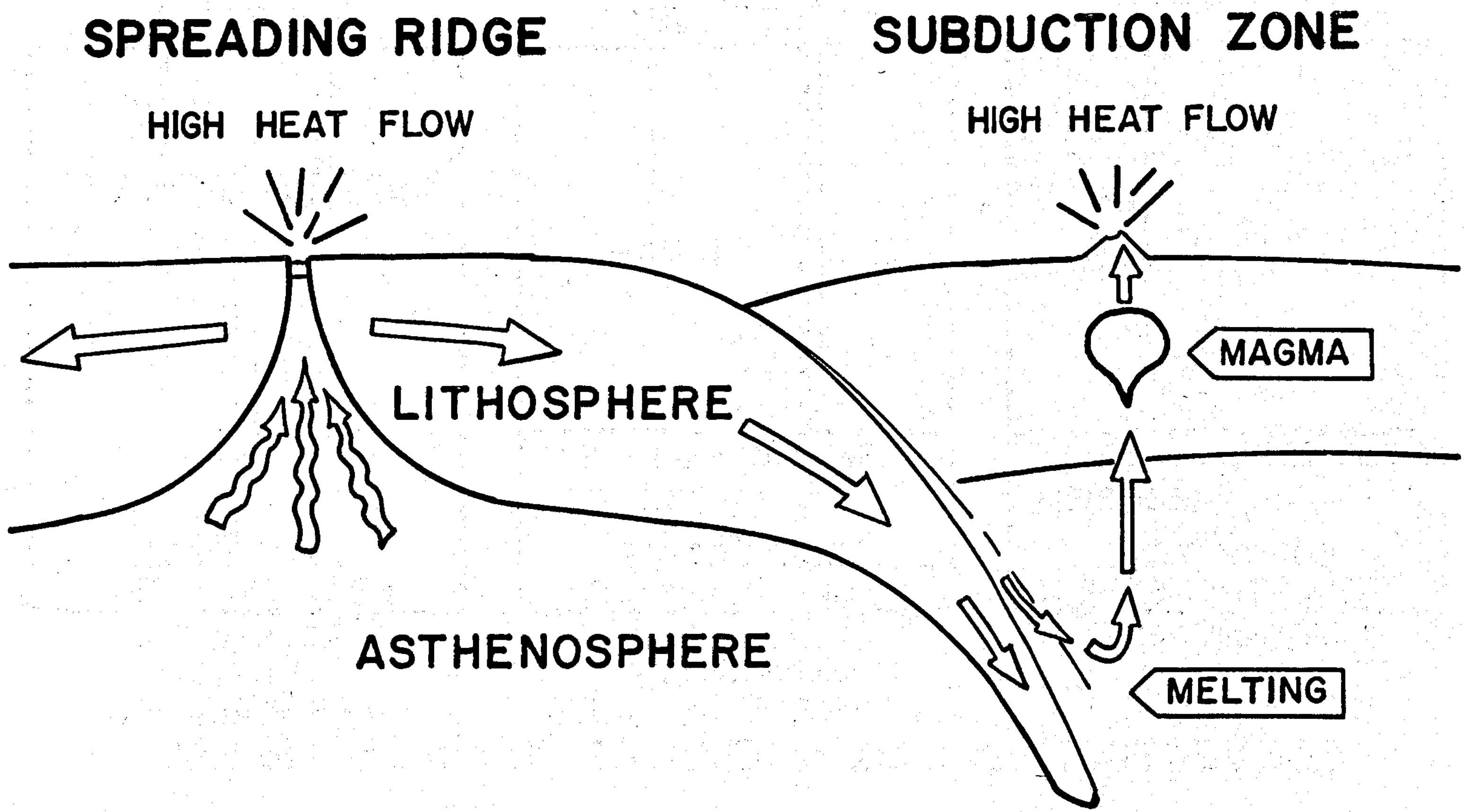


Figure 2

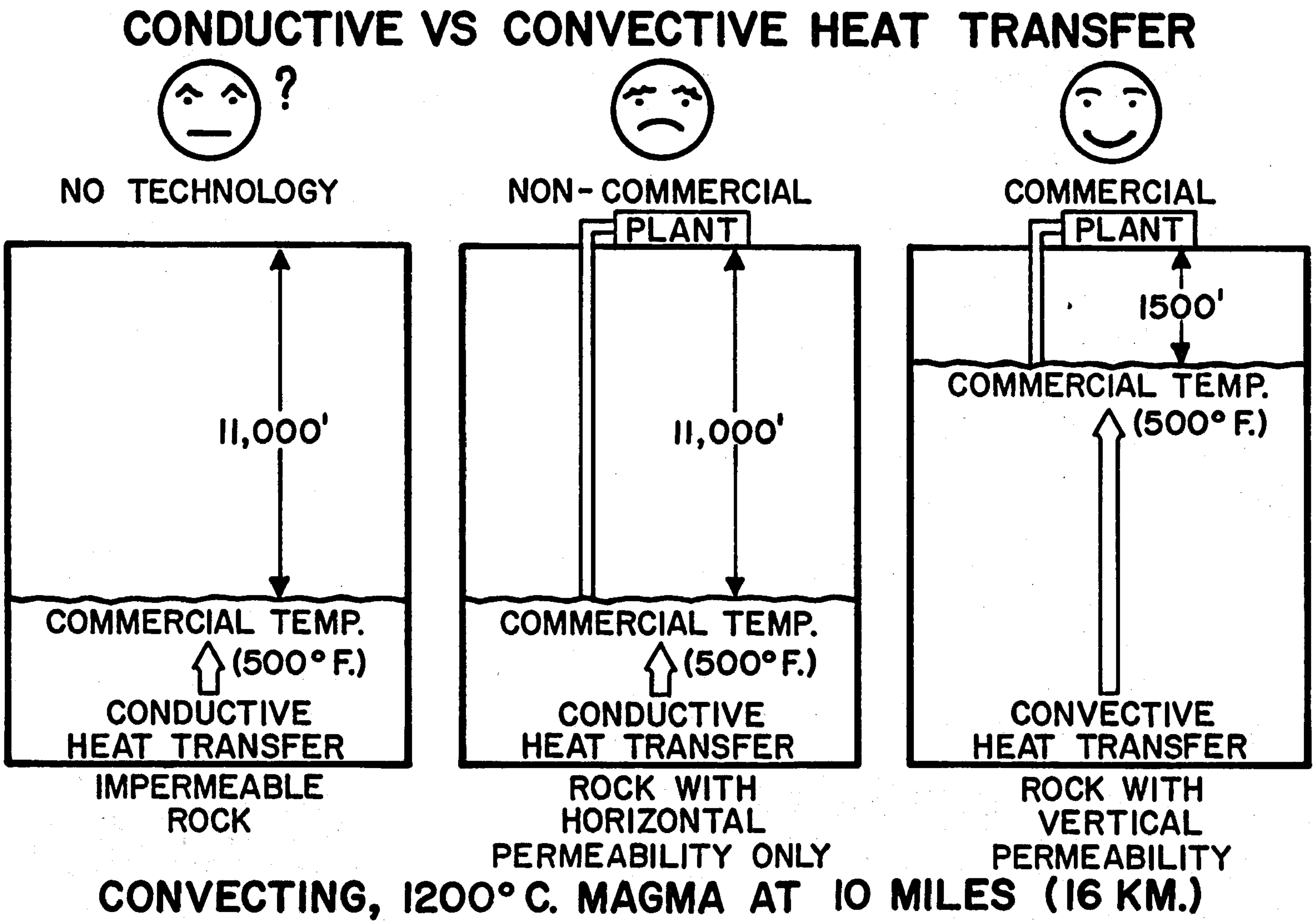

CONDUCTIVE VS CONVECTIVE HEAT TRANSFER
?
NO TECHNOLOGY
NON-COMMERCIAL
COMMERCIAL
PLANT
PLANT
11,000'
11,000'
1500'
COMMERCIAL TEMP.
(500° F.)
CONDUCTIVE
HEAT TRANSFER
COMMERCIAL TEMP.
(500° F.)
CONDUCTIVE
HEAT TRANSFER
COMMERCIAL TEMP.
(500° F.)
CONVECTIVE
HEAT TRANSFER
IMPERMEABLE
ROCK
ROCK WITH
HORIZONTAL
PERMEABILITY ONLY
ROCK WITH
VERTICAL
PERMEABILITY
CONVECTING, 1200° C. MAGMA AT 10 MILES (16 KM.)

Figure 3

HOT WATER GEOTHERMAL SYSTEM

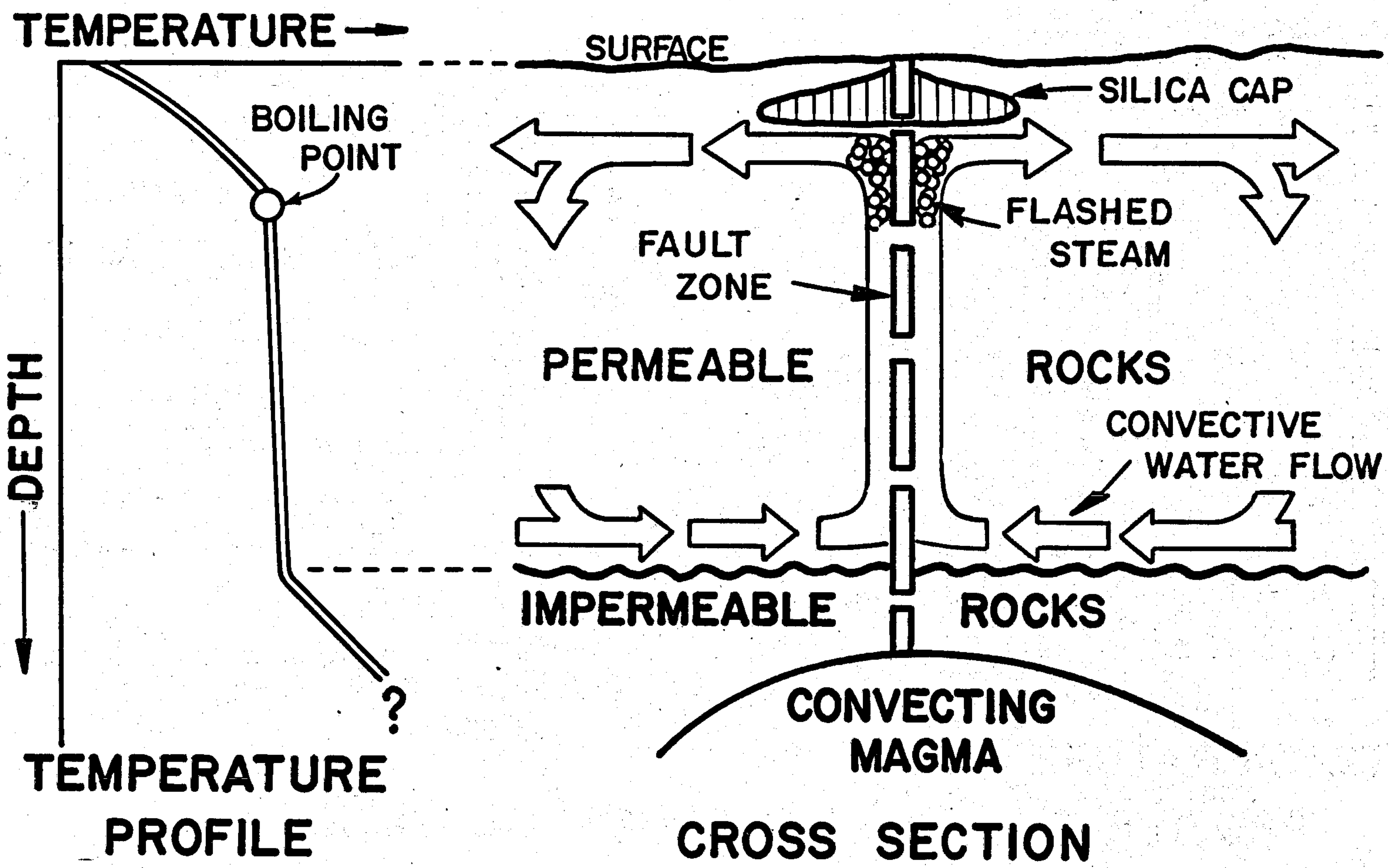
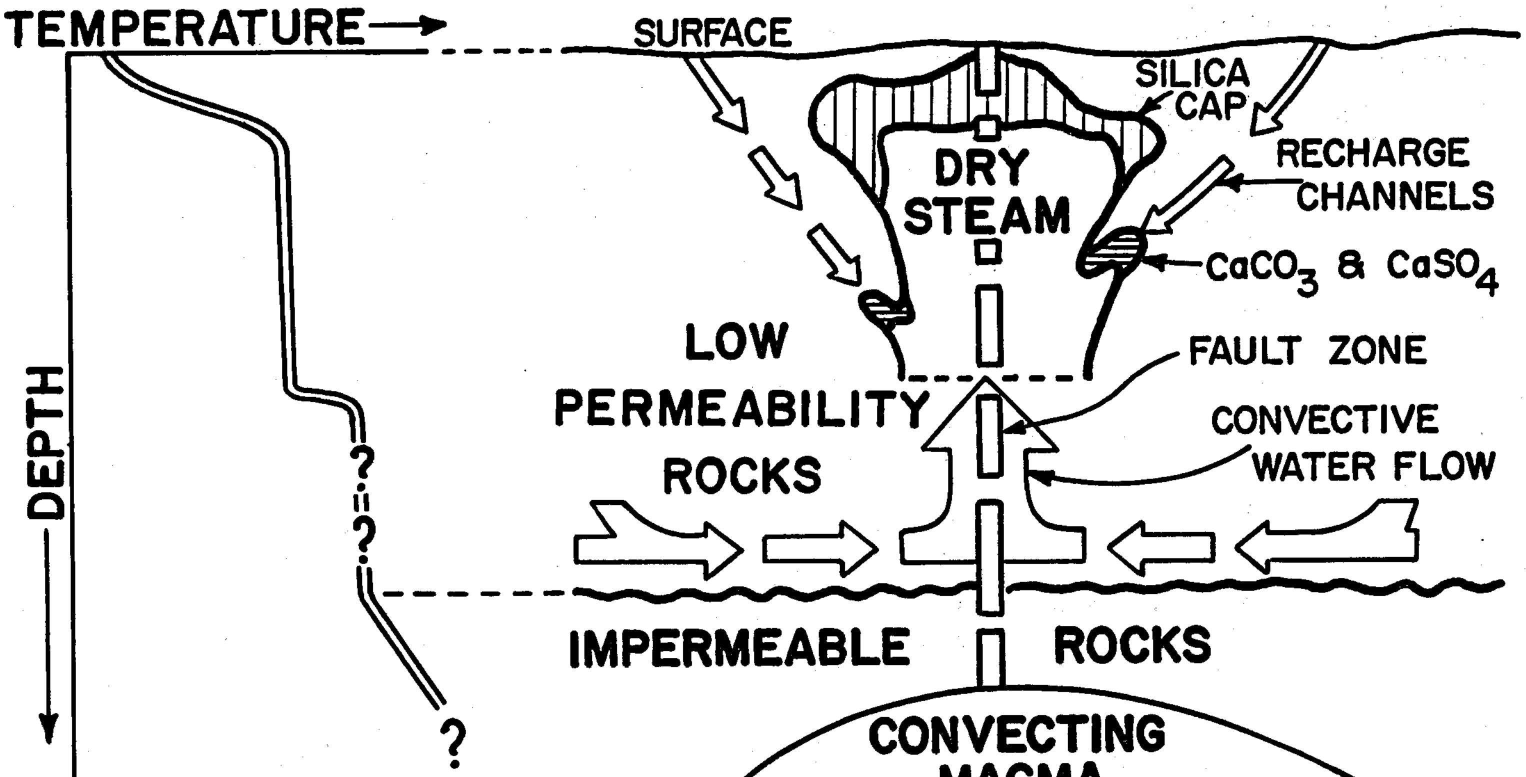


Figure 4

HOT WATER GEOTHERMAL SYSTEM
(WITH DRY STEAM RESERVOIR)



TEMPERATURE PROFILE

CROSS SECTION

Figure 5

GEOTHERMAL SYSTEMS

- HOT WATER
- HOT WATER WITH DRY STEAM RESERVOIR
- GEOPRESSURED
- DRY HOT ROCK
- NORMAL GRADIENT

Figure 6

GEOTHERMAL POWER PLANT

DRY STEAM RESERVOIR

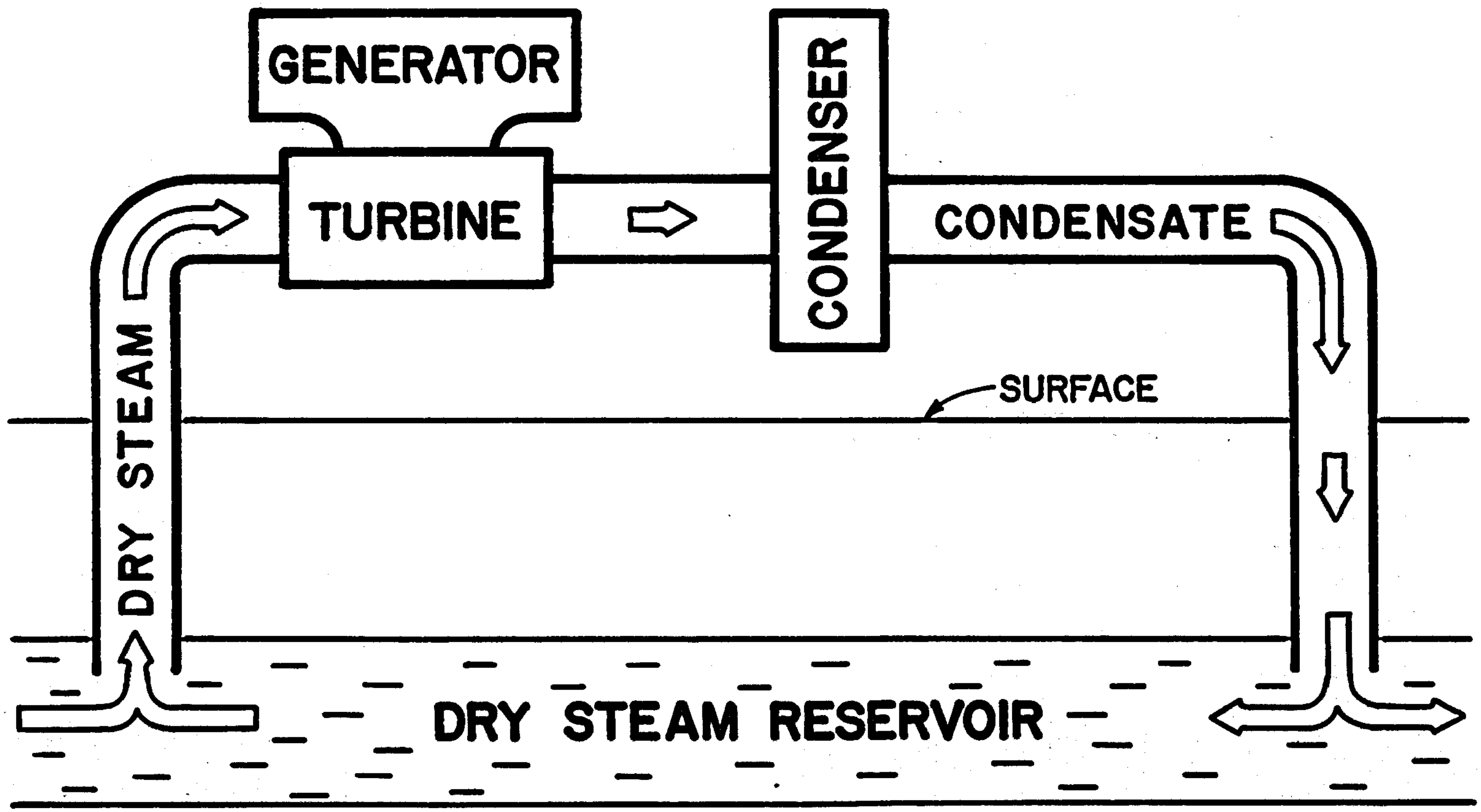


Figure 7

GEOTHERMAL POWER PLANT

HOT WATER RESERVOIR-FLASHED STEAM

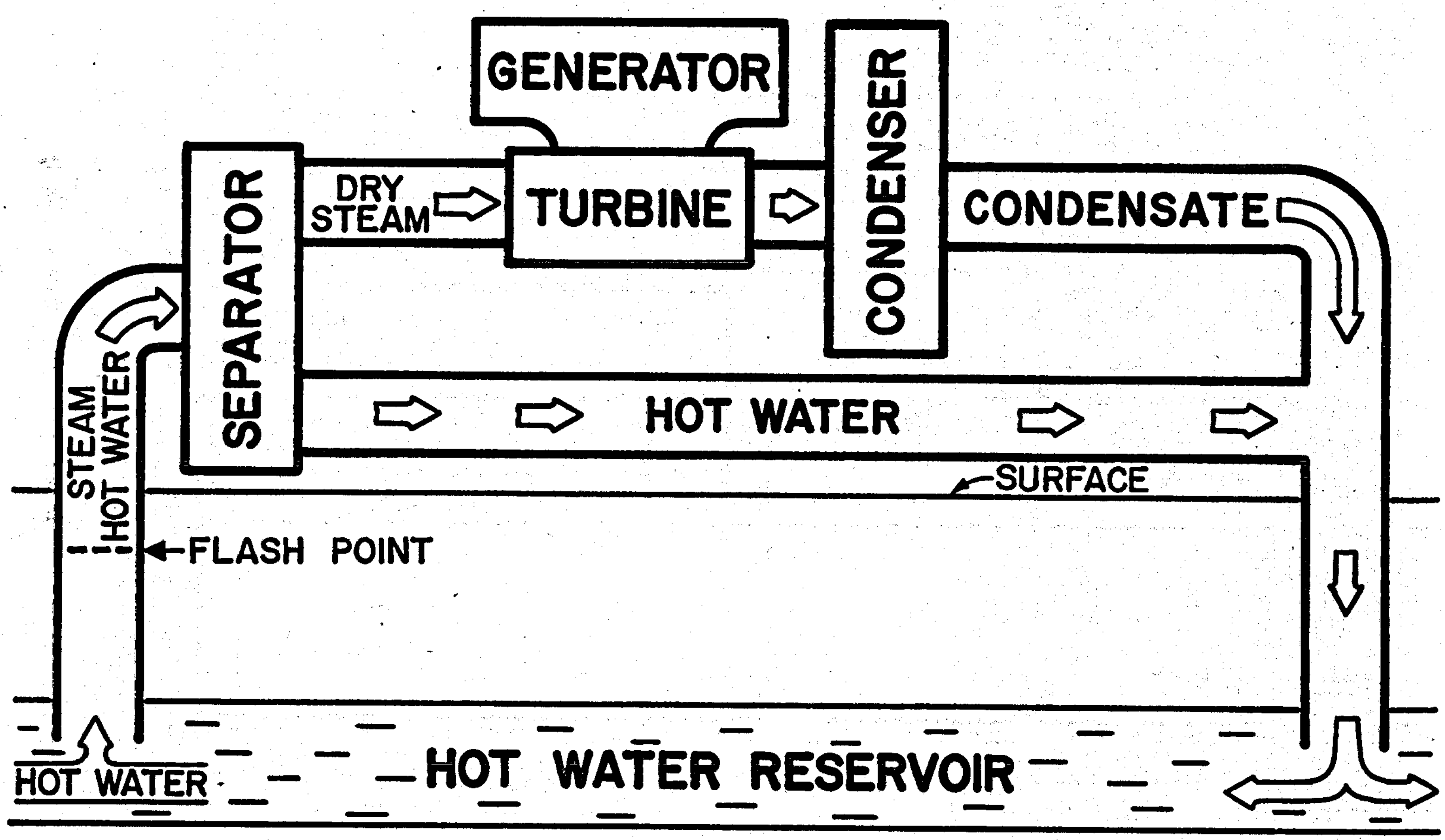


Figure 8

GEOTHERMAL POWER PLANT

HOT WATER RESERVOIR

BINARY CYCLE HEAT EXCHANGE

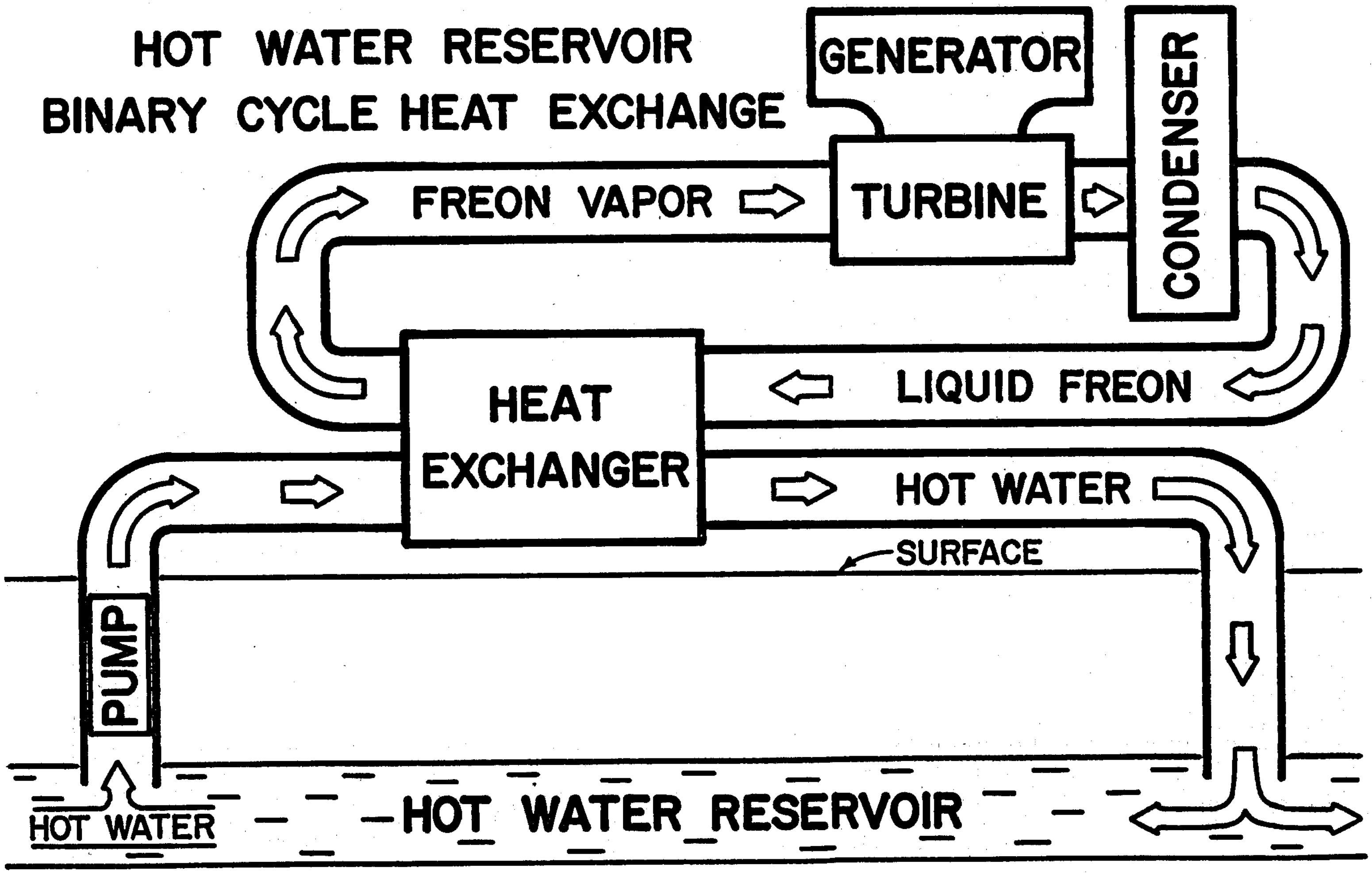
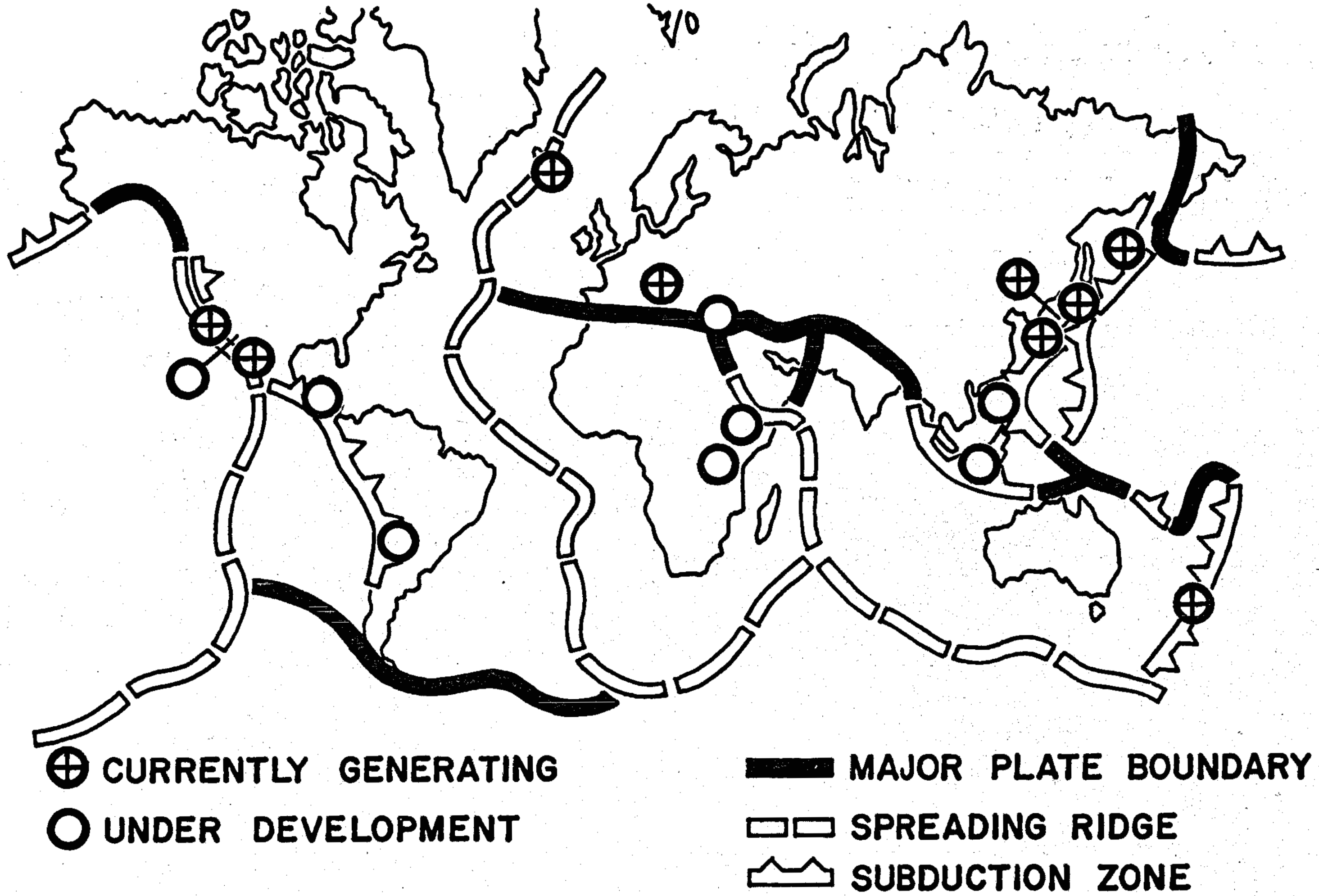


Figure 9



GEOTHERMAL POWER DEVELOPMENTS

Figure 10

U. S. ENERGY BALANCE - INITIAL APPRAISAL

NATIONAL PETROLEUM COUNCIL, 1971

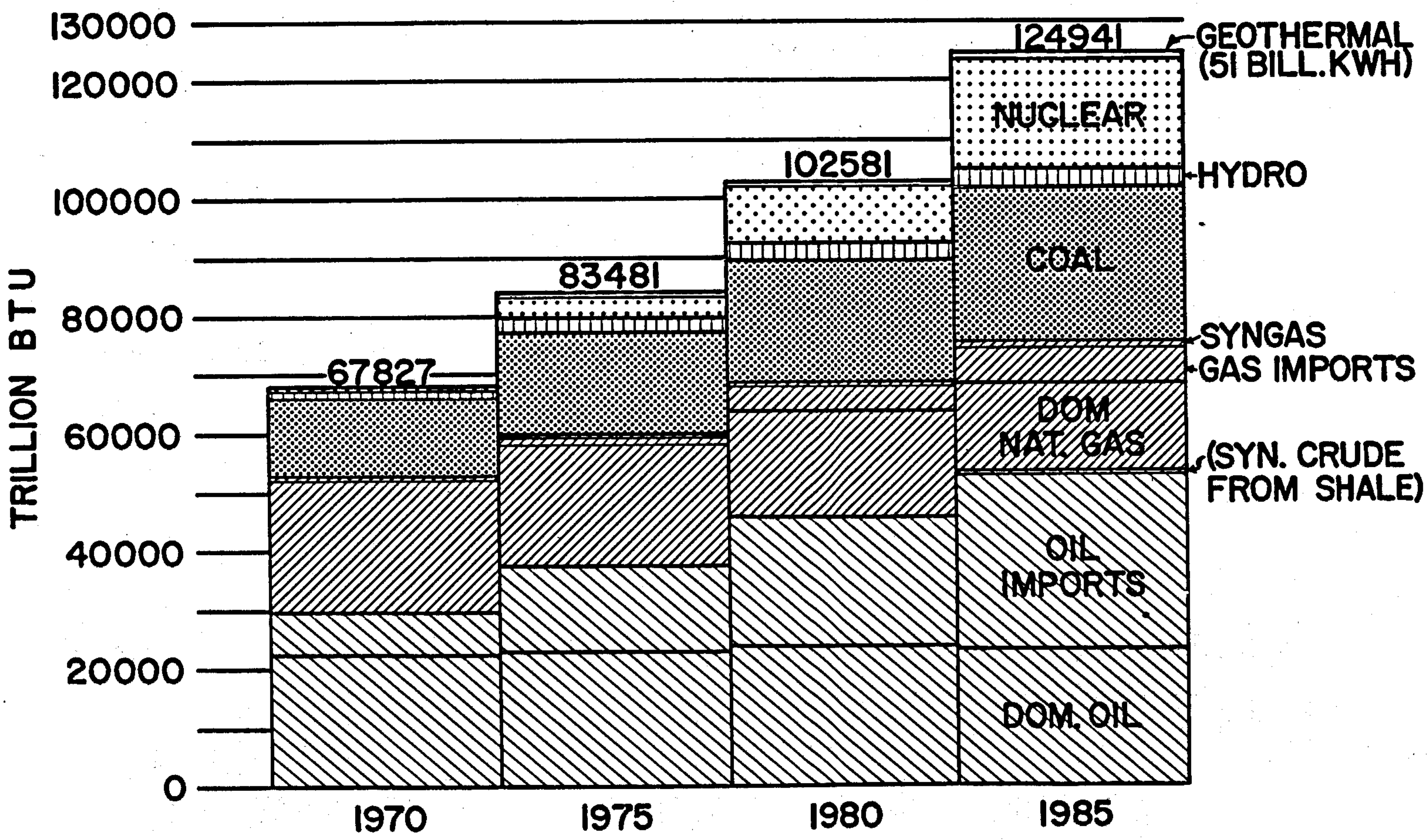
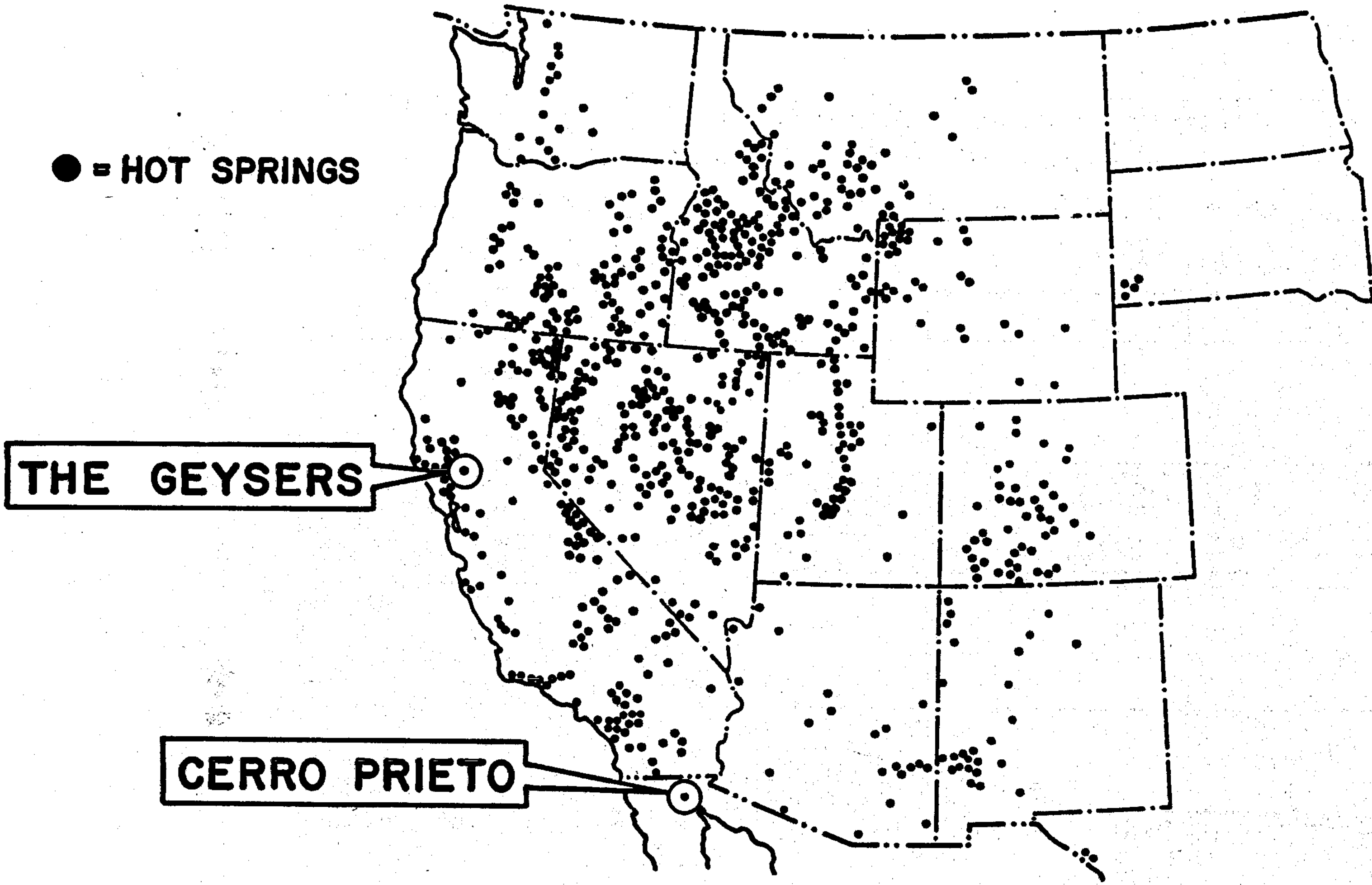
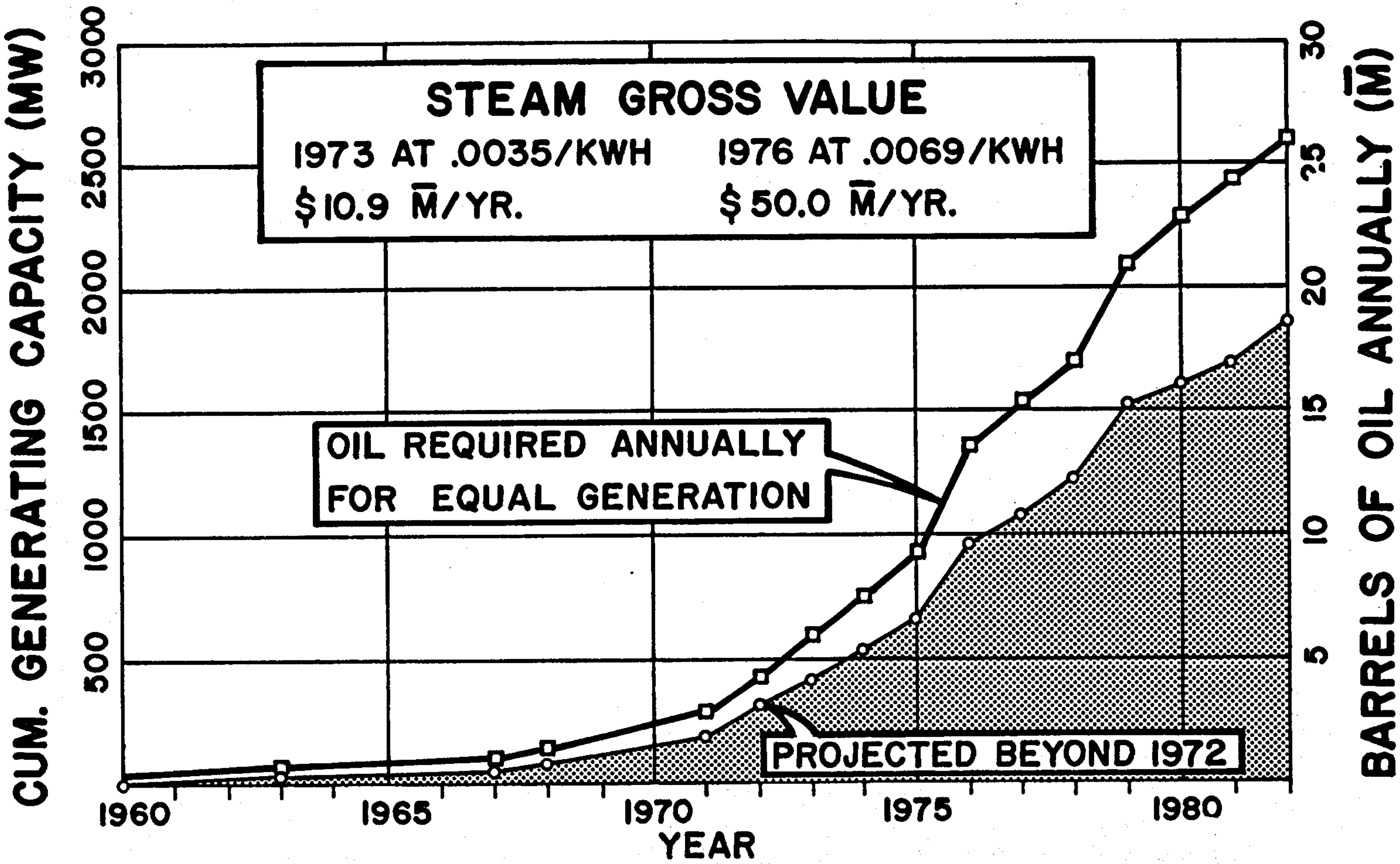


Figure II



GEOTHERMAL AREAS – WESTERN U.S.A.

Figure 12



THE GEYSERS GEOTHERMAL FIELD

MAGMA ANNUAL REPORT, 1972

Figure 13

Paleogene Geography of California

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U.S. Geological Survey, Menlo Park, California 94025

ABSTRACT

Paleogeographic maps of California have been prepared for the Ynezian (Paleocene), late Penutian (early Eocene), Narizian (late Eocene) and Refugian (late Eocene or early Oligocene) Pacific Coast foraminiferal Stages. Major persistent physiographic features included, from east to west: (1) a continental landmass that extended southeastward through the areas of the present Sierra Nevada, Mojave Desert, and Peninsular Ranges; (2) an elongate marginal sea in the area of the present San Joaquin Valley and adjacent eastern Coast Ranges of central California; (3) a northwest-trending, irregular continental borderland in the area presently occupied by the Salinian block of the Coast Ranges; (4) an east-trending marine embayment at the south end of the borderland in the area of the present Transverse Ranges; and perhaps (5) a trench that extended from the present northern Coast Ranges southward along the western margin of the borderland.

The present Great Valley comprised a shallow-marine shelf in the east and a basin in the west, separated by a west-facing slope. During much of the Paleogene, this region probably was divided into the Sacramento basin to the north and the San Joaquin basin to the south by a west-trending structural and physiographic high, the Stockton arch. The marine region west of the present Peninsular Ranges was underlain by a broad shelf thought to have been incised by a submarine canyon which funneled detritus westward into a deep basin.

Thick sequences of coarse-grained sediments were deposited as submarine fans at bathyal to abyssal depths in the areas of the present southwestern Sacramento Valley, western San Joaquin Valley, Coast Ranges, central and western Transverse Ranges and southern California borderland. Major source areas lay to the east in the present region of the Sierra Nevada, Mojave Desert and Peninsular Ranges, and to the west in the Paleogene borderland, where islands supplied large volumes of detritus.

Regional marine transgressions occurred during early Paleocene and early and middle Eocene time. An extensive marine regression began in late Eocene time and culminated in the Oligocene with widespread deposition of nonmarine sediments.

INTRODUCTION

Information from recent studies of the history of offset along the San Andreas and related faults and of Paleogene sedimentation and bathymetry necessitates the revision of paleogeographic maps of California. Based on our interpretations of evidence from these studies and field work in the San Joaquin Valley, central and southern Coast Ranges, Transverse and Peninsular Ranges, and southern California borderland (fig. 1), we have prepared maps depicting the geography of California during four intervals of the Paleogene: Ynezian (Paleocene), late Penutian (early Eocene),

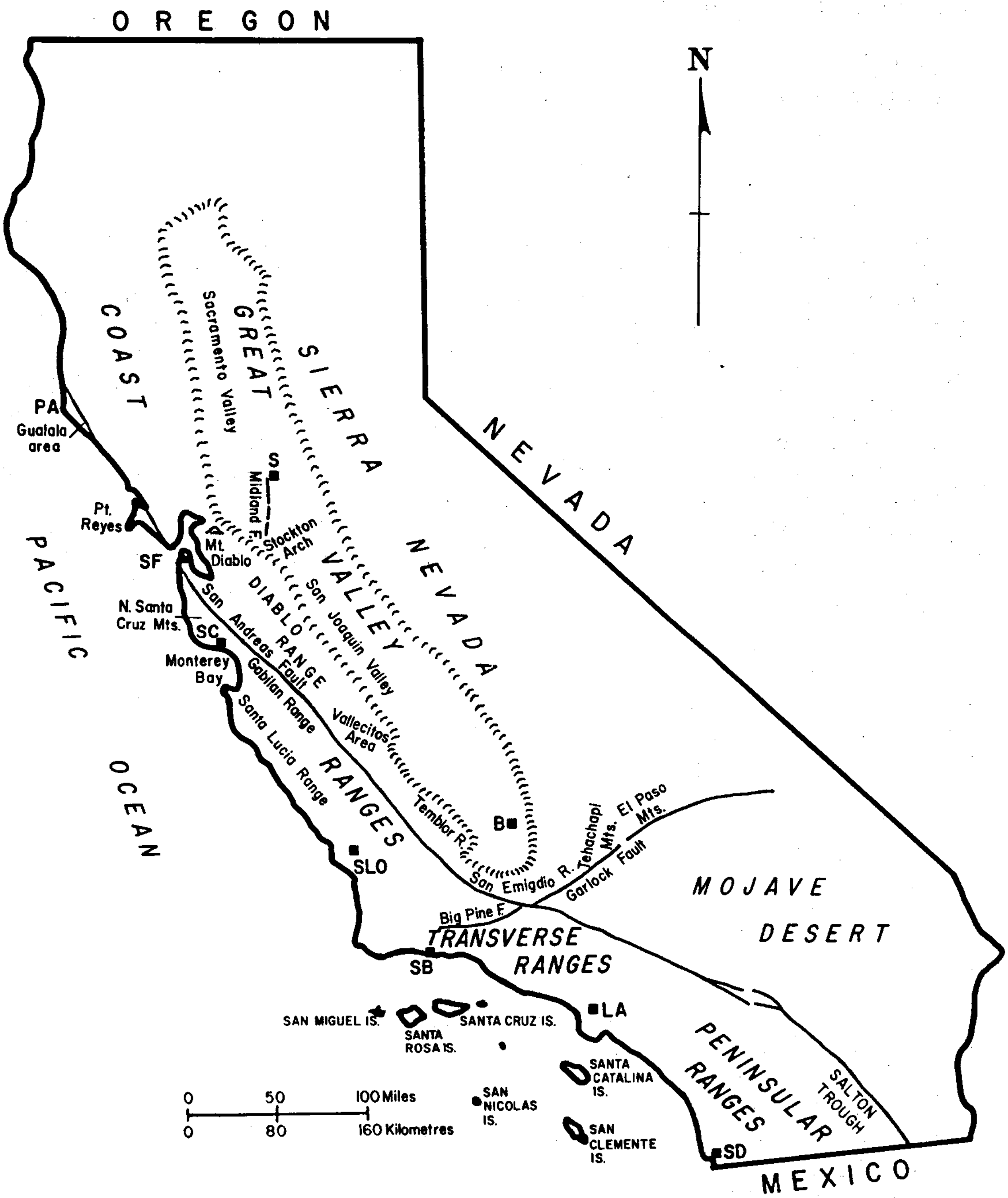

Figure 1. Map of California showing geographic localities and physiographic features referred to in text. SD - San Diego; LA - Los Angeles; SB - Santa Barbara; SLO - San Luis Obispo; B - Bakersfield; SC - Santa Cruz; SF - San Francisco; S - Sacramento; PA - Point Arena.

Narizian (late Eocene) and Refugian (late Eocene or early Oligocene). The maps are generalized, but show major geographic elements such as inferred continental and island source terranes, areas of marine and nonmarine sedimentation, and submarine shelves, slopes, basins, canyons and fans. These maps depict our concept of the geographic evolution of California from Paleocene to Oligocene time. Hopefully they will provide a useful regional background for future detailed studies and stimulate new research directed at revising and refining existing knowledge of the regional geography.

The western margin of California has been altered by extensive post-Paleogene faulting and compression. Consequently, a palinspastic reconstruction of this region was necessary before the paleogeography could be treated. This reconstruction was made by using major strike-slip faults to outline tectonic blocks (fig. 2a), and then reversing the inferred post-Paleogene displacements of faults bounding these blocks to restore them to their probable relative positions during the Paleogene (fig. 2b). No attempt was made to correct for small overlaps and gaps between blocks, as such adjustments are beyond the limits of precision of this study. Palinspastic adjustments were made for the following offsets: (a) 210 km (kilometres) of right-slip on the San Andreas fault in southern California (Crowell, 1962); (b) 50 km of right-slip on the San Gabriel fault (Crowell, 1952); (c) 305 km of right-slip on the San Andreas fault in central and northern California (Clarke and Nilsen, 1973); (d) 20 km of right-slip on the Elsinore fault (Sage, 1973); (e) 25 km of right-slip on the San Jacinto fault (Sharp, 1967); (f) 60 km of right-slip on the Rinconada fault system (Dibblee, 1972); (g) 180 km of right-slip on the postulated East Santa Cruz Basin fault (Howell and others, 1974); (h) 15 km of left-slip on the Big Pine and Santa Ynez faults (Hill and Dibblee, 1953; Schroeter, 1972); (i) 60 km of left-slip on the Garlock fault (Smith, 1962; Michael, 1966); (j) 90 km of left-slip on the Malibu Coast fault system (Yerkes and Campbell 1971; Sage, 1973); and (k) 15 km of north-south compression in the Transverse Ranges.

The precision of biostratigraphic correlations varies widely within the Paleogene of California. As a result, the paleogeographic maps represent time intervals ranging from as little as about one million years (late Penutian) to as much as about 11 million years (Ynezian) (Berggren, 1972). The earliest reconstruction is representative of the Ynezian Stage; however, strata slightly older and younger than Ynezian may be included where the Paleocene has not been subdivided in parts of western and southern California. The next youngest interval, the late Penutian, was marked by a major marine transgression. Strata of this age are widely distributed, and paleontologic and lithologic data are plentiful. The Narizian reconstruction also is based on abundant data, and coincides with the beginning of a major marine regression. The Refugian reconstruction is based on scant paleontologic evidence, as it was a time of widespread continental sedimentation; our map depicts the greatest extent of the major marine regression that marked the close of the Paleogene in much of California.

Several well-known stratigraphic units, mostly Ulatisian (middle Eocene) in age, have been omitted because their known age ranges do not coincide with the time intervals we depict. These units, some of which define major paleogeographic features in California (Nilsen and Clarke, 1975; Howell,

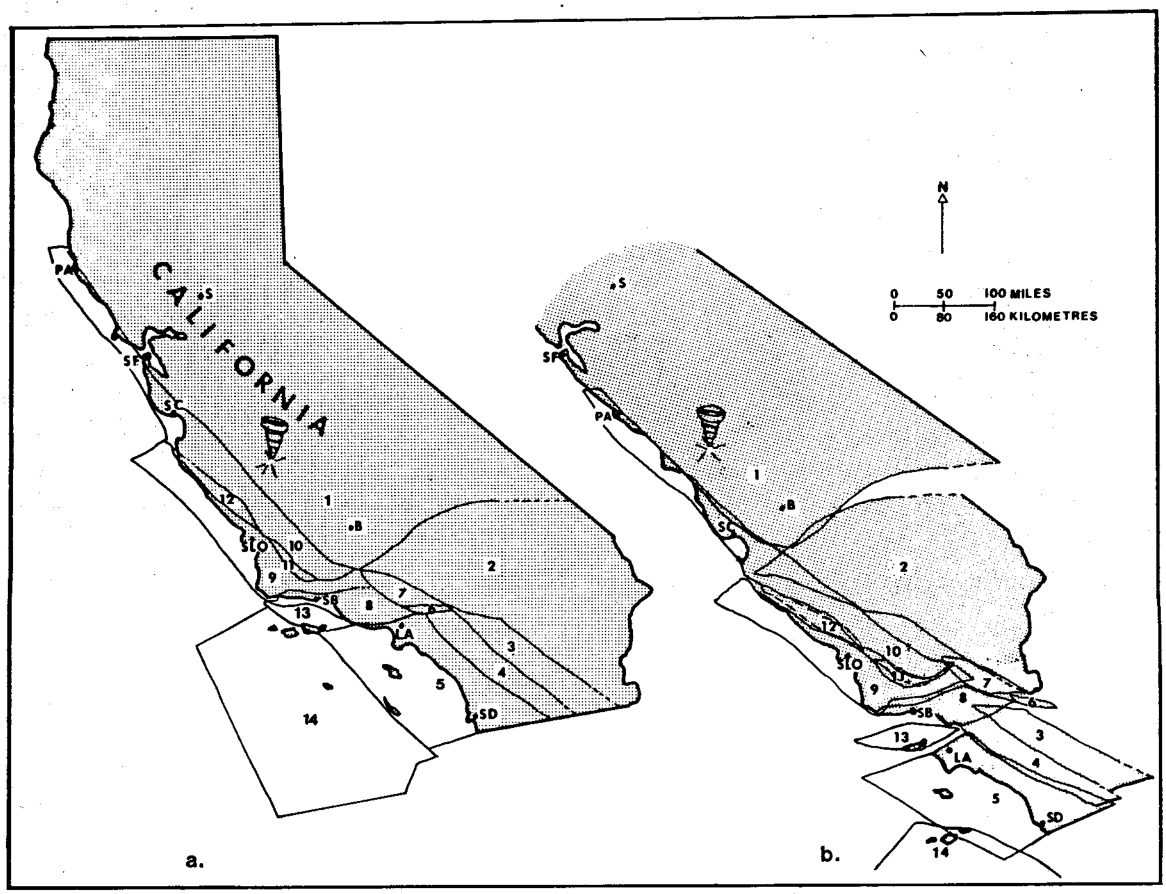

Figure 2. (a) Map of California showing the present locations of the 14 tectonic blocks and bounding faults used in the early Tertiary palinspastic reconstruction. (b) Palinspastic map of California, showing the 14 tectonic blocks of Figure 2a restored to their inferred relative positions during early Tertiary. Block 1, located east of the San Andreas fault and north of the Garlock fault is assumed to be fixed. See text for displacements used in this reconstruction, and Figure 1 for names of cities shown above.

this vol.), include: (1) auriferous gravels deposited in the Sierra Nevada area by westward-flowing rivers; (2) the Ione Formation, deposited along the west flank of the Sierra Nevada in northern California in shoreline and shallow-marine environments; (3) the Domengine Formation, deposited in the Diablo Range and southern Sacramento Valley areas in shallow-marine environments; (4) the Avenal Sandstone, deposited in the southern Diablo Range area in shallow-marine environments; (5) the Matilija Sandstone, deposited largely as a submarine fan complex in the central Transverse Ranges area, and (6) nonmarine gravels of middle or late Eocene(?) age deposited in the Peninsular Ranges by westward-flowing rivers.

Current or definitive sources of information concerning important stratigraphic units or areas are listed at the end of the paper. These references are keyed numerically to each of the paleogeographic maps. Citations in the text have been minimized for brevity and continuity. More comprehensive bibliographies concerned with Paleogene geographic reconstructions are listed by Nilsen and Clarke (1975) and in unpublished Ph.D. theses by Clarke (1973), Sage (1973) and Howell (1974).

PALEOGENE GEOGRAPHY

A northwest-trending continental landmass embraced much of the present area of the Sierra Nevada, Mojave Desert and Peninsular Ranges of California and northern Mexico during earliest Tertiary time. To the west lay the Pacific Ocean. By latest Cretaceous or possibly Paleocene time, 220 to 420 km of right-lateral displacement along a postulated proto-San Andreas fault zone had resulted in the emplacement of an irregular, granitic continental borderland ("Salinia") which extended northwestward about 300 km from the present southern Sierra Nevada (Suppe, 1970; Nilsen and Clarke, 1975). As a result of this displacement, basement rocks of the Franciscan Complex of Berkland and others (1972) in the area of the present Diablo and northern Temblor Ranges probably were juxtaposed with Salinian granitic rocks in the borderland to the west. The borderland partially separated the Pacific Ocean from an elongate marginal basin which occupied the present San Joaquin Valley and adjacent eastern part of the Coast Ranges. This marginal basin also probably was separated at times from the Sacramento basin to the north by a west-trending structural and physiographic high, the Stockton arch. Right-slip apparently ceased by early Paleocene time, but similar large-scale displacement resumed after early Miocene time with development of the present San Andreas fault system (Atwater, 1970; Clarke and Nilsen, 1973).

Marine sedimentary basins and upland source areas apparently began to form along the proto-San Andreas fault zone as early as Late Cretaceous time, when thick, coarse-grained, mostly marine deposits began to accumulate in the Gualala, Sierra Madre and Santa Ynez areas (Wentworth, 1966, 1968; Gower and others, 1966; Vedder and others, 1967; Vedder and Brown, 1968; Chipping, 1972a; Sage, 1973; Dibblee, 1950). These basins may have originated as oblique pull-apart basins (Crowell, 1974), formed by crustal extension along the fault zone at the same time that local compression elevated adjacent areas. In early Tertiary time, a major east-trending embayment apparently marked the south end of the borderland in the present area of the Transverse Ranges and southern Coast Ranges (Stauffer, 1967; Gibson, 1972, 1973; Sage, 1973).

A deep-sea trench located west of California during the Paleogene has been inferred from sea floor spreading data (Atwater, 1970), and from field studies of early Tertiary rocks in the northern Coast Ranges (O'Day and Kramer, 1972; O'Day, 1974; Kleist, 1974). A trench located along the central part of the present Coast Ranges during late Eocene and early Oligocene time also has been suggested on the basis of different evidence (Travers, 1972). However, this site and timing appear to be incompatible with the regional paleogeography presented here. If present, the trench probably extended from the northern Coast Ranges southward along the western margin of the Paleogene continental borderland.

The major features of each paleogeographic map are summarized in the following pages. These summaries cover the study area generally from north to south, in the following order: the Sacramento basin and adjoining areas, the San Joaquin basin and adjoining areas, the Paleogene continental borderland, the Transverse Ranges area and, finally, the region to the south which encompassed present-day southern California westward from the Peninsular Ranges.

Ynezian Stage (Paleocene)

The extent of Paleocene marine deposition in northern California is unknown because strata of this age are truncated by unconformities in many areas. Thick, mostly shallow-marine clastic deposits on the north flank of Mount Diablo and in klippen at several localities in the present northern Coast Ranges suggest that shallow seas covered much of this region (fig. 3). Deep-marine strata are exposed along the northwest flank of the Diablo Range (Vine Hill Sandstone of Weaver, 1953; Pinehurst Shale), indicating that the Sacramento basin deepened southwestward. This bathymetric trend is consistent with the abrupt thickening of the Paleocene section west of the Midland fault (Pacific Sec., Am. Assoc. Petroleum Geologists, 1951, 1967a). Sediments deposited in the Sacramento basin probably were derived chiefly from Sierran sources. However, Franciscan clasts and minor coal seams are found in Paleocene strata in a klippe in the northern Coast Ranges, suggesting that parts of this region also were emergent (Berkland, 1973).

The San Joaquin basin consisted largely of a broad stable shelf having a southward and westward slope. Shale containing littoral and neritic faunas (lower part of the Lodo Formation) blankets most of the present southwestern San Joaquin Valley south of the Vallecitos area. Nonmarine deposits of probable Paleocene age (lower part of the Walker Formation) in the eastern part of the Valley define the eastern extent of marine deposition (Pacific Sec., Am. Assoc. Petroleum Geologists, 1969). The lithologic change from shale (Lodo Formation) to coarser grained, shallow-marine and brackish water deposits along the east flank of the northern Diablo Range (Laguna Seca Formation of Payne, 1951, and Tesla Formation) reflects a northward shoaling of the basin. A westward deepening to lower neritic and bathyal, and perhaps greater depths is suggested by benthonic foraminifera from the northern Temblor Range and Vallecitos area (lower part of the Lodo Formation) and from the central Coast Ranges southeast of San Francisco (Bolado Park Formation of Sullivan, 1965; unnamed strata of Carter, 1970, and McLaughlin, 1973).

Although the principal source of sediments in the San Joaquin basin appears to have been the Sierra Nevada, parts of the present Diablo Range were

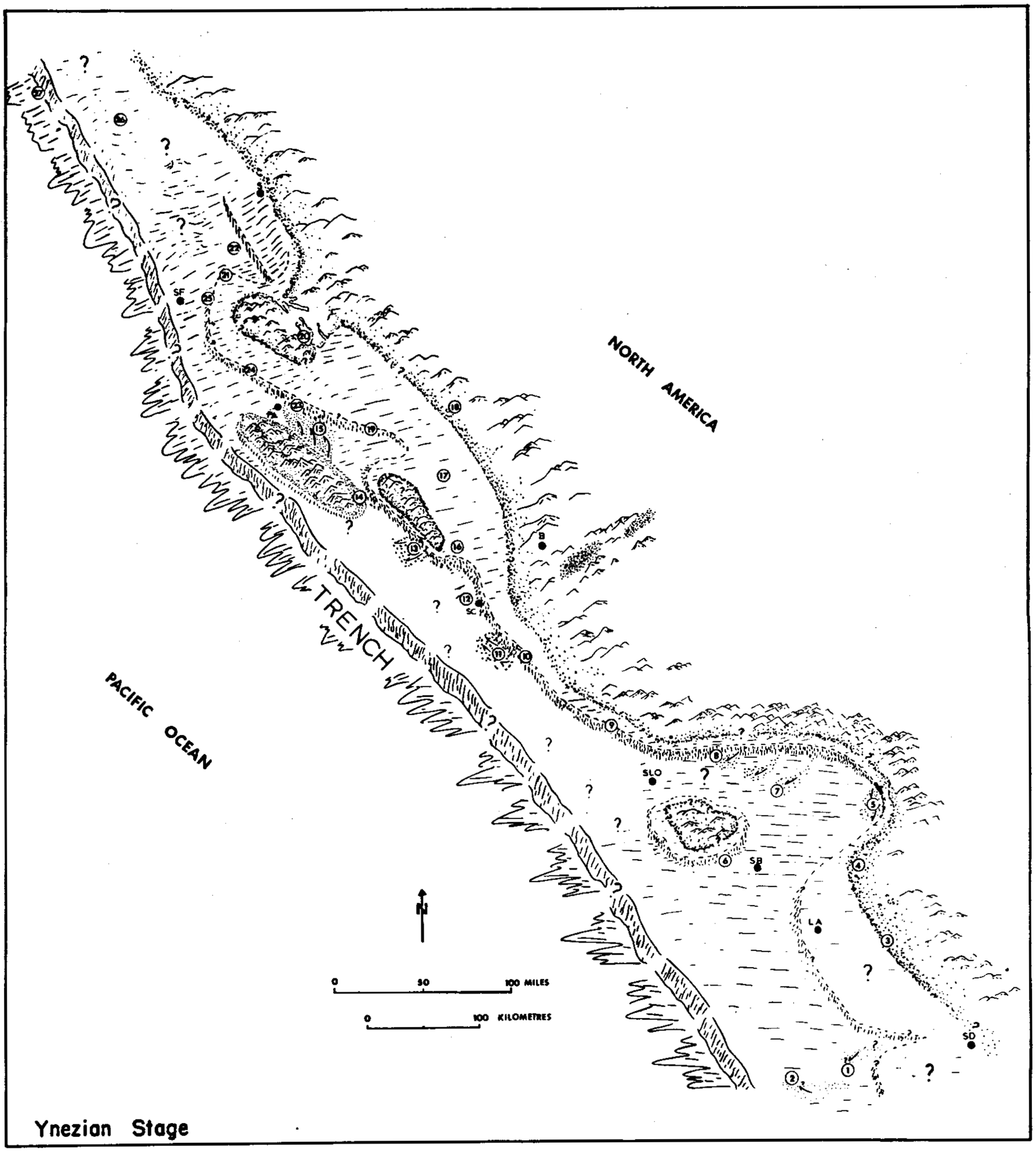

Figure 3. Paleogeographic map of California for Ynezian (Paleocene) time. Selected data sources are listed by locality number in the reference table. City names are given in Figure 1.

	Southern California Borderland	Peninsular Ranges	Salton Trough	Transverse Ranges	West of San Andreas fault		San Joaquin Valley	Sacramento Valley	East of San Andreas fault	
					Coast Ranges (South of Monterey Bay)	Coast Ranges (North of Monterey Bay)			Central Coast Ranges	Northern Coast Ranges
Ynezian Stage (Paleocene)	1. Pozo Fm. of Doerner (1969) 2. undifferentiated Pozo-Cañada Fms. of Weaver and Doerner (1969)	3. Silverado Fm. Woodring and Popenoe (1945), Sage (1973)		4. Martinez Fm. and unnamed sandstone (Simi Hills and Santa Monica Mts.) Sage (1973) 5. San Francisquito Fm. Sage (1973) 6. Sierra Blanca Ls. and Anita Sh. of Kelley (1943) Gibson (1972, 1973)	7. Pattiway Fm. of Hill and others (1958), Sage (1973) 8. unnamed strata of Vedder and others (1967), Chipping (1972a), Sage (1973) 9. Dip Creek Fm. of Taliaferro (1944); unnamed strata of Durham (1974) 10. unnamed strata of Dickinson (1965), Kleinpell and others (1967), Durham (1974) 11. Carmelo Fm. of Bowen (1965), Nili-Esfahani (1965)	12. Locatelli Fm. of Brabb (1960), Cummings and others (1962) 13. unnamed strata of Darrow (1963), Clark (1968), Chipping (1972b) 14. Laird Ss. Galloway (1961) 15. German Rancho Fm. of Wentworth (1966, 1968)	16. Lodo Fm. of Mallory (1959, 1970) 17. Lodo Fm. of Hackel (1966), Pac. Sec., AAPG (1957b, 1959) 18. Walker Fm. of Pac. Sec., AAPG (1969) 19. Cerros Sh. Mbr. of Lodo Fm. White (1940) 20. Laguna Seca Fm. of Payne (1951), Briggs (1953); Tesla Fm. of Huey (1948), Booth (1950), Payne (1951), Briggs (1953)	21. Martinez Fm. of Colburn (1961); Vine Hill Ss. of Weaver (1953), Smith (1957) 22. Martinez Fm. of Lachenbruch (1962), Pac. Sec., AAPG (1960, 1967a, 1967b)	23. Bolado Park Fm. of Sullivan (1965), Kaar (1962) 24. unnamed strata of McLaughlin (1973); unnamed mudstone of Carter (1970) 25. Pinehurst Sh. Case (1968)	26. Martinez Fm. of Clark (1940), Brice (1953), Swe and Dickinson (1970); Martinez Fm. (?) of Berkland (1973); unnamed sandstone of Berkland (1972) 27. Coastal belt, Franciscan Complex of Berkland and others (1972), O'Day and Kramer (1972), Kleist (1974), O'Day (1974); Coastal belt, Franciscan assemblage of Bailey and others (1964)

Note: Following are abbreviations used in figures 3, 4, 5, and 6:

- Fm. - Formation
- Gr. - Group
- Mbr. - Member
- Ls. - Limestone
- Sh. - Shale
- Ss. - Sandstone

emergent. The Martinez Formation on the north flank of Mount Diablo overlaps Cretaceous units and contains clasts apparently derived from Mesozoic rocks to the south in the Diablo Range (Colburn, 1961). Sandstone in the Tesla Formation in the northern Diablo Range contains glaucophane, indicating at least a partial Coast Range origin. The presence of shallow-marine and brackish water strata near the Stockton arch and absence of Paleocene rocks on the arch suggest that it also may have been emergent.

Thick sequences of nonmarine sand and gravel (Witnet and Goler Formations) were deposited in the Tehachapi and El Paso Mountains areas southeast of Bakersfield (figs. 1 and 3) (Dibblee, 1952, 1967). These strata apparently were deposited by alluvial processes in a northeast-trending lowland between highlands in the present Mojave Desert and southern Sierra Nevada.

The Salinian continental borderland was emergent in west-central California, forming the inferred source terrane for a thick deep-sea fan deposit in the Gualala area (German Rancho Formation of Wentworth, 1966, 1968). Clastic sediments deposited on this fan are thought to have had a southwestern source area, possibly an island. Other submarine fan deposits located near San Francisco at Point San Pedro (unnamed strata of Chipping, 1972b) and south of Monterey Bay at Point Lobos (Carmelo Formation of Bowen, 1965) may have been derived from western borderland source areas or from the Sierra Nevada. The Point San Pedro deposits also may have been recycled from Cretaceous sedimentary rocks in parts of the southern Diablo and northern Temblor Ranges which stood adjacent to this area and which presently are not covered by Paleocene strata. These areas are flanked by relatively shallow marine Ynezian deposits (Mallory, 1959, 1970) and may have undergone uplift throughout much of the Paleogene. Isolated remnants of Paleocene deposits are present elsewhere in the central and northern parts of this ancient borderland, but little is known of their facies relations, depositional environments and paleogeographic implications. A thin basal conglomerate and sandstone are present at Point Reyes (Laird Sandstone), a basal shallow-marine conglomerate is overlain by deep-marine shale in the Santa Cruz Mountains (Locatelli Formation of Brabb, 1960), and conglomerate, sandstone and shale probably representing shallow to deep-marine environments are present in the northern and central Santa Lucia Range (unnamed strata of Dickinson, 1965, and Dip Creek Formation of Taliaferro, 1944). It appears that shallow seas initially covered much of the central and northern parts of the borderland; these seas probably deepened through time in some areas.

Near the south end of the Paleogene borderland, a thick sequence of unnamed nonmarine, shallow-marine and deep-marine sediments, apparently derived from the continental region to the east, was deposited in the Sierra Madre basin. Submarine fan deposits are prominent in the east and west parts of this basin. The San Rafael high may have formed an emergent area along the southwest edge of the basin, which apparently merged to the southeast with a large, east-trending deep-marine embayment. A thick southwest-prograding submarine fan complex (San Francisquito Formation) was deposited in the east end of this embayment, the present eastern Transverse Ranges. Sands and gravels were deposited at shallow to intermediate depths along the eastern and southern margins of the embayment (Martinez Formation and unnamed sandstone of Sage, 1973; Pattiway Formation). To the west, deep-marine muds and silts containing thin turbidites (lower part of the Anita

Shale of Kelley, 1943) accumulated south of the San Rafael high in the present Santa Ynez Mountains. Algal limestone associated with these fine-grained deposits (Sierra Blanca Limestone) indicates local shoal conditions.

In southern California, a shoreline and a broad stable shelf probably extended southward along the west edge of the Peninsular Ranges into Baja California. Sediments presumably were shed westward onto this shelf from emergent areas in the Peninsular Ranges. However, in California these sediments are represented solely by paralic deposits at the north end of the Peninsular Ranges (Silverado Formation). If other Paleocene marine strata were present, they must have been eroded completely prior to the deposition of lower and middle Eocene transgressive sand and gravel. Ynezian turbidites are present on San Miguel Island (undifferentiated Pozo-Cañada Formation of Weaver and Doerner, 1969), suggesting that a submarine fan may have begun to develop in this region. Shelf environments are suggested by sandstone and siltstone containing neritic faunas nearby on Santa Cruz Island (Pozo Formation of Doerner, 1969).

The Coastal belt of the Franciscan Complex of Berkland and others (1972), located in the western part of the present northern Coast Ranges, comprises strata of Late Cretaceous to late Eocene age (O'Day and Kramer, 1972; O'Day, 1974). Olistostrome-like deposits in these rocks are inferred to have accumulated in a tectonically unstable submarine trench (Kleist, 1974), perhaps the Paleogene equivalent of the Mesozoic trench system in which similar but older Franciscan rocks are thought to have been deposited. If present, the trench probably extended from the northern Coast Ranges southward along the western margin of the Paleogene continental borderland of central California.

Late Penutian Stage (early Eocene)

Glauconitic siltstone and claystone (Capay Formation) containing neritic faunal assemblages are widespread in the Sacramento Valley. These deposits reflect low energy, slow rates of deposition and locally stagnant bottom conditions following a major early Eocene marine transgression (fig. 4). They coarsen eastward in the probable direction of land. Similar strata are present in klippen in the northern Coast Ranges, suggesting that shallow seas extended westward well beyond the present limits of the Sacramento Valley. Continued subsidence in the southwest Sacramento basin is indicated by abrupt thickening of the Capay Formation west of the Midland fault. Likewise, paleobathymetric interpretations from foraminiferal assemblages suggest greater depths in this part of the basin (Smith, 1957). The Capay or Princeton gorge, a south-trending erosional feature in the western Sacramento Valley, cuts into lower Tertiary and Cretaceous strata and is filled by 650 m (metres) or more of lower Eocene mudstone, sandstone and minor conglomerate (Safonov, 1962; Redwine, 1972). This gorge has been interpreted as a submarine canyon whose position was at least partly controlled by subsidence of the basin to the south.

The central San Joaquin basin apparently persisted as a broad shelf on which fine-grained hemipelagic sediments (Lodo Formation) accumulated. Neritic depths are inferred from fossil assemblages along the west side of the present San Joaquin Valley. Along the east side of the Valley, nonmarine strata (lower part of the Walker Formation) indicate the eastern

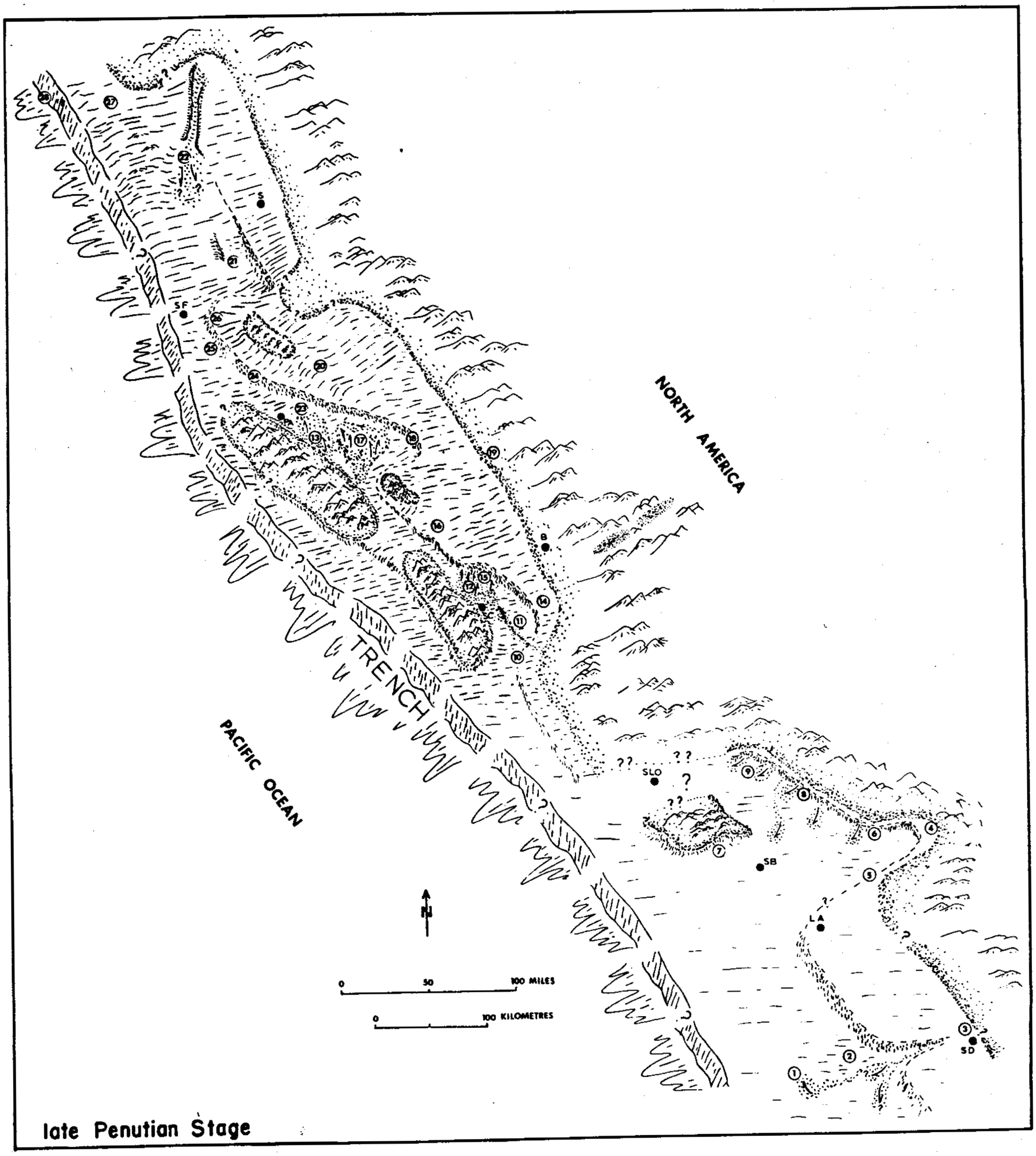

Figure 4. Paleogeographic map of California for late Penutian (early Eocene) time. Selected data sources are listed by locality number in the reference table. City names are given in Figure 1.

					West of San Andreas fault				East of San Andreas fault	
	Southern California Borderland	Peninsular Ranges	Salton Trough	Transverse Ranges	Coast Ranges (South of Monterey Bay)	Coast Ranges (North of Monterey Bay)	San Joaquin Valley	Sacramento Valley	Central Coast Ranges	Northern Coast Ranges
late Penutian Stage (early Eocene)	1. undifferentiated Pozo-Cañada Fms. of Weaver and Doerner (1969), Howell (1974) 2. Cañada Fm. of Doerner (1969)	3. basal part of La Jolla Group Kennedy and Moore (1971)	4. Maniobra Fm. of Crowell and Susuki (1959), Howell (1974)	5. Llajas Fm. of Cushman and McMasters (1936); Santa Susana Fm. of Clark (1924), Mallory (1959) 6. Juncal Fm. of Howell (1974) 7. Anita Sh., Sierra Blanca Ls. and Juncal Fm. of Gibson (1972, 1973), Howell (1974)	8. unnamed strata of Vedder and others (1967), Chipping (1972a) 9. unnamed strata of Carman (1964) 10. Junipero Ss. of Thorup (1941); Lucia Mudstone of Dickinson (1965), Durham (1974), Nilsen and Link (1975) 11. San Juan Bautista Fm. of Kerr and Schenck (1925), Castro (1967), Clark and Reitman (1973)	12. Butano Ss. of Cummings and others (1962), Clark (1968), Nilsen and Simoni (1973) 13. German Rancho Fm. of Wentworth (1966, 1968)	14. Tejon Fm. of Nilsen (1973) 15. Point of Rocks Ss. (Penutian?) of Clarke (1973) 16. Middle Lodo, Mabury and Acebedo Mbrs. of Lodo Fm. of Mallory (1959, 1970), Clarke (1973) 17. Cantua Ss. Mbr. of Lodo Fm. Nilsen and others (1974) 18. Lodo Fm. of Mallory (1959), Hackel (1965), Pac. Sec., AAPG (1957b, 1959) 19. Walker Fm. of Hackel (1966), Pac. Sec., AAPG (1969) 20. Laguna Seca Sm. of Payne (1951), Briggs (1953); Tesla Fm. of Allen (1947), Huey (1948), Booth (1950), Payne (1951), Briggs (1953)	21. Capay Fm. of Safonov (1962), Hackel (1966), Pac. Sec., AAPG (1951, 1960, 1967a, 1967b) 22. "Capay gorge" and gorge fill of Safonov (1962), Redwine (1972)	23. Tres Pinos Ss. of Kerr and Schenck (1925), Nilsen and others (1974) 24. unnamed strata of McLaughlin (1973); unnamed lower Eocene(?) mud-stone of Carter (1970) 25. unnamed strata of Beaulieu (1970) 26. unnamed lower Eocene(?) strata of Case (1968)	27. unnamed glau-conitic sand-stone of Berkland (1973); Capay Fm. of Clark (1940) 28. Coastal belt, Franciscan Complex of Berkland and others (1972), O'Day and Kramer (1972), Kleist (1974), O'Day (1974); Coastal belt, Franciscan assemblage of Bailey and others (1964)

limit of marine sedimentation (Pacific Sec., Am. Assoc. Petroleum Geologists, 1969). The beginning of an eastward transgression which continued into late Eocene time is marked by basal conglomerate and sandstone (Uvas Conglomerate Member of the Tejon Formation) at the south end of the San Joaquin Valley (Nilsen, 1973). A northwest-trending trough in the Vallecitos area of the west-central San Joaquin basin, formed during late Paleocene time, continued to subside to lower neritic to bathyal depths. This trough received thick submarine fan deposits (Cantua Sandstone Member of the Lodo Formation and possibly the Tres Pinos Sandstone of Kerr and Schenck, 1925), apparently derived from a granitic source in the continental borderland to the west (Nilsen and others, 1974). Coeval silts and sands were deposited at similar depths in the central Coast Ranges southeast of San Francisco (McLaughlin, 1973).

Northward shoaling of the San Joaquin basin is indicated by the lithologic change from shale (Lodo Formation) to shallow-marine sandstone (Laguna Seca Formation of Payne, 1951, and Tesla Formation) along the present northeast flank of the northern Diablo Range. This shoaling, together with the absence of lower Eocene rocks to the east, suggests that the Stockton arch was a physiographic high. Parts of the present Diablo Range almost certainly were emergent. Glaucophane in shallow-marine sandstone (Tesla Formation) in the northeast part of the Diablo Range probably was derived from Franciscan rocks to the west (Morris, 1962). On the west flank of the Diablo Range, coarse-grained Franciscan detritus apparently derived from the east is abundant in sandstone deposited at shelf depth near San Francisco (Beaulieu, 1970). Shallow-marine strata overlap Cretaceous sedimentary rocks in parts of the southern Diablo Range; at one locality serpentine in shallow-marine sandstone (lower part of the Acebedo Member of the Lodo Formation of Mallory, 1959) appears to have been derived from a nearby northern source area (Herrera, 1951). In the southernmost Diablo and northern Temblor Ranges, very shallow depths are indicated by fossil assemblages from late Penutian marine sandstones (Mabury and Middle Lodo Members of the Lodo Formation of Mallory, 1959; 1970; Dickinson, 1966).

Nonmarine sandstone and conglomerate (Witnet and Goler Formations) in the Tehachapi and El Paso Mountains areas indicate alluvial deposition in a northeast-trending lowland between the present southern Sierra Nevada and Mojave Desert. These strata are incompletely dated; however, the great thickness of section above a Paleocene vertebrate fauna suggests that deposition continued into Eocene time (Dibblee, 1967).

Granitic islands in the Paleogene continental borderland shed coarse-grained sediments northward onto major submarine fans in the Gualala and Santa Cruz Mountains areas (German Rancho Formation of Wentworth, 1966, 1968; Butano Sandstone). These submarine fan deposits probably spilled eastward onto the floor of the adjacent marginal sea, and are represented now by co-genetic strata east of the San Andreas fault in the Vallecitos area, southeastern part of the Coast Ranges and southwestern San Joaquin Valley. The German Rancho Formation may be equivalent to the Cantua Sandstone Member and possibly the Tres Pinos Sandstone of the Vallecitos area (Nilsen and others, 1974). Similarly, Penutian strata in the Butano Sandstone may be equivalent to the lower part of the Point of Rocks Sandstone (Clarke, 1973; Clarke and Nilsen, 1973). The coarseness, freshness and angularity of detrital grains and thickness of these fan deposits suggest that the island source areas had substantial relief and underwent rapid erosion.

Shallow-marine transgressive sand was deposited on an uneven topographic surface on crystalline basement in the northern Santa Lucia Range (Junipero Sandstone of Thorup, 1941). Coeval shale in the northern Gabilan Range (lower part of the San Juan Bautista Formation of Kerr and Schenck, 1925) and superjacent mudstone in the Santa Lucia Range (Lucia Mudstone of Dickinson, 1965) record offshore sites of deposition and greater depths as the transgression proceeded. The transgressive sequence here resembles correlative deposits in the Tejon Formation in the San Joaquin Valley, and it is probable that these two areas were contiguous sites of deposition during the Paleogene (Nilsen and Link, 1975).

Farther south, coarse-grained sediments were transported west- and southwestward onto submarine fans in the Sierra Madre basin (Chipping, 1972a). This northwest-trending basin occupied the present area of the southernmost Coast Ranges. To the southwest it was bounded by the emergent San Rafael high; shoaling adjacent to this high is indicated by algal limestone (Sierra Blanca Limestone) which locally contains detritus of the Franciscan Complex. To the southeast the Sierra Madre basin merged with an east-trending marine embayment in the present Transverse Ranges. Deep-marine sand, silt and mud (Anita Shale) were deposited in the central and western parts of this embayment, while shelf and shallow-marine sediments (Santa Susana Formation of Clark, 1924, Llajas Formation of Cushman and McMasters, 1936, and Maniobra Formation of Crowell and Susuki, 1959) were deposited along the landward margins to the southeast and east.

Basal shallow-marine sandstone and conglomerate (basal part of the La Jolla Group) near San Diego mark the beginning of a major eastward transgression across a broad stable shelf which probably extended southeastward from Los Angeles into Baja California. The shelf deposits contain granitic debris, probably derived from the Peninsular Ranges, and silicic volcanic clasts, probably derived from a volcanic terrane farther east. This shelf apparently was incised by a submarine canyon through which shelf sediments were transported onto a submarine fan now located in the northern part of the southern California borderland (undifferentiated Pozo-Cañada Formations of Weaver and Doerner, 1969). Coeval shale and fine-grained sandstone (Cañada Formation of Doerner, 1969) reflect low energy environments and lower neritic and bathyal depths in areas adjacent to this fan.

The continued presence of a submarine trench along the west side of the present northern Coast Ranges is inferred from olistostrome-like deposits in the Coastal belt of the Franciscan Complex of Berkland and others (1972). If present, this trench probably extended southward along the western margin of the Paleogene continental borderland of central California.

Narizian Stage (late Eocene)

The extent of Narizian marine deposition in northern California is unknown, as rocks of this age generally are truncated by an unconformity. A broad shelf probably occupied much of the southern Sacramento basin. Hemipelagic shale with thin sandstone beds and mostly sublittoral faunas (upper part of the Nortonville Shale Member of the Kreyenhagen Shale) characterizes deposition in this region (fig. 5). The Markley gorge, a 350 m deep sub-

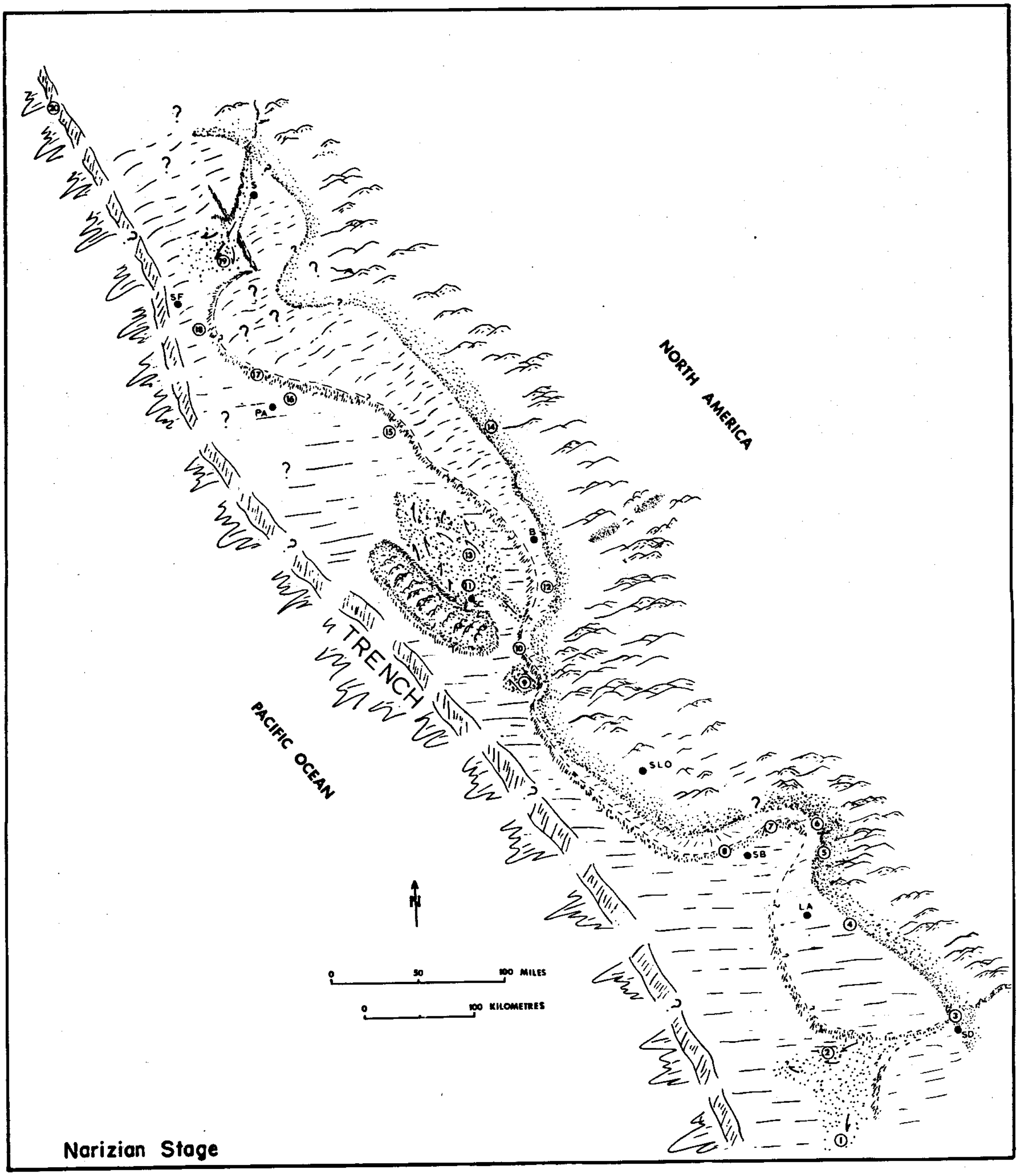

Figure 5. Paleogeographic map of California for Narizian (late Eocene) time. Selected data sources are listed by locality number in the reference table. City names are given in Figure 1.

					West of San Andreas fault				East of San Andreas fault	
	Southern California Borderland	Peninsular Ranges	Salton Trough	Transverse Ranges	Coast Ranges (South of Monterey Bay)	Coast Ranges (North of Monterey Bay)	San Joaquin Valley	Sacramento Valley	Central Coast Ranges	Northern Coast Ranges
Narizian Stage (late Eocene)	1. Units 15-30 of Vedder and Norris (1963) 2. Jolla Vieja Fm. and Cozy Dell Sh. of Doerner (1969); South Point Fm. of Weaver and Doerner (1969)	3. Poway and La Jolla Groups Kennedy and Moore (1971) 4. Santiago Fm. Woodring and Popenoe (1945), Yerkes and others (1965)		5. Sespe Fm. Stock (1931) 6. unnamed nonmarine strata of Kriz (1947) 7. Coldwater Ss. and Cozy Dell Sh. Vedder and others (1973) 8. Coldwater Ss., Cozy Dell Sh. and Sacate Fm. of Kelley (1943), Weaver and Molander (1964), O'Brien (1973)	9. The Rocks Ss. of Thorup (1941), Dickinson (1965), Link (1975), Nilsen and Link (1975) 10. San Juan Bautista Fm. of Kerr and Schenck (1925), Castro (1967), Kleinpell and others (1967), Clark and Reitman (1973)	11. Butano Ss. and San Lorenzo Fm. of Cummings and others (1962), Brabb (1964), Clark (1968), Nilsen and Simoni (1973)	12. Tejon and Tecuya Fms. of Nilsen (1973) 13. Point of Rocks Ss., Kreyenhagen Sh., Famosa sand of Hackel (1966), Walker Fm. Clarke (1973) 14. Walker Fm. of Pac. Sec., AAPG (1969) 15. Kreyenhagen Sh. of Booth (1950), Briggs (1953), Pac. Sec., AAPG (1957b, 1958) Mallory (1959), Hackel (1966)	16. Markley Fm. of Clark and Campbell (1942), Nortonville Sh. Mbr. of Kreyenhagen Sh. Mallory (1959), Colburn (1961), Safonov (1962), Hackel (1966), Pac. Sec., AAPG (1951, 1960, 1967a, 1967b)	17. upper part of Los Muertos Creek Fm. of Wilson (1943), Kaar (1962), Kleinpell and others (1967) 18. unnamed upper Eocene(?) strata of Ortalda (1948) Carter (1970), McLaughlin (1973) 19. unnamed strata of Beaulieu (1970), Page and Tabor (1967)	20. Coastal belt, Franciscan Complex of Berkland and others (1972), O'Day and Kramer (1972), Kleist (1974), O'Day (1974); Coastal belt, Franciscan assemblage of Bailey and others (1964)

marine canyon cut into this shelf during Eocene time, apparently funneled sediments southwestward across the Midland fault into the subsiding southwestern part of the basin. A thick sequence of sandstone derived from Sierran sources and deposited largely by turbidity currents (Markley Formation of Clark and Campbell, 1942) may represent a large submarine fan that accumulated at the mouth of this canyon. Bathyal or greater depths are suggested for this part of the basin by microfossils from coeval shale (Mallory, 1959).

The San Joaquin depositional basin consisted of a shallow-marine shelf in the east and a deep basin in the west, separated by a northwest-trending, west-facing slope. At the south end of the San Joaquin Valley, shale containing bathyal to abyssal microfaunas grades eastward in outcrop into shallow-marine sandstone (Tejon Formation), indicating the transition from deep basin to inner shelf environments (Nilsen, 1973). Still farther east are nonmarine deposits which probably are partly coeval (Tecuya Formation) (Nilsen, 1973). The same transition is apparent farther north, where shale and siltstone (Kreyenhagen Shale) containing bathyal, and locally perhaps abyssal, microfossils grade eastward in subsurface into sandy shale and finally into shallow-marine sandstone (Famosa sand of Hackel, 1966) (Clarke, 1973). These marine strata interfinger farther east with nonmarine deposits (Walker Formation). The basin was deepest in the southwest, in the area now occupied by the western San Emigdio Range, southwestern San Joaquin Valley and adjacent southeastern Coast Ranges. In this area, thick coarse-grained submarine fan deposits (Point of Rocks Sandstone), which are inferred to have been derived from the Salinian block to the west, were deposited at bathyal to abyssal depths (Clarke, 1973). The extent of this deep basin is unknown because Eocene strata are missing throughout most of the present Diablo Range. However, bathyal or greater depths have been inferred for isolated outcrops of shale and sandstone in the central part of the Coast Ranges northwestward nearly to San Francisco (upper part of the Los Muertos Creek Formation of Wilson, 1943; unnamed strata of McLaughlin, 1973; unnamed strata of Beaulieu, 1970).

The San Joaquin basin apparently shelved northward toward the Stockton arch. Narizian shale (Kreyenhagen Shale) in the northern part of the San Joaquin Valley is sandy and locally contains neritic faunas and carbonaceous matter (Booth, 1950; Briggs, 1953; Hackel, 1966). The present northern Diablo Range area was positive and may have been emergent locally. Franciscan rocks in the core of the Range have been suggested as a partial source for upper Eocene (?) sandstone southeast of San Francisco (Ortalda, 1948; Carter, 1970; McLaughlin, 1973).

The undated upper parts of thick nonmarine deposits (Witnet and Goler Formations) in the Tehachapi and El Paso Mountains areas may contain late Eocene or younger strata. Alluvial deposition in a northeast-trending lowland has been inferred for these deposits (Dibblee, 1967).

In the Paleogene continental borderland, older sedimentary and granitic rocks in the Monterey Bay area continued to shed detritus northward onto a submarine fan (Nilsen and Simoni, 1973). This fan is thought to be represented by thick, coarse-grained sandstone in the Santa Cruz Mountains (Butano Sandstone) and in the southern Diablo and northern Temblor Ranges east of the San Andreas fault (Point of Rocks Sandstone) (Clarke and

Nilsen, 1973). Coincident with fan deposition, fine-grained, outer shelf or slope sediments (middle part of the San Juan Bautista Formation of Kerr and Schenck, 1925) were deposited southeast of Santa Cruz. When fan growth ceased, hemipelagic sediments accumulated over the entire depositional area (Twobar Shale Member of Brabb, 1960, of the San Lorenzo Formation in the Santa Cruz area; Kreyenhagen Shale in the southwestern San Joaquin Valley area). Another, apparently smaller submarine fan (The Rocks Sandstone of Thorup, 1941), probably derived from a southeastern source, was deposited at the same time in the area of the northern Santa Lucia Range (Link, 1975).

Farther south, silt and mud (Cozy Dell Shale; Sacate Formation of Kelley, 1943) accumulated in deep-marine areas, while fossiliferous sand (Coldwater Sandstone of Kerr and Schenck, 1928) was deposited in littoral and sublittoral environments in the central and eastern parts of the east-trending embayment in the present Transverse Ranges. By late Eocene time, shelf seas which earlier had occupied the southeast and northeast margins of the embayment had been replaced by areas of nonmarine deposition (Stock, 1931; Kriz, 1947). Toward the close of the Narizian, shallow-marine sands in the central and western parts of the embayment prograded westward. Nonmarine sands (upper part of the Santiago Formation) were deposited locally in the northern part of the Peninsular Ranges, and deltaic sand and gravel (Poway Group of Kennedy and Moore, 1971) were deposited in the San Diego area. Sediment probably derived from sources in the Peninsular Ranges and farther to the east continued to be funneled westward onto a large submarine fan (Jolla Vieja Formation and Cozy Dell Shale of Doerner, 1969; South Point Formation of Weaver and Doerner, 1969; units 15[?]-30 of Vedder and Norris, 1963) now located in the southern California borderland.

The continued presence of a submarine trench along the west side of the present northern Coast Ranges is suggested by possible late Eocene marine deposits in the Coastal belt of the Franciscan Complex (O'Day and Kramer, 1972; O'Day, 1974). This trench, if present, probably extended southward west of the continental borderland of central California.

Refugian Stage (late Eocene or early Oligocene)

In the Sacramento Valley marine Refugian strata are preserved locally and continental deposits of this age are difficult to distinguish from younger nonmarine strata in subsurface; consequently, reconstructions of the Refugian Sacramento basin are questionable. Shallow-marine conglomerate and sandstone (Wheatland Formation of Clark and Anderson, 1938) adjacent to andesite mudflow breccias (Reeds Creek Andesite of Clark and Anderson, 1938) suggest a marine margin in the southeast part of the Valley, near the apparent landward end of the Markely gorge (Durrell, 1966) (fig. 6). This submarine canyon is filled by upper Eocene to lower Miocene(?) marine shale and sandstone (Almgren and Schlax, 1957; Pacific Sec., Am. Assoc. Petroleum Geologists, 1967a, 1967b). In the southern part of the basin, tuffs and marine sands (Kirker Tuff and subjacent sandstone) were deposited at relatively shallow depths.

In the southeastern San Joaquin Valley, late Eocene or Oligocene nonmarine deposits (Walker and Tecuya Formations) prograde westward over Narizian and Refugian shallow-marine strata (Famosa sand of Hackel, 1966; Tejon

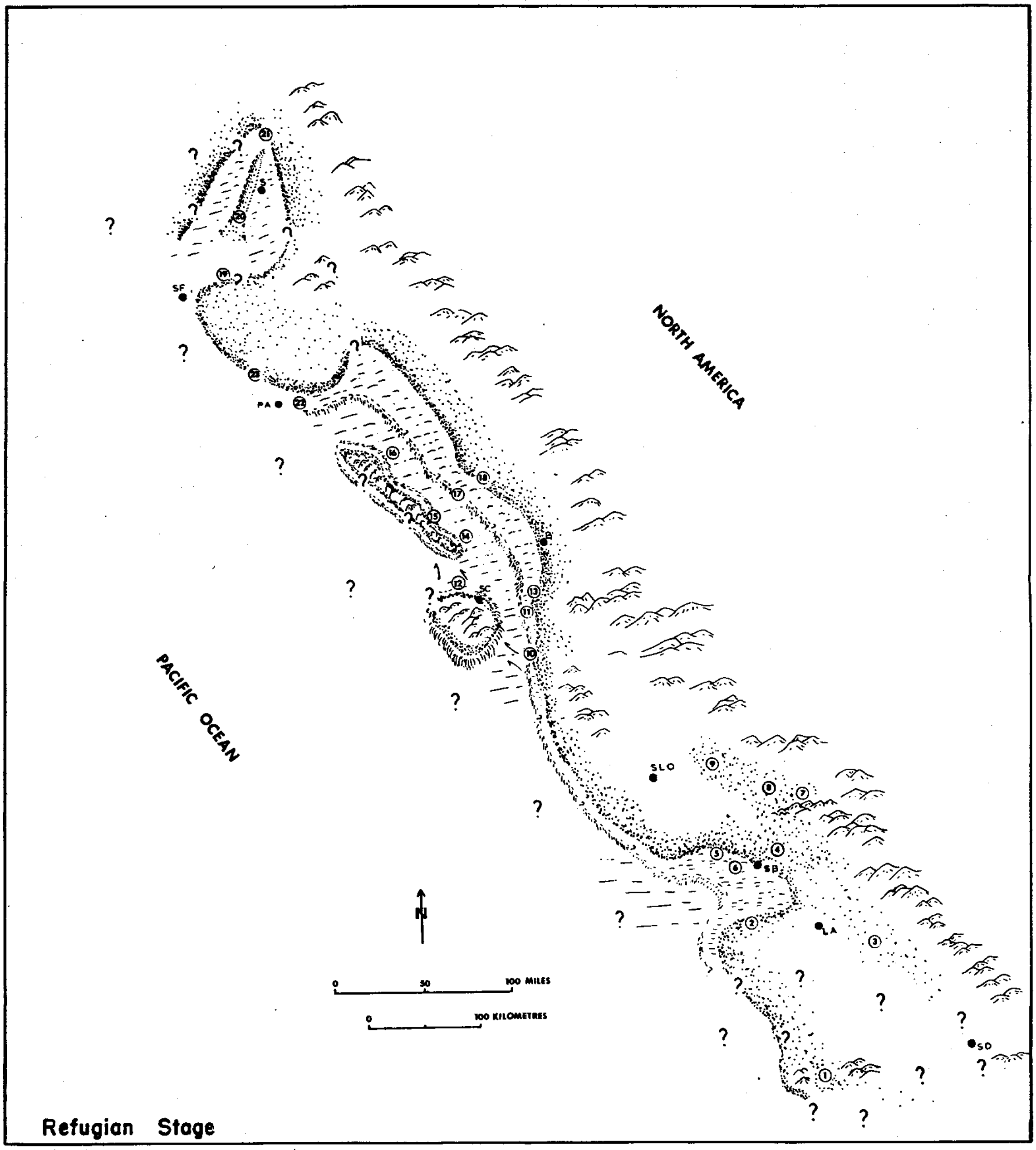

Figure 6. Paleogeographic map of California for Refugian (late Eocene or early Oligocene) time. Selected data sources are listed by locality number in the reference table. City names are given in Figure 1.

	Southern California Borderland	Peninsular Ranges	Salton Trough	Transverse Ranges	West of San Andreas fault Coast Ranges (South of Monterey Bay)	Coast Ranges (North of Monterey Bay)	San Joaquin Valley	Sacramento Valley	East of San Andreas fault Central Coast Ranges	Northern Coast Ranges
Refugian Stage (late Eocene or early Oligocene)	1. Sespe Fm. Weaver and others (1969) 2. Oligocene(?) strata in subsurface Weaver and others (1969, p. 47)	3. Sespe Fm. Vedder and others (1957)		4. Sespe Fm. Flemal (1967), McCracken (1972) 5. Sespe and Alegria Fms. Kleinpell and Weaver (1963) 6. Sacate Fm. of Kelley (1943), Alegria Fm. O'Brien (1973)	7. Plush Ranch Fm. (Oligocene?) of Carman (1964) 8. Simmler Fm. Hill and others (1958), Schwade and others (1958), Bartow (1974), Bohannon (1974) 9. Sespe Fm. Hill and others (1958), Schwade and others (1958), Bartow (1974), Bohannon (1974) 10. Berry and Church Creek Fms. Dickinson (1965), Addicott (1968), Brabb and others (1971), Durham (1974) 11. San Juan Bautista Fm. of Kerr and Schenck (1925), Castro (1967) Gribi (1967)	12. San Lorenzo Fm. Cummings and others (1962), Brabb (1964), Clark (1966, 1968)	13. San Emigdio, Pleito, and Tecuya Fms. Nilsen and others (1973) 14. Oceanic sand of Hackel (1966), Seiden (1964), Foss and Blaisdell (1968) 15. Wagonwheel Fm. Smith (1956) 16. Tumey Ss. of Atwill (1935) Zimmerman (1944), Phillips and others (1974) 17. Tumey Fm. of Atwill (1935), Pac. Sec., AAPG (1957a, 1957b, 1958, 1959) Hackel (1966), Phillips and others (1974) 18. Walker Fm. of Hackel (1966), Pac. Sec., AAPG (1969)	19. Kirker Tuff and underlying "Kirker Ss." Colburn (1961), Hackel (1966) 20. "Markley gorge" fill of Almgren and Schlax (1957), Safonov (1962), Pac. Sec., AAPG (1967a) 21. Wheatland Fm. and Reeds Creek Andesite of Clark and Anderson (1938), Durrell (1966)	22. Indart Ss. (Refugian?) of Taliaferro (1945) Kleinpell and others (1967) 23. unnamed Oligocene(?) strata of McLaughlin (1973)	? ? ? ?

and San Emigdio Formations), indicating a major marine regression. The nonmarine deposits interfinger westward in outcrop with shallow-marine sandstone (lower part of the Pleito Formation) at the south end of the Valley. The shallow-marine units in turn grade northwestward into deep-marine shale (upper part of the Kreyenhagen Shale; Tumey Formation of Atwill, 1935). Bathyal depths and restricted access to the open ocean are suggested by microfaunas from shale in the western San Joaquin Valley (Mallory, 1959; Phillips and others, 1974). Lenticular, mostly shallow-marine sandstones (Oceanic sand of Hackel, 1966; sandstone in the lower part of the Wagonwheel Formation [Smith, 1956]; Tumey Sandstone of Atwill, 1935; and an unnamed sandstone in the Vallecitos area [Phillips and others, 1974]), which appear to have been derived from older sedimentary rocks to the west, occur within these fine-grained hemipelagites. These sandstones probably were deposited along the east flank of a landmass in the present area of the southern Diablo and Temblor Ranges.

Marine and nonmarine strata are also present in the area of the Paleogene continental borderland. Hemipelagic mud (Rices Mudstone Member of Brabb, 1960, 1964, of the San Lorenzo Formation) accumulated at bathyal to neritic depths in a basin having restricted access to the open ocean in the Santa Cruz Mountains area. Sand and silt (upper part of the San Juan Bautista Formation of Kerr and Schenck, 1925, and Church Creek Formation) were deposited in shoreline to upper slope environments at the north end of the present Gabilan Range and in the northern Santa Lucia Range (Brabb and others, 1971; Clark and Rietman, 1973), while nonmarine sand and gravel (Berry Formation) were deposited to the southeast (Dickinson, 1965; Nilsen and Link, this vol.). Nonmarine sand and gravel (Sespe and Simmler Formations; Plush Ranch Formation of Carman, 1964) also were deposited in the central and eastern parts of the persistent, east-trending embayment at the south end of the Paleogene borderland and in the region to the northeast. Clasts apparently derived from the Franciscan Complex in the San Rafael high to the northwest are present in nonmarine conglomerate in the central part of this embayment (Flemal, 1967; McCracken, 1972). Shallow-marine and coastal environments are indicated by sandstone and shale (Gaviota Formation of Effinger, 1936) farther west.

Nonmarine strata (Sespe Formation) are present in the northern and western Peninsular Ranges; in the latter area they overlie Eocene marine rocks, reflecting a marine regression. Nonmarine deposits (Sespe Formation) also are present on Santa Rosa Island but appear to be missing on Santa Cruz and San Miguel Islands to the east and west.

CONCLUSIONS

Terrigenous and hemipelagic sediments containing littoral and neritic faunas were deposited on northwest-trending, stable shelves about 20-80 km wide which occupied most of the present Sacramento Valley, eastern San Joaquin Valley, south-central Transverse Ranges and western Peninsular Ranges. These deposits generally grade eastward into nonmarine strata and westward into deep-marine shale. Major transgressions occurred during early Paleocene and early and middle Eocene time; a major regression began in late Eocene time and culminated during the Oligocene. Subsidence on the west side of the Midland fault in the southwestern Sacramento basin strongly influenced Paleogene marine sedimentation in northern California. The late

Paleocene to early Eocene Meganos gorge, early Eocene Princeton (Capay) gorge, and late Eocene and Oligocene Markley gorge appear to be submarine canyons that funneled large volumes of sediment southward and westward into this area. Major submarine fans also were deposited during the Eocene in the southwestern part of the San Joaquin basin. The west side of the San Joaquin Valley and adjacent Coast Ranges were active tectonically during the Paleogene. Parts of the present northern Diablo Range probably were emergent during Paleocene and early and middle Eocene time, and uplift occurred in the Diablo and northern Temblor Ranges in early and middle Eocene and during late Eocene or early Oligocene time. These uplifted areas are inferred to have been the sources for Paleocene to middle Eocene deposits that contain glaucophane, serpentine and clasts of the Franciscan Complex. Their eastern flanks probably formed the depositional sites for lower to middle Eocene and Oligocene shallow-marine sedimentary rocks in the present southwestern San Joaquin Valley.

Submarine fan deposits that are coarse-grained, thick and areally limited are the most prominent depositional features of the Paleogene continental borderland of west-central California. These fans apparently were derived from nearby highlands and deposited at lower neritic to bathyal depths in relatively small, localized basins. Some fans spilled eastward onto the floor of the adjacent marginal sea, and subsequently were truncated by Neogene offsets along the San Andreas fault. At the south end of the borderland, a large east-trending marine embayment occupied the area of the present Transverse Ranges throughout most of Paleogene time, but probably had its greatest extent during the Paleocene and early Eocene when it merged with the Sierra Madre basin of the present southernmost Coast Ranges. The San Rafael high northwest of the present Transverse Ranges shed detritus southward into this embayment during Eocene and possibly Paleocene time, and also may have formed the southwest margin of the Sierra Madre basin. Late Eocene or Oligocene nonmarine deposits containing Franciscan clasts probably were derived from this upland.

A submarine canyon apparently cut the continental shelf in southern California. Sediments transported through this canyon supplied a major submarine fan to the west. Growth of this fan continued throughout the Eocene, but was most active during middle and late Eocene time.

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Upper Cretaceous and Paleogene Stratigraphy along the Western Big Pine fault, Santa Barbara County, California

by

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ABSTRACT

Approximately 4130 meters of Upper Cretaceous and Paleogene rocks are exposed in a 70 square kilometer area along the Big Pine fault in northern Santa Barbara County. The lithology consists predominantly of arkosic sandstones, siltstones and silty mudstones. Minor conglomerates, shales and limestones are also present. The strata are concordant from Upper Cretaceous through Middle Eocene, and include a previously unreported Paleocene sequence. The rock sequences are significantly different on opposite sides of the Big Pine fault, with the Sierra Blanca Limestone lying only to the south of the fault, and with lithologic contrasts in the separate undifferentiated Eocene sequences.

Upper Cretaceous rocks were deposited in bathyal depths by proximal turbidity currents from a granitic and siliceous metavolcanic landmass to the northeast. Paleocene silty mudstones were deposited in outer bathyal (1000m to 2000m) depths. The Sierra Blanca Limestone represents several Eocene algal bank lithofacies of Penutian(?) Age associated with a local topographic high to the southwest. This local high disappeared in the Middle Eocene and turbidite deposits again came from the northeast.

INTRODUCTION

The Big Pine fault trends east-west across Santa Barbara, Ventura and Kern Counties, California, at the boundary between the Coast and Transverse Ranges. (Fig. 1) The western portion of the fault extends through rugged San Rafael Wilderness Area, where problems of access and poor rock exposure have limited previous studies to reconnaissance methods only (Fairbanks, 1894; Nelson, 1925; Vedder et al, 1967). Upper Cretaceous and Paleogene rocks are exposed both north and south of the Big Pine fault in this area. Approximately 4100m of section was recorded in a 70 square km area in northern Santa Barbara County (Fig. 2).

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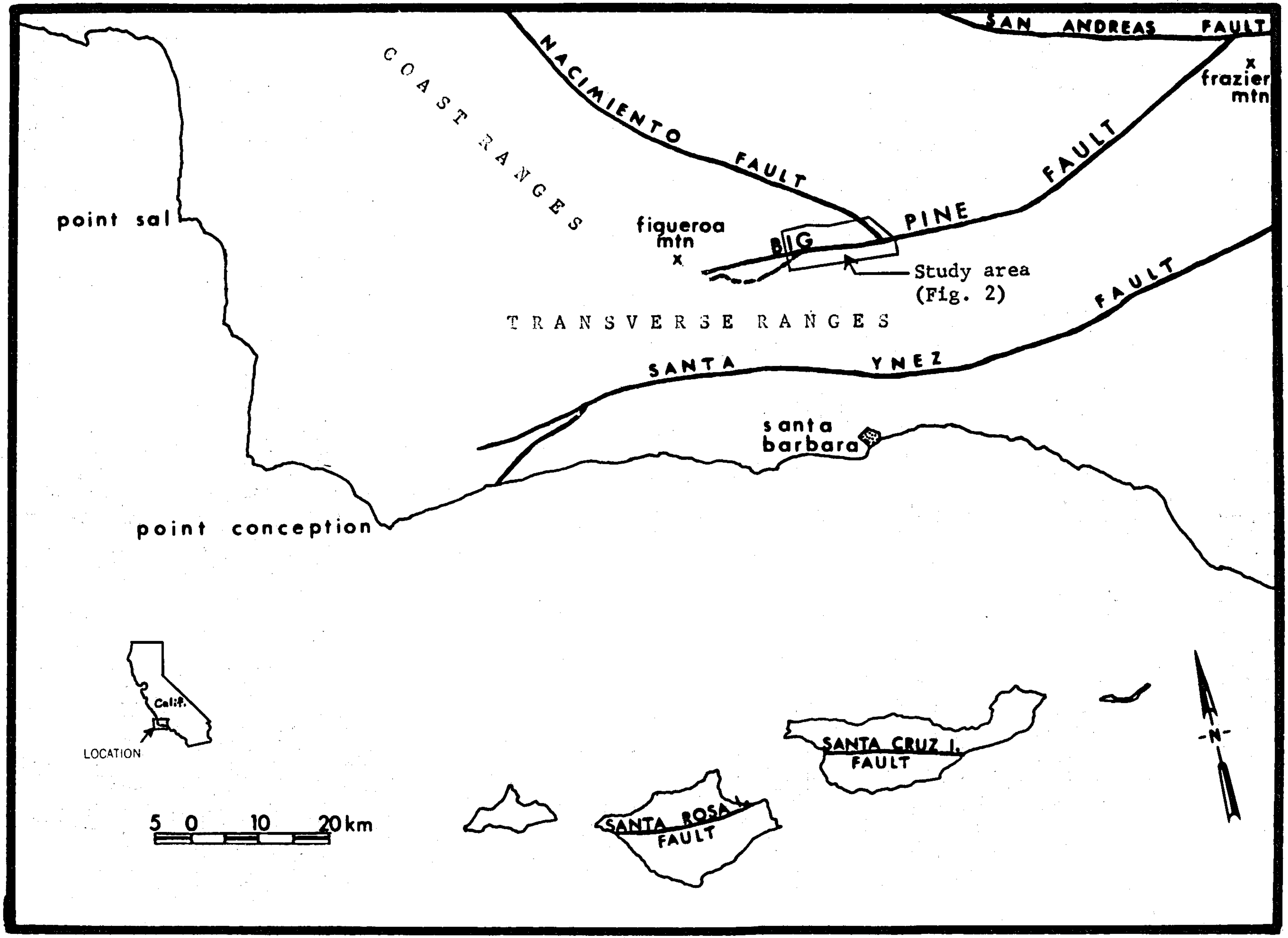
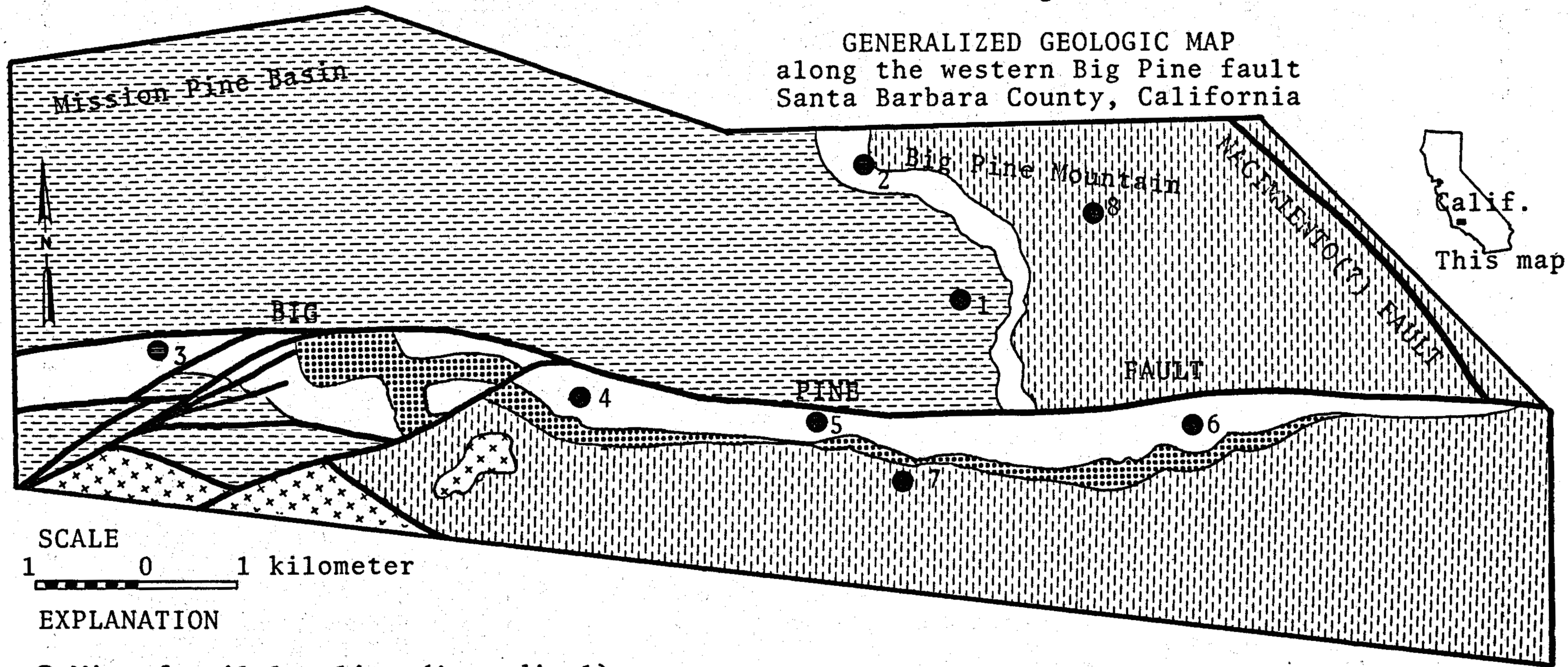


Figure 1. Index map.

Figure 2

GENERALIZED GEOLOGIC MAP
along the western Big Pine fault
Santa Barbara County, California



EXPLANATION

● Microfossil locality (Appendix 1)

Miocene	Monterey(?)	Siliceous shale and silty claystone	
Eocene	Juncal(?)	Sandstone and siltstone w/minor conglomerate & shale	
Eocene	Sierra Blanca Limestone	Limestone w/interbedded limy to silty mudstone	
Paleocene	Anita(?)	Silty mudstone, limy siltstone & very fine sandstone	
Upper Cretaceous	Unnamed	Sandstone, siltstone and conglomerate	

STRATIGRAPHY

CRETACEOUS

Lithology

Approximately 1830m of Upper Cretaceous rocks are exposed in the mapped area north of the Big Pine fault. These rocks consist mainly of approximately equal thicknesses of (a) dark colored, very thin to medium bedded, very fine grained sandstone, siltstone and massive silty mudstone, interbedded in gross intervals with (b) light colored, thick to very thick bedded, coarse grained sandstone and subordinate conglomerate. The sandstones are generally lithic arkose and the conglomerate clasts are predominantly siliceous metavolcanic and coarse grained granitic, with lesser amounts of quartzite.

The coarse grained units (b) are interpreted as proximal turbidite facies according to the criteria established by Walker (1967). Evidence supporting this interpretation includes (1) the lenticular and channeled nature of the bedding; (2) the thick, coarse-grained and massive lithology of the sandstone units; (3) the absence of shales or abundant very fine grained equivalents; and (4) the abundance of sedimentary structures associated with the high energy flow regime.

The most common lithologic trend encountered in these coarse-grained units is a fining upward sequence from conglomerate to siltstone, and containing most elements of an idealized turbidite structure sequence (Bouma, 1962). Pelitic divisions were rarely observed, however, and the uppermost exposed division of parallel laminations in each sequence is most often convoluted and/or biogenically disturbed. The lower and upper 10cm to 1m of thick to very thick bedded sandstone divisions are usually graded, while the central portions may be massive and structureless or contain dish and aleutriation (de-watering) features.

The lower contacts of the coarse-grained units most often display channels, scour marks, flute casts, striations, prod marks, tool marks and other primary sedimentary structures normally associated with a high energy flow regime (Walker, 1967). These features, along with shale "rip-ups" and overturned convolutions and flames in the finer-grained units are interpreted as paleotransport direction indicators (Fig. 3).

Paleocurrent directions are interpreted from measurements of sedimentary structures such as ripples, foresets, trough laminations and others commonly found in the finer-grained units of the Upper Cretaceous sequence (Fig. 4). These fine-grained units (a) are interpreted as turbidite and marine lutite facies, and are composed predominantly of parallel laminated and ripple laminated very thin to thin bedded siltstones and massive silty mudstones.

Approximately 550m(?) of Upper Cretaceous rocks of both the proximal turbidite and turbidite and marine lutite facies are very poorly exposed south of the North Branch of the Big Pine fault in the western portion of the mapped area (Fig. 2).

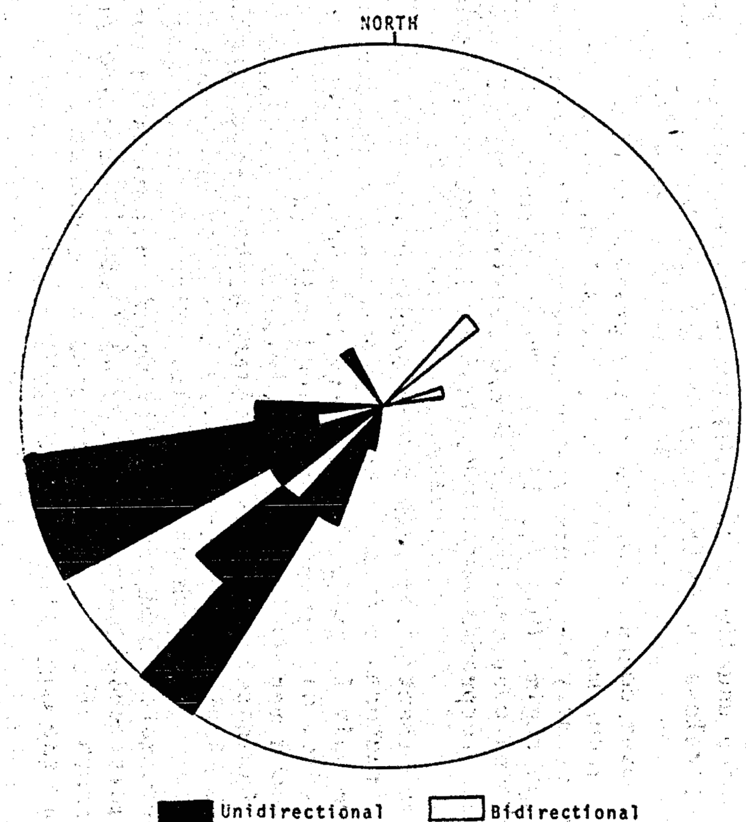


Figure 3. Paleotransport direction rose for 58 Upper Cretaceous sedimentary structure readings. Data from north of the Big Pine fault and south of West Big Pine Mountain. Interval for bearing 10 degrees; circle at 12 unit distance.

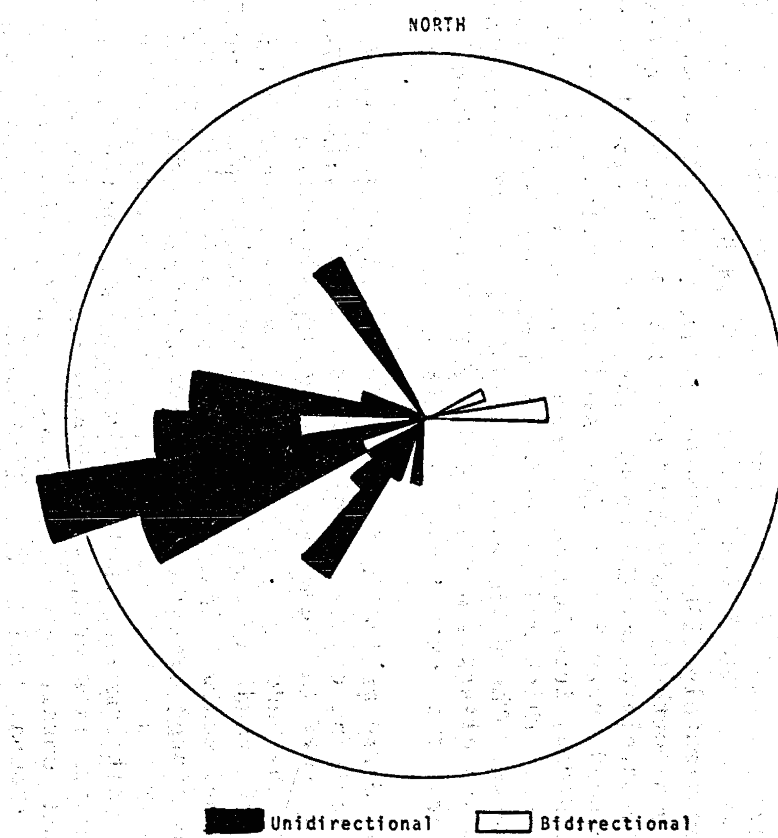


Figure 4. Paleocurrent direction rose for 67 Upper Cretaceous sedimentary structure readings. Data from north of the Big Pine fault and south of West Big Pine Mountain. Interval for bearing 10 degrees; circle at 12 unit distance.

Age

The base of the Cretaceous sequence is not exposed in the mapped area. To the northwest, near Figueroa Mountain (Fig. 1), this section unconformably overlies both Jurassic and Lower Cretaceous Espada(?) rocks (Dibblee, 1950). Vedder and others (1967) assigned a "Cretaceous" age to microfossils from this section. Samples collected for this study yielded an assemblage indicative of early Maestrichtian and/or late Campanian, Upper Cretaceous (App. 1).

Paleogeography

Paleocurrent and paleotransport data from the Cretaceous rocks of this area indicate sediment movement from east-northeast to west-southwest (Figs. 3 and 4).

Limited trace fossils included in the Nereites ichnofacies of Seilacher (1967) suggest deposition at bathyal or slightly shallower depths in an area of turbidity current deposition.

Outer bathyal (1000-2000m) depths of deposition are suggested by the microfaunal assemblages of this sequence (App. 1). The Bathysiphon eocenicus - Rhabdammina eocenica assemblage of sample 744-3-3 is ecologically characteristic of the outer bathyal environment. Additionally, Bulimina spinata and Gyroidina-like forms of sample Bp-5m characterize these depths.

PALEOCENE

Rocks of Paleocene age have not previously been reported from this general region. The nearest known exposures of Paleocene rocks are (1) the Pattiway Formation of the Caliente Range and San Emigdio Mountains, 35 Km northeast of the study area and (2) the lower 60 meters of the Anita Formation in the western Santa Ynez Mountains, 65 Km southwest of the study area (Sage, 1973).

Lithology

In the study area, these rocks are greenish gray to olive green, thin bedded silty mudstones and interbedded gray to brownish gray, thin bedded, limy siltstones and very fine-grained, thin bedded sandstones. They occur both north and south of the Big Pine fault.

Age

This rock sequence is conformable with the underlying Upper Cretaceous rocks, is concordantly overlain by the Sierra Blanca limestone south of the Big Pine fault, and appears conformable with the overlying Eocene rocks north of the fault. Microfossil samples from this interval both north and south of the Big Pine fault yielded age determinations of Upper Paleocene (Bulitian ?) (App. 1). Key species in these determinations, those whose occurrences are restricted to the Paleocene, include Globigerina velascoensis, Globorotalia brodermanni and Spiroplectammina gryzbowski. Several other foraminifers whose most common occurrence is in the Paleocene, such as Pelosina complanata, Dorothia bulletta and Haplophragmoides eggeri, were found in abundance in these samples.

The Gyroidina faunules, Bathysiphon eocenicus - Rhabdammina eocenicus assemblages and diverse arenaceous assemblages indicate outer bathyral (1000-2000m) depths of deposition. The diverse planktonic foraminifers are characteristic of open ocean influence. Sparse directional sedimentary structure data from this unit are presented in Figure 5.

SIERRA BLANCA LIMESTONE

The Sierra Blanca Limestone Formation has been mapped and described by many workers as discontinuous lenses throughout many parts of Santa Barbara and Ventura Counties (summarized by Vedder, 1972, p. D2 and D5).

The formation crops out along a series of ridges south of and generally parallel to the Big Pine fault across most of the mapped area (Fig 2).

Thickness of the formation varies throughout the region from as little as a few centimeters, to the 68 M section at the type locality (Keenan, 1932). The unit thins to less than a meter in the central study area, thickens east and west to approximately 100m, and pinches out(?) entirely to the east. The Sierra Blanca Limestone is not exposed north of the Big Pine fault.

Lithology

The rocks are generally interbedded limestone, limy to silty mudstone and siltstone. Lithology and internal structures allow classification of these rocks into several lithofacies which are inferred to represent deposits of: 1) an algal bank; and associated 2) shelf; 3) breccia; 4) talus slope; and 5) transgressive sand.

In the westernmost exposures of the formation limestone occurs in thirty or more individual thin to medium thick beds interbedded with silty to massive mudstones. The thin bedded limestones are generally micrite or biomicrite. The medium thick beds commonly grade upwards from a basal pebbly-sandy, biosparrudite or microfossiliferous intrasparrudite into micrite or biomicrite. This lithologic assemblage contains large miliolid and orbitoid Foraminifera up to 4.5mm in diameter as well as abundant carbonaceous woody plant material. These rocks are indicative of the shallow water, shelf facies.

Massive, predominantly biolithite beds, formed of calcareous algal bioherms, may comprise as much as 20-30% of the lithology in the west-central map area.

The breccia lithofacies is represented by thick beds of blocky, angular fragments of algal clusters and other broken allochemical rocks and intraclasts, 1mm to 20cm in diameter, cemented with sparry calcite. These rocks are noted immediately east and west of the algal bank lithofacies.

Further east, individual limestone beds are less abundant, much thinner bedded in general, and exclusively intrasparrudites with

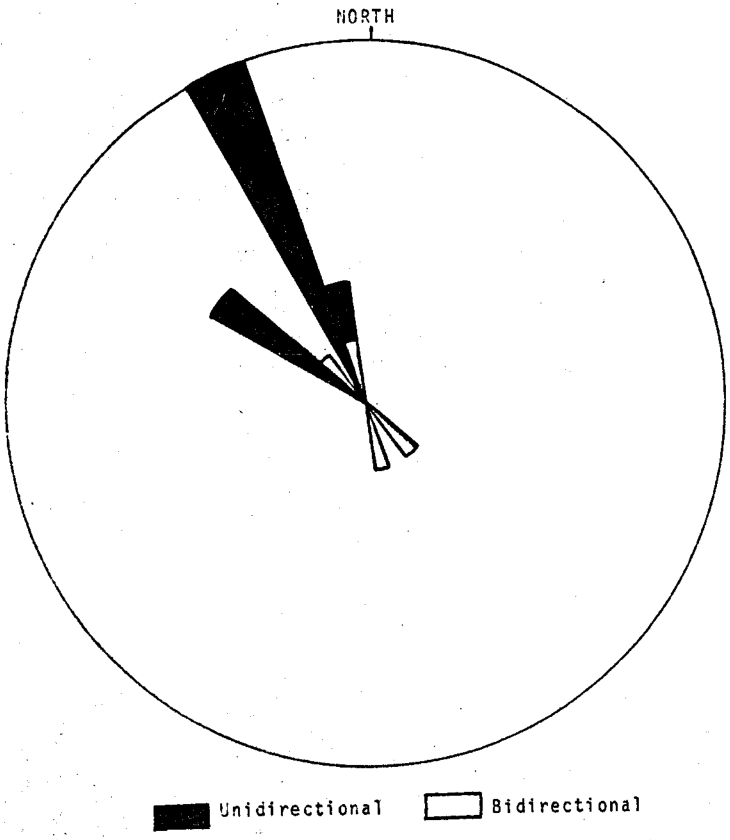


Figure 6. Paleocurrent/paleotransport direction rose for 12 Sierra Blanca Limestone sedimentary structure readings. Data from vicinity of Big Pine Mountain jeep trail. Interval for bearing 10 degrees; circle at 6 unit distance.

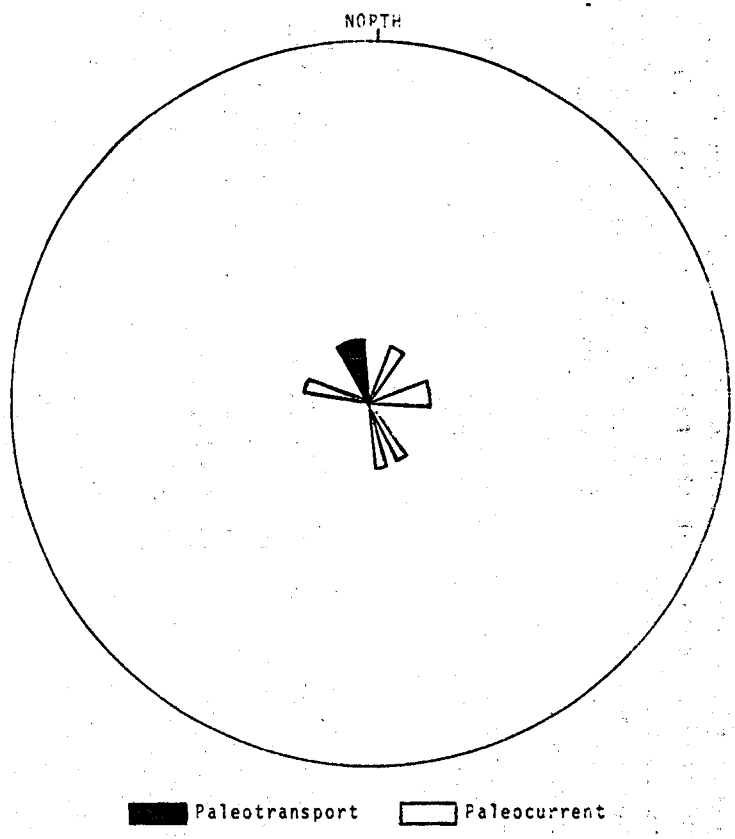


Figure 5. Paleocurrent/paleotransport direction rose for 8 Unnamed Paleocene sedimentary structure readings. Data from Grapevine trail and Big Pine Mountain jeep trail, south of the Big Pine fault. Interval for bearing 10 degrees; circle at 6 unit distance.

subordinate structureless orthochemical beds. Here, interbedded limy to silty mudstones, massive claystones and thin bedded limy quartzitic siltstones yield planktonic dominated microfossil assemblages. These rocks are inferred to represent the talus slope facies. The top of this sequence is in the form of a lenticular, light gray, medium to coarse grained limy sandstone or laterally equivalent sandy limestone. This facies overlies all others in the formation and is interpreted as a transgressive sand.

Limited directional sedimentary structures from the formation indicate movement from south to north-northwest (Fig. 6).

Age

Johnson (1968) summarizes previous authors' evidence for the age of Sierra Blanca Limestone. Mallory (1959) assigns a late Penutian Age (lower Eocene) for this unit based on important orbitoid Foraminifera. A microfossil sample from the unit 2.8 Km south of the study area suggests a Middle(?) Eocene Age (Vedder, et al, 1967). Schroeter (1972) described Foraminifera and reported nannoplankton from the formation 18 Km south of the present study area, which were supportive of a Penutian Age. Gibson (1972) suggests a "medial Paleocene age," based on planktonic microfossils, for the Sierra Blanca Limestone in the Moonshine Canyon area 70 Km southeast of the study area. Gibson (1972) argues that on this basis the benthonic Foraminifera must have longer ranges than previously supposed and are therefore inadequate for biostratigraphic age determinations.

However, paleoenvironmental reconstruction of the regional exposures of the formation by Johnson (1968) and more detailed local paleogeography interpreted by Schroeter (1972) suggest that the sequence was transgressive toward the north and east. In such a transgression, the formation would necessarily be older in the southwest than in the northeast. Thus, it may be the Sierra Blanca Limestone that is time transgressive and not the benthonic Foraminifera, as suggested by Gibson (1972).

EOCENE

Eocene rocks are exposed concordantly above the Sierra Blanca Limestone south of the Big Pine fault and concordantly above the Paleocene sequence north of the fault. They were assigned to the widely applied "Juncal" formation by Dickenson (1969) and Vedder et al (1973). This sedimentary sequence may be in part equivalent to the Juncal, Matilija and Cozy Dell formations of western Santa Ynez Mountains (Dibblee, 1950).

Lithology

South of the fault, the 925 m of this unit within the mapped area is composed primarily of sandstone and siltstone, with a few thin lenses of pebble conglomerate and minor amounts of mudstone and shale. The thick bedded, medium grained lithic arkoses and thinly interbedded siltstones which dominate the sequence display evidences of turbidity current origin.

North of the fault, the sequence is considerably thicker and coarser than the Eocene rocks to the south. The approximately 1500 M of these rocks exposed within the mapped area are predominantly gray to yellowish-brown, medium to very coarse grained sandstone, with numerous lenses of pebble to boulder conglomerates. Interbedded brownish-gray siltstones occur locally.

Age

Gower and others (1966) suggest an age range from Lower(?) to Middle Eocene for the strata. Vedder and others (1967) indicate a Middle(?) Eocene age for these rocks. Howell (1975) suggests a Penutian(?)/Ulitisian (Lower(?)/Middle Eocene age). Foraminiferal species Globorotalia aequa and Globigerina soldadoensis are present in a sample from the sequence north of the fault. The former is noted by Mallory (1959) as last occurring in the Ulitisian stage, and the latter noted by Schmidt (1970) as last occurring in his "Subbotina" senni zone (Lower Eocene). Sedimentary structures collected from this sequence indicate a change in paleotransport directions from north to southwest a few tens of meters from the base of the section (Figs. 7 and 8).

MIOCENE

An estimated 500(?) meters of light colored, thinly bedded siliceous shale and minor sandstone unconformably overlie the Eocene rocks in the western portion of the study area. Vedder and others (1967) suggest a Relizian(?) Age for these rocks.

SUMMARY

Upper Cretaceous rocks were deposited in 1000m to 2000m depths in this area by turbidity currents from a granitic and siliceous metavolcanic landmass to the northeast. Paleocene age sediments were deposited in bathyal depths by low energy regime processes. An abrupt regression occurred in Upper Paleocene to Lower Eocene times as reflected by the shallow water deposits of the Sierra Blanca Limestone Formation. During the time of Sierra Blanca deposition, there was a localized high in the south central portion of the study area. Here, a calcareous algal bioherm and associated singular corals and molluscan fauna were immediately flanked by brecciated deposits of this bank complex. To the west, a shallow shelf environment was dominated by biomicritic deposition. To the north and east, deeper water and open ocean influence affected the deposition of predominantly intrasparrudite assemblages. Further east, and north of the present Big Pine fault shallow water limestones were not deposited. A transgression followed in the Lower Eocene and turbidity current deposits again came from the northeast. An Oligocene regression was followed by Miocene deposition of siliceous shales and sandstones unconformably upon the older rocks.

Acknowledgements A. Marianos and A. Joerger of Exxon Company USA, Englewood, Colorado, examined and interpreted the microfossils collected for the study. Field work was partially supported by the Exxon Foundation, Mobil Oil Corporation, and the Union Oil Company financial support for Lower Tertiary studies, as administered by the Department of Geological Sciences graduate support fund, University of California at Santa Barbara.

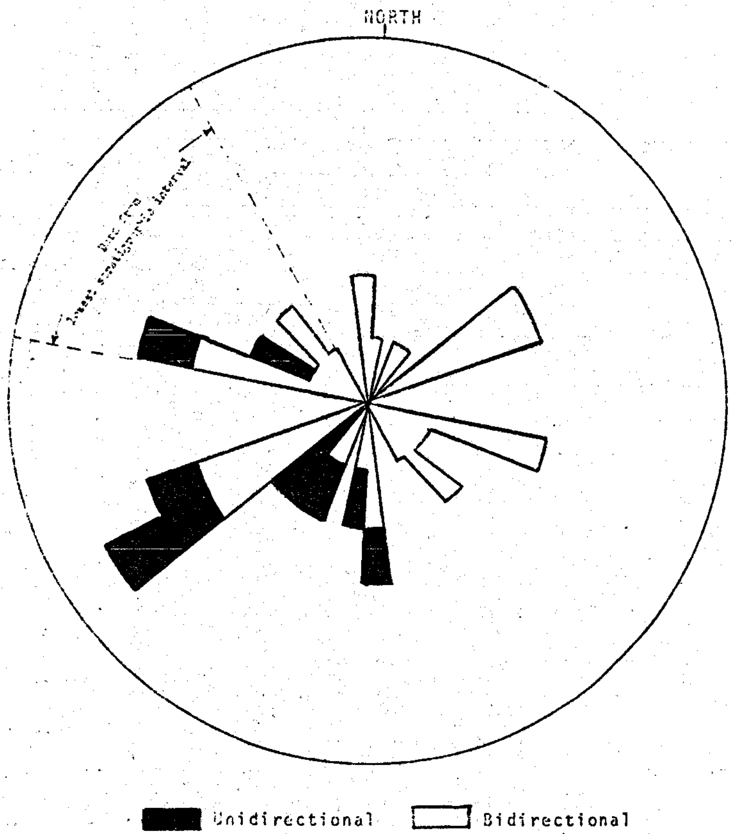


Figure 8. Paleocurrent/paleotransport direction rose for 18 Undifferentiated Eocene sedimentary structure readings, collected by D.G. Howell, UCSB. Data from Indian Creek, south of the Big Pine fault. Interval for bearing 10 degrees; circle at 6 unit distance.

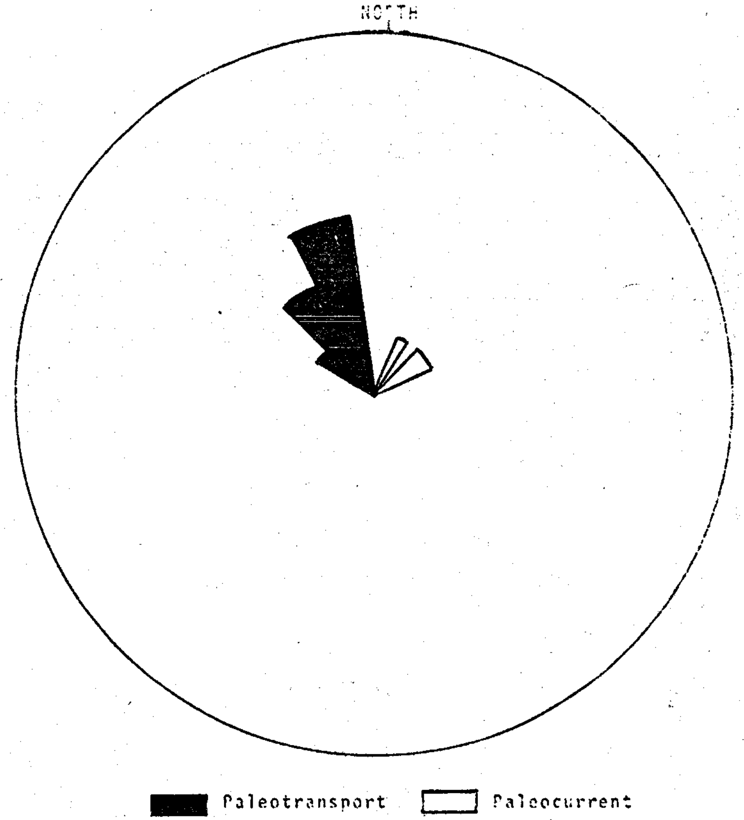


Figure 7. Paleocurrent/paleotransport direction rose for 14 Undifferentiated Eocene sedimentary structure readings. Data from vicinity of Dutch Oven Campground, south of the Big Pine fault. Interval for bearing 10 degrees; circle at 6 unit distance.

Partial Foraminiferal Checklist

	1	2	3	4	5	6	7	8
Sample locality (Fig.2)	1	2	3	4	5	6	7	8
Sample number	Bp-5m	Bp-4m	741-6-1	Bp-11m	Bp-11-4m	744-12-3	DGH-11-91	Bp-3m
Ammodiscus cf. A. incertus			R				Penutian/Ulatisian assemblage (Howell,1975)	
Anomalina rubiginosa	F							
Bathysiphon eocenicus			A			N		
B. sp.	C							
Bulimina spinata	VR							
B. sp					R			
Cibicides susanaensis				R				
C. spp.				R		R		N
C. sp.			N					
Clavulinoides californicus				R				
Cribrostomoides cretaceous	C							
Cyclammina sp.		R	R					
Dentalina spp.	VR			R	N			
Discorbis sp.		R	R					
Dorothia bulletta			N					
D. oxycona				R		R		N
Eponides sp.				R				
Gaudryina bentonensis	R							
G. pyramidata	R							
G. sp.			R					
Globigerina soldadoensis						R		N
G. soldadoensis angulosa								R
G. triloculinoides				A	R			A
G. velascoensis				N	R			
G. cf. G. mitidus					R			
Globorotalia aequa				R				R
G. brodermanni						R		
G. elongata				R				
G. imitata					R			
G. pseudobulloides				R				
G. velascoensis				R				
Gyroidina florealis	VR							
G. soldianii				R				
G. cf. G. aequilateralis	R							
Gyroidinoides quadrata								R
Haplophragmoides eggeri		A	A			R		
H. sp.		A			N	R		
Karreriella media-aquaensis		R						
Lagena sp.					R			R
Nonion sp.			R					
Pelosina complanata					N	R		
Pleurostomella alazanensis var. cubensis					R			
P. sp.				R				
Pullenia quinqueloba				R				
Rhabdammina eocenica			R		N	R		
Robulus sp.	VR		R	R	R	R		
Silicosigmolina californica	C	A						
Spiroplectammina gryzbowski		R	A					
Textularia subconica	VR							
T. cf. T. gryzbowski				R				
Trochammina globigerinaformis	VR							
Verneuilina sp.				R				
AGE INTERPRETATION	U.Cret.	U.Paleo.					Eocene	

EXPLANATION

A abundant
C common
F frequent
N noted
R rare
VR very rare

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SEDIMENTOLOGY OF THE SOUTH POINT FORMATION (EOCENE), SANTA ROSA ISLAND, CALIFORNIA

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INTRODUCTION

On the Continental Borderland of Southern California (Shepard and Emery, 1941) are found the northern Channel Islands: Anacapa, Santa Cruz, Santa Rosa, and San Miguel. This east-west trending island chain forms the offshore extension of the Santa Monica Mountains and marks the southernmost boundary of the Transverse Ranges Province, characterized by generally east-west structural trends. Santa Rosa (see fig.1) is the second largest island in the chain with a maximum width of 10 miles (16 km) and length of 15 miles (24 km) and is approximately 30 miles (48 km) southwest of Santa Barbara, California.

The geology of Santa Rosa Island was first discussed by Smith (1900) with reference only to the effects of lithology on various physiographic features. Kew (1927) made a reconnaissance of the island from which he delineated the basic stratigraphy. A preliminary paleontological analysis of the Miocene molluscan fauna was presented by Hertlein (1927). Redwine (1949) summarized the stratigraphy of the northern portion of the island; and in 1952 the American Association of Petroleum Geologists, Pacific Section included in its correlation charts and sections of the Ventura Basin generalized geologic columns of Santa Rosa Island (Redwine, et al., 1952). Avila (1968) studied the middle Tertiary sequence. The most recent and detailed discussion of the geology of Santa Rosa Island is included in "Geology of the Northern Channel Islands, Southern California Borderland" by Weaver, et al., (1969). The South Point Formation crops out only on the southern portion of Santa Rosa Island at the base of a structurally complicated sequence of Quaternary and Tertiary marine and non-marine rocks, volcaniclastic rocks, and basaltic intrusives (see fig.2). The sandstones, siltstones, and mudstones of this formation are the oldest rocks exposed on the island and are the object of this study.

SOUTH POINT FORMATION

Age and Correlation

No megafossils have been found in the South Point Formation. In the finer grained intervals foraminifers are locally common. Weaver et al. (1969) have shown that deposition of the South Point Formation occurred during the middle and latter part of the Eocene; that is during Ulatisian and Narizian time (terminology of Mallory, 1959). The fauna is characterized by such forms as *Robulus welchi*, *Uvigerina garzaensis*, and *Valvulineria chirana*. Age-equivalent rocks crop out in small areas of the Continental Borderland and extensively in the adjacent areas of Southern California.

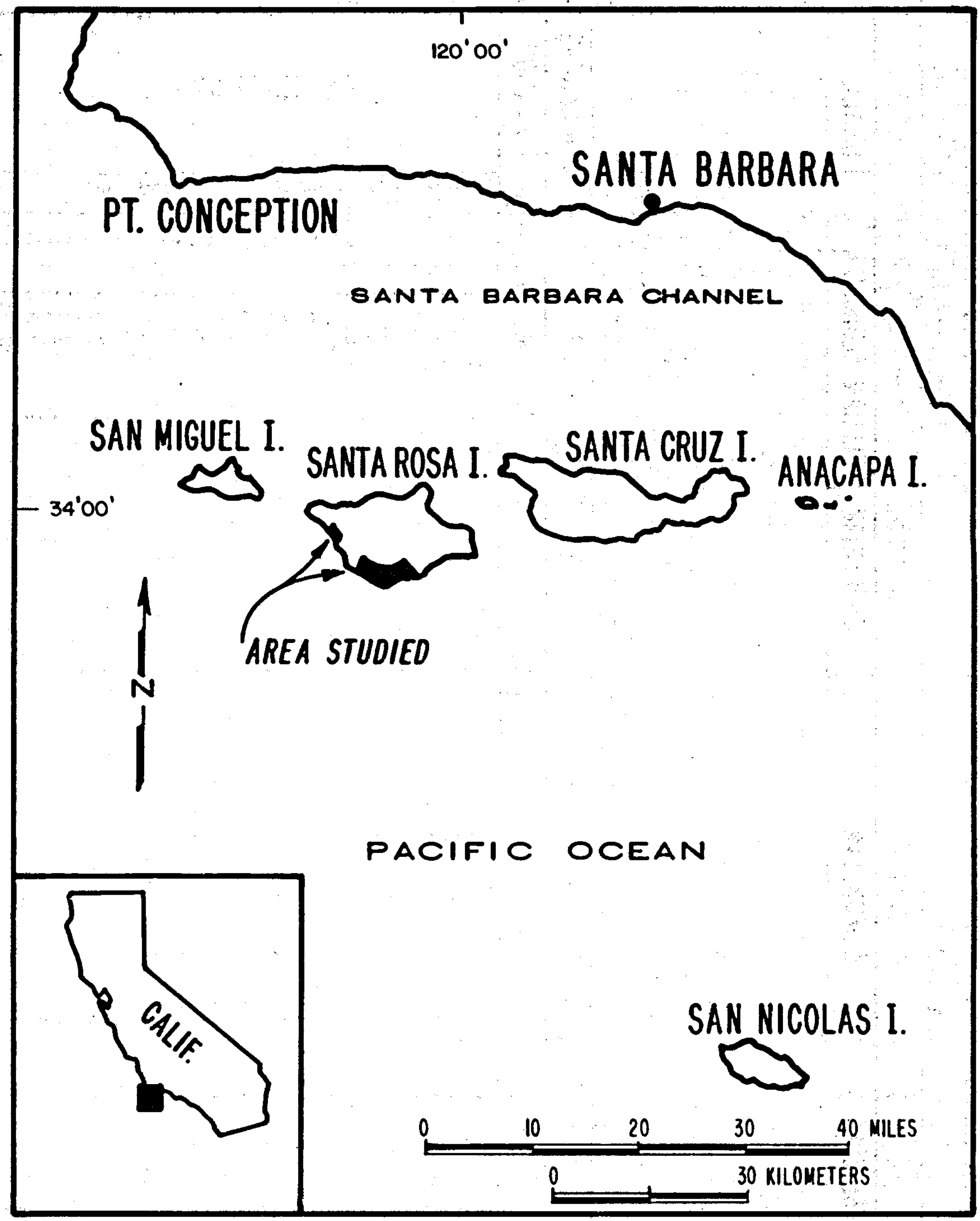


Fig. 1. Location map.

GENERALIZED GEOLOGIC COLUMN
SOUTHERN SANTA ROSA ISLAND, CALIFORNIA
(AFTER WEAVER et.al., 1969)

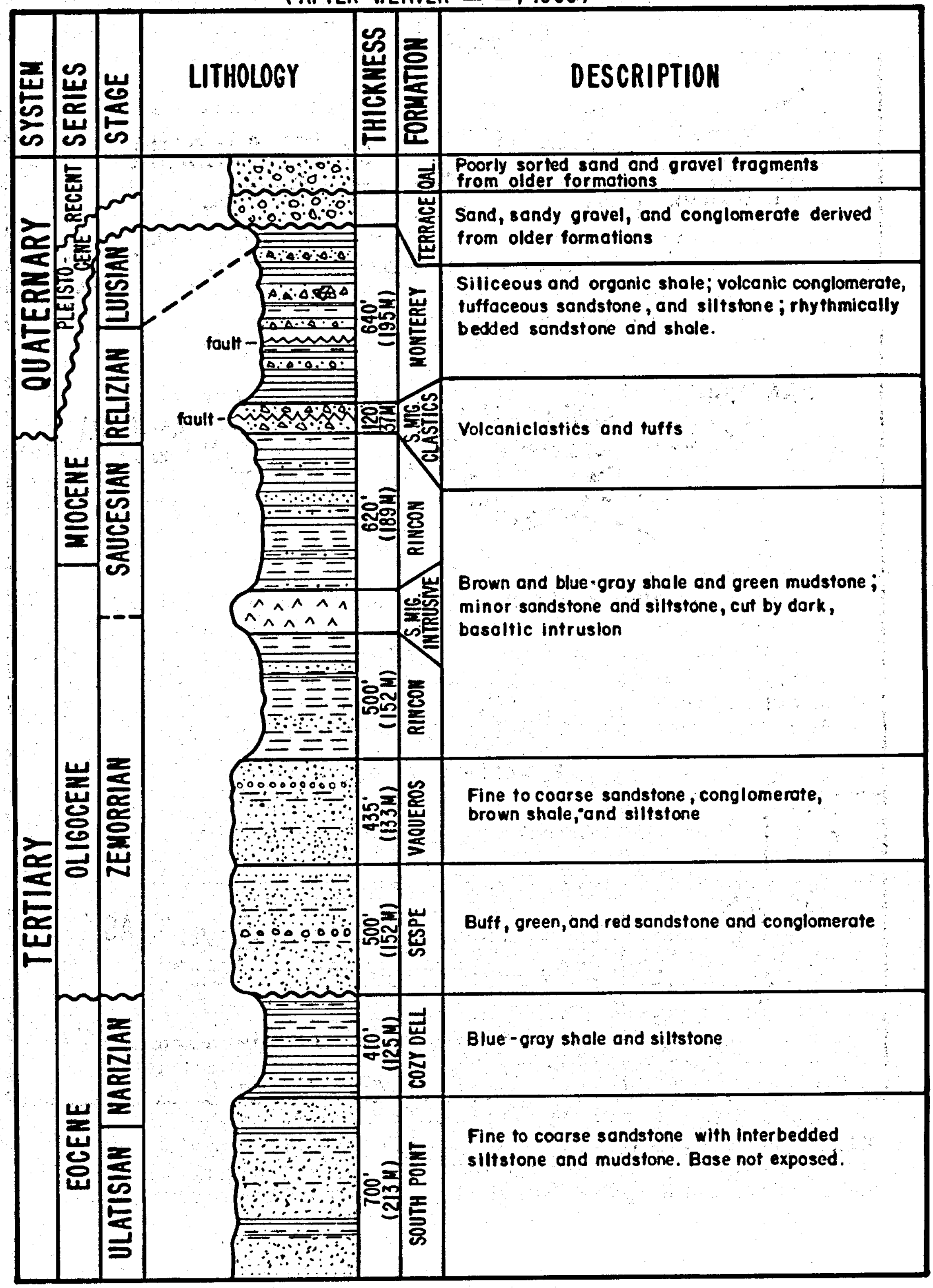


Fig. 2. Generalized geologic column of southern Santa Rosa Island, California.

To the west on San Miguel Island sandstones and mudstones of Ulatisian and Narizian age are assigned to the South Point Formation (Weaver et al., 1969). On Santa Cruz Island the mudstone and siltstone beds of the upper portion of the Cañada Formation have been assigned a Ulatisian and Narizian age. The overlying Jolla Viega and Cozy Dell Formations are of Narizian age (Doerner, 1968 and 1969).

The thick sequence of sandstones, conglomerates, and finer grained clastic rocks exposed on San Nicolas Island contain foraminifers and nannoplankton that indicate Narizian and Ulatisian ages for all these unnamed rocks (D.W. Weaver, 1975, personal commun.). Southward and eastward from San Nicolas Island in the San Diego area, Kennedy and Moore (1971) report that the LaJolla and Poway Groups are of middle and late Eocene age. These groups are inferred to be partially, if not entirely, age-correlative with the South Point Formation.

To the north of Santa Rosa Island along the Santa Barbara coast, Kleinpell and Weaver (1963) show the Matilija Sandstone to be largely of Ulatisian age. The upper portions of this formation as well as the overlying mudstone and sandstone of the Cozy Dell and Sacate Formations are of Narizian age.

General Description

The South Point Formation is a sequence of clastic marine sedimentary rocks composed predominantly of buff to yellow brown, well indurated, fine to coarse-grained sandstones with lesser amounts of siltstone and mudstone and rare pebbly sandstone. The sandstones vary from single, thin bedded (Ingram, 1954) units to the abundant thick and very thick, single and amalgamated units. Siltstones are laminated to medium bedded and the mudstones are laminated to massive. The total thickness exposed is 700 feet (213 m), but 3445 feet of sandstones and mudstones assignable to the South Point Formation is reported from the Standard Oil, Santa Rosa No. 1 well (Weaver, et al., 1969).

Bottom contacts of the sandstone beds are sharp, though slightly undulose due to minor erosion and loading. Sole markings include flute casts, groove marks, load casts, and tracks and trails. The sole marks are rarely seen due to limited bottom exposures. Where scouring has not removed the upper portion of sand beds, the top contacts are rapidly transitional to siltstone and mudstone. Lateral variation in thickness is rarely seen, perhaps owing to limited exposures along strike and to structural complications. One sandstone bed, however, was traced approximately 2000 feet (610m) with no apparent variation in thickness.

Sedimentary structures found within the sand beds of the South Point Formation include graded bedding, even to slightly undulose continuous and discontinuous laminations, dish structures (see Wentworth, 1967 and Stauffer, 1967), floating clasts, flame structures, contorted laminations, rip-up structures, cross lamination, and cross bedding. Of these, the graded bed is most common and when complete is marked by a "coarse" massive base overlain by an interval of parallel laminations, followed by contorted laminations, parallel laminations of fine sand and silt, and then clay. Such a vertical sequence (see fig.3) can be described by the Bouma sequence (1962); however, two major variations of the classic Bouma sequence are present in the graded beds of the South Point Formation. First, grading is present only in the uppermost portions of the beds instead of throughout them. Secondly, contorted laminations instead of ripple laminations are found in the Bouma "C" interval. Cross laminations, when present, are found above the interval of contorted laminations. The upper, finer portions are often absent due to nondeposition and/or erosion.

Further complicating of this simple Bouma type sequence is caused by the presence of dish structures, which can occur at any level of a bed below the contorted laminations (see fig.4). Also, dish structures are replaced within the same bed along strike by the Bouma A and/or B intervals. The significance of this lateral change from a "non"-Bouma interval to Bouma intervals will be discussed later in the section dealing with "Environment and Mode of Deposition."

The zone of contorted laminations, when present, is the most distinctive feature of a graded bed. These folded layers of fine sand, silt and clay often have a preferred orientation and have amplitudes ranging from two to fourteen inches (5 to 36 cm). The origin of contorted laminations is somewhat problematical. Arguments for and against a primary origin for these structures have been presented by Dzulynski and Smith (1963), Dott (1963), and Sanders (1960). The presence of partially truncated contorted laminations (see fig.5) strongly suggests that these structures are contemporaneous with deposition of the containing bed and are the consequence of internal instability caused by flow and deposition. Small, poorly developed flame structures on the contorted laminations further suggests that frictional drag and loading caused by the deposition of the overlying bed may contribute further to the deformation of the contorted laminations.

The floating clasts are composed of elongate, planar fragments of mudstone up to fourteen inches (36 cm) long and 2 inches (5 cm) thick, or pebbles and cobbles with a maximum diameter of two and one-half inches (6.4 cm) all set in a matrix of sand-sized particles. The elongate mudstone clasts are randomly oriented or imbricated (see fig.6).

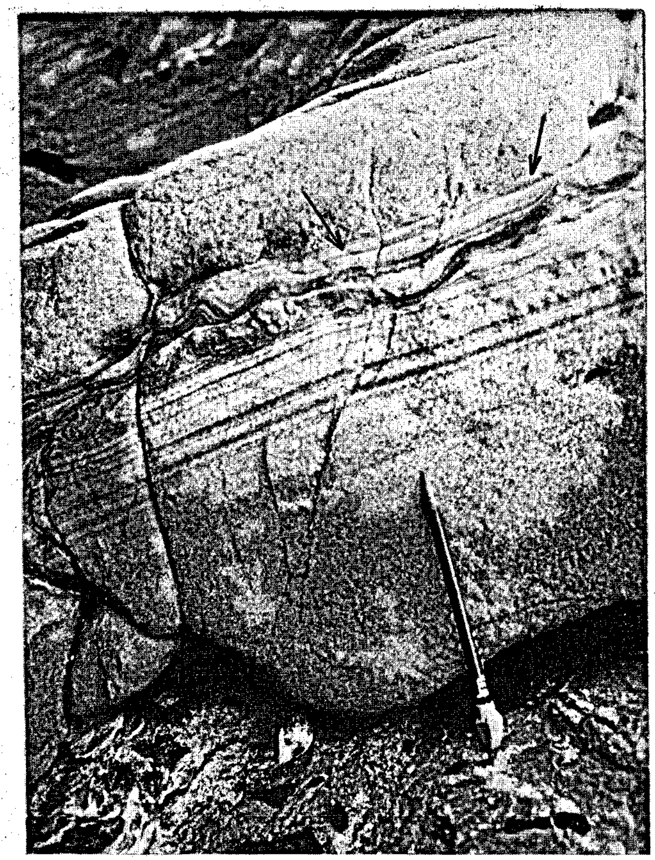


Fig. 3. Photograph of graded bed. Laminations of the upper interval (arrows) are truncated by the overlying bed.

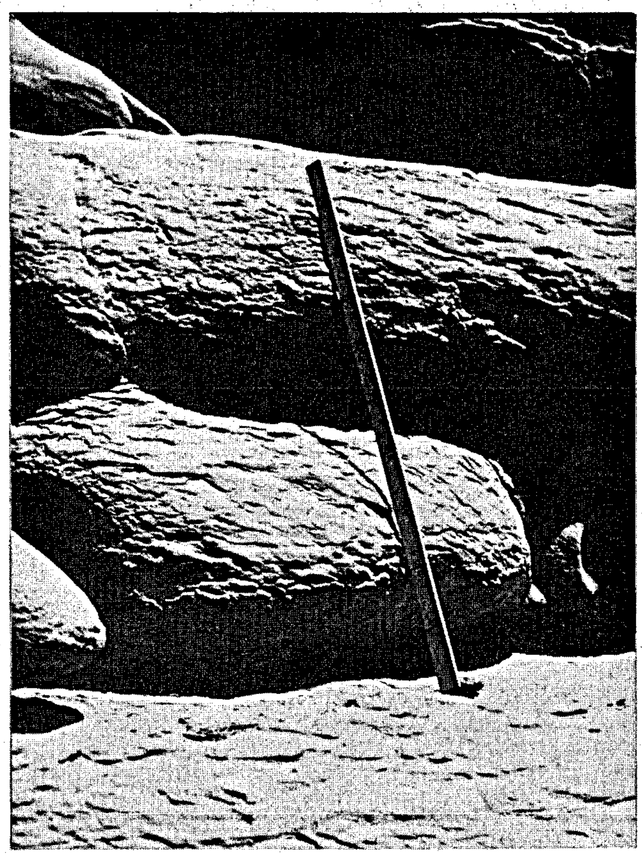


Fig. 4. Photograph of graded beds containing dish structures. Scale is 1 meter long.

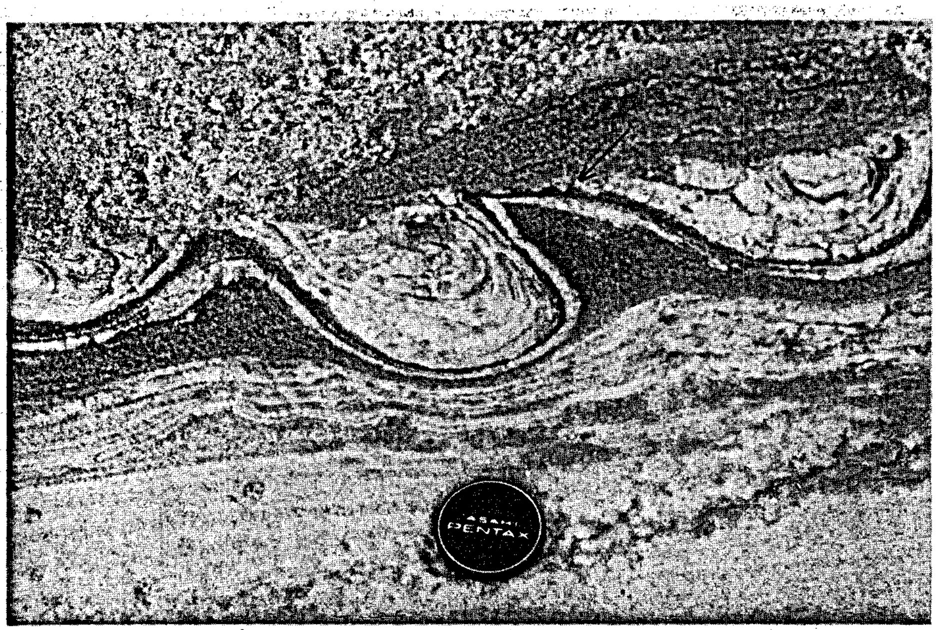


Fig. 5. Photograph of contorted laminations which are partially truncated. Flame structures (arrow) can also be present on these features.

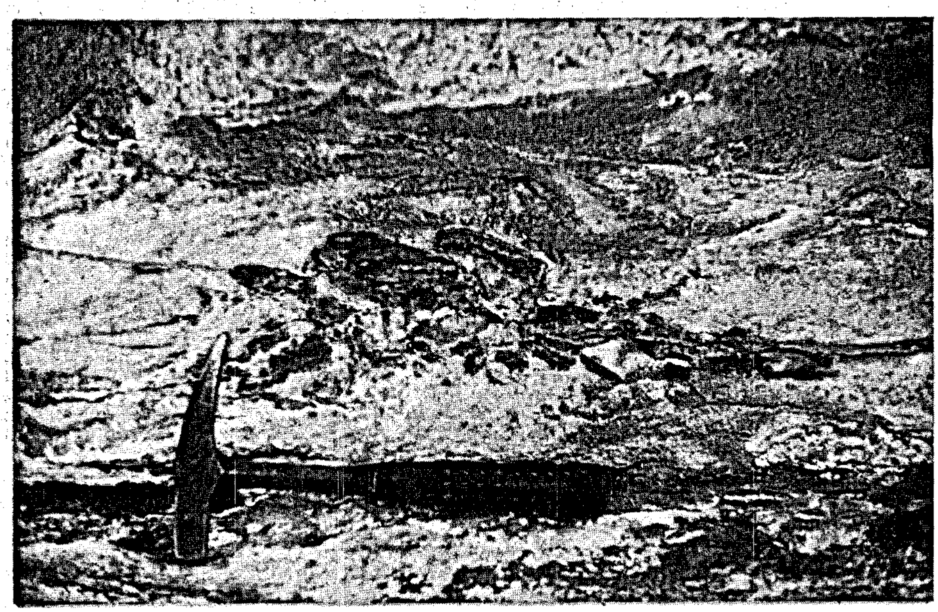


Fig. 6. Photograph of imbricated mudstone clasts.

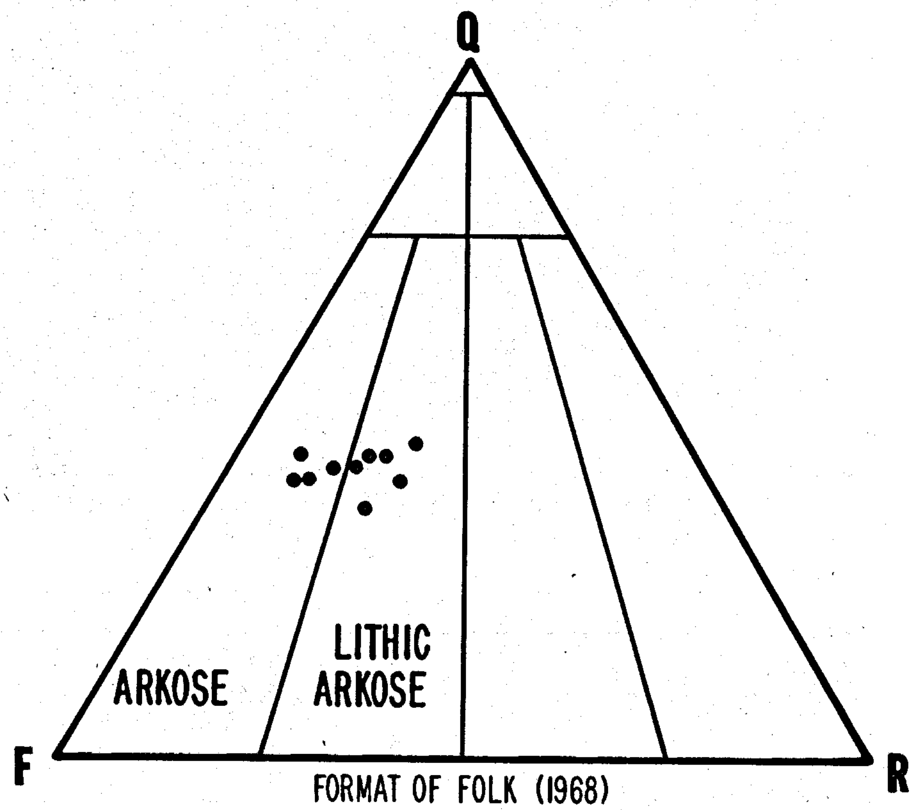
Petrographic study of 10 thin sections having a mean grain size (Folk, 1968) from .19 to .41mm (fine to medium sand) shows that these South Point sandstones are poorly to moderately sorted and are composed of predominantly angular and subangular (Powers, 1953) closely packed grains. The grains are generally randomly oriented; however, elongate or platy grains may be oriented parallel to bedding or imbricated. Considering the "coarse" size of these sands, silt and detrital clay are quite abundant, ranging from 2.8 to 12.6 percent of the total. Cement composes up to five percent of the thin sections studied. Sparry calcite is the most common followed by chlorite and rare silica. Field observations, however, indicate that sparry calcite cement is locally more abundant in concretionary zones and in the finer grained intervals. Due to the poor sorting, high silt and clay content, grain angularily, close packing, and the presence of cement, the porosity is interpreted to be low.

Following the scheme of Folk (1968), the sandstones are classified as arkoses and lithic arkoses (see fig.7). The most abundant terrigenous grain types are quartz, feldspars, silicic volcanic rock fragments, and granitic rock fragments. Less abundant components (included under "Others" in figure 7) are micas, detrital clay, sedimentary and low grade metamorphic rock fragments, chert, heavy minerals, and organic particles. The average composition for all samples is shown in figure 7.

Paleoslope Interpretation

Ninety-seven directional and thirty-one bi-directional sedimentary structures, interpreted to indicate the paleoslope direction or to give only the sense of the paleoslope, were measured in the South Point Formation with a Brunton compass. The bearings of the longitudinal or fold axes, which are inferred to be normal to the paleoslope, were taken for contorted laminations, flame structures, and rip-up structure. When these structures exhibited a preferred orientation, the paleoslope direction was determined by adding or subtracting 90° from the bearing of the fold axis. The direction of preferred orientation is inferred to be in the downslope direction. Flute casts, cross-bedding, (see fig.8) and grove marks were measured directly. Cross-laminations are not included in the study, since when present they occur at the top of the graded sequence above the contorted laminations, and are believed to be formed by oceanic currents. They, therefore, are not necessarily related to the paleoslope and may, in fact, be normal to the paleoslope (Hollister and Heezen, 1967). When dips were greater than 25°, corrections for tectonic tilt were made on a stereonet. The data was treated by the method of vector analysis as outlined by Potter and Pettijohn (1963, p. 264-265).

SOUTH POINT FORMATION
SANTA ROSA ISLAND, CALIFORNIA



AVERAGE COMPOSITION

QUARTZ	38 %
PLAGIOCLASE	22
SILICIC VOLCANIC FRAGMENTS	13
POTASSIUM FELDSPAR	12
GRANITIC FRAGMENTS	7
OTHERS	8

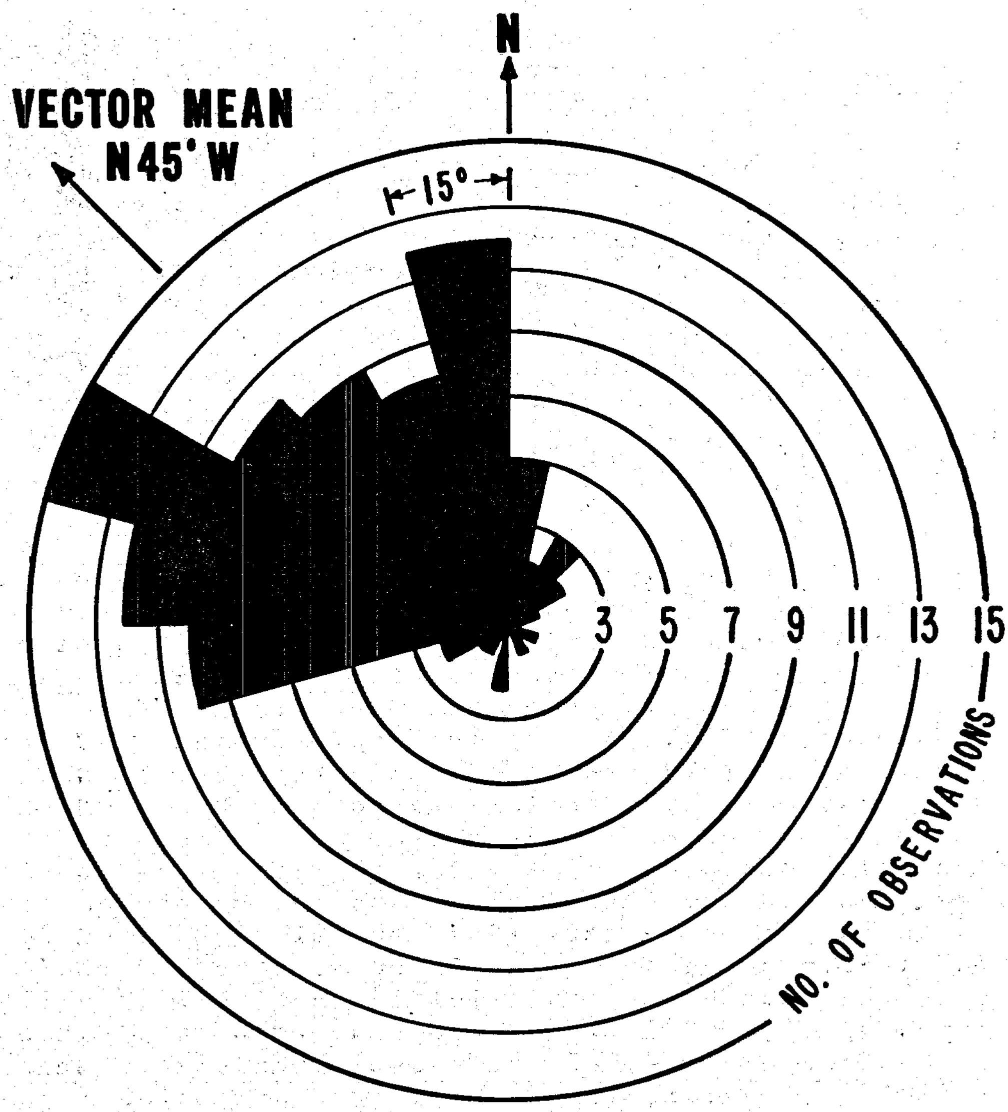
Fig. 7. Compositional diagram and average composition of ten South Point sandstones.

Fig. 8 Photograph of cross-bedding indicating a paleoslope of N79°W (right to left). Scale is 15 cm long.

Directional Structures	Number of Observations	Vector Mean
Flute Casts	5	N 34 W
Flame Structures	5	N 76 W
Imbrication	4	N 45 W
Rip-up	1	N 5 E
Cross Bedding	1	N 79 W
Contorted Lamination with preferred orientation	81	N 47 W
All Structures	97	N 45 W
Bi-Directional Structures	**Number of Observations**	**Mean Sense**
Groove Marks	7	N42W-S42E
Contorted Lamination without preferred orientation	24	N41W-S41E
All Structures	31	N41W-S41E

Table 1. Directional and bi-directional paleoslope indicators of the South Point Formation, Santa Rosa Island.

PALEOSLOPE MEASUREMENTS, SOUTH POINT FORMATION
SANTA ROSA ISLAND, CALIFORNIA



97 MEASUREMENTS

5 FLUTE CASTS
5 FLAME STRUCTURES
4 IMBRICATION
1 RIP-UP STRUCTURE
1 CROSS BEDDING
81 CONTORTED LAMINATIONS WITH PREFERRED ORIENTATION

Fig. 9.

The results of the paleoslope analysis are given in Table 1. A paleoslope direction of N 45° W was determined from all directional sedimentary structures (see fig.9), of which contorted laminations with a preferred orientation are dominant. The mean sense of N41°W-S41°E determined from all bi-directional sedimentary structures is in close agreement with this direction. The apparent bi-modal nature of all directional indicators was found not to be related to stratigraphic position, geographic position, or type of sedimentary structure.

Environment and Mode of Deposition

Fossil foraminifers collected from the mudstone intervals of the South Point Formation by Weaver, et al. (1969) are characterized by abundant small, costate, and spinose buliminids, uniserial lagenids, and small cassidulinas, whose recent analogues are most abundant at bathyal depths (Bandy, 1956). Even though the sandstone beds are unfossiliferous, they are interpreted to have been deposited along with the mudstone beds at bathyal depths. The material in the mudstone beds is interpreted to have settled from suspension; however, the suite of sedimentary structures in the coarser intervals suggests another and markedly different depositional process for them.

The presence of repeated graded beds, flute casts, rip-up structures, floating clasts, erosional surfaces, and variations in bed thickness indicates that the sandstone beds were deposited from a flow system characterized by high particle concentrations and varying and declining flow energy: that is, from mass flows or sediment gravity flows (Middleton and Hampton, 1973). Attempting to determine, however, if deposition occurred from a specific type of flow system based upon various and hypothetical support mechanisms, which are inferred from sedimentary structures, is impractical for the South Point sandstones. A major criterion for recognition of various types of flow mechanisms is the presence of dish structures (see Stauffer, 1967, and Middleton and Hampton, 1973). As mentioned earlier, dish structures were replaced within the same bed by parallel laminations. Middleton and Hampton (p.14, 1973) also noted that dish structures are "...found in massive beds or closely associated with diffuse parallel or lensitic lamination: the lamination may be either above or below the dish structures (or both)." To use the presence or absence of dish structures as a criterion to indicate different flow mechanisms in coarse grain sediment gravity flows is, therefore, unwarranted. Furthermore, the basic criteria used in the classification of all sediment flow deposits are the preserved sedimentary structures.

The fundamental assumption, however, is that different suites of sedimentary structures _must_ be produced by different flow mechanisms. This assumption is undoubtedly valid for debris flow deposits, which represent one possible end member of flow type. This assumption, however, must be openly questioned for the realm of sediment gravity flow deposits of which the South Point sandstones are typical.

If the classification schemes of Bouma (1962), Stauffer (1967), and Middleton and Hampton (1973) are followed three different mechanisms of flow are needed for the sand deposition: turbidity current, grain flow, and fluidized sediment flow. Occasionally different flow mechanisms would be required within a single bed. If the concept of a fluxoturbidite (Dzulynski _et al_. 1959) is accepted a fourth mechanism of flow is required. With the following qualifications deposition from flows having one mechanism of sediment support, admittedly with unknown and perhaps mysterious properties, is suggested for the South Point sandstones. First, the sedimentary structures record deposition from the flow and not the mechanism of flow. Second, dish structures can be found in the Bouma A and/or B intervals and can be replaced by the normally massive area and/or parallel laminations of these intervals. This relationship is present in outcrop. Third, the flow system is capable of erosion, which is documented by exposures (see fig.3). Fourth, at any given locality the finer portions of a flow may not be segregated out by deposition; and fifth, after deposition sedimentary structures may be altered or destroyed by such processes as loading and dewatering. Figure 10 shows how various deposits, attributed to different flow mechanisms, can be generated by a single flow mechanism.

Possible mechanisms of flow for sand size particles have been thoroughly reviewed and discussed by Middleton and Hampton (1973). The purpose of the previous discussion was not to suggest any new flow mechanisms, but merely to suggest that a simple explanation exists for the presence of the varied suite of sedimentary structures found within the commonly thick to very thick bedded, fine to coarse sandstone deposits, including the South Point Formation, that have been attributed to deposition by various sediment gravity flow mechanisms. Continued study and reevaluation of such deposits may perhaps reveal enough similarities that multiple flow (transport) mechanisms need not be called upon to explain depositional or postdepositional features.

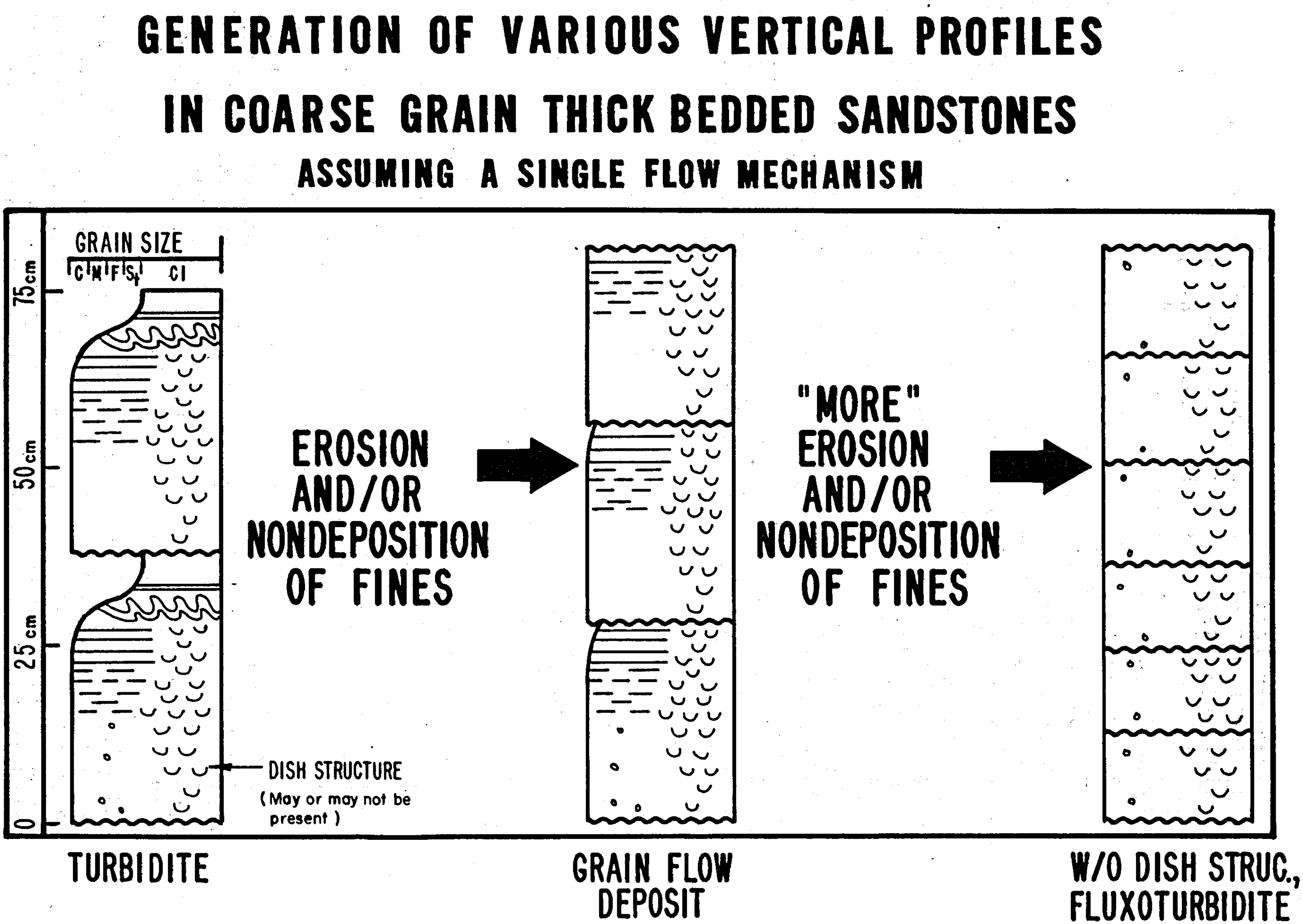


Fig. 10. Diagram showing the generation of various vertical profiles by deposition from sediment flows having a single mechanism of sediment support.

Sedimentary Facies

The rocks of the South Point Formation can be described by four primary and one secondary sedimentary-lithological facies. The deep water environment of deposition and the similarity of these facies to those described for recent and ancient submarine fans (see for example Nelson and Nilsen, 1974; Mutti, 1974; Walker and Mutti, 1973; Nelson and Kulm, 1973; Stanley and Unrug, 1972, Normark, 1970; and Jacka *et al*, 1968) leads the author to conclude that the site of the South Point deposition was a submarine fan complex. The facies preserved in outcrop and described below are 1) thick bedded sandstone, 2) thin bedded sandstone, 3) interbedded sandstone and mudstone, 4) mudstone, and 5) chaotic slump. The relative abundance of these facies suggests that deposition occurred primarily on the channelized portions of the middle fan areas and on the upper fan area (see Walker and Mutti, 1973, for discussion of terminology).

Thick Bedded Sandstone Facies. Rocks assignable to the thick bedded sandstone facies are the most common in outcrop and are characterized by thick to very thick (Ingram, 1954), individual and amalgamated beds composed generally of poorly to moderately well sorted medium to coarse sand. Dish structures, floating clasts and erosional surfaces are common within the beds. Graded beds and contorted laminations may or may not be present due to erosion and amalgamation by the mass flow units. Interbedded siltstone and mudstone beds are rare.

Thin Bedded Sandstone Facies. This facies is composed of single, thin to thick bedded fine to coarse sandstones, which are poorly to occasionally well sorted. Complete graded sequences or those lacking only the Bouma E interval are common. Dish structures and floating clasts are often present. Where observed in outcrop, this facies grades upward and downward into the thick bedded sandstone facies.

Interbedded Sandstone and Mudstone. This facies contains rythmically interbedded, very thin to thin bedded, very fine to fine sandstones and very thin to laminated siltstones and dark mudstones. The sandstones and siltstones are moderately to well sorted, commonly calcite cemented, parallel laminated, and are occasionally marked by nearly horizontal burrows. This facies is best exposed in a small fault block, bounded by the Pacific Ocean, just west of South Point and is possibly the oldest exposure of the South Point Formation on Santa Rosa Island.

Mudstone Facies. This facies is characterized by dark grayish and brownish, massive to laminated mudstone with rare interbeds of thin to very thin, fine to very fine sandstone and siltstone. Maximum thickness for this facies is estimated to be 100 feet (30 m). Foraminifers are locally common.

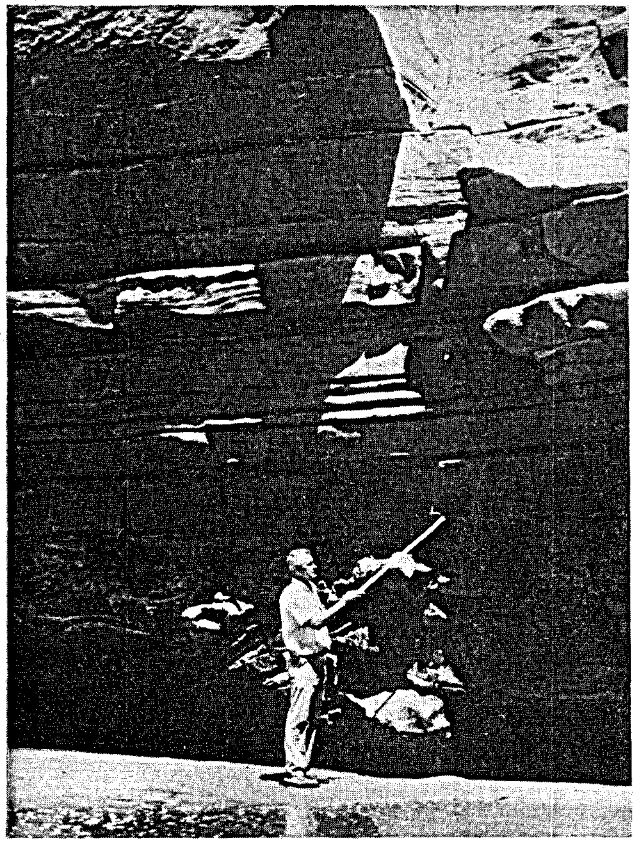


Fig. 11. Photograph of chaotic slump facies depositionally overlain by beds of the thick bedded sandstone facies.

Chaotic Slump Facies. This facies contains a massive chaotic mixture of broken and contorted beds of fine to coarse sandstone and interbedded siltstone and mudstone that are inferred to have moved en masse, downslope after original deposition. This facies, therefore, does not represent a primary sedimentary facies. Primary sedimentary structures in the broken and contorted beds are still preserved indicating that downslope movement occurred after consolidation. Resedimentation of these beds was by plastic and elastic movement. A depositional process with these properties is by definition slumping (Dott, 1963). The chaotic slump facies is overlain directly and depositionally by beds of the thick bedded sandstone facies (fig.11), which further indicates that slumping occurred before the deposition of the overlying beds. The chaotic slump facies is represented by exposures in only one locality where the base is not exposed. Total thickness is 6.2 feet (190 cm).

VERTICAL PROFILES IN SUBMARINE FAN DEPOSITS

Recently, Mutti (1974) and Walker and Mutti (1973) have presented a depositional model for ancient submarine fan deposits based upon the recognition of various sedimentary facies and vertical facies associations. From this model one should be able to determine local depositional settings, for example the middle or outer fan. Such a model seems applicable to the South Point Formation even though faulting and limited exposures preclude any indepth vertical or lateral facies analysis. The model, however, has two serious (and perhaps closely related) shortcomings. The model will not apply to those fans which would be composed of fine grained material, such as those that might be present in the Tertiary clastic province of the Gulf Coast area of the United States, or to those fans characterized by numerous lateral shifts in the site of deposition, which could be caused by a smaller grainsize availability or differences in the amount and rate of slope change. During any given unit of time and with the lateral shifting of depositional sites, the vertical sequences preserved at various locations within a major unit of the submarine fan complex (for example the middle fan) could lead to various interpretations as to the site of deposition. The best solution to such a problem is to have enough control to generate a three-dimensional picture of sedimentation during any given time interval. Outcrops, however, rarely provide this control. Even so, in the study and evaluation of submarine fan deposits, regardless of the maximum clast size available for sedimentation, the recognition and the understanding of the sedimentological implications of the four vertical sequence shown in figure 12 is necessary.

Figure 12A represents a rapid initiation of "coarse" clastic deposition followed by a gradual cessation of "coarse" deposition by sediment restriction or a gradual lateral migration of the "coarse" material. Figure 12B represents a gradual initiation of "coarse" clastic deposition followed by its abrupt termination. Figure 12C represents both a rapid initiation and termination of "coarse" clastic sedimentation, and Figure 12D represents both a gradual initiation and cessation of "coarse" sedimentation. In all cases a relative change in individual bed thickness is assumed to correspond to changes in average grainsize. Processes responsible for gradual initiation or termination of "coarse" sedimentation are progradation, lateral migration, regional transgression, or tectonic changes which restrict the grainsize available for deposition. Abrupt changes from or to "coarse" sedimentation can be explained by rapidly diverting the "coarse" material to another area of the submarine fan by a process similar to the formation of crevasse fans in the fluvial-deltaic environment. Tectonism or slumping may also cause a rapid cessation of the "coarse" clastic sedimentation.

VERTICAL SEQUENCES IN SUBMARINE FAN DEPOSITS

(see text for discussion)

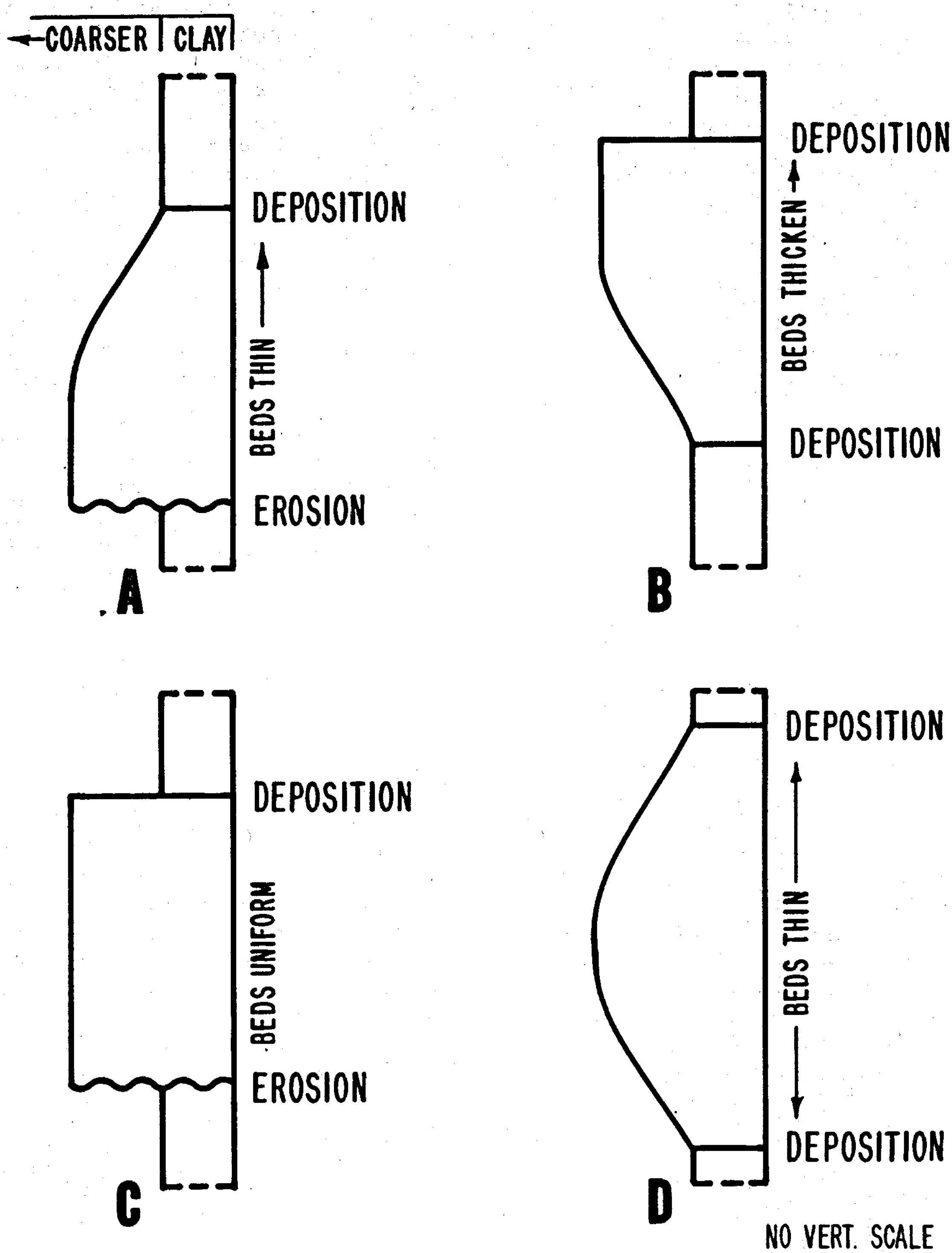


Fig. 12.

Summary and Conclusions

During the Ulatisian and Narizian stages of the Eocene, coarse clastics were being shed westward to bathyal depths onto a submarine fan. Parts of this fan are preserved in outcrop on Santa Rosa Island. The relative abundance of the thick bedded sandstone facies indicates that deposition occurred primarily on the channelized portions of the middle fan areas and on the upper fan. The poorly to moderately well sorted, quartz and feldspar rich sandstones were deposited from sediment gravity flows. Even though the various suites of sedimentary structures can be interpreted to represent various mechanisms of sediment support and transportation, only one type of sediment gravity flow is needed to account for the sand deposition. Models for submarine fan deposition presented in the literature are applicable to the South Point Formation but may not be for fans characterized by lateral migration of deposition or with a fine grained sediment source.

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PETROLOGY OF SOME MIDDLE AND LATE EOCENE SANDSTONES FROM THE SOUTHERN CALIFORNIA BORDERLAND

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INTRODUCTION

The presence of middle to late Eocene (Ulatisian and Narizian age) rocks on the islands of San Miguel, Santa Rosa, Santa Cruz, and San Nicolas of the Continental Borderland of Southern California is now well established (Weaver et al., 1969; Doerner, 1968; and Vedder and Norris, 1963). Paleoecological indicators show that deposition occurred in marine waters at bathyal depths (Weaver, et al., 1969; Doerner, 1968; and D. W. Weaver, 1975, personal commun.). Paleoslope and sedimentological studies show that the sediments were derived from an eastern source and that the "coarse" clastics were deposited from sediment gravity flows on submarine fans (Erickson, 1972; Cole, 1970; Merschat, 1968 and 1971; and Parsley, 1972).

With such limited outcrops in an area as vast and geologically complex as the Southern California Borderland, one might assume that these Eocene rocks would warrant little attention in the geological literature until more data has become available. To the contrary, in the last three-quarters of a decade numerous articles, discussion of articles, replies to discussions of articles and unpublished theses have appeared, all of which contain proposals for total or partial paleogeographic or tectonic reconstruction of the Borderland; the islands containing these rocks have been individually or collectively rifted and rafted, rotated, and strike-slipped by these various authors whose reconstructions are seemingly sprinkled with assumptions (Yeats, 1968; Cole, 1970; Yeats et al., 1970; Erickson, 1972; Yeats et al., 1974; Howell et al., 1974; Cole et al., 1975; Howell et al., 1975; Howell, 1975; and Gastil, 1975). The only geological calamity not yet ascribed to these Eocene rocks by the shamans of tectonic pinball is the perversion of subduction.

As a part of the author's most recent sojourn in the experience of higher education, thin sections from the middle to late Eocene sandstones from the South Point Formation of San Miguel and Santa Rosa Islands, from the Jolla Vieja Formation of Santa Cruz Island, from the unnamed rocks of San Nicolas Island, and from the Torrey Sand, Scripps Formation, and Stadium Conglomerate of the San Diego area (see fig.1) were studied petrographically to determine textural parameters and mineral composition and to make provenance interpretations (Erickson, 1972). The findings and interpretations derived from that endeavor are presented here for

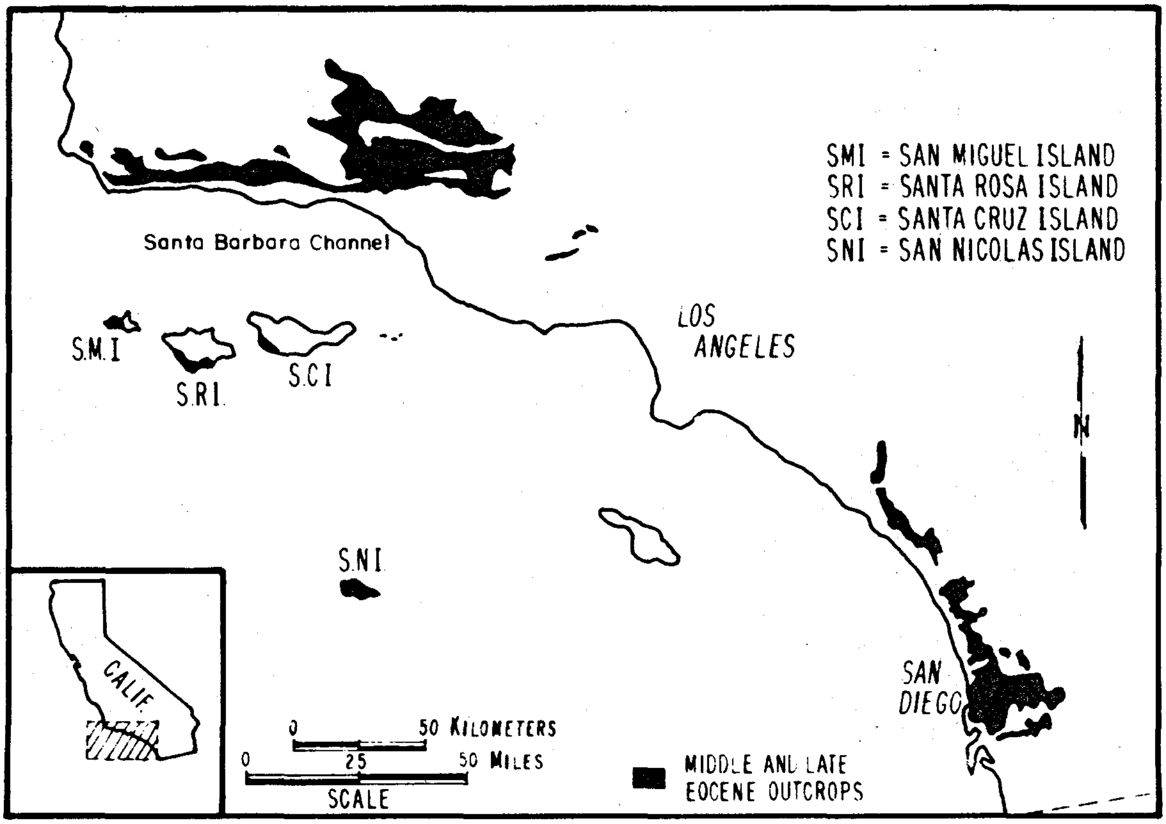


Fig. 1. Index map showing locations of middle and late Eocene outcrops in the Southern California Borderland and adjacent areas.

purposes of general information and perusal in the belief that a little data can never hurt a good geological interpretation. Furthermore, no discussion of these above-mentioned regional reconstructions will be made. After all, the stage of a petrographic microscope is not the place from which to make such discussions.

Methods and Procedures

Twenty-eight thin sections were analysed in the study. One sample from each of the San Diego area formations was utilized. Ten samples from Santa Rosa Island and five samples from each of the remaining islands were studied. The samples from San Nicolas Island were borrowed from R. M. Norris at the University of California at Santa Barbara. The remaining samples were collected by the author. All samples collected by the author were cut normal to bedding and stained for potassium feldspars. The thin sections from San Nicolas Island were unstained. Point counts, utilizing a mechanical stage, to a total of 100 essential grains (quartz, feldspars, and rock fragments) were made. The abundance of heavy minerals was determined by systematically scanning each thin section under high power and counting the number of grains that came into the field of view. The threefold subdivision of sandstone composition (Folk, 1968) into terrigenous, allochemical, and orthochemical components is followed. In the following discussions, "locality" will refer to each individual island or San Diego. Classification and the determination of mean grain size, sorting, and roundness (Powers, 1953) follow the methods outlined by Folk (1968).

COMPOSITION

Terrigenous Components

The terrigenous components - those grains derived from land outside the basin of deposition - include quartz, feldspars, rock fragments, micas, detrital clay, heavy minerals, and miscellaneous organic fragments. The feldspars are plagioclase, orthoclase and microcline and the rock fragments are silicic volcanic, granitic, fine grain sedimentary and low grade metamorphic. All samples, except for one feldspathic litharenite, are arkoses and lithic arkoses and are plotted on the diagram in figure 2. Individual grain percentages, as well as the average composition for each locality, are given in Tables 1 to 3 at the end of the paper. Individual grain percentages are quite variable but the average percentages for each locality show a close similarity in composition. The average compositions are plotted in the histograms of figure 3.

Quartz. Quartz is the most abundant mineral ranging from 28.9 to 45.3 percent of the terrigenous grains. The highest concentration of quartz is seen in the samples from the San Diego area. The most common type of quartz grain is monocrystalline with undulose extinction. Less than ten percent of the grains are polycrystalline or monocrystalline with straight extinction. Parallel alignment of muscovite was seen in some of the polycrystalline grains. Less than a fraction of a percent contain overgrowths, which are interpreted to have been present before deposition. Within the quartz grains, mineral inclusions or fluid-filled vacuoles are rare. Microlites consist of zircon, apatite, acicular inclusions (rutile?), tourmaline, biotite, orthoclase, plagioclase, and opaque minerals. The fluid vacuoles are randomly oriented or are in trains.

Feldspars. The feldspar group is represented by plagioclase, orthoclase, and microcline. Total feldspars range from 21.4 to 46.0 percent. Plagioclase is the most common feldspar ranging from 43.4 to 74.9 percent of the total. Less than one to 16.7 percent of the feldspars are microcline and 16.6 to 46.4 percent are orthoclase.

The plagioclase composition is quite uniform; most grains are oligoclase (An_{10}-An_{30}). Minor amounts of albite (An_0-An_{10}) and andesine (An_{30}-An_{50}) are also present. A few grains exhibiting oscillatory zoning and antiperthitic texture were observed. Both untwinned and twinned grains are present. Twinning types are albite, pericline, carlsbad, or combination. Orthoclase and microcline both show perthitic texture,

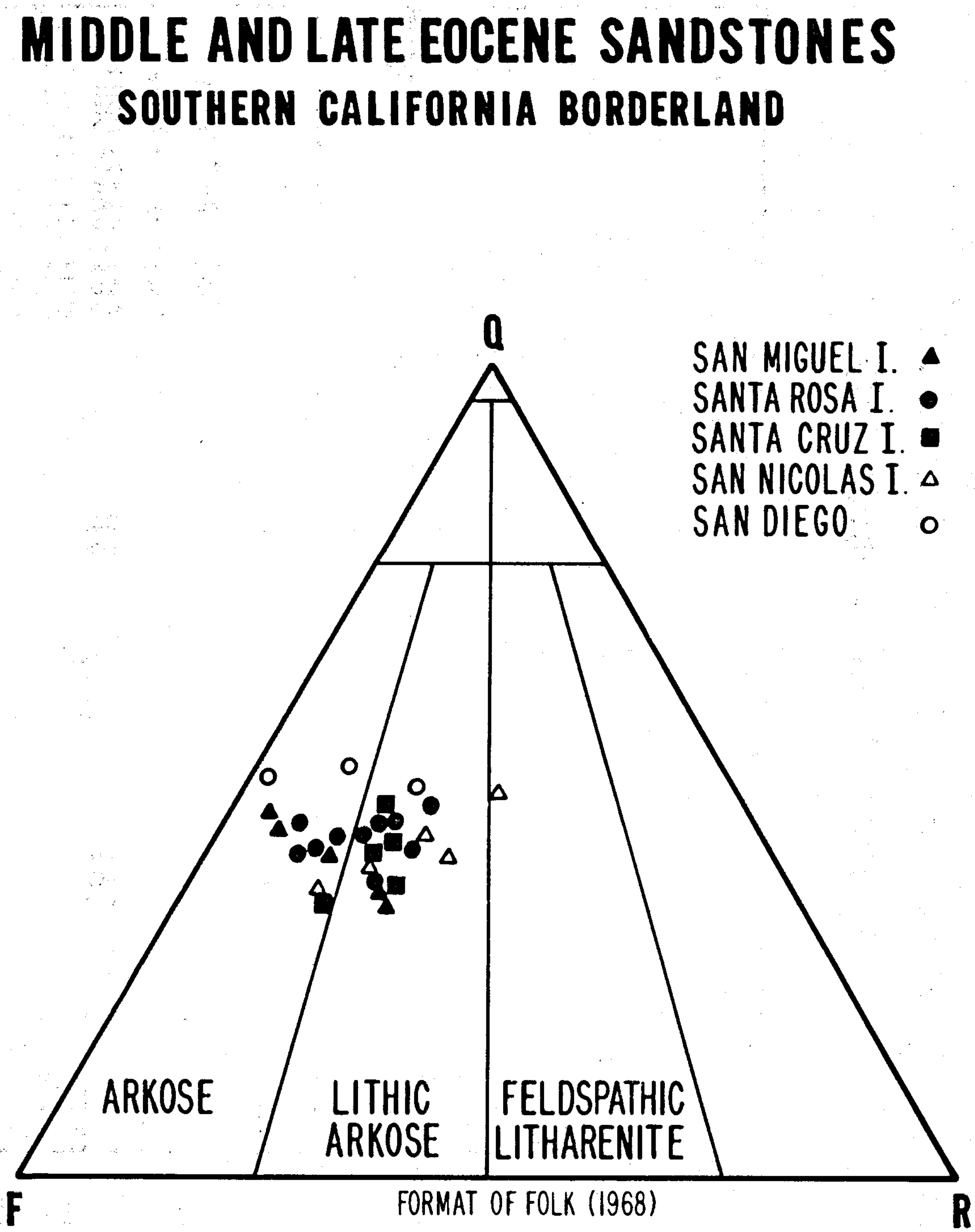


Fig. 2. Compositional diagram of middle and late Eocene sandstones from the Southern California Borderland and the San Diego area.

AVERAGE COMPOSITIONS
MIDDLE TO LATE EOCENE SANDSTONES
SOUTHERN CALIFORNIA BORDERLAND

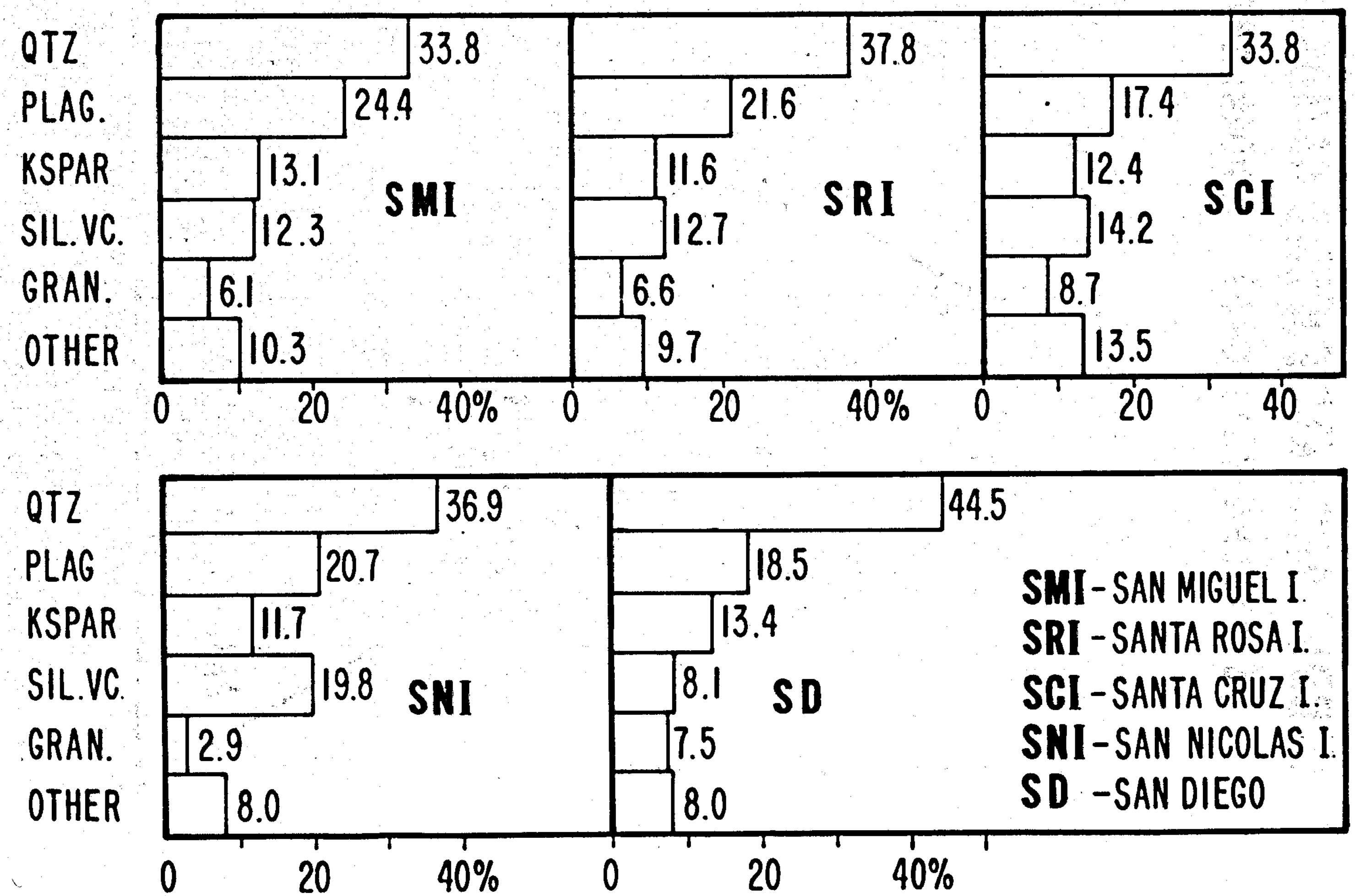


Fig. 3. Histograms showing average terrigenous compositions for middle and late Eocene sandstones from the Southern California Borderland and the San Diego area.

but most commonly do not show this exsolution texture. Orthoclase is untwinned, only occasionally exhibiting the Carlsbad form. The microcline is twinned, showing the typical, albite-pericline, gridiron texture.

Both fresh and altered feldspars are present; however, altered forms are estimated to be the most common, especially in the plagioclase. Seritization is most common in the plagioclase. Other types of alteration observed are kaolinization, vacuolization, and sauceritization.

Rock fragments. This general grouping includes silicic volcanic, granitic, fine grain sedimentary, and metamorphic rock fragments. Of these the silicic volcanics and the granitic fragments are most common ranging from 1.9 to 25.0 and less than one to 13.8 percent of the terrigenous grains. Except for one sample from Santa Rosa Island, the sedimentary and metamorphic rock fragments are minor constituents in all samples analyzed.

Three types of silicic volcanic fragments were observed. The most common type contains a microgranular matrix of quartz and orthoclase occurring alone or with subhedral to euhedral phenocrysts of quartz (which may be embayed), orthoclase, and/or plagioclase. Finely disseminated opaque minerals may also be present. Figure 4 shows a typical example of this type of grain. These fragments are believed to have been derived from devitrified, silicic, ash-flow tuffs (Ross and Smith, 1960). The second and third type of volcanic fragments compose less than five percent of the total and consist of a microgranular matrix showing spherulitic texture and relict shards (?) or a microcrystalline arrangement of orthoclase, plagioclase and quartz. This last type is thought to have been derived from volcanic flow rocks or hypabyssal intrusions.

The granitic rock fragments contain allotriomorphic and hypidiomorphic granular intergrowths of orthoclase, plagioclase, and quartz; microcline, plagioclase and quartz; or a two-mineral combination of orthoclase, microcline, plagioclase, quartz, biotite or muscovite. Myrmekitic, micrographic, and granophyric intergrowths are also present. The composition of these granitic fragments suggests a source having a quartz monzonitic to granodioritic composition.

Sedimentary rock fragments include mudstone, siltstone and chert, which is treated separately in the tables. The anomalously high abundance of chert particles, including, radiolarian chert, in sample 11 from Santa Rosa Island is unexplained. Except for this sample, the sedimentary rock fragments are a minor portion of the terrigenous components.

The metamorphic fragments include pelitic phyllites,

Fig. 4. Photograph of silicic volcanic fragment consisting of a microgranular matrix of quartz and orthoclase and a subhedral phenocryst of plagioclase. Bar length is .10mm. Crossed nicols.

quartz-albite-muscovite schists, and semischists (see Williams, Turner, and Gilbert, 1954, p.205). These forms are all indicative of a low grade regionally metamorphosed terrane. Metamorphic rock fragments, when present, compose less than two percent of the terrigenous grains.

Micas. The micas consist of biotite, muscovite, and chlorite. An estimated twenty percent of the micas are muscovite and an insignificant fraction are chlorite. Muscovite occurs as fresh flakes, whereas biotite may be fresh, bleached, or partially altered to magnetite-hematite or chlorite. The chlorite grains are possibly completely altered biotite.

Terrigenous Clay. Terrigenous clay, believed to have an illitic composition on the basis of petrographic properties (Folk, 1968, p.91), occurs in interstitial areas and is yellowish-brown, the result of staining by iron oxide. All samples contain varying amounts of terrigenous clay. The maximum amount observed is 5.4 percent.

Heavy minerals. The heavy minerals observed include the epidote group (includes epidote, allanite, clinozoisite, and piedmontite), sphene, zircon, garnet, opaque minerals (magnetite and ilmenite), tourmaline, hornblende, apatite, spinel and clinopyroxene. Even though this group represents a minor percentage of the terrigenous grains, the heavy minerals represent the only significant variation in abundances that were observed for samples from the various localities. The opaque minerals are present in all samples.

As shown in Figure 5, the epidote group and sphene are most abundant (see "methods and procedure" for discussion) in the thin sections from San Miguel Island, Santa Cruz Island, and from the San Diego area. These two groups are absent or uncommon in the thin sections from Santa Rosa and San Nicolas Islands. Such variations could be the result of local source contributions, selective concentration by erosional processes before deposition, or intrastratal solution effects. Zircon, garnet, and tourmaline are strikingly less abundant (0-10 grains per thin section) but are represented at each locality. Hornblende, apatite, spinel, and clinopyroxene are very rare, represented by one or two grains when present, and are also not restricted to any specific locality.

Miscellaneous carbonaceous material. Fine grained plant or wood fragments are present in few samples and are therefore an insignificant fraction of the terrigenous components.

Allochemical Components

Allochemical components, reworked precipitates formed in the basin of deposition, comprise less than a percent of the total in every thin section. Glauconite pellets and rounded calcareous shell debris were the only allochemical components observed.

Orthochemical Components

The interstitial cements or the orthochemical components include sparry calcite and rare silica and chlorite. The amount of sparry calcite cement reaches 25 percent for sample 16 from Santa Cruz Island. All samples, but 14, from San Nicolas Island contain greater than 10 percent calcite cement. All other samples contain five percent or less.

TEXTURE

All textural parameters are presented in Table 4 at the end of the paper. All of the samples analysed have mean grain sizes which fall within the range of fine and medium sand (Wentworth, 1922). All but the sample from the Stadium Conglomerate are poorly to moderately sorted. Packing of the grains is close except where calcite cement has disrupted the grains, and the porosity is low. The average roundness of the grains is angular to subangular. A comparison of the average roundness of the fine to medium grain fragments of quartz, feldspars, and the silicic volcanic fragments indicates that the silicic volcanic fragments are better rounded. As shown by figure 6, 89 and 86 percent, respectively, of the silicic volcanic fragments are better rounded (plotting above the solid line) than quartz and the feldspars. Figure 7 shows the typical textural properties of middle and late Eocene sandstones from the Borderland area.

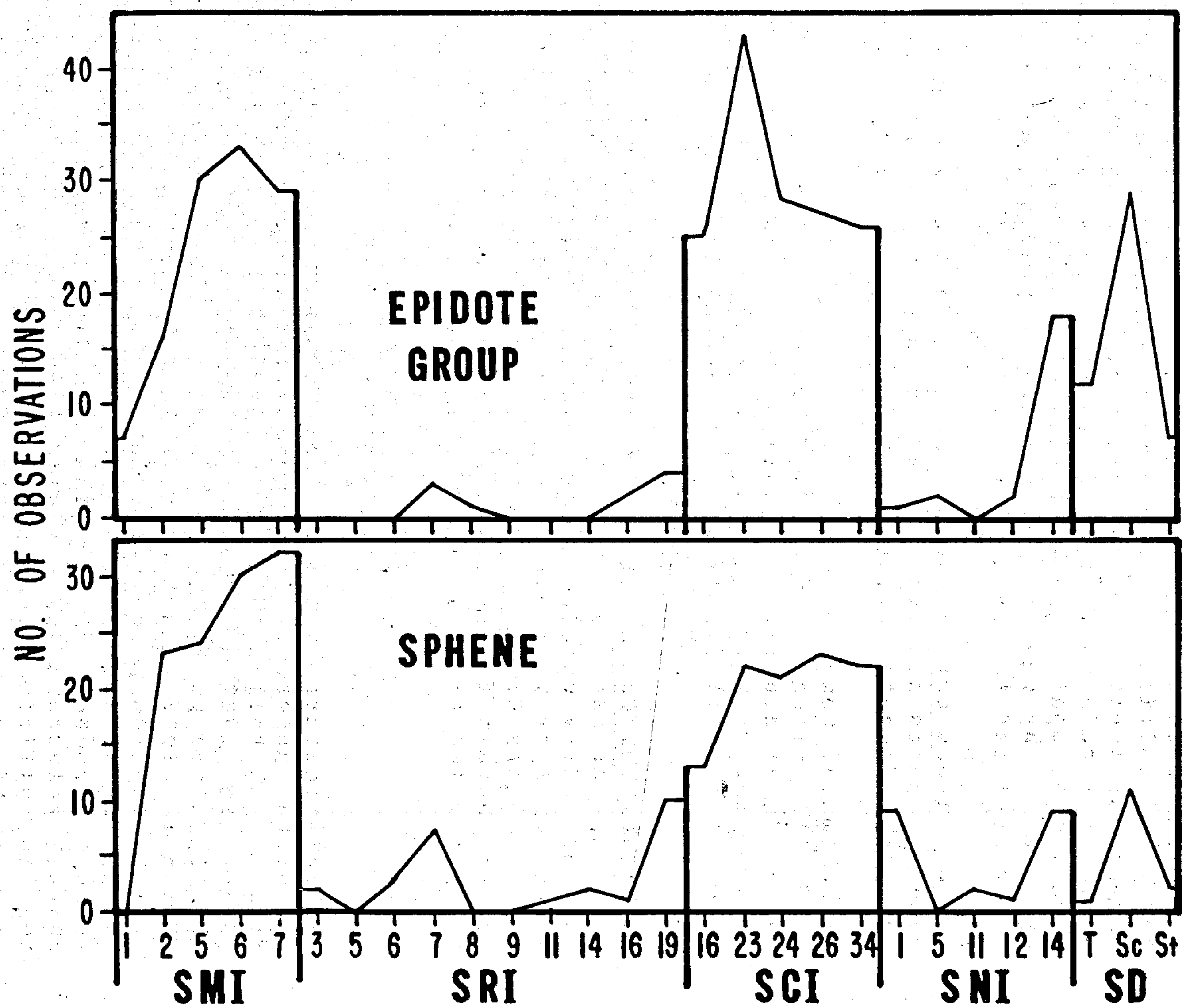
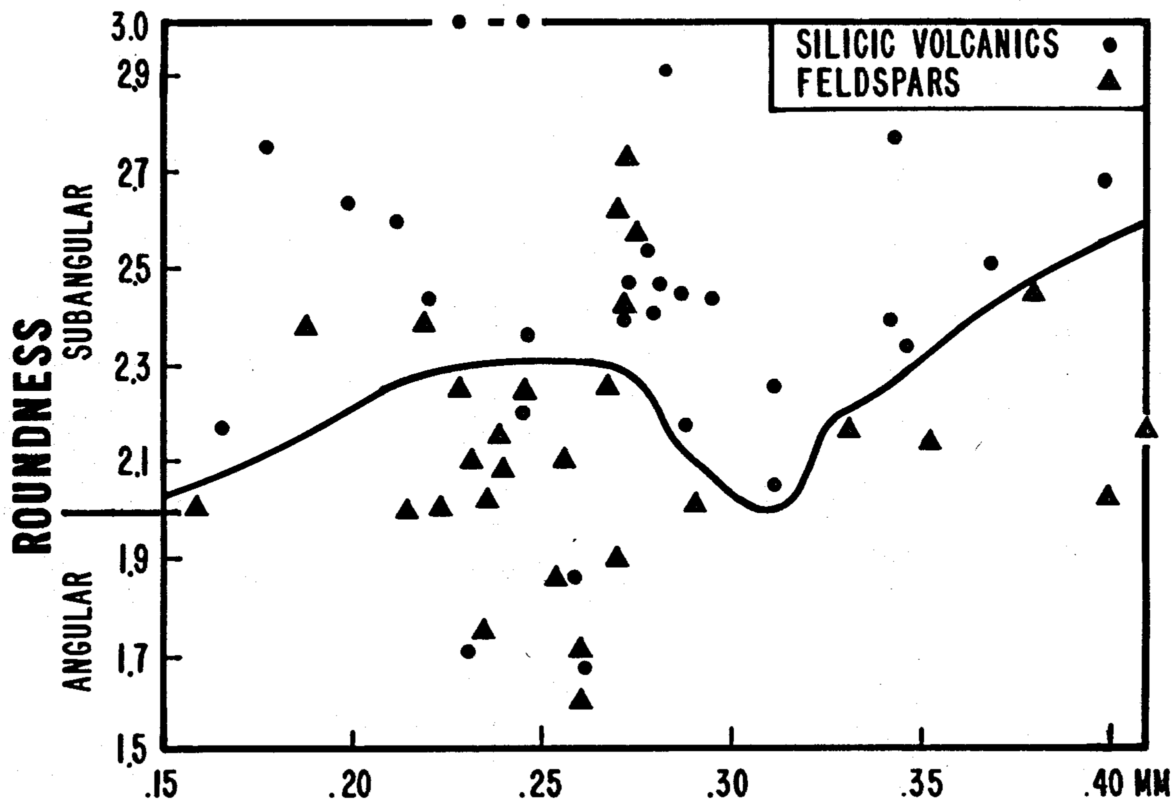


Fig. 5. Diagrams showing the thin section abundance of the epidote group and sphene in middle to late Eocene sandstones from the Southern California Borderland and the San Diego area.



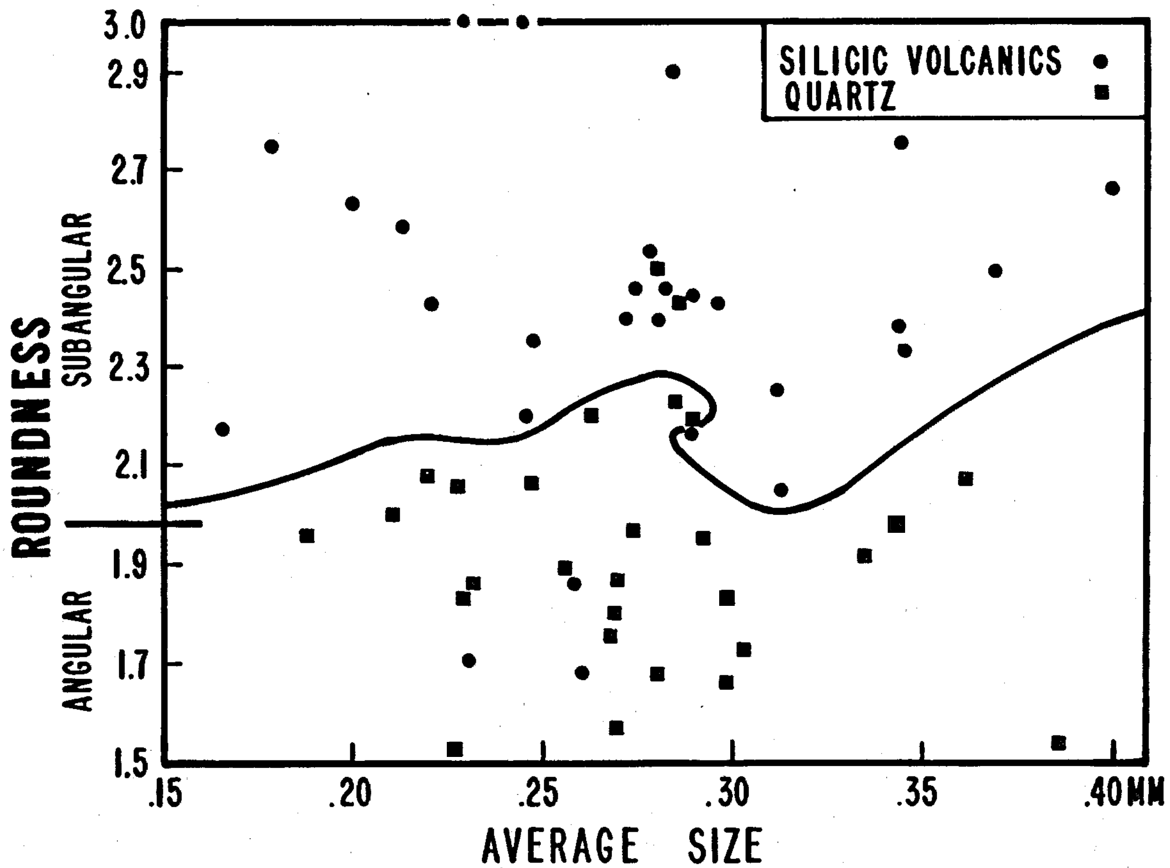


Fig. 6. Diagrams of the average roundness versus average grain size of fine to medium size particles of quartz, feldspars, and silicic volcanic fragments.

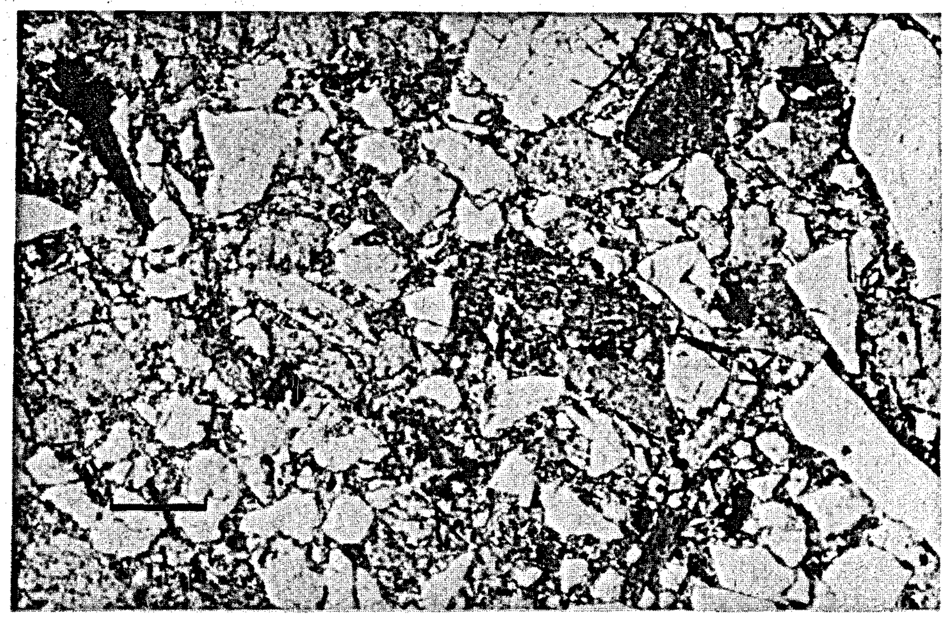


Fig. 7. Photograph of a thin section from Santa Cruz Island showing the typical textural properties of middle and late Eocene sandstones from the Southern California Borderland. The sample is poorly sorted with mostly angular and subangular grains. Bar length is .35mm. Plane light.

PROVENANCE INTERPRETATION

Caution must be used when attempting to determine the provenance of sandstones from thin section analysis. Such factors as selective weathering or transportation can greatly affect the grain composition and therefore the provenance interpretation. Recognizing such limitations, a generalized provenance interpretation can still be made for these sandstones. The suite of terrigenous grains combined with their textural parameters suggests that the Eocene borderland sediments were derived mainly from granitic rocks of a quartz monzonite to granodiorite composition. Lesser contributions of material originated in a silicic volcanic terrane consisting of devitrified ash-flow tuffs, flows, and hypabyssal intrusions. Minor amounts of material were derived from fine grain sedimentary rocks and low rank regionally metamorphosed rocks.

Granitic basement rocks older than Eocene crop out on Santa Cruz Island and on the mainland in the Southern California Batholith. On Santa Cruz the basement consists of hornblende diorite, tonalite, and minor amounts of trondhjemite, gabbro, hornblendite, and olivine clinopyroxenite (Weaver et al., 1969, and Hill, 1974). Such a mafic rich source is not indicated by the sandstone composition.

Larsen (1948) and Jahns (1954) report that the Southern California Batholith contains rocks ranging in composition from gabbro to granite with the average composition in the tonalite range. Ninety percent of the exposed portions are also reported to have compositions ranging from gabbro to granodiorite. Taking into consideration the affects of selective weathering and transportation, this writer believes that these rocks contain too little potassium feldspar and plagioclases too high in anorthite composition to have contributed significantly to the middle and late Eocene sediments. Possibly the sediments were derived from a more acidic, but now eroded, upper portion of the pluton. Direct evidence of source rock composition is given by the compositions of two granitic cobbles which were found in a conglomeratic interval of the Jolla Vieja Formation of Santa Cruz Island. Petrographic analysis shows one sample to be an aplitic quartz monzonite containing 50 percent quartz, 24 percent microcline, 12 percent orthoclase, and 14 percent plagioclase. The other sample is also a quartz monzonite but contains 30 percent quartz, 30 percent plagioclase (of an oligoclase composition), 34 percent microcline, and 3 percent each of biotite and muscovite.

The silicic volcanic fragments are believed to be sand-sized particles of Poway clasts, for which no known source exists (Bellemin and Merriam, 1958; Woodford et al., 1968; and Peterson, et al., 1967). Since these particles are better rounded than the feldspars and quartz and are apparently of comparable hardness, the silicic volcanic particles are interpreted to have been reworked from an older sedimentary deposit. Possible source rocks for the low grade metamorphic fragments occur both onshore and in the Borderland. Fine grain schist, argillite, and quartzite are found in the Bedford Canyon Formation of the Santa Ana, Elsinore and Santa Margarita Mountains, in the Julian Schist of the Agua Tibia and Laguna Mountains, and in northern Baja California (Jahns, 1954). On Santa Cruz Island metasediments and low grade schists are present (Weaver et al., 1969; Howell et al., 1974 and 1975).

SUMMARY AND CONCLUSIONS

The middle and late Eocene sandstones on the islands in the Southern California Borderland have grain compositions suggesting they were derived from the same or a similar source. A similar composition for age equivalent rocks from the San Diego area is consistent with an eastern source for the offshore rocks. All rocks are interpreted to have been derived predominantly from igneous rocks of a quartz monzonite to granodiorite composition and older sediments that originated in a silicic volcanic terrane.

SANTA ROSA ISLAND

SAMPLE	16	19	11	5	6	7	8	9	3	14	AVE.
Quartz	37.6	39.6	42.1	35.1	35.4	38.9	38.7	37.0	33.3	40.2	37.8
Plagioclase	20.2	21.7	22.4	20.7	18.6	24.1	19.8	23.1	25.0	20.6	21.6
Orthoclase	6.4	11.3	8.4	15.3	9.7	8.3	9.0	12.0	8.3	11.2	10.0
Microcline	1.8	1.9	.9	2.7	2.7	2.7	T	.9	1.9	T	1.6
Total Feldspar	(28.4)	(34.9)	(31.7)	(38.7)	(31.0)	(35.1)	(28.8)	(36.0)	(35.2)	(31.8)	(33.2)
Silicic Vol. R.F.	11.0	7.5	9.3	8.1	18.6	13.9	15.3	10.2	16.7	15.9	12.7
Granitic R.F.	13.8	11.3	T	7.2	2.7	4.6	6.3	9.3	5.6	5.6	6.6
Sedimentary R.F.	.9	T				T					
Chert		.9	10.3	.9	T	T					
Metamorphic R.F.					.9		.9		1.8		
Micas	6.4	2.8	.9	4.5	8.8	5.6	5.4	3.7	5.6	4.6	4.8
Clay	1.8	2.8	2.8	5.4	1.8	1.9	4.5	3.7	.9	1.9	2.8
Heavies	T	T	.9	T	.9	T	T	T	.9	T	
Organic			1.9			T	T				
Total	99.9	99.8	99.9	99.9	100.1	100.0	99.9	99.9	100.0	100.0	

Table 1. Individual percentages of terrigenous components in thin sections from the South Point Formation, Santa Rosa Island, California. (T: present in thin section but not touched by point count.)

SAMPLE	SANTA CRUZ ISLAND 23	24	16	34	26	Ave.	SAN MIGUEL ISLAND 1	2	5	6	7	Ave.
Quartz	28.9	32.5	42.1	29.9	35.4	33.8	38.6	36.4	29.7	31.2	33.0	33.8
Plagioclase	22.8	19.7	13.1	17.9	13.3	17.4	27.2	20.9	24.3	25.7	24.1	24.4
Orthoclase	10.7	7.7	12.1	10.3	7.1	9.6	11.4	8.2	9.0	10.1	15.2	10.8
Microcline	5.3	3.4	.9	1.7	2.7	2.8	1.8	4.5	1.8	1.8	1.8	2.3
Total Feldspar	(38.8)	(30.8)	(26.1)	(29.9)	(23.1)	(29.8)	(40.4)	(33.6)	(35.1)	(37.6)	(41.1)	(37.5)
Silicic Vol. R.F.	12.3	14.5	14.0	15.4	15.0	14.2	3.5	10.0	18.9	19.3	9.8	12.3
Granitic R.F.	6.1	6.8	10.3	6.8	13.3	8.7	5.3	10.9	5.4	3.7	5.4	6.1
Sedimentary R.F.	.9				.9							
Chert	.9	.9		1.7	.9				T			
Metamorphic R.F.			.9	1.7								
Micas	4.4	7.7	5.6	6.8	6.2	6.1	7.9	6.4	6.3	5.5	7.2	6.7
Clay	5.3	4.3	T	2.9	2.7	3.0	1.8	1.8	.9	1.8	1.8	1.6
Heavies	2.7	2.7	.9	4.8	2.7		2.6	.9	2.7	.9	1.8	
Organic												
Total	100.3	100.2	99.9	99.9	100.2		100.1	100.0	99.0	100.0	100.1	

Table 2. Individual percentages of terrigenous components in thin sections from the Jolla Vieja Formation, Santa Cruz Island and from the South Point Formation, San Miguel Island, California.
(T: present in thin section but not touched by point count.)

SAMPLE	San Nicolas Island: 15	San Nicolas Island: 5	San Nicolas Island: 11	San Nicolas Island: 12	San Nicolas Island: 1	San Nicolas Island: Ave.	San Diego: Torrey	San Diego: Scripps	San Diego: Stadium	San Diego: Ave.
Quartz	37.2	37.0	42.9	32.2	35.4	36.9	45.3	43.2	45.1	44.5
Plagioclase	18.6	17.9	14.3	32.2	20.6	20.7	18.9	19.0	17.6	18.5
Orthoclase	12.4	8.0	7.1	10.6	8.8	9.4	18.9	8.6	3.9	10.5
Microcline	T	2.2	T	3.2	5.9	2.3	5.7	.9	2.0	2.9
Total Feldspar	(31.0)	(28.1)	(21.4)	(46.0)	(35.3)	(32.4)	(43.5)	(28.5)	(23.5)	(31.9)
Silicic Vol. R.F.	24.8	18.7	25.0	12.9	17.7	19.8	1.9	6.8	15.7	8.1
Granitic R.F.	1.8	4.2	1.8	.9	5.9	2.9	3.8	6.8	11.8	7.5
Sedimentary R.F.		.9		T						
Chert			T						2.0	
Metamorphic R.F.								.9		
Micas	3.6	5.6	4.5	5.5	3.6	4.6	3.8	8.5	2.0	4.8
Clay	1.8	4.7	3.6	3.2	1.8	3.0	1.9	3.4	T	1.8
Heavies	T	.9	.9	T	T		T	1.7	T	
Organic										
Total	100.2	100.1	100.1	100.7	99.7		100.2	99.8	100.1	

Table 3. Individual percentages of terrigenous components in thin sections from middle and late Eocene sandstones from San Nicolas Island and from San Diego, California.
(T: present in thin section but not touched by point count.)

	SAMPLE	MEAN GRAIN SIZE	SORTING		AVERAGE ROUNDNESS	
		mm	σ	verbal	ρ	verbal
SAN MIGUEL I.	1	.18	1.01	poor	1.92	angular
	2	.24	1.63	poor	2.10	subangular
	5	.22	1.10	poor	2.13	subangular
	6	.18	1.18	poor	1.91	angular
	7	.17	1.23	poor	1.89	angular
SANTA ROSA I.	16	.25	1.28	poor	2.37	subangular
	19	.31	1.17	poor	2.24	subangular
	11	.27	1.46	poor	2.08	subangular
	5	.22	1.50	poor	1.95	angular
	6	.20	1.31	poor	1.64	angular
	7	.26	.94	moderate	1.83	angular
	8	.31	1.07	poor	1.91	angular
	9	.41	.96	moderate	2.34	subangular
	3	.25	1.11	poor	1.81	angular
	14	.19	1.12	poor	1.60	angular
SANTA CRUZ I.	23	.18	1.40	poor	2.24	subangular
	24	.19	1.10	poor	2.10	subangular
	16	.27	.86	moderate	2.23	subangular
	34	.17	1.15	poor	2.00	subangular
	26	.24	1.21	poor	2.42	subangular
SAN NICOLAS I.	14	.16	.78	moderate	2.20	subangular
	5	.19	1.01	poor	2.10	subangular
	11	.21	.88	moderate	2.12	subangular
	12	.21	.89	moderate	2.19	subangular
	1	.22	1.07	poor	2.06	subangular
SAN DIEGO	Torrey	.15	.72	moderate	2.17	subangular
	Scripps	.27	.87	moderate	2.41	subangular
	Stadium	.38	.35	well	2.60	subangular

Table 4. Textural parameters of middle and late Eocene sandstones from the Southern California Borderland and from the San Diego Area.

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STRATIGRAPHY AND PALEONTOLOGY OF THE
TYPE BLAKELEY AND BLAKELY HARBOR FORMATIONS

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ABSTRACT

The type section of the Blakeley Formation as defined by Weaver is exposed in three discontinuous beach sections. Each profile contains all or a portion of the two lithologic members characterizing this formation. The Orchard Point or lowermost member is composed of coarse clastic sediments interbedded with relatively minor amounts of fine-grained sandstone and siltstone. This member is most completely exposed along the southwestern shore of Sinclair Inlet, where it is approximately 2600 feet thick. The overlying Restoration Point Member is characterized by fine-grained sandstone, siltstone, and shale with minor amounts of pebbly sandstone. The strata assigned to this member are best exposed along the southern and southeastern shores of Bainbridge Island. Here the Restoration Point Member is approximately 4500 feet thick.

Both lithologic members are composed predominantly of volcanic debris derived from two distinct source areas. Basaltic debris is usually the dominant volcanic element of the coarser clastic sediments. The matrix of the sandstone and conglomerates, in addition to much of the silt and clay size material present in the finer clastics, is composed of light colored felsitic tuff. The basaltic debris was eroded from nearby areas of Crescent or Coast Range basalt and felsitic tuff was supplied from the Cascade volcanic provenance to the east.

The typical Blakeley Formation contains a rich molluscan and foraminiferal fauna. The molluscan elements comprise the *Acila gettyburgensis* association of Weaver and the *Echinophoria rex* assemblage of Durham. The lower 850 feet of the Orchard Point Member is characterized by a foraminiferal faunule of Refugian Age. The remainder of the formation is characterized by a foraminiferal association of Zemorrian Age.

The organic and inorganic elements characteristic of the Blakeley Formation suggests that both lithologic and biologic mixing has taken place during the Blakeley depositional cycle. This mixing is more conspicuous but not restricted to the coarser clastic units of this formation. Lithologic mixing displayed by these beds is characterized by rounded to subangular grits, pebbles, cobbles, and sometimes boulders of basalt associated with abundant fine-grained intergranular matrix composed of light colored felsitic tuff. Biologic mixing on the other hand is characterized by a fossil faunal association composed of elements belonging to shallow water, subtropical molluscan and coral assemblages mixed with deeper cold water benthonic foraminifers.

The poorly sorted, mixed character of the biologic and lithologic elements of the coarser clastic strata of this formation suggest the possibility of submarine slumping and transport by turbidity currents to deep water.

INTRODUCTION

During the past fifty years, the formational term Blakeley has been applied in several different ways, frequently implying different stratigraphic, biostratigraphic and chronologic meaning. The multiplicity of this usage has resulted in considerable confusion with respect to the typical lithologic character, correlation and time-rock nomenclature. It is the purpose of this paper to define and to restrict the Blakeley Formation, to describe its lithologic character, and to figure and describe the contained foraminiferal faunules. The term Blakeley was first applied in a formational sense to a thick sequence of sedimentary strata exposed along the beaches of Bainbridge Island and Sinclair Inlet by Weaver in 1912. This formational unit received its name from the nearby village of Port Blakely and its harbor. The more common geographic spelling was not retained by Weaver possibly because the name "Blakely" had been previously used by Ulrich in 1911 for a sandstone unit of Lower Ordovician age. The uppermost portion of Weaver's type Blakeley Formation was deposited in a nonmarine environment and is lithologically distinct from the underlying strata. It appears advisable, therefore, to restrict the Blakeley Formation to the marine deposits and to rename the superadjacent unit. The molluscan faunules of the Blakeley Formation have been studied in detail by Weaver in 1912, 1916, and 1942; Tegland in 1933, and more recently by Durham in 1944. Additional work on the molluscs has not been undertaken.

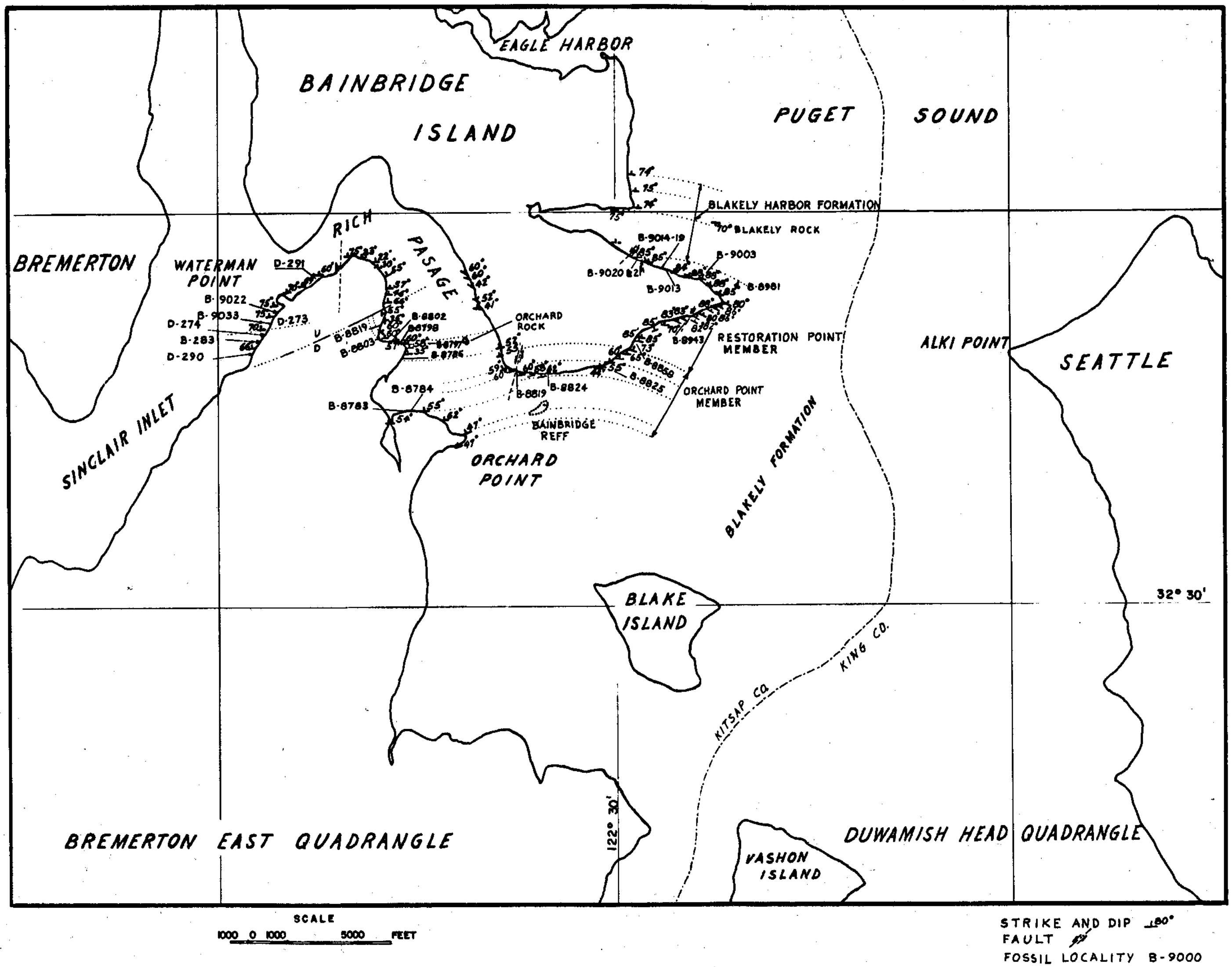
The Blakeley Formation of Weaver occupies an important biostratigraphic position in the Pacific Coast, Oligocene-Miocene chronology. This importance is in part historical as the megainvertebrate fossils collected from the presently recognized Blakeley and Astoria Formations were among the first studied from the Pacific Northwest. The fossil associations of these formations have since been used for formational recognition, stage assignment and regional (Pacific Coast) correlation.

The typical Blakeley Formation also contains rich and well-known foraminiferal faunules that can be correlated with the Refugian and Zemorrian stages of California. The joint occurrence of the molluscan, coral, and foraminiferal assemblages associated with the characteristic felsitic tuff matrix affords an excellent correlation between Keechelus Series and similar Cascade volcanic rocks and the standard Marine Tertiary sequence. Thus additional biostratigraphic, lithologic, and structural data are available for evaluation of the Oligocene and its boundary problems. Problems which have been emphasized elsewhere (Schenck 1935, Kleinpell 1938, Goudkoff and Porter 1942, Eames, Banner, Blow, and Clarke 1962, and Kleinpell and Weaver 1963).

The writer is indebted to Dr. V. Standish Mallory for his review and many valuable suggestions. Special recognition is also due Anna Muldrow and Martha Johnson for their work in typing the manuscript.

HISTORICAL REVIEW

Arnold (1906) described two species of the genus *Pecten* from beds (presently assigned to the Orchard Point Member) exposed near Bean Point. These species were considered by Arnold to be Oligocene-Miocene in age.


EAGLE HARBOR
BAINBRIDGE ISLAND
PUGET SOUND
BLAKELY HARBOR FORMATION
BLAKELY ROCK
RICH PASAGE
BREMERTON
WATERMAN POINT
ORCHARD ROCK
RESTORATION POINT MEMBER
ALKI POINT
SEATTLE
ORCHARD POINT MEMBER
BAINBRIDGE REFF
SINCLAIR INLET
ORCHARD POINT
BLAKELY FORMATION
BLAKE ISLAND
32° 30'
KING CO.
KITSAP CO.
122° 30'
BREMERTON EAST QUADRANGLE
DUWAMISH HEAD QUADRANGLE
VASHON ISLAND
D-291
B-9022
B-9033
D-273
D-274
B-283
D-290
B-8819
B-8803
B-8802
B-8798
B-8786
B-8784
B-8783
B-8819
B-8824
B-8825
B-8943
B-9014-19
B-9020
B-9013
B-9003
B-8981
SCALE
1000 0 1000 5000 FEET
STRIKE AND DIP 80°
FAULT
FOSSIL LOCALITY B-9000

Dall (1909) collected and described several molluscan species from strata (now assigned to the Restoration Point Member) exposed near Restoration Point. These new faunal elements were considered by Dall to be Oligocene in age. As a result of these two early papers, surprisingly accurate age determinations were made prior to formational or lithologic defination.

Weaver (1912) formally named the Blakeley Formation and designated the type section, "at Restoration Point, Kitsap County, opposite Seattle." In the discussion concerning this newly named formation, Weaver (1912, p. 16) implies that the type section also includes strata exposed on the mainland from Orchard Point to the vicinity of Waterman Point on Sinclair Inlet. The composite nature of the type section was clarified in later papers by Weaver (1916 a, b, c, d, and 1937).

The molluscan fauna characteristic of this newly named formation was recognized by Weaver (1912, p. 17) from several other localities in Western Washington. These isolated localities were referred to as the "Blakeley Beds." The exposures at Alki Point and Georgetown, now within the city of Seattle and the so-called Blakeley Beds exposed in the New-castle Hills and near the village of Cathcart are lithologically similar to the type section of the Blakeley formation. However, the "Blakeley Beds" exposed in Chehalis County, on the Quimper Peninsula, and at various points along the Strait of Juan de Fuca differed in lithologic character and were later assigned to other formations. It is important to note that the type section of the Blakeley Formation and the more widely spread molluscan association characteristic of this formation were recognized by Weaver at approximately the same time.

Later in the same year, Arnold and Hannibal (1912) referred the upper portion of the type Blakeley Formation of Weaver, to the Seattle Formation and the lower portion, to the San Lorenzo Formation. In addition, a four-fold division of the Pacific Coast Oligocene based on molluscan assemblages was recognized. The Sooke Formation of south Vancouver Island was considered the oldest followed by the San Lorenzo, Seattle, and Twin Rivers Formations. It is now obvious that the formations recognized by Arnold and Hannibal were based on faunal similarities rather than lithologic character.

In 1916, Weaver published four papers that included discussions of the typical Blakeley Formation and its contained molluscan fauna. In this work he followed the philosophy of Arnold and Hannibal and other early workers in formational recognition based on the composition of its contained molluscan fauna. He also presented at this time a more accurate stratigraphic measurement and lithologic description of the strata exposed in the typical sections of the Blakeley and Blakely Harbor Formations. The strata exposed along the shore of Riche Passage and Sinclair Inlet were included in the measured section. The entire stratigraphic sequence was divided into seven lithologic belts (A to G) which were recognized as uppermost Oligocene in age.

Subsequently, Van Winkle (1918) described two new molluscan species collected from beds exposed near Restoration Point and followed Weaver in assigning these beds to the upper Oligocene. In the same year Clark (1918) correlated the typical Blakeley Formation with a portion of the

San Lorenzo Formation of the Mt. Diablo area of central California. Clark and Arnold (1923) correlated the Sooke Formation of Vancouver Island with the Blakeley "horizon" referring it to the upper Oligocene or lower Miocene. Several new molluscan species were collected and described by Clark (1925) from Blakeley strata exposed on Bainbridge Island. In the same year, Hertlein and Crickmay (1925) continued to regard the typical Blakeley Formation as upper Oligocene in age. Tegland (1933) described in more detail the known molluscan fauna of the type of Blakeley Formation and presented a comparison of this association with other molluscan assemblages reported from the Astoria, Lincoln, San Lorenzo, and Sooke Formations. She also employed Weaver's 1916 stratigraphic terminology.

Weaver (1938) summarized several years of geologic study in his monograph on the Tertiary Stratigraphy of Western Washington and Northwestern Oregon. In this important work, the lithologic character of the various Tertiary formations was emphasized. The typical Blakeley originally recognized in 1912 was redefined more accurately in terms of lithology. The age assignment of the contained molluscan assemblage remained unchanged and the names "Blakeley Horizon" and "Blakeley Beds" of the earlier papers were discarded.

Seven new megafaunal zones of the Oligocene of Northwestern Washington were proposed by Durham (1944). Both members of the Blakeley Formation, here recognized, were included in the *Echinophoria rex* Zone. Durham thus followed Weaver in assigning the typical Blakeley Formation to a single zone.

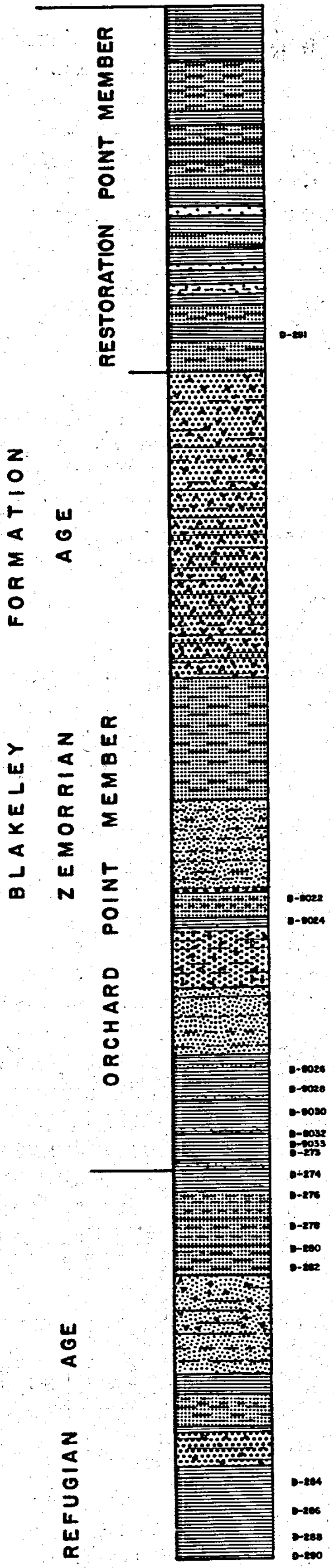
STRATIGRAPHY OF THE BLAKELEY FORMATION

The type section of the Blakeley Formation as defined by Weaver in 1912, 1916. and 1937, is exposed in three discontinuous beach sections (Sinclair Inlet, Orchard Point, and Restoration Point). Each profile contains all or a portion of the two lithologic members characterizing this formation. The base of the Blakeley is exposed south of Waterman Point near the village of Waterman on Sinclair Inlet. Elsewhere the lowest beds exposed (Bean Point and Orchard Point) represent deposition at higher stratigraphic positions than the base of the formation exposed near the village of Waterman. The exact stratigraphic position of the lowermost beds exposed at Bean and Orchard Points has not been accurately determined; however, while the basal Orchard Point beds are older, geometric projections of the strike of these beds suggest that not more than a few hundred feet of basal strata are unexposed at Bean Point.

The uppermost strata included in the Sinclair Inlet section are separated by a fault from the uppermost strata measured in the Orchard Point section. The stratigraphic throw along this fault has not been accurately determined but rough measurements again suggest that this parameter probably does not exceed a few hundred feet.

The upper portion of the Blakeley Formation is not exposed in the beach section from Orchard Point northwest to Middle Point. This portion of the formation is, however, well exposed in the Restoration Point section on Bainbridge Island. The lower Blakeley is exposed in the vicinity of

SINCLAIR INLET SECTION



Hard, massive, dark gray, dense, well indurated shale

Thinly bedded, tuffaceous sandy shale interbedded with fine-grained basaltic sandstone

Hard, dark-gray, brittle, well compacted shale

Thinly-bedded, tuffaceous, sandy shale interbedded with fine-grained basaltic sandstone

Interbedded reddish brown fine to medium grain tuff-sandstone and dark gray hard fissil shale

SCALE
100 Feet

WATERMAN POINT CONGLOMERATE

Massive to thin bedded pebble to cobble conglomerate composed of rounded to subrounded clasts of basalt, basaltic andesite and andesite, interbedded with coarse-grained tuffaceous, basaltic sandstone, fine-grain sandstone, and tuffaceous siltstone relatively thin bedded and locally very fossiliferous near the base

Fine to medium grain, thinly bedded, tuffaceous, argillaceous, poorly sorted basaltic sandstone and tuffaceous siltstone

Thin bedded, medium to coarse-grained, basaltic sandstone weathering to a dark brown color

Basaltic pebble and cobble conglomerate

Interbedded fine grained, tuffaceous sandstone, dark gray siltstone and clay shale

Interbedded coarse to medium-grain basaltic sandstone and basaltic and andesitic pebble to cobble conglomerate

Massive, fine to medium grain brown basaltic sandstone with lighter colored badly weathered felsitic fragments

Minor thin beds of darker gray tuffaceous siltstone

Gray-brown, thinly bedded sandy tuffaceous shale interbedded with minor thin beds of siltstone and fine-grained argillaceous brown sandstone

Interbedded gray-brown tuffaceous siltstone and darker brown sandstone with lighter colored felsitic tuffaceous fragments, massive to thick bedded tuffaceous sandstone and minor siltstone

Tuffaceous sandy siltstone and minor thin beds of fine-grain sandstone

Pebble and cobble conglomerate composed of basaltic, andesitic and brown sandstone clasts with coarse sand matrix, interbedded thin layers of gray-brown siltstone

Massive, fine to medium grain tuffaceous sandstone locally gritty, interbedded with micaceous dark gray siltstone

Hard dense dark gray fissile shale with silica cement

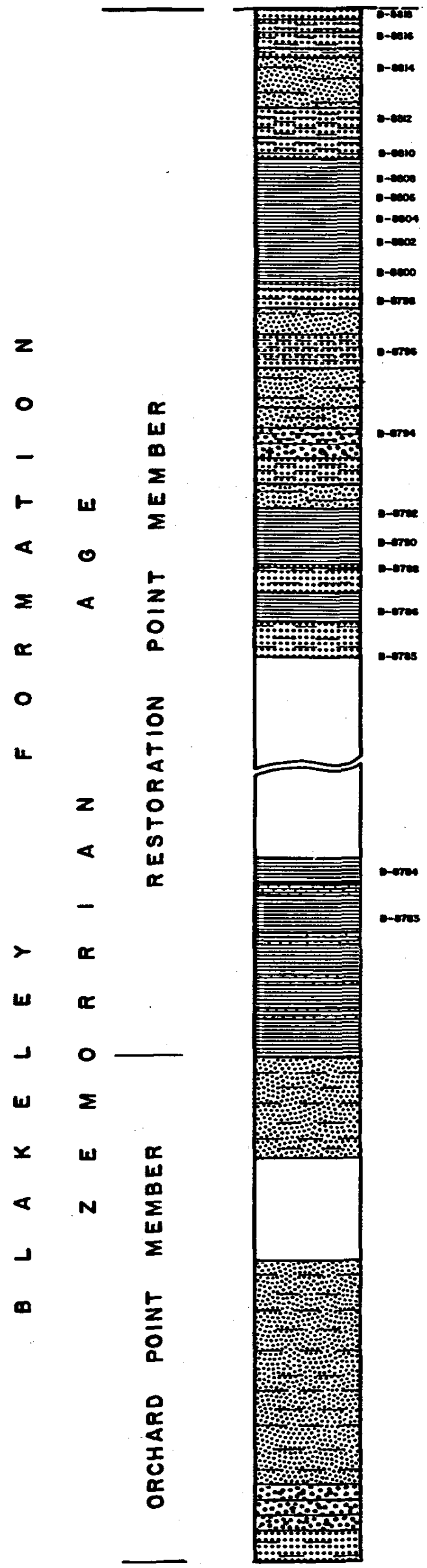
Massive dark brown tuffaceous sandstone interbedded with thin layers of dark gray micaceous siltstone and shale

Massive poorly sorted pebble conglomerate composed of sub-rounded fragments of basalt and brown tuffaceous sandstone

Dark gray-brown sandy siltstone and more massive dark gray micaceous shale

ORCHARD POINT - MIDDLE POINT SECTION

SCALE
100 Feet



FAULT

Dark gray-brown fine grain tuffaceous sandstone and shale

Massive fine to medium grain tuffaceous basaltic sandstone with thin siltstone and mudstone interbeds

Dark gray-brown fine grain tuffaceous sandstone interbedded with equal amount of siltstone and shale

Dark gray hard micaceous tuffaceous thinly bedded shale siltstone and very fine grain sandstone

Fine grain tuffaceous sandstone and siltstone

Massive brown poorly sorted coarse grain pebbly basaltic sandstone

MIDDLE POINT
Well bedded dark brown sandstone siltstone and shale

Massive poorly sorted fine to medium grain basaltic sandstone interbedded with minor amount of tuffaceous siltstone

Massive coarse grain basaltic sandstone with local lenes of pebble conglomerate
Alternating beds of fine sandstone and tuffaceous siltstone

Brown basaltic massive coarse grain poorly sorted locally gritty sandstone
Dark gray-brown tuffaceous siltstone and thinner bedded harder micaceous tuffaceous shale

Massive fine grain tuffaceous siltstone and sandstone interbedded with micaceous and tuffaceous shale

CLAM BAY

Unexposed interval representing approximately 1850 feet of section

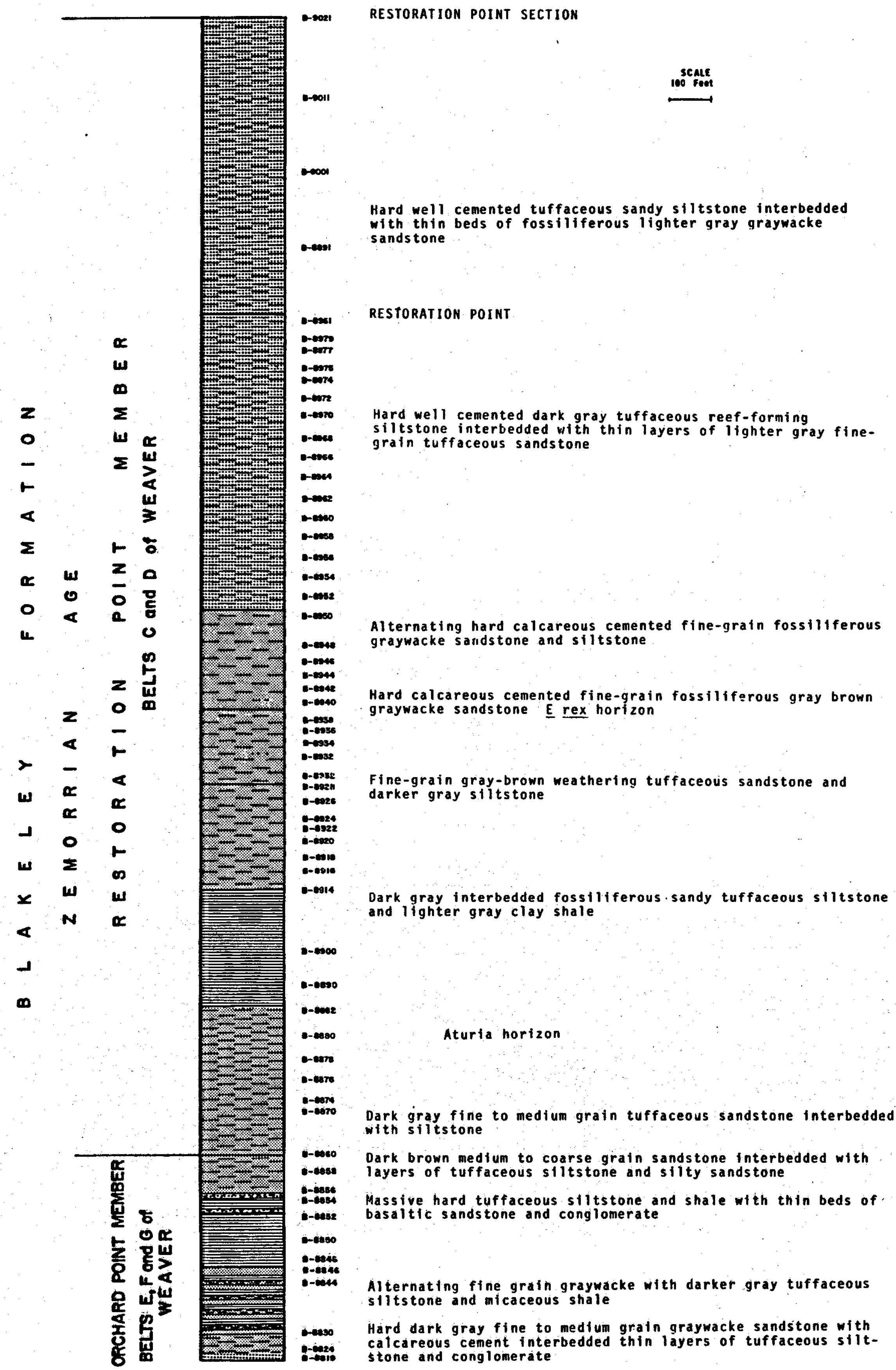
Dark gray-brown thinly bedded tuffaceous micaceous siltstone and shale interbedded with well cemented fine grain brown sandstone varying in thickness from 1 to 3 feet

Massive brown coarse-grain poorly sorted basaltic sandstone with thin beds and lenes of basaltic pebble conglomerate

Covered

Massive poorly sorted coarse-grain basaltic sandstone with lighter colored felsitic fragments and well rounded pebbles of basalt in thin beds, two or three pebbles thick

Massive poorly sorted basaltic pebble conglomerate interbedded with coarse sandstone, cobble and boulder conglomerate and a few thin beds of sandstone and siltstone


RESTORATION POINT SECTION
SCALE
100 Feet
BLAKELEY FORMATION
ZEMORRIAN AGE
RESTORATION POINT MEMBER
BELTS C and D of WEAVER
ORCHARD POINT MEMBER
BELTS E, F and G of WEAVER
Hard well cemented tuffaceous sandy siltstone interbedded with thin beds of fossiliferous lighter gray graywacke sandstone
RESTORATION POINT
Hard well cemented dark gray tuffaceous reef-forming siltstone interbedded with thin layers of lighter gray fine-grain tuffaceous sandstone
Alternating hard calcareous cemented fine-grain fossiliferous graywacke sandstone and siltstone
Hard calcareous cemented fine-grain fossiliferous gray brown graywacke sandstone E rex horizon
Fine-grain gray-brown weathering tuffaceous sandstone and darker gray siltstone
Dark gray interbedded fossiliferous sandy tuffaceous siltstone and lighter gray clay shale
Aturia horizon
Dark gray fine to medium grain tuffaceous sandstone interbedded with siltstone
Dark brown medium to coarse grain sandstone interbedded with layers of tuffaceous siltstone and silty sandstone
Massive hard tuffaceous siltstone and shale with thin beds of basaltic sandstone and conglomerate
Alternating fine grain graywacke with darker gray tuffaceous siltstone and micaceous shale
Hard dark gray fine to medium grain graywacke sandstone with calcareous cement interbedded thin layers of tuffaceous siltstone and conglomerate

Bean Point but the actual base of the formation is covered by the waters of Puget Sound.

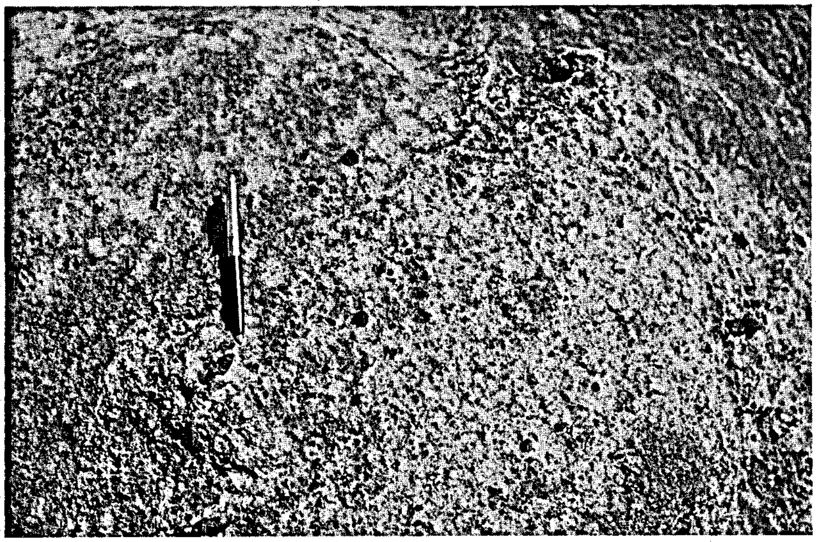
THE ORCHARD POINT MEMBER

The Orchard Point Member represents the lower and coarser clastic portion of the Blakeley depositional cycle. The upper portion of this member is finer grained than the lower and appears to grade generally upward into the overlying Restoration Point Member. The lower beds of typical Orchard Point Member lithology exposed southwest of Waterman Point conformably overlie a dark gray, thinly bedded, poorly exposed, tuffaceous, fossiliferous, clay shale. This fine clastic interval is approximately 200 feet thick and may represent the uppermost portion of an older unnamed formation. The interval is poorly exposed and has been included in the basal Blakeley Member because of its gross lithologic similarity to the finer grained units of this member and because of its limited geographic extent. This interval was also included in the typical Blakeley formation by Weaver, although he recognized the possibility that it might represent a portion of the Lincoln "Formation." These beds do not contain diagnostic molluscs, but a typical offshore Refugian foraminiferal faunule is present.

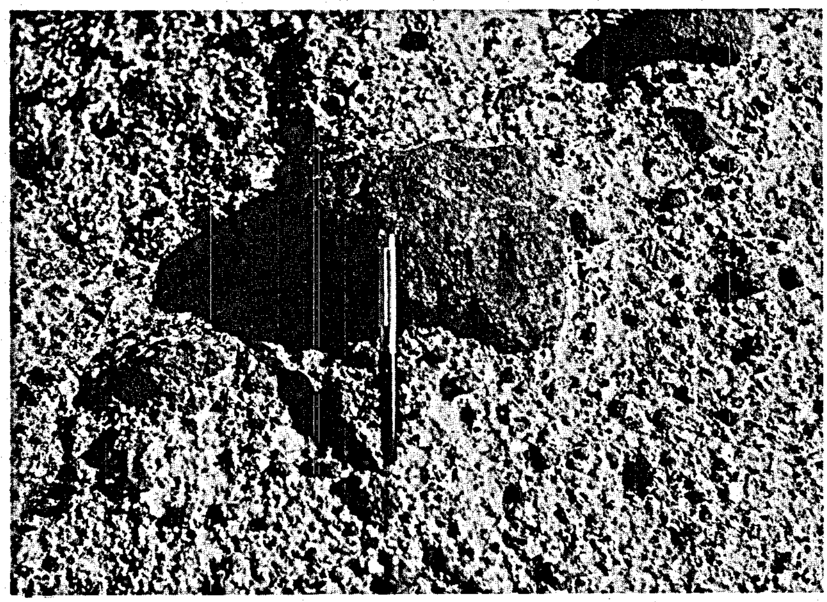
The maximum thickness of the Orchard Point Member was measured in the Sinclair Inlet section where approximately 2600 feet of strata are exposed. This figure includes the Refugian shale exposed at the base. Elsewhere, approximately 1000 feet of strata assigned to this member are exposed at the Orchard Point/Middle Point section and about 800 feet of similar strata are well exposed in the lower part of the Restoration Point section on Bainbridge Island. The reduced thickness measured in these sections is probably due to concealment by younger glacial deposits and water cover. The lithologic description and fossil collection stations and the individual lithic units of the Orchard Point Member are shown on the accompanying columnar sections. Figures 1 (a-c) display the general outcrop characteristics of this member.

LITHOLOGIC CHARACTER

The Orchard Point Member is characterized by coarse clastic sediments interbedded with lesser amounts of fine to medium-grained sandstone, siltstone, and tuffaceous clay shale. The coarser clastic elements of this member are thick to massive, poorly sorted conglomerates composed of pebbles, cobbles, and sometimes boulders of well-rounded to angular fragments of Crescent basalt associated with varying amounts of light colored felsite matrix, greenish gray, fine-grained andesite and rare fragments of white vein quartz. The basaltic pebbles and cobbles are generally quite uniform in their mineral composition, however, they display considerable varation in texture, grain size, and degree of alteration.



1 a



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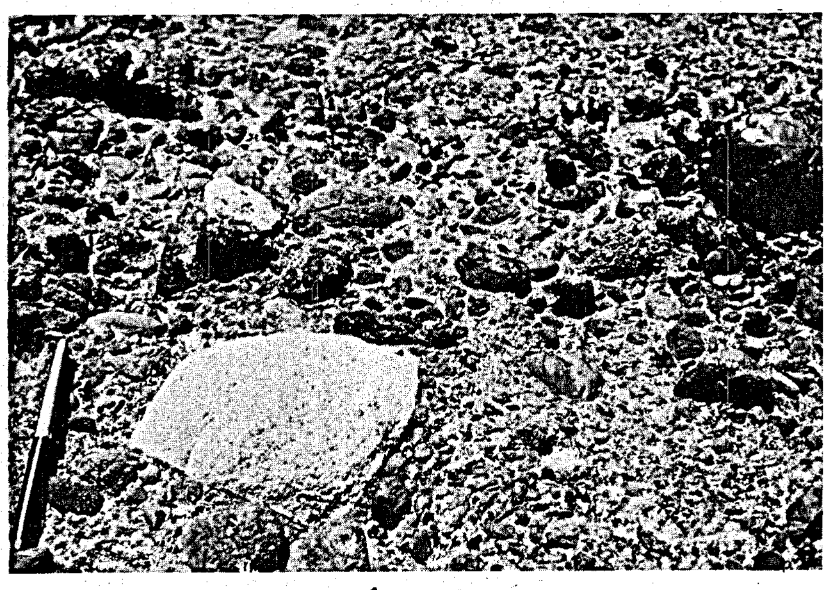


1 c

Exposures of the Orchard Point Member

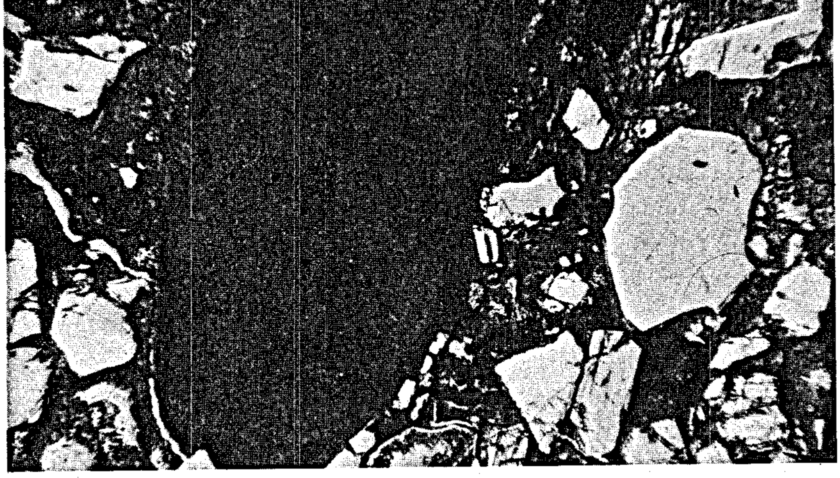
a-c Basaltic debris dark color, felsitic tuff light color

The light colored felsitic tuff matrix that characterized the conglomerate and some of the finer clastic beds is composed of glass and devitrified glass shards, both frequently much altered to kaolin and sometimes replaced by carbonate and zeolite cement. Under the microscope this matrix is dark, fine-grained, usually much altered material of low birefringence. Some of the thinner bedded, pebbly intervals contain only minor amounts of tuffaceous material; other beds contain approximately equal amounts of basaltic debris and tuffaceous matrix; and in other, more poorly sorted beds, the basaltic pebbles are isolated and appear to "float" in a predominantly altered tuffaceous host. Authigenic zeolite and carbonate material are very common mineral cements throughout the exposed Blakeley Formation. They form interstitial cements that commonly replace glass in tuffaceous lithic fragments, pumice, and individual shards. McLean (1968) has determined by x-ray and selective staining the composition of the zeolitic cement. He concludes the zeolite present in the Blakeley Formation is Clinoptilolite and not Heulandite as previously considered by the writer. Coombs (1954) and Deffeys (1959) consider the formation of Clinoptilolite to result from the diagenetic alteration of volcanic glass. Heulandite is very similar in both chemistry and geologic occurrence but appears to be more locally related to the alteration of basaltic glass of the Crescent Formation. Heulandite is well developed in the vugs and voids in the Crescent basalt exposed in a large quarry of Basalt Point, Mats Bay. This locality is approximately 30 miles northwest of the type Blakeley area, on the Olympic Peninsula, at the north end of the Hood Canal. Photomicrographs displaying the microscopic characteristics of the altered felsitic matrix are shown on Figure 2 a-c.

Overlying the basal conglomeritic strata, in all three of the principal sections are alternating thick beds of poorly sorted, tuffaceous, coarse-grained, brown, basaltic sandstone and finer, less massive, tuffaceous sandstone, thinly bedded siltstone, and clay shale. The strata of the latter character appears to grade upward into beds that are generally finer grained and less massive than those of the Orchard Point Member, but similar in mineralogic composition. These beds have been assigned to the Restoration Point Member.

The top of the Orchard Point Member and the base of the Restoration Point Member were selected arbitrarily as the top of the uppermost exposed bed of coarse, tuffaceous, brown sandstone containing scattered subround pebbles and grits of basalt. Beds similar in lithologic character were found in all three of the typical profiles. This lithologic defination of the members' boundary is not intended to be absolute or have more than local stratigraphic significance. There are a few similar coarse, pebbly conglomerate beds exposed at higher stratigraphic positions. These beds belong to the Restoration Point Member and are underlain and overlain by thick intervals of less massive, fine-grained, clastic sediments more typical of the Restoration Point Member. These occurrences of coarse clastic sediments may possibly represent local events of higher energy turbity transport to deeper offshore environments.

The sandstone and siltstone beds characterizing the upper portion of the Orchard Point Member are similar in mineralogical composition to the coarser and more massive strata just described. The main difference



2 a

2 b

2 c

FIGURE 2

2a Angular plagioclase fragments, basalt pebble with zeolite and calcite cement. Plane light 25x

2b Angular plagioclase fragments—cemented zeolite [clinoptilolite] x-nicols 25x

2c Finer grained plagioclase fragments with small rounded grains of basalt cemented with zeolite [clinoptilolite] and calcite. Plane light 25x is one of grain size and increasing percentages of clay minerals and mineral cements. The cementing agents of the finer clastic beds consist of altered tuffaceous and argillaceous material, iron oxide, calcium carbonate, and zeolitic cement.

The "heavy" mineral assemblages characterizing the sandstone beds of this member are composed of mineral species common to the Crescent Basalt, associated with very minor amounts of garnet and zircon possibly derived from older sedimentary rocks of Eocene age. The basaltic suite of "heavy" minerals includes olivine, green pyroxene, basaltic hornblende, magnetite, ilmenite and its alteration mineral, leucoxene.

THE RESTORATION POINT MEMBER

The Restoration Point Member represents the upper and fine-grained portion of the Blakeley depositional cycle. The strata of this member are well-bedded, less massive than the lower Orchard Point Member and are composed of fine to medium-grained, tuffaceous, brown sandstone, and thin-bedded siltstone and shale. The tuffaceous siltstone and clay shale are dark gray in color and usually very fossiliferous. The dark colored shale is locally hard, brittle, sometimes fissile and frequently contains both siliceous and calcareous cement.

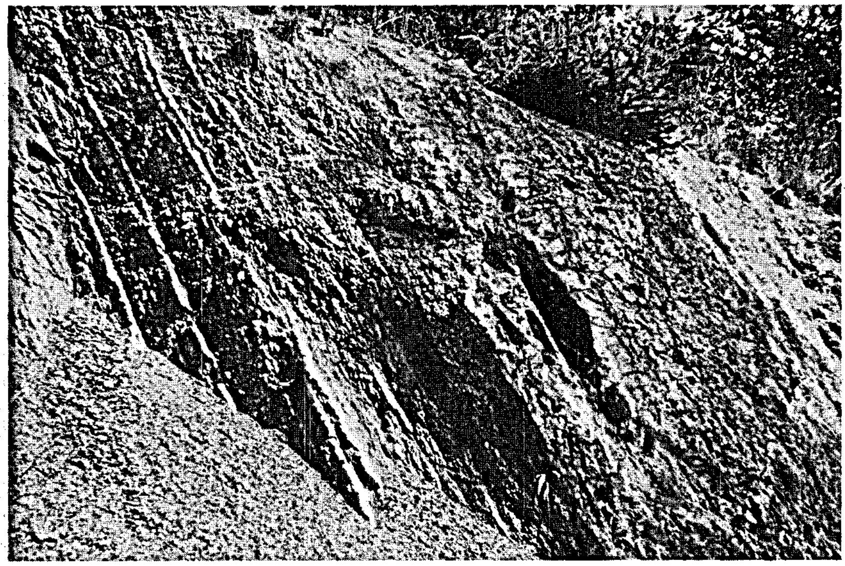
A well exposed section is found along the beaches on the south end of Bainbridge Island where both the base and the top of this member are present. Here approximately 4600 feet of finer clastic, very fossiliferous strata have been measured. This member is also represented in part by approximately 3550 feet of strata outcropping in the vicinity of Middle Point on the mainland, and by approximately 1800 feet of similar appearing beds exposed along Sinclair Inlet. The general outcrop characteristics of the sandstone and interbedded tuffaceous siltstone and shale units of this member are shown on Figure 3 (a-b).

The petrographic character of the sandstone beds of the Restoration Point Member are nearly identical with the sandstone and conglomerate beds of the subjacent member. Both members appear to have been derived from essentially the same source areas; each contain the same basaltic "heavy" mineral suite and display similar microscopic characteristics.

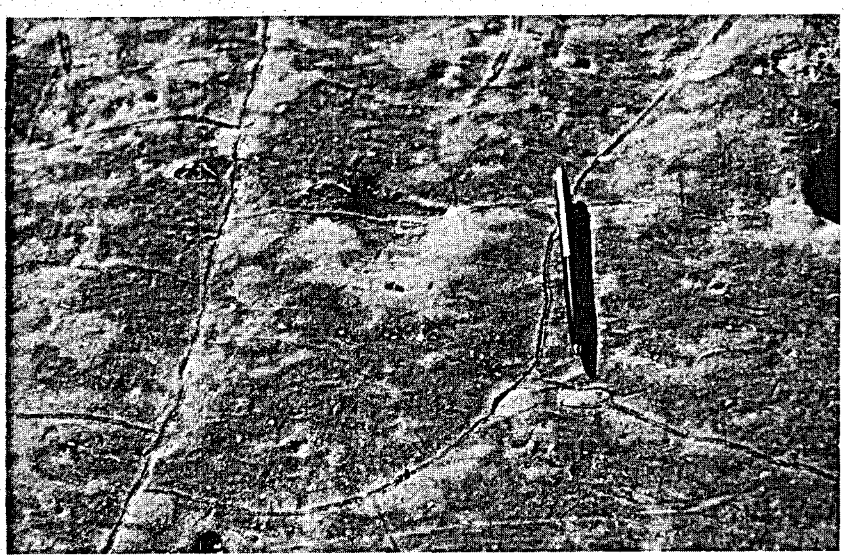
The main difference between the two recognized members of the Blakeley Formation is one of gross grain size. The fine-grained upper or Restoration Point Member represents deposition at lower energy levels than the coarser subjacent Orchard Point Member. The petrographic character of the sandstone beds assigned to the Restoration Point Member are shown on the photomicrographs, Figure 4.

THE BLAKELY HARBOR FORMATION

The name Blakely Harbor Formation is here proposed for nonmarine, massive, basaltic, conglomeratic strata formerly included in the uppermost Blakeley Formation of Weaver (Belts A and B, 1916, and Members A and B, 1937). The strata assigned to this formation are well exposed along the shores of Blakely Harbor and northward along the east beach of Bainbridge Island, toward the village of Winslow. Nearly identical

3a


3b


3c


3a Thinly bedded sandstone, siltstone and claystone

3b Fine-grained sandstone exposed at Restoration Point

3c Fossiliferous Restoration Point siltstone

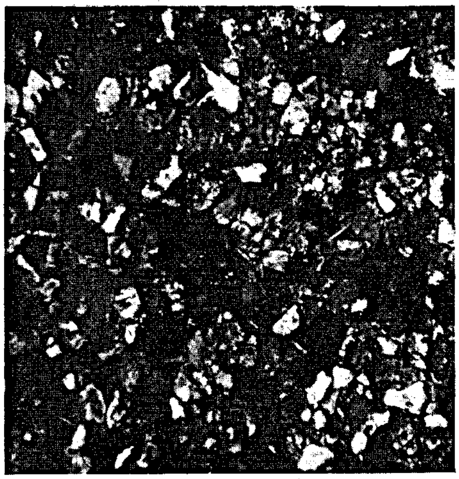


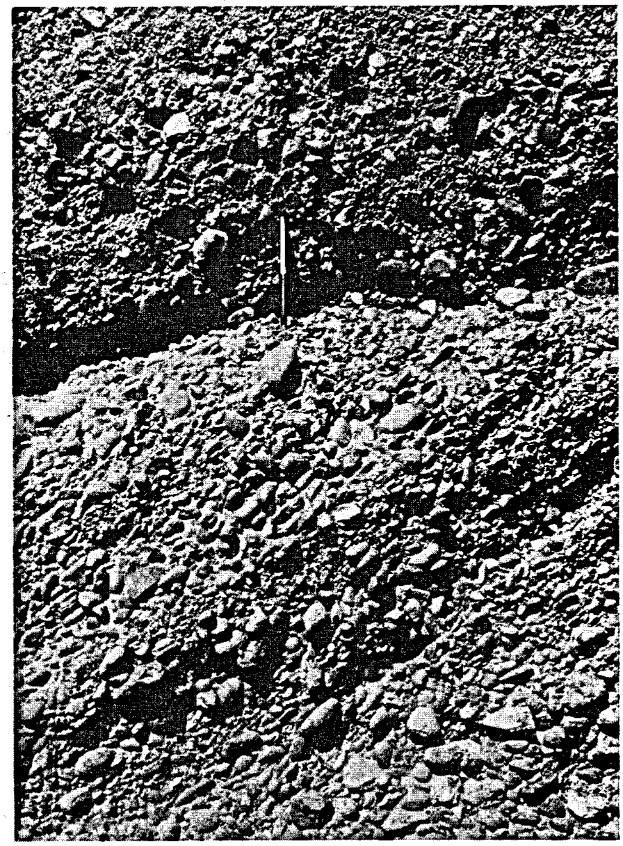
FIGURE 4

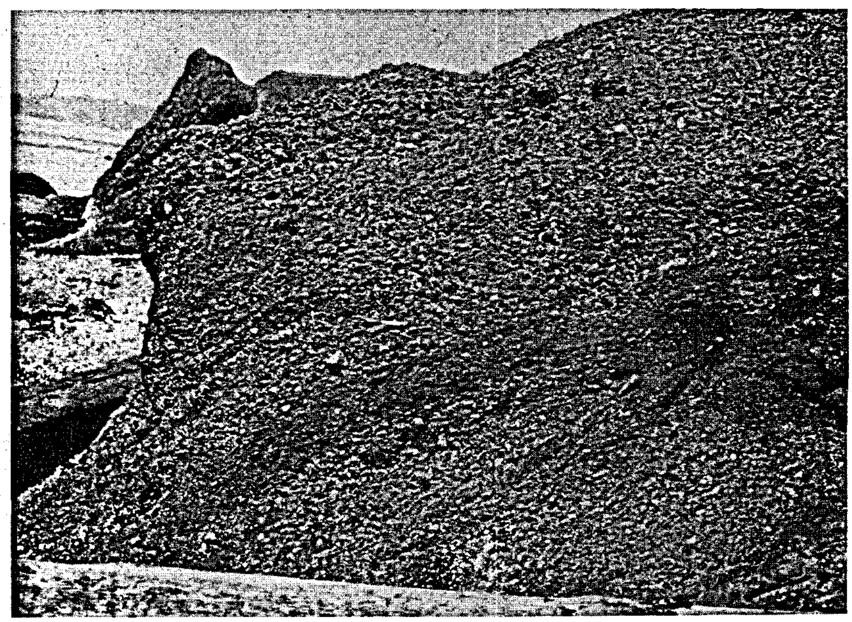
Photomicrography of fine-grained sandstone exposed at Restoration Point.

Quartz and plagioclase grains with associated clay and calcareous cement.

x-nicols, 25x

5 a



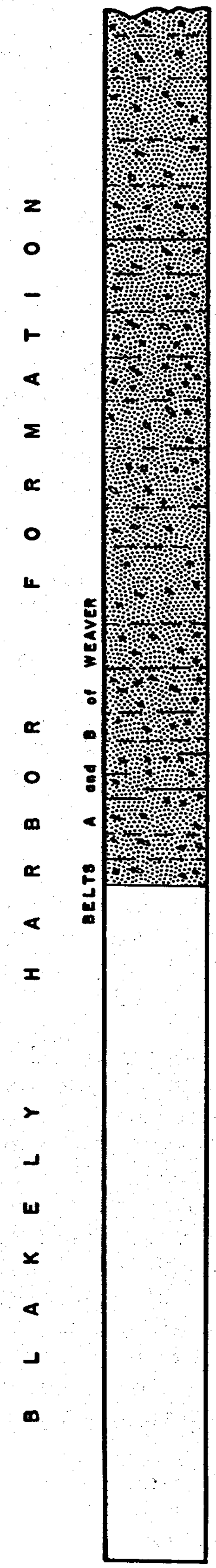


5 b

FIGURE 5

Exposures of the Blakeley Harbor Formation.

BLAKELY HARBOR SECTION, BAINBRIDGE ISLAND



Top of the Exposed Section

SCALE
100 Feet

Massive to moderate bedded, dark reddish-brown cobble to boulder conglomerate well cemented matrix of coarse-grained, poorly sorted sandstone. The sandstone and conglomerate are composed of subangular to well rounded clasts of basalt, andesite, hard well-cemented basaltic sandstone, dark gray siltstone and a few quartzose and metamorphic rock fragments. Thin layers of lighter gray-brown clay mudstone, carbonaceous siltstone and coal are interbedded.

Carbonized tree

Unexposed interval covered by Blakely Harbor

Thin coal beds interbedded with gray carbonaceous siltstone, claystone and mudstone exposed at the base of the section.

strata are also exposed to the east, and offshore, at Blakely Rocks. All of these exposures are typical and are hereby designated as belonging to the type section of this formation. The general outcrop character of the Blakely Harbor Formation is shown on Figure 5.

The base of this lithic unit was selected at the lowest strata containing thin coal layers interbedded with dark gray carbonaceous siltstone. These beds appear to be conformable with the underlying fine-grained, fossiliferous sandstone and siltstone comprising the uppermost beds of the subjacent Blakeley Formation. The overlying strata are similar in color, grain size, and lithology but are poorly exposed and deeply weathered and much of the lower 1400 feet of this formation is covered by the mud flats of Blakely Harbor. The few poor exposures available suggest that this interval is composed of soft, easily weathered dark gray, carbonaceous claystone and brown siltstone with interbedded layers of lignitic coal. Carbonized vegetative material are common throughout this interval but fossil foraminifera and molluscs were not found in any of the samples collected from this formation.

Overlying this poorly exposed interval is a much better exposed section of massive, brown, well-rounded, basaltic conglomerate. The lowermost stratigraphic occurrence of this conglomerate is an isolated exposure located on the south shore near the western end of Blakely Harbor. Here the conglomerate is composed of massive, firmly cemented pebbles of basalt in a matrix of poorly sorted basaltic sandstone, argillaceous and zeolite cement. The general attitude of this resistant bed appears to be nearly identical with both the basal beds of this formation and the underlying marine strata of the restricted Blakeley Formation.

Massive beds of basaltic conglomerate, similar in lithologic character, are well exposed along the north shore of Blakely Harbor near the old pier at Port Blakely. Here the conglomerate beds strike due east toward Blakely Rocks offshore. Similar conglomerate is well exposed, to the north, along the east shore of Bainbridge Island for approximately a mile; here the massive basaltic conglomerate is unconformably overlain by glacial tillite. The total thickness of the exposed portion of the Blakely Harbor Formation is approximately 3400 feet including the poorly exposed basal interval. The conglomerate characterizing the upper and better exposed portion of this formation are composed of massive, bedded, dark reddish-brown, poorly sorted, well-rounded, pebbles, cobbles and boulders of Crescent Basalt. These clasts are cemented with poorly sorted basaltic sandstone, iron oxide, and calcite. Associated with the basalt clasts are subangular, well-rounded pebbles and cobbles of greenish-gray andesite, hard, well cemented basaltic sandstone, siltstone, hard, dense well-rounded metamorphis clasts containing prehnite and a few dark colored chert fragments. A pebble count of the conglomerate exposed at the north entrance of Blakely Harbor contained the following rock types:

Crescent basalt	85 percent
Dense metamorphic rocks	7 percent
Andesite	3 percent
Basaltic sandstone	2 percent
Hornblende dacite	1 percent

Massive white vein quartz	1 percent
Dark green dense chert	1 percent

The massive and thick bedded conglomerates described above, are interbedded with thin layers of lighter gray-brown sandstone, carbonaceous clay mudstone and siltstone. Locally, thin layers of coal and carbonized wood are also interbedded with the conglomerate. The Blakely Harbor conglomerates differ from the older conglomerate beds of the Orchard Point Member of the typical Blakeley Formation in that the light colored felsitic tuff matrix, characteristic of the latter, is not present in the younger conglomerate strata. Also lacking are the rich molluscan, coral, and foraminiferal fossil associations.

The age of the Blakely Harbor Formation can only be stated in terms relative to the underlying fossiliferous Blakeley Formation. It is clear that the Blakely Harbor Formation is younger than Zemorrian Age and that these strata may represent the lower portion of a younger depositional cycle. This cycle of deposition began after a renewed uplift of the nearby Crescent and older terrain, and the weathered detritus was deposited in local areas that appear to have been above sea level. This uplift, subsequent erosion, and deposition may have been confined to the eastern portion of the present Olympic Mountains. If so, eastward flowing streams transported the eroded debris to the Blakeley basin during an interval of time characterized by a relative reduction of volcanic activity in the Cascade area further to the east.

The presence of coarse clastic strata characterizing much of the Clallam Formation of the northwest Olympic Peninsula suggests, however, the possibility that this uplift was more widespread geographically and perhaps a precursor to the late Miocene orogenic events that compressionally folded both the Blakeley and Blakely Harbor Formations. It is quite possible that the Blakely Harbor Formation may correlate in part with the Astoria and Nye Formations of Oregon or the Clallam Formation of the northwest Olympic Peninsula. However, a more accurate age assignment will require detailed study of the fossil pollen assemblages present in the finer grained intervals of the formation.

PALEONTOLOGY OF THE BLAKELEY FORMATION

The megafaunal elements (mollusc, coral, echinoderm, brachypod, pteropod, scaphopod, crinoid, and annelid) of the Blakeley Formation have been studied and described in detail in the previously cited work of several writers. This portion of the fauna has not been restudied and will not be discussed except when various elements of this group can supply information regarding a new environmental interpretation.

The typical Blakeley Formation contains, in addtion to the already described megafauna, a foraminiferal continuum from Refugian at the base, through Zemorrian above. The composition of the foraminiferal faunule of Refugian Age is similar in conposition to other faunal sequences of this age described from various localities in California (Wilson 1954, H. P. Smith 1956, R. K. Smith 1971; Sullivan 1962; Kleinpell and Weaver 1963; and Tipton, Kleinpell, and Weaver 1973).

The basal beds of the typical Blakeley Formation exposed along the shore of Sinclair Inlet, contain a *Uvigerina cocoaensis/Uvigerina atwilli* offshore assemblage. These characteristic species are here associated with *Cibicides elmaensis, Epistomina eocenica, Cyclammina pacifica, Nodosaria frizzelli, Cassidulina galvinensis, Gyroidina orbicularis planata,* and *Anomalina californiensis.* The latter two species become more dominant in and characterize the microfaunal assemblage of the overlying strata. The assemblage referred to above constitutes the *Cibicides/Uvigerina* faunule and clearly represents the *Uvigerina cocoaensis* Zone of Cushman and Simonson (1944) and the typical offshore lower Refugian of the Santa Barbara embayment. The stratigraphic occurrence and frequency of these and other foraminiferal species are shown on the accompanying check list. The absence of a near shore, upper Refugian foraminiferal or molluscan assemblage, similar in character to the shallow water faunule of the Lincoln Formation is interesting. A similar condition has been reported (Sullivan 1962) in the middle San Lorenzo Formation, Santa Cruz Mountains, California.

The overlying, conformable, coarse clastic sediments of the Orchard Point Member and the superadjacent beds of the Restoration Point Member are characterized by the dominance of four species. These are *Anomalina californiensis, Gyroidina orbicularis planata, Cibicides elmaensis,* and *Cassidulina galvinensis.* Each of these species is well known and have stratigraphic ranges extending into strata both older and younger than the type Blakeley Formation. The frequency of these four characteristic species of the microfaunal assemblage varies somewhat from profile to profile and from member to member. For this reason, and because of important differences in the occurrence of the less common elements of the microfaunal assemblage, three faunules have been recognized and indicated on the check list. These are: the *Anomalina/Gyroidina* faunule, the *Anomalina/Gyroidina/Cibicides* faunule and the *Anomalina/Gyroidina/Cassidulina* faunule.

The Orchard Point strata exposed along the shore of Sinclair Inlet and in the vicinity of Orchard Point are characterized by the *Anomalina/Gyroidina* faunule. This assemblage is composed of common to abundant *Anomalina californiensis* and *Gyroidina orbicularis planata* associated with less common *Uvigerina auberiana, Gyroidina condoni* and *Valvulineria willapaensis*. The beds of this lithic member, exposed in the Bainbridge Island profile, are characterized by the *Anomalina/Gyroidina/Cibicides* faunule which is composed of common to abundant *Anomalina californiensis, Gyroidina orbicularis planata,* and *Cibicides elmaensis* and much less common *Uvigerinella obesa impolita, Uvigerina gallowayi, Valvulineria willapaensis,* and *Cassidulina galvinensis.*

The strata assigned to the Restoration Point Member exposed along Sinclair Inlet section are characterized by *Anomalina/Gyroidina* in abundance, in addition to *Uvigerina auberiana, Eponides mansfieldi oregonensis, Cibicides lmaensis, Cassidulina galvienensis* and *Nonion blakeleyensis* n. sp. A similar assemblage characterizes this member in the Bainbridge Island section, however, *Cibicides elmaensis* was found again to be a dominant element and *Bulimina alligata, Nonion blakeleyensis, Dentalina quadrulata, Eponides mansfieldi oregonensis,* and *Bolivina marginata adelaidana* are more conspicuous.

LEGEND

X RARE
O FEW
● COMMON
■ ABUNDANT

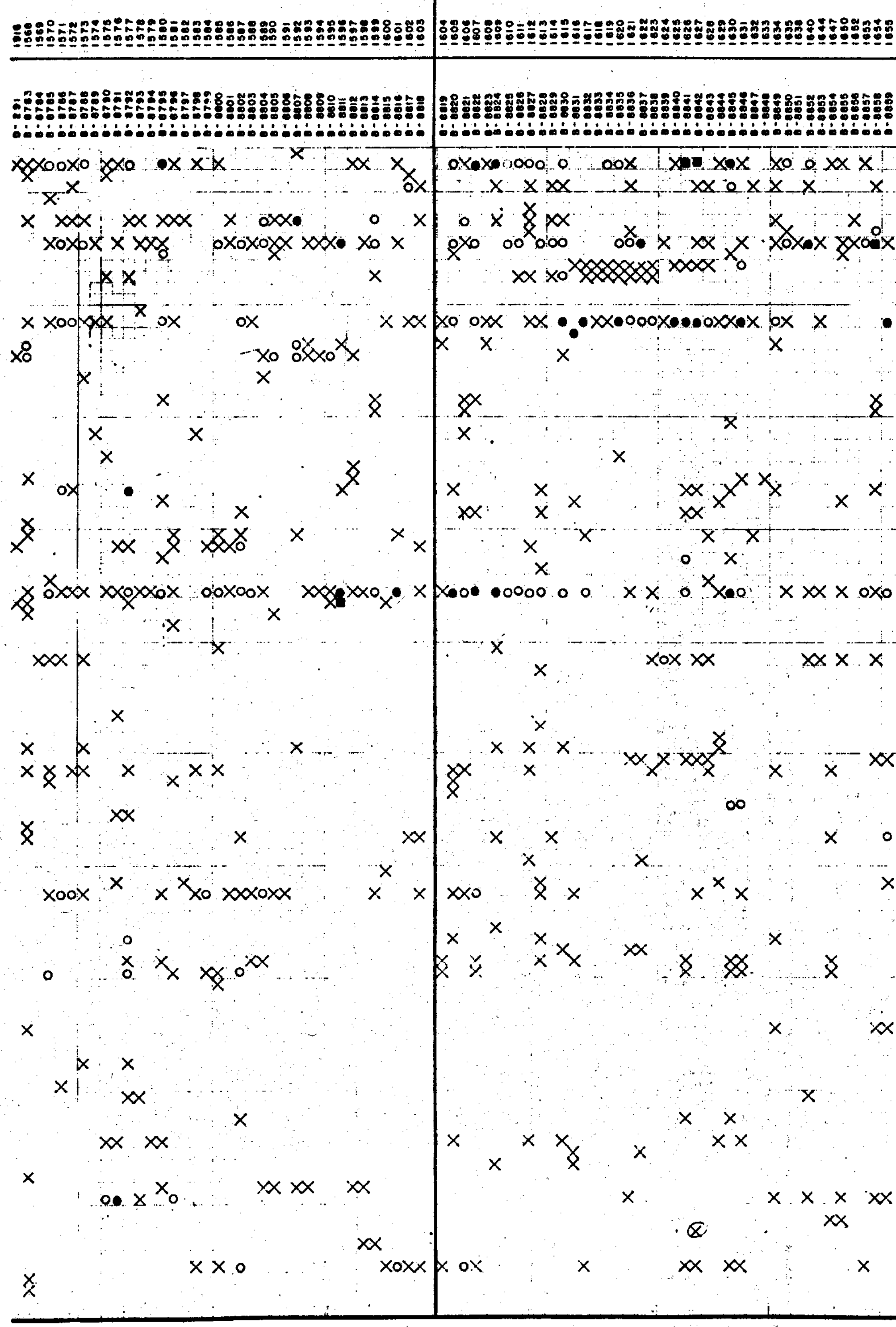
FORMATION	
SECTION	SINCLAIR INLET
MEMBER	ORCHARD POINT
STAGE-AGE	REFUGIAN
FAUNULE	CIBICIDES — UVIGERINA / ANOMALINA — GYRODINA

LOCALITY NUMBERS: UNIVERSITY of WASHINGTON / UNIVERSITY of CALIFORNIA

SPECIES	1929 D-290	1925 D-289	1924 D-288	1923 D-287	1922 D-286	1921 D-285	1920 D-284	1918 D-283	1914 D-282	1913 D-281	1912 D-280	1911 D-279	1910 D-278	1909 D-277	1908 D-276	1906 D-275	1905 D-274	1904 D-273	1902 D-9033	1901 D-9032	1900 D-9031	1899 D-9030	1897 D-9029	1896 D-9028	1895 D-9027	1892 D-9026	1891 D-9025	1884 D-9024	1883 D-9023	1882 D-9022
Allomorphina cf. A. macrostomata Karrer																														
Anomalina californiensis Cushman and Hobson	o							o	o	x	o	x	o	o	o	x	●	x	●	o	o	o		x	■		x		x	x
Bathysiphon eocenica Cushman and G. D. Hanna								x																						
Bolivina marginata var. adelaidana Cushman and Kleinpell																														
Bulimina alligata Cushman and Laiming																														
Bulimina blakeleyensis n. sp.																														
Bulimina ovata d' Orbigny					x	o	x		x			x	x	x	x		x	x	x	x		x			x					
Buliminella bassendorfensis Cushman and Parker									x																					
Cassidulina galvinensis Rau									x	●					●		o	o		o	x	x							x	x
Cassidulina modeloensis Rankin								x																						
Cassidulina cf. C. punctata Reuss																													x	
Cassidulina subglobosa H B Brady									x					x																
Cassidulinoides sp.																														
Ceratobulimina washburnei Cushman and Schenck			x								o		x																	
Chilostomella oolina Schwager																														
Cibicides elmaensis Rau					x				x	●	●	x	o	x	o			x	o		o	o			o	x	x			
Cornuspira byramensis Cushman			x																											
Cyclammina cancellata var. obesa Cushman and Laiming																														
Cyclammina incisa (Stache)																		x												
Cyclammina pacifica Beck	x		●	x	o			x		x	o	x			x			x												
Dentalina cf. D. consobrina d'Orbigny																														
Dentalina nasuta Cushman																														
Dentalina cf. D. pioneerensis Kleinpell																														
Dentalina cf. D. quadrulata Cushman and Laiming																														
Elphidium minutum (Reuss)																														
Entosolenia sp						x																								
Epistomina eocenica Cushman and M. A. Hanna		x		x	x	o	x		x	o		x	o				x													
Epistomina ramonensis Cushman and Kleinpell																														
Eponides gaviotae Wilson																														
Eponides healdi R. E. and K. C. Stewart																	x													
Eponides mansfieldi var. oregonensis Cushman, R. E. and K. C. Stewart																														
Eponides umbonatus (Reuss)			o	o		o	x	x	x	x		x	x	x			x						x							
Gaudryina triangularis Cushman																														
Gaudryina ?/ sp.								x																						
Globigerina bulloides d'Orbigny			o					x					x						x			o				x				
Globigerina conglomerata Schwager																										x				
Guttulina frankei Cushman and Ozawa											x				x				x	x		x				x				
Guttulina irregularis (d'Orbigny)										x																				
Gyrodina condoni (Cushman and Schenck)										x							x	x	x			■	x							
Gyrodina orbicularis planata Cushman	o		o			x	x		x	x	o	x	o	x	x		●	●	●	o	■				o	x	x		x	
Haplophragmoides trullissata (H. B. Brady)																														
Haplophragmoides sp.																														
Lagena aculicosta Reuss																														
Lagena cf. L. laevis (Montagu)																														
Lagena strumosa Reuss																				x										
Lagena cf. L. substriata Williamson											x											x						x		
Lenticulina convergens (Bornemann)																														
Lenticulina cf. L. crassa (d'Orbigny)																														
Marginulina subbullata Hantken																														
Marginulina sp.																														
Nodogenerina sanctaecrucis Kleinpell				x																										
Nodosaria grandis Reuss															x					x										
Nodosaria hamilii Kleinpell																														
Nodosaria longiscata d' Orbigny		x	x	o	x	o	x		x	x				x	x															
Nonion cf. N. affinis (Reuss)																														
Nonion blakeleyensis n. sp.																														
Nonion incisum (Cushman)																														
Nonion incisum var. kernensis Kleinpell																														
Nonion pacificum Cushman																														
Nonion tuberculatum (d' Orbigny)																														
Plectofrondicularia cf. P. californica Cushman and Stewart															x															
Plectofrondicularia miocenica var. directa Cushman and Laiming																														
Plectofrondicularia packardi var. packardi Cushman and Schenck									x					x			x													
Plectofrondicularia vaughni Cushman																														
Polymorphina sp.																									x					
Pseudoclavulina communis (d'Orbigny)																														
Pseudoglandulina inflata (Bornemann)												x			x		x					x			x					
Pseudoglandulina nallpeensis Rau																						x								
Pseudoparrella parva (Cushman and Laiming)																														
Pseudopolymorphina sp.																														
Pullenia quinquelobata (Reuss)											x																			
Pullenia cf. P. salisburyi R. E and K. C. Stewart						x																								
Quinqueloculina imperalis Hanna and Hanna																														
Quinqueloculina minuta Beck																		x											x	x
Robertina cf. R. declivis (Reuss)																														
Robulus budensis Hantken							x																							
Robulus calcar (Linne)														x							x									
Robulus chehalisensis Rau				x	x				x	x	x			x			x			x	x	x								
Robulus inornatus (d' Orbigny)														x								x								
Robulus cf. R. miocenicus (Chapman)																														
Robulus sp.																														
Robulus wormani Barbat and von Estorff																														
Sarcenaria schencki Cushman and Hobson					x	x																								x
Sigmoidina cf S. pacifica Cushman and Ozawa																														x
Sigmoilina tenuis (Czjzek)																														
Sigmorphina schencki Cushman and Ozawa														x	x			x		x	x	x								
Sigmorphina undulata Rau															x					x										
Silicosigmoilina kleinpelli n sp.																														
Siphonodosaria frizzelli Rau			x	o					x	o		x	o	x	x		x	x		x		x								x
Sphaerodina variabilis Reuss																														
Spiroloculina texana Cushman and Ellisor																														
Textularia ? sp.																														
Trochammina cf. T. parva Cushman and Laiming									x	x	x																			
Uvigerina auberina d' Orbigny																														
Uvigerina cocoaensis Cushman														●		x	■													
Uvigerina gallowayi [illegible]																														
Uvigerinella obesa var. impolita Cushman and Laiming																														
Vaginulinopsis cf. V. saundersi (Hanna and Hanna)																														
Valvulineria araucana (d' Orbigny)																														
Valvulineria willapaensis Rau													x			x		x			x	x					x			
Verneuilina aff. V. compressa Andreae																														
Verneuilina ? sp.																														

TYPE BLAKELEY

ORCHARD POINT – MIDDLE POINT	RESTORATION POINT
RESTORATION POINT	ORCHARD POINT
ZEMORRIAN	
ANOMALINA – GYRODINA	ANOMALINA – GYRODINA – CIBICIDES



FORMATION	B L A K E L E Y
SECTION	
MEMBER	R E S T O R A T I O N
STAGE-AGE	
FAUNULE	A N O M A L I N A — G Y R O D I N A

LEGEND

- X RARE
- O FEW
- ● COMMON
- ■ ABUNDANT

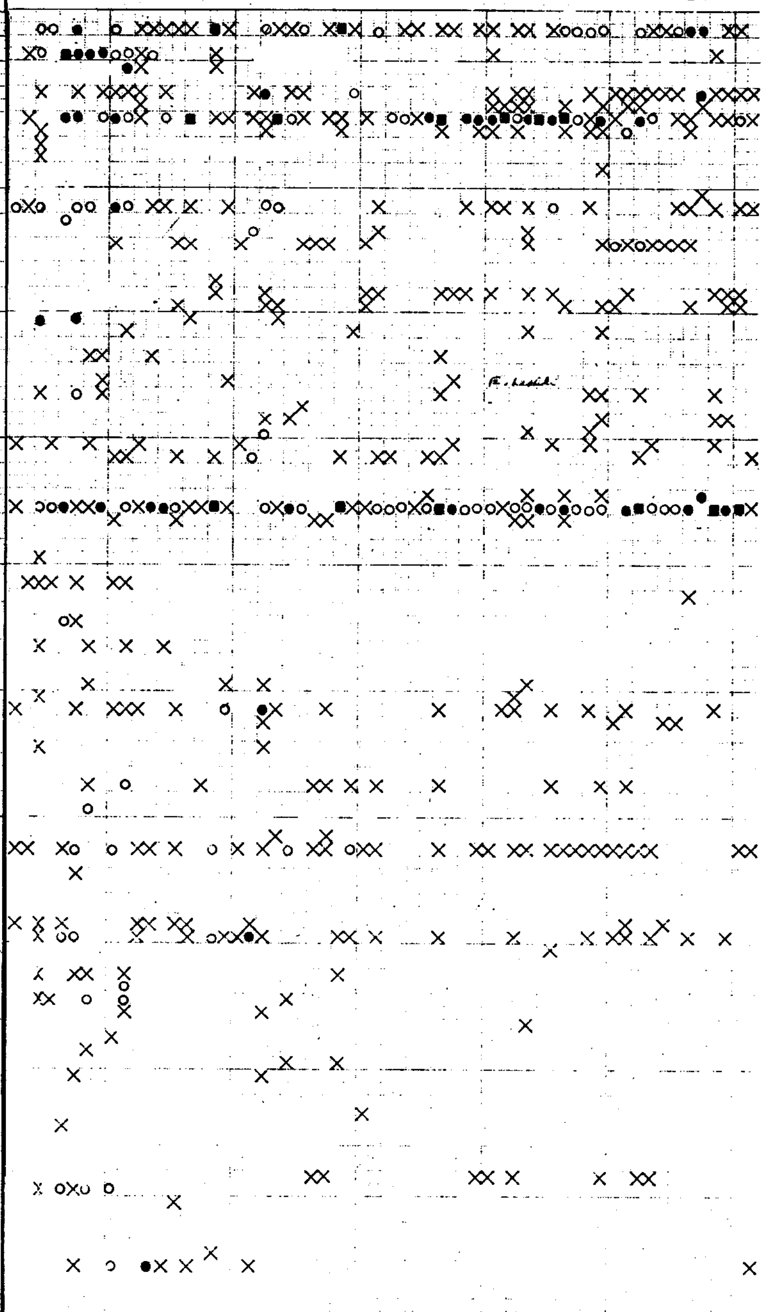
SPECIES

LOCALITY NUMBERS

UNIVERSITY of WASHINGTON: 1656, 1657, 1658, 1659, 1660, 1661, 1662, 1663, 1664, 1665, 1666, 1667, 1668, 1669, 1671, 1672, 1673, 1674, 1675, 1676, 1677, 1678, 1679, 1680, 1681, 1682, 1683, 1684, 1685, 1686, 1687, 1688, 1689, 1690, 1691, 1692, 1693, 1694, 1695, 1697, 1698, 1699, 1700, 1701, 1702, 1703, 1704, 1705, 1706, 1707, 1708, 1709, 1710, 1711, 1712, 1713, 1715, 1716, 1717, 1718

UNIVERSITY of CALIFORNIA: B-8860, B-8861, B-8862, B-8863, B-8864, B-8865, B-8866, B-8867, B-8868, B-8869, B-8870, B-8871, B-8872, B-8873, B-8874, B-8875, B-8876, B-8877, B-8878, B-8879, B-8880, B-8881, B-8882, B-8883, B-8884, B-8885, B-8886, B-8887, B-8888, B-8889, B-8890, B-8891, B-8892, B-8893, P-8894, B-8895, B-8896, B-8897, B-8898, B-8899, B-8900, B-8901, B-8902, B-8903, B-8904, B-8905, B-8906, B-8907, B-8908, B-8909, B-8910, B-8911, B-8912, B-8913, B-8914, B-8915, B-8916, B-8917, B-8918, B-8919

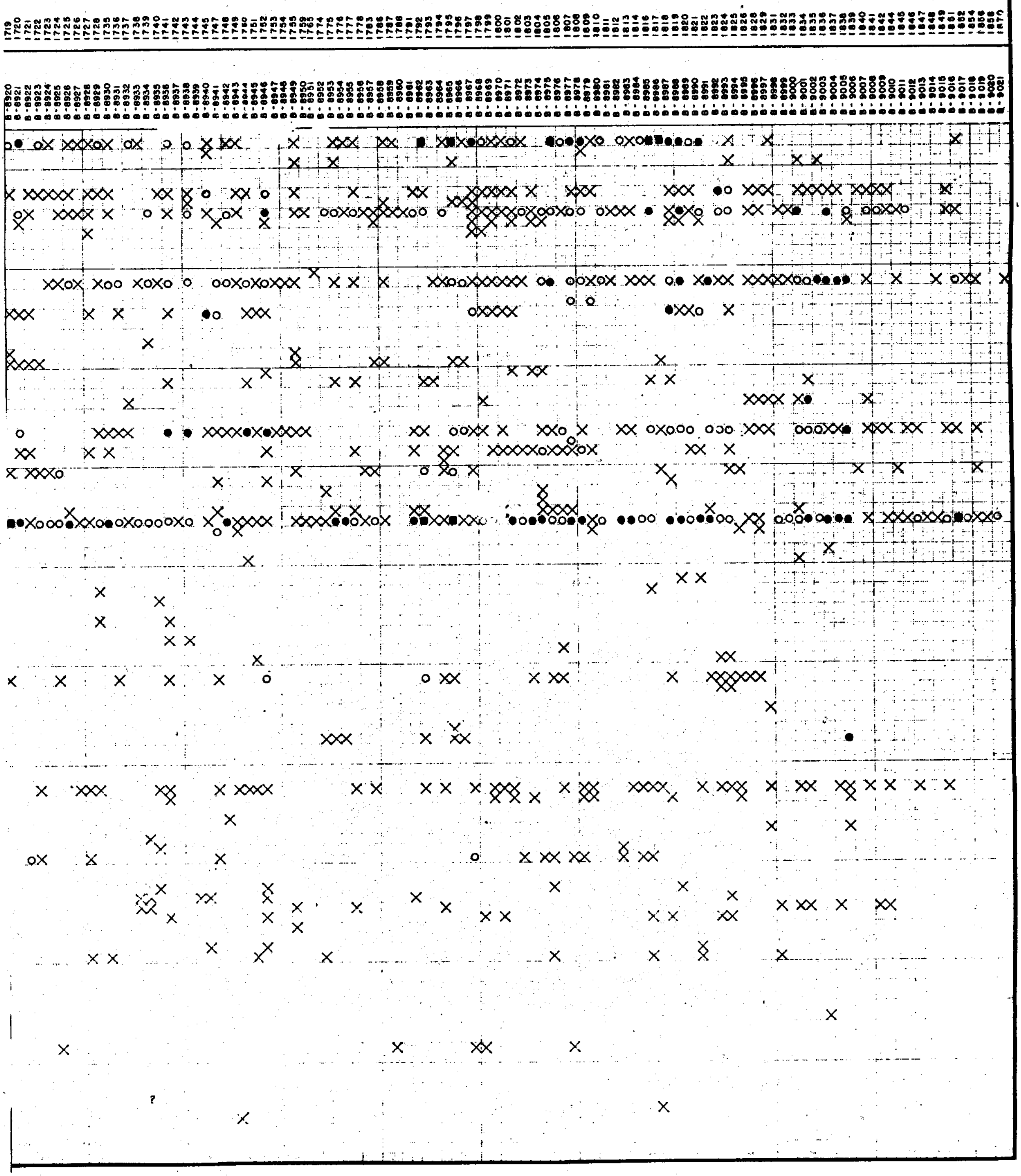
Allomorphina cf. A. macrostomata Karrer
Anomalina californiensis Cushman and Hobson
Bathysiphon eocenica Cushman and G. D. Hanna
Bolivina marginata var. adelaidana Cushman and Kleinpell
Bulimina alligata Cushman and Laiming
Bulimina blakeleyensis n. sp.
Bulimina ovata d'Orbigny
Buliminella bassendorfensis Cushman and Parker
Cassidulina galvinensis Rau
Cassidulina modeloensis Rankin
Cassidulina cf. C. punctata Reuss
Cassidulina subglobosa H. B. Brady
Cassidulinoides sp.
Ceratobulimina washburnei Cushman and Schenck
Chilostomella ooling Schwager
Cibicides elmaensis Rau
Cornuspira brymanensis Cushman
Cyclammina cancellata var. obesa Cushman and Laiming
Cyclammina incisa (Stache)
Cyclammina pacifica Beck
Dentalina cf. D. consorbrina d'Orbigny
Dentalina nasuta Cushman
Dentalina cf. D. pioneerensis Kleinpell
Dentalina cf. D. quadrulata Cushman and Laiming
Elphidium minutum (Reuss)
Entosolenia sp.
Epistomina eocenica Cushman and M. A. Hanna
Epistomina ramonensis Cushman and Kleinpell
Eponides gaviotae Wilson
Eponides healdi R. E. and K. C. Stewart
Eponides mansfieldi var. oregonensis Cushman, R. E. and K. C. Stewart
Eponides umbonatus (Reuss)
Gaudryina triangularis Cushman
Gaudryina ? sp.
Globigerina bulloides d'Orbigny
Globigerina conglomerata Schwager
Guttulina frankei Cushman and Ozawa
Guttulina irregularis (d'Orbigny)
Gyrodina condoni (Cushman and Schenck)
Gyrodina orbicularis planata Cushman
Haplophragmoides trullissata (H. B. Brady)
Haplophragmoides sp.
Lagena acuticosta Reuss
Lagena cf. L. laevis (Montagu)
Lagena strumosa Reuss
Lagena cf. L. substrata Williamson
Lenticulina convergens (Bornemann)
Lenticulina cf. L. crassa (d'Orbigny)
Marginulina subbullata Hantken
Marginulina sp.
Nodogenerina sanctaecrucis Kleinpell
Nodosaria grandis Reuss
Nodosaria hamilti Kleinpell
Nodosaria longiscata d'Orbigny
Nonion cf. N. affinis (Reuss)
Nonion blakeleyensis n. sp.
Nonion incisum (Cushman)
Nonion incisum var. kernensis Kleinpell
Nonion pacificum Cushman
Nonion tuberculatum (d'Orbigny)
Plectofrondicularia cf. P. californica Cushman and Stewart
Plectofrondicularia miocenica var. directa Cushman and Laiming
Plectofrondicularia packardi var. packardi Cushman and Schenck
Plectofrondicularia vaughni Cushman
Polymorphina sp.
Pseudoclavulina communis (d'Orbigny)
Pseudoglandulina inflata (Bornemann)
Pseudoglandulina nallpeensis Rau
Pseudoparrella parva (Cushman and Laiming)
Pseudopolymorphina sp.
Pullenia quinqueloba (Reuss)
Pullenia cf. P. salisburyi R. E. and K. C. Stewart
Quinqueloculina imperialis Hanna and Hanna
Quinqueloculina minuta Beck
Robertina cf. R. declivis (Reuss)
Robulus budensis Hantken
Robulus calcar (Linne)
Robulus chehalisensis Rau
Robulus inornatus (d'Orbigny)
Robulus cf. R. miocenicus (Chapman)
Robulus sp.
Robulus wormani Barbat and von Estorff
Sarcenaria schencki Cushman and Hobson
Sigmoidina cf. S. pacifica Cushman and Ozawa
Sigmoilina tenuis (Czjzek)
Sigmorphina schencki Cushman and Ozawa
Sigmorphina undulata Rau
Silicosigmoilina kleinpelli n. sp.
Siphonodosaria frizzelli Rau
Sphaeroidina variabilis Reuss
Spiroloculina texana Cushman and Ellisor
Textularia ? sp.
Trochammina cf. T. parva Cushman and Laiming
Uvigerina auberina d'Orbigny
Uvigerina cocoaensis Cushman
Uvigerina gallowayi var. [illegible]
Uvigerinella obesa var. impolita Cushman and Laiming
Vaginulinopsis cf. V. saundersi (Hanna and Hanna)
Valvulineria araucana (d'Orbigny)
Valvulineria willapaensis Rau
Verneuilina aff. V. compressa Andreae
Verneuilina ? sp.



RESTORATION POINT

ZEMORRIAN

— CASSIDULINA



AGE RELATIONSHIP OF THE BLAKELEY FAUNULES

The *Cibicides/Uvigerina* faunule that characterizes the fine, tuffaceous, clastic sediments of the basal Blakeley Formation clearly represents the *Uvigerina cocoaensis* Zone of Cushman and Simonson (1944) and the tropical offshore lower Regufian of the Santa Barbara embayment. Most of the species of this assemblage have been reported from widespread localities in California by Kleinpell 1938, H. P. Smith 1956, Sullivan 1962, Kleinpell and Weaver 1963, R. K. Smith 1971, and Tipton, Kleinpell, and Weaver 1973; in Oregon by Cushman and Schenck 1928; and in Washington by Rau 1951 and 1958.

Gyroidina orbicularis planata, Epistomina eocenica, and *Cyclammina pacifica* are members of this faunule representing a group of "holdovers" from middle and upper Eocene time. *Cassidulina galvinensis* occurs commonly here and in the Lincoln Formation; *Cibicides elmaensis* and *Nodosaria frizzelli* occur commonly in this faunule and in similar assemblages described from the Porter Formation of the Chehalis basin.

Anomalina californiensis, Gyroidina orbicularis planata, Cassidulina galvinensis and *Cibicides elmaensis* are the predominant species throughout the Blakeley Formation; for this reason, they are used in faunule definition. These species have relatively long stratigraphic ranges but they can be important as bathymetric indicators, because of their abundance.

The *Gyroidina/Anomalina* and the *Gyroidina/Anomalina/Cibicides* faunules of the Orchard Point Member include several species that are much less abundant, but have a more restricted stratigraphic range. For this reason, they are more diagnostic as chronologic indicators. The species listed below have varying stratigraphic ranges but they do not occur in the *Uvigerina/Cibicides* faunule that characterizes the basal Blakeley beds nor are they known to range down into the *Uvigerina cocoaensis* Zone of the Refugian Stage elsewhere. These are:

Uvigerina gallowayi
Epistomina ramonensis
Verneuilina aff. V. compressa
Uvigerinella obesa impolita
Trochammina parva
Dentalina quadrulata
Bolivina marginata adelaidana
Eponides mansfieldi oregonensis
Eponides healdi
Elphidium minutum
Cassidulina modeloensis
Nonion blakeleyensis n. sp.
Nonion incisum kernensis
Nonion incisum
Uvigerina auberiana

The first three species appear to be restricted to the *Uvigerina gallowayi* Zone (Kleinpell 1938, p. 110) of the Zemorrian Stage. *Trochammina parva* and *Nonion incisum kernensis* were found here only in the Orchard Point Member but, elsewhere, these two species are known from younger horizons. The other individuals listed are also present in the sediments of the superadjacent Restoration Point Member. The overlapping ranges of these species associated with the more restricted individuals previously noted, suggest that the Orchard Point faunules represent the *Uvigerina gallowayi* Zone of the Zemorrian Stage as defined by Kleinpell (1938).

The overlying Restoration Point Member contains many taxa present in the *Uvigerina cocoaensis* and the *Uvigerina gallowayi* Zones, in addition to several species that make their first local appearance here. The species listed below do not occur abundantly in the strata of this member but, as an association, they are important age indicators. These species are:

Valvulinera araucana
Plectofrondicularia miocenica directa
Pseudoparrella parva
Robulus warmani
Nodogenera sanctaecrucis
Haplophragmoides trullissata
Bulimina alligata

The above locally restricted species are associated with several species that make their first Blakeley appearance in the Orchard Point Member but are more abundant in the overlying Restoration Point strata. These species are:

Bolivina marginata adelaidana
Elphidium minutum
Eponides mansfieldi oregonensis
Nonion blakeleyensis n. sp.
Nonion incisum
Uvigerina auberiana
Uvigerinella obesa impolita

Several of these species have been reported from the Astoria Formation of Oregon (Cushman, Stewart, and Stewart) and they have been previously recorded from California strata of Saucesian and younger age. On the other hand, species belonging to the genus *Siphogenerina* and other forms characteristic of Saucesian assemblages elsewhere in Western Washington, Oregon, and California are conspicuous by their absence.

The total aspect and stratigraphic position of the Restoration Point assemblage clearly suggests that this association is chronologically late Zemorrian (*Uvigerinella sparsicostata* Zone). A comparison of typical California upper Zemorrian faunules with the Restoration Point faunules reveals, however, only a few individuals in common. Kleinpell (1938, p. 111) restricts *Trochammina parva* and *Nonion incisum* to this zone, both occur in the Orchard Point Member. However, from an excellent upper Zemorrian faunule (L. S. J. U. 1771) collected by D. E. Taylor, Kleinpell (p. 113) records *Robulus warmani*, *Bolivina marginata*, and *Uvigerina obesa impolita*. These species are present in the Restoration Point Member.

The gross differences in composition of the more restricted elements of the *Uvigerinella sparsicostata* Zone and the Restoration Point faunule may be attributed to zoogeographic characteristics. If the compositional difference is of provincial magnitude, as suggested by the distribution of stratigraphic ranges of the associated faunule elements, it would seem advisable to erect for biostratigraphic convenience a new zone, chronologically equivalent to the *Uvigerinella sparsicostata* Zone of the typical Zemorrian Stage.

The overlapping ranges of the previously listed, more restricted species of the Restoration Point Member define the stratigraphic limits of such a zone. The name *Nonion blakeleyensis* Zone is here proposed for this new uppermost zone of the Zemorrian Stage. This new species is not confined stratigraphically to this horizon, as the lowermost known occurrence of this species has been noted previously in the *Uvigerina gallowayi* Zone. The known upper occurrence of this species extends through the *Siphogenerina transversa* and the *Plectofrondicularia miocenica* Zones of the Saucesian Stage.

Nonion blakeleyensis n. sp. is very similar in morphologic character to *Nonion belridgensis* described by Barbat and Johnson from California. The latter species occurs rather commonly in foraminiferal assemblages of Mohnian and Delmontian age. This species occurs with other individuals identified here as *Cassidulina modeloensis, Eponides healdi, Valvulineria araucana* and *Plectofrondicularia miocenica var. directa.* Very similar forms have also been reported from the Astoria formation of Oregon. Both the Blakeley and Astoria individuals are morphologically similar, and perhaps ancestral to the better known species that occur in the California sections in later Miocene times.

The typical Blakeley Formation has been zoned on the basis of its contained molluscan fauna by Weaver (1916), and Durham (1944). More recently Rau (1958) has proposed a zonation based on fossil foraminiferal of the marine Tertiary strata of Western Washington that includes the typical Blakeley formation and correlative strata. It is clear from the work of these writers that each has applied the term zone in a different manner. According to Wheeler, et al, (1950, p. 2364), a zone is a "fundamental para-rock-time unit," as such it is basically indivisible and the stuff that composes a stage. In other words, a zone must be a sub-set of a stage; this particular property of a zone has been emphasized much earlier by Kleinpell (1938); however, the *Acila getteysburgensis* Zone of Weaver (1916), the *Echinophoria rex* Zone of Durham (1944), and the *Pseudoglandulina aff. P. inflata* Zone of Rau (1958) are not subdivisions of any recognized or defined stage. The zonation proposed by Rau has an additional serious defect in that the various foraminiferal facies present in his assemblages have not been recognized and, therefore, these associations have not been reduced to a common denominator. An analysis of this problem has been fully discussed by Kleinpell (1938, p. 83) and need not be repeated here.

DEPOSITIONAL HISTORY

The Oligo-Miocene marine transgression began locally in Refugian time following a regional regression that characterized the close of the Eocene Epoch. This transgression is believed to have reached its marine zenith sometime during the deposition of the upper Blakeley in Zemorrian time. Early andesitic and rhyolitic terrestrial volcanic eruptions along the present trend of the Cascade Mountains that begin about the same time as the Refugian marine transgression in Western Washington and Oregon futher reflect changing tectonic conditions. The felsitic tuffaceous matrix characteristic of the conglomerates and finer clastic sediments of the Blakeley formation is considered to have been supplied from this source. The bulk of the sedimentary debris, that later became lithified to form the Blakeley and Blakely Harbor Formations, was derived from nearby land masses of Crescent or Coast Range basalt. Much of this basalt was extruded as submarine volcanic flows, covering most of Western Washington and Oregon.

The Blakeley and Blakely Harbor Formations, in addition to the other post-basalt sediments, were deposited in depressions formed between and around these major centers of basalt accumulation. Some of these basinal depressions in Refugian time were at or above sea level; others were covered by shallow marine water, still others, as the Blakeley depositional site, relatively deep marine troughs with nearby basaltic highlands. Such highlands were locally subjected to subaerial erosion throughout the entire depositional history of the Blakeley and Blakely Harbor Formations. The bathymetric conditions of deposition can best be determined by relative abundance of foraminiferal species comprising the association. The foraminifera faunules of the Blakeley Formation contain representatives of many genera, some of which are usually found in shallow water, others in deeper environments down to abyssal depths. The shallow water genera (*Haplophgramoides*), the medium depth genera (*Robulus* and other lagenids), and the moderate depth genera (*Plectofrondicularia, Uvigerinella,* and inflated buliminids) are well represented but are not the dominant elements of the Blakeley foraminiferal faunules. The deeper water genera (*Gyroidina, Anomalina, Cyclammina,* and carinate cassidulinids) are the dominant elements of each faunule and best reflect the general bathymetric conditions at the time of deposition. Carinate cassidulinids are reported by Cushman (1911, pp. 96-100) from the North Pacific in deep cold water; *Gyroidina orbicularis planata,* a form similar to *Gyroidina soldanii* has been reported from the North Pacific Challanger and Albatross stations living at bathyal to abyssal depths (Cushman 1915, p. 71); and *Anomalina californiensis* a form similar to *Nonion umbilicatulum* (Montague) which is recorded from the North Pacific Challanger and Albatross stations in waters of bathyal and abyssal depths (Cushman 1914, p. 24).

In contrast to the deep, cold water, abundant foraminifera present in the Orchard Point Member are the warm, shallow water, subtropical corals belonging to the genera *Siderastrea* and *Eusmilia*. These genera are presently confined, according to Durham (1942, pp. 88-89), to the Gulf of California in subtropical waters. He states, "Most of the corals are found in conglomerates that contain boulders up to two feet in diameter, but interbedded with the conglomerates are occasional beds as much as six inches thick that are composed largely of the crushed tests of spatangoid echinoids, suggesting moderate depth of water. In addition, the associated molluscan fauna does not contain any species limited to an extremely shallow depth."

It is clear that well-rounded basaltic cobbles and boulders associated with delicate, subtropical corals and deep cold water foraminifera contained in a tuffaceous andesitic matrix require some rather special depositional characteristics. Currents and wave action strong enough to round basalt boulders and cobbles and remove these clasts from the beach areas to sites below wave base where the corals could survive, will also winnow the felsitic tuffaceous material to deeper and quieter shelf environments. Initially the undaform surface of the Blakeley depositional basin (Rich 1951, p. 2) may have been characterized by relatively thick accumulations of basaltic debris composed of material from silt-size tuffaceous material to boulders overlying a gently sloping surface of eroded Crescent basalt. The clinoform surface by contrast (Rich 1951, p. 2), may have been characterized by finer basaltic debris and thick accumulations of felsitic, tuffaceous material overlying a more steeply dipping surface of submarine extruded basalt.

Large scale submarine landslides may have developed from time to time during the course of Blakeley deposition, produced as a result of seismic events or at times when the static loading of the coarser clastic material exceeded the cohesive strength of the finer grained tuffaceous material. The net effect of such gravity sliding and slumping could produce biologic and lithologic mixing found in the Blakeley Formation. Many of the physical conditions visualized here are also common to marine environments that have been known to produce turbidity currents. The question arises, did turbidity currents aid in the transport of the coarser clastic material into deeper water environments? This question cannot be answered directly as the horizontal distance of transport and the original shelf slope characteristics are not known.

Graded clastic series similar to those described by Migliorini (1944) and Bouma (1962) frequently characterize the internal stratigraphic detail of the Blakeley Formation. The graded sequential relationships are more pronounced in the Orchard Point Member because of its much coarser character. The graded succession of subunits composing each member are similar and characterized by a coarser clastic graded interval at the base, overlain by thinner, silty-arenaceous interval characterized by parallel lamination. The mid-subunits of this sequence include a superadjacent arenaceous interval characterized by current ripple lamination, overlain by a silty-arenaceous interval also characterized by parallel lamination. This subunit is capped by a pelitic interval of varying thickness.

Other features usually associated with submarine slumping and turbidity deposition are also present and locally characterize portions of the Blakeley strata. There are:

1. "Crinkled" bedding
2. Pull-apart fragments of laminated beds
3. Irregular and convolute bedding
4. Flute casts and sole markings

In summary, the sediments of the Blakeley formation appear to have been finally deposited in a relatively deep, cold, marine environment by submarine slumping and turbidity currents that mixed diverse biologic and lithologic elements. The Blakely Harbor Formation, by contrast, was deposited in a low-lying, nonmarine environment indicating a major change in configuration of the depositional basin. The source of the basaltic material appears to have been from the nearby land masses composed of Coast Range or Crescent basalt of Eocene age and some older rock types. The tuffaceous material, on the other hand, is thought to have originated in the Cascade Mountain volcanic province to the east and been transported to the Blakeley basin by both streams and wind.

SAMPLE LOCALITIES

Description of the sample localities are on file at the University of California (UC locality numbers) and at the University of Washington (UW locality numbers).

SYSTEMATIC LISTING OF FORAMINIFERA

University of California Museum of Paleontology type numbers are indicated by UC. University of Washington type numbers are indicated by UW.

NEW SPECIES AND VARIETIES

Bulimina blakeleyensis n. sp.
Pl. 6, Fig. 3a, b, c.

Bulimina sp., Rau, 1951, p. 65, fig. 17.

Bulimina alsatica Cushman and Parker, Rau, 1964, p. 18, pl. 5, fig. 16.

Bulimina cf. B. alsatica Cushman and Parker, Rau, 1964, p. 18, pl. 5, fig. 14.

Test small, tapered but rapidly expanding in the last whorl; initial end pointed with short spine; chambers indistinct except those of the last whorl; early sutures less distinct, later sutures depressed; wall of last whorl smooth except basal fringe of small, thin, pointed costae not crossing the suture; early chambers costate; aperture loop-shaped. This species is similar to *Bulimina alsatica* Cushman and Parker, but differs in being smaller, less robust, and having smaller, thinner, more acicular costae. It differs from *Bulimina macilenta* Cushman and Parker in being less tapering and more inflated in the ultimate whorl, and having sharper and more distinct costae.

Holotype UC 46735, Loc. B-8827; Paratype UW 20796, Loc. 1612.

Nonion blakeleyensis n. sp.
Pl. 5, Fig. 2a, b, 3a, b.

Nonion sp., Rau, 1951, p. 437, pl. 64, figs. 23, 24.

Nonion cf. N. belridgensis Barbat and Johnson, Cushman, Stewart, and Stewart, 1947, p. 15, pl. 2, fig. 1.

Test involute, bilaterally symmetrical, more elongate than broad, slightly umbilicate; umbilicus partially filled; periphery acute; 8-10 chambers in ultimate whorl; sutures very slightly limbate, more depressed near umbilicus; wall smooth, calcareous, finely perforate; apertural face subtriangulate, widest at the ventral margin. This species differs from *Nonion belridgensis* Barbat and Johnson in having fewer chambers and in having a more subtriangulate, less inflated apertural face.

Holotype UC 46785, Loc. B-8792; Paratype UW 20828, Loc. 1577; Paratype UC 46832, Loc. B-8792.

Silicosigmoilina kleinpelli n. sp.
Pl. 1, Fig. 12a, b.

Test in early stages nearly planispiral, later becoming sigmoid; wall finely arenaceous with siliceous cement; aperture at end of tubular chamber without apparent apertural teeth. This species is larger, more oval and the sutures are less well marked than *Silicosigmoilina californica* Cushman and Church. It is also less quinqueloculine in form than *Silicosigmoilina greenlandica* (Cushman) of Loeblich and Tappan. *Silicosigmoilina kleinpelli* occurs rarely in the Zemorrian and lower Saucesian of western Washington and Oregon and has been found in oil well cores.

Holotype UC 46817, Loc. B-8888.

Uvigerina gallowayi Cushman *var. blakeleyensis n. var.*
Pl. 6, Fig. 5a, b, c.

The Blakeley specimens referred to this variety differ from the typical forms in being thinner, less inflated, with more numerous but less heavy, straighter costae. These individuals occur mostly in the Orchard Point Member of the Blakeley Formation.

Holotype UC 46825, Loc. B-8854; Paratype UW 20866, Loc. 1650.

REFERENCES TO IDENTIFIED SPECIES AND VARIETIES

Original descriptions and illustrations of taxa are not necessarily cited.

Allomorphina cf. A. macrostoma Karrer. Rau, 1948a, p. 173, pl. 31, figs. 4, 5. Hypotype UC 46730, Loc. B-8807; pl. 9, fig. 6.

Anomalina californiensis Cushman and Hobson, 1935, p. 64, pl. 9, fig. 8. Hypotype UC 46731, Loc. B-8786, UW 20792, Loc. 1571; pl. 10, fig. 4.

Bathysiphon eocenica Cushman and Hanna, 1927, p. 210, pl. 13, figs. 2, 3. Hypotype UC 46732, Loc. B-8783, UW 20793, Loc. 1568; pl. 1, fig. 1.

Bolivina marginata Cushman *var. adelaidana* Cushman and Kleinpell, 1934, p. 10, pl. 1, figs. 1, 2. Hypotype UC 46733, Loc. B-8818, UW 20794, Loc. 1603; pl. 6, fig. 12.

Bulimina alligata Cushman and Laiming. Cushman, Stewart, and Stewart, 1947a, p. 18, pl. 2, fig. 11. Hypotype UC 46734, Loc. B-8785, UW 20795, Loc. 1570; pl. 6, fig. 2. They may represent a new variety in that each successive chamber displays a more rapid expansion. The test is somewhat less robust than typical and the costae are more crowded and slender. The apertural face is more elongate and somewhat pointed at the apex.

Bulimina ovata d'Orbigny. Rau, 1951, p. 440, pl. 65, fig. 10. Hypotype UC 46736, Loc. B-8804, UW 20797, Loc. 1589; pl. 6, fig. 6.

Buliminella bassendorfensis Cushman and Parker, 1947, p. 66, pl. 17, fig. 6. Hypotype UC 46737, Loc. B-8827, UW 20798, Loc. 1612; pl. 6, fig. 1.

Cassidulina galvinensis Cushman and Frizzell, 1940, p. 43, pl. 8, fig. 10a--c. Hypotype UC 46738, Loc. B-8800, UW 20799, Loc. 1585; pl. 9, fig. 1. Individuals assigned to this species are identical to typical specimens from the Lincoln Creek Formation.

Cassidulina modeloensis Rankin. Cushman and Kleinpell, 1934, p. 23, pl. 3, fig. 12. Hypotype UC 46739, Loc. B-8795, UW 20800, Loc. 1580; pl. 9, fig. 2. They are very similar to the Astoria forms but somewhat more keeled than the typical Modelo forms.

Cassidulina cf. C. punctata Reuss. Hypotype UC 46740, Loc. D-283, UW 20801, Loc. 1911; pl. 9, fig. 3. Individuals referred to this species were collected from both members of the Blakeley Formation at the Sinclair Inlet section. They are similar to *Cassidulina punctata* figured by Cushman (1926, p. 56, pl. 9, figs. 23, 24). However Marks (1951, p. 68) places Reuss' species in synonym with *Cassidulina laevigata* d'Orbigny. The Blakeley individuals are quite distinct from *Cassidulina laevigata var. carinata* from Nye shale of Oregon and other correlative strata of Oregon and Washington.

Cassidulina subglobosa H. B. Brady. Cushman, 1929, p. 100, pl. 14, fig. 11. Hypotype UC 46741, Loc. B-8814, UW 20802, Loc. 1599; pl. 9, fig. 4.

Cassidulinoides sp., Hypotype UC 46742, Loc. B-8907; pl. 9, fig. 5. It is similar to *Cassidulinoides sp.* Rau, 1964, p. 23, pl. 7, fig. 2, from correlative strata of the Twin River Formation, northern Olympic Peninsula of Washington.

Ceratobulimina washburnei Cushman and Schenck, 1928, p. 314, pl. 45, fig. 1. Hypotype UC 46743, Loc. D-280, UW 20803, Loc. 1613; pl. 8, fig. 5. The latter individuals were poorly preserved and eroded, suggesting that these forms may have been reworked from the subjacent beds.

Chilostomella oolina Schwager, 1878, p. 527, pl. 1, fig. 16. Hypotype UC 46744, Loc. B-8793; pl. 9, fig. 8.

Cibicides elmaensis Rau, 1948 a, p. 173, pl. 31, figs. 18-26. Hypotype UC 46745, Loc. B-8842, UW 20804, Loc. 1628; pl. 10, fig. 5.

Cornuspira byramensis Cushman. Rau, 1948a, p. 160, pl. 128, figs. 6 & 7. Hypotype UC 46746, Loc. D-288; pl. 2, fig. 3.

Cyclammina cancellata var. obesa Cushman and Laiming, 1931, p. 94, pl. 9, fig. 10. Hypotype UC 46747, Loc. B-8811; pl. 1, fig. 5.

Cyclammina incisa (Stache). Cushman and Laiming, 1931, p. 93, pl. 9, fig. 6. Hypotype UC 46748, Loc. B-8812, UW 20806, Loc. 1597; pl. 1, fig. 6.

Cyclammina pacifica Beck, 1943, p. 591, pl. 98, figs. 2 & 3. Hypotype UC 46749, Loc. D-281, UW 20807, Loc. 1911; pl. 1, fig. 7.

Dentalina cf. D. consobrina d'Orbigny. Hypotype UC 46750, Loc. B-8788, UW 20808, Loc. 1573; pl. 3, fig. 7. A few broken specimens are similar to the forms figured by Cushman, 1929, p. 86, pl. 12, figs. 27, 29.

Dentalina nasuta Cushman, 1939b, p. 57, pl. 10, figs. 10 & 11. Hypotype UC 46751, Loc. B-8934, UW 20809, Loc. 1739; pl. 3, fig. 11.

Dentalina cf. D. pioneerensis Kleinpell. Hypotype UC 46752, Loc. B-8795, UW 20810, Loc. 1580; pl. 3, fig. 9. Positive identification will depend upon better preserved individuals.

Dentalina cf. D. quadrulata Cushman and Laiming. Hypotype UC 46753, Loc. B-8814; pl. 3, fig. 10. A few broken individuals resemble the figured specimen of Cushman and Laiming, 1931, p. 90, pl. 10, fig. 13.

Elphidium minutum (Reuss). Hypotype UC 46754, Loc. B-8845; pl. 4, fig. 12.

Entosolenia sp. Hypotype UC 46755, Loc. B-8789, UW 20813, Loc. 1574; pl. 6, fig. 8.

Epistomina eocenica Cushman and Hanna, 1927, p. 53, pl. 5, figs. 4 & 5, Hypotype UC 46756, Loc. D-285, UW 20814, Loc. 1921; pl. 8, fig. 3. They have been compared with typical California specimens and similar individuals assigned to this species that were recorded from several Oregon and Washington localities.

Epistomina ramonensis Cushman and Kleinpell, 1934, p. 15, pl. 3, fig. 1. Hypotype UC 46757, Loc. B-8866, UW 20815, Loc. 1662; pl. 8, fig. 4. The Blakeley individuals appear to be nearly identical to the typical Kirker specimens.

Eponides gaviotaensis Wilson, 1954, p. 143, pl. 16, fig. 11. Hypotype UC 46758, Loc. B-8812, UW 20818, Loc. 1597; pl. 8, fig. 1. The Blakeley specimens have been compared with topotypes from the Gaviota Formation. The test wall of the Blakeley individuals are smoother and less heavy than the typical forms from the Gaviota.

Eponides healdi Stewart and Stewart, 1930, p. 70, pl. 8, fig. 8. Hypotype UC 46759, Loc. B-8812, UW 20817, Loc. 1597; pl. 7, fig. 5.

Eponides mansfieldi var. oregonensis Cushman, Stewart, and Stewart, 1947a, p. 48, pl. 6, fig. 4. Hypotype UC 46760, Loc. B-8842, UW 20817, Loc. 1597; pl. 8, fig. 2. It has also been recorded from the Astoria Formation of Oregon and from strata of Blakeley equivalent age in southwestern Washington and on the northern Olympic Peninsula.

Eponides umbonatus (Reuss). Kleinpell and Weaver, 1963, p. 179, pl. 12, fig. 3. Hypotype UC 46761, Loc. D-288, UW 20819, Loc. 1924, pl. 7, fig. 6.

Gaudryina triangularis Cushman. Cushman and Parker, 1931, p. 2, pl. 1, fig. 1. Hypotype 46762, Loc. B-8803, UW 20829, Loc. 1588; pl. 1, fig. 10.

Gaudryina sp., Hypotype UC 46763, Loc. B-8783; pl. 1, fig. 11. Restoration Point Member, Blakeley Formation. A single specimen differing from *Gaudryina triangularis* Cushman in that the triserial portion is not triangular in cross section and the late chambers are more inflated.

Globigerina bulloides d'Orbigny. Kleinpell, 1938, p. 343, pl. VII, fig. 17. Hypotype UC 46764, Loc. B-8800, UW 20821, Loc. 1585; pl. 10, fig. 2.

Globigerina conglomerata Schwager. Cushman and Laiming, 1931, p. 117, pl. 14, fig. 5. Hypotype UC 46765, Loc. B-8803; pl. 10, fig. 3.

Guttulina frankei Cushman and Ozawa. Cushman and Frizzell, 1943, p. 84, pl. 14, figs. 17 & 18. Hypotype UC 46766, Loc. B-8795, UW 20825, Loc. 1580; pl. 4, fig. 10.

Guttulina irregularis (d'Orbigny). Rau, 1948a, p. 169, pl. 80, figs. 7 & 8. Hypotype UC 46767, Loc. D-281; pl. 4, fig. 11. A few rare individuals from the lower portion of the Orchard Point Member exposed on Sinclair Inlet are very similar to the Porter forms and to the figured specimens of Cushman and Ozawa, 1930, pp. 25-27, pl. 7, figs. 1 & 2.

Gyroidina condoni (Cushman and Schenck). Kleinpell and Weaver, 1963, p. 179, pl. 11, fig. 3. Hypotype UC 46768, Loc. B-8843, UW 20823, Loc. 1629; pl. 7, fig. 2.

Gyroidina orbicularis var. planata Cushman. Rau, 1951, p. 447, pl. 66, figs. 4--6. Hypotype UC 46769, Loc. B-8795, UW 20824, Loc. 1580; pl. 7, fig. 3.

Haplophragmoides trullissata (H. B. Brady). Cushman and Laiming, 1931, p. 93, pl. 9, fig. 5. Hypotype UC 46770, Loc. B-8792, UW 20826, Loc. 1577; pl. 1, fig. 2.

Haplophragmoides sp., Hypotype UC 46771, Loc. B-8783; pl. 1, fig. 3. A few flattened individuals with crenulated peripheries resemble flattened forms of *Haplophragmoides obliquicameratus* Marks.

Lagena acuticosta Reuss. Kleinpell, 1938, p. 224, pl. VII, fig. 13. Hypotype UC 46772, Loc. B-8796, UW 20827, Loc. 1581; pl. 4, fig. 1.

Lagena cf. L. laevis (Montagu). Hypotype UC 46773, Loc. B-8944; pl. 4, fig. 2. A single individual from the Restoration Point Member appears to be very similar to *Lagena cf. L. laevis* figured by Cushman and Stainforth, 1945, p. 3, pl. 4, fig. 22.

Lagena strumosa Reuss. Galloway and Morrey, 1929, p. 20, pl. 2, fig. 8. Hypotype UC 46774, Loc. B-8800, UW 20828, Loc. 1585; pl. 4, fig. 3.

Lagena cf. L. substriata Williamson. Hypotype UC 46775, Loc. B-8788; pl. 4, fig. 4. It is similar in character to *Lagena cf. L. substriata* Beck, 1943, p. 602, pl. 107, fig. 30, from the Cowlitz Formation of Washington.

Lenticulina convergens (Bornemann). Kleinpell, 1938, p. 205, pl. III, figs. 5, 8, 10. Hypotype UC 46776, Loc. B-8929, UW 20828, Loc. 1734; pl. 3, fig. 1.

Lenticulina cf. L. crassa (d'Orbigny). Kleinpell and Weaver, 1963, p. 169, pl. 5, fig. 8. Hypotype UC 46777, Loc. B-8935, UW 80830, Loc. 1740; pl. 3, fig. 2.

Marginulina subbullata Hantken. Cushman and Laiming, 1931, p. 99, pl. 10, fig. 8. Hypotype UC 46778, Loc. B-8865, UW 20831, Loc. 1661; pl. 3, fig. 4.

Marginulina sp., Hypotype UC 46779, Loc. B-8929, UW 20832, Loc. 1734; pl. 3, fig. 5.

Nodogenerina sanctaecrucis Kleinpell, 1938, p. 246, pl. IV, fig. 22. Hypotype UC 46780, Loc. B-8866, UW 20836, Loc. 1662, pl. 5, fig. 8.

Nodosaria grandis Reuss. Rau, 1948a, p. 167, pl. 30, fig. 9. Hypotype UC 46781, Loc. D-276, UW 20833, Loc. 1908; pl. 3, fig. 12. Individuals collected from the Restoration Point Member are identical to the Porter forms.

Nodosaria hamilli Kleinpell, 1938, p. 218, pl. IV, figs. 4 & 5. Hypotype UC 46782, Loc. B-8976, UW 20834, Loc. 1806; pl. 3, fig. 13.

Nodosaria longiscata d'Orbigny. Kleinpell, 1938, p. 218, pl. IX, fig. 16. Hypotype UC 46783, Loc. D-285, UW 20835, Loc. 1922; pl. 3, fig. 14

Nonion cf. N. affinis (Reuss). Hypotype UC 46784, Loc. B-8858, UW 20837, Loc. 1654; pl. 5, fig. 1. Orchard Point Member specimens are similar to the figured specimen *Nonion affinis* (Reuss), Cushman, 1929, p. 89, pl. 13, fig. 24, and to *Nonion affinis* (Reuss), Kleinpell, 1938, p. 229, pl. VI, figs. 3, 7. The Blakeley specimens are less inflated and the umbilical region has a greater amount of shell filling.

Nonion incisum (Cushman). *Nonionina incisa* Cushman, 1926b, pp. 90-91, pl. 18, fig. 3. Hypotype UC 46786, Loc. B-8820, UW 20839, Loc. 1605; pl. 5, fig. 5.

Nonion incisum (Cushman) *var. kernensis* Kleinpell, 1938, pp. 232-233. Hypotype UC 46787, Loc. B-8820; pl. 5, fig. 4. A single individual characterized by a more compressed test and a more convex and rounded apertural form than the typical forms.

Nonion pacificum (Cushman). Cushman, 1939b, p. 25, pl. 6, fig. 25. Hypotype UC 46788, Loc. B-8846; pl. 5, fig. 6. A few individuals are very similar to the Recent Pacific species described by Cushman.

Nonion tuberculatum (d'Orbigny). Cushman, 1939b, p. 13, pl. 3, figs. 12, 16, 17. Hypotype UC 46789, Loc. B-8792, UW 20840, Loc. 1572; pl. 5, fig. 7. Individuals from the Restoration Point Member have less inflated chambers but are otherwise similar to the figured specimens of Cushman.

Plectofrondicularia cf. P. californica Cushman and Stewart. Hypotype UC 46790, Loc. B-8965; pl. 5, fig. 9. It differs from the typical forms by having heavier and longer ribs on the central portion of the test.

Plectofrondicularia miocenica Cushman *var. directa* Cushman and Laiming, 1931, p. 105, pl. II, fig. II. Hypotype UC 46791, Loc. B-8818; pl. 5, fig. 10.

Plectofrondicularia packardi var. packardi Cushman and Schenck, 1928, p. 311, pl. 43, figs. 14 & 15. Hypotype UC 46792, Loc. D-274, UW 20843, Loc. 1905; pl. 5, fig. 11.

Plectofrondicularia vaughani Cushman. Cushman and Hobson, 1935, p. 59, pl. 9, fig. 1. Hypotype UC 46793, Loc. B-8866; pl. 5, fig. 12.

Polymorphina sp., Hypotype UC 46794, Loc. B-8815; pl. 4, fig. 5. Megalospheric specimen.

Pseudoclavulina communis (d'Orbigny). *Clavulina communis* d'Orbigny, Kleinpell, 1938, p. 193, pl. III, figs. 3 & 4. Hypotype UC 46795, Loc.B-8797; pl. 1, fig. 4.

Pseudoglandulina inflata (Bornemann). Cushman and Frizzell, 1943, p. 84, pl. 14, fig. 14. Hypotype UC 46796, Loc. B-8787, UW 20845, Loc. 1572; pl. 3, fig. 15. The Blakeley individuals appear to be identical to specimens from the type Lincoln Creek Formation.

Pseudoglandulina nallpeensis Rau, 1951, p. 435, pl. 64, fig. 8. Hypotype UC 46797, Loc. B-9030, UW 20846, Loc. 1899; pl. 3, fig. 16. These individuals have fewer chambers (3-4) than the typical form from the Willapa River section. They are more elongate, less inflated than *Pseudoglandulina inflata.*

Pseudoparrella parva (Cushman and Laiming). *Pulvinulinella parva* Cushman and Laiming, 1931, p. 115, pl. 13, fig. 5. Hypotype UC 46798, Loc. B-8865, UW 20847, Loc. 1661; pl. 8, fig. 6.

Pseudopolymorphina sp., Hypotype UC 46799, Loc. B-8942; pl. 4, fig. 6.

Pullenia quinqueloba (Reuss). Mallory, 1959, p. 247, pl. 34, fig. 1. Hypotype UC 46800, Loc. B-8849, UW 20848, Loc. 1637; pl. 9, fig. 9.

Pullenia cf. P. salisburyi R. E. and K. C. Stewart. Hypotype UC 46801, Loc. D-285; pl. 9, fig. 7.

Quinqueloculina imperialis Hanna and Hanna, 1924, p. 58, pl. 13, figs. 8, 9, 10. Hypotype UC 46802, Loc. B-8795, UW 20849, Loc. 1580; pl. 1, fig. 13.

Quinqueloculina minuta Beck, 1943, p. 593, pl. 99, figs. 5-7. Hypotype UC 46803, Loc. B-8799, UW 20850, Loc. 1584; pl. 1, fig. 14.

Robertina cf. R. declivis (Reuss). Hypotype UC 46804, Loc. B-8800; pl. 6, fig. 4. The ultimate chamber of this individual is less inflated than the specimens figured by Cushman and Parker, 1946, p. 94, pl. 16, figs. 8-12. This specimen differs from *Robertina angusta* (Cushman), Cushman and Frizzell, 1943, p. 85, pl. 14, fig. 15, in being much less inflated and in the location of the aperture.

Robulus budensis (Hantken). Rau, 1948a, p. 161, pl. 28, figs. 12 & 13. Hypotype UC 46805, Loc. D-284, UW 20854, Loc. 1920; pl. 2, fig. 5.

Robulus calcar (Linne). Rau, 1951, p. 431, pl. 63, figs. 23 & 24. Hypotype UC 46806, Loc. B-8866, UW 20851, Loc. 1662; pl. 2, fig. 6.

Robulus chehalisensis Rau, 1951, p. 431, pl. 64, fig. 25. Hypotype 46807, Loc. D-286; pl. 2, fig. 7.

Robulus inornatus (d'Orbigny). Beck, 1943, p. 595, pl. 104, figs. 1-4, 10, 14. Hypotype UC46808, Loc. B-9030, UW 20853, Loc. 1899; pl. 2, fig. 8.

Robulus cf. R. miocenicus (Chapman). Hypotype UC 46809, Loc. B-8985; pl. 2, fig. 9. A few rare individuals are very similar to *Robulus miocenicus* (Chapman), Kleinpell, 1938, p. 199, pl. IV, fig. 9.

Robulus warmani Barbat and von Estorff. Kleinpell, 1938, p. 204, pl. VIII, fig. 2. Hypotype UC 46810, Loc. B-8792; pl. 2, fig. 10.

Robulus sp., Hypotype UC 46811, Loc. B-8949; pl. 3, fig. 6. A few poorly preserved specimens may be assigned to the genus *Robulus*.

Saracenaria schencki Cushman and Hobson, 1935, p. 57, pl. 8, fig. 11. Hypotype UC 46812, Loc. B-8940, UW 20855, Loc. 1745; pl. 3, fig. 8.

Sigmoidina cf. S. pacifica Cushman and Ozawa. Hypotype UC 46813, Loc. B-8786, UW 20856, Loc. 1571; pl. 4, fig. 9. Specimens collected display considerable variation in size and number of visible chambers. They appear to be similar to the figured form of Cushman and Ozawa, 1929, p. 77, pl. XIV, figs. 12 & 13.

Sigmoilina tenuis Czjzek. Rau, 1951, p. 430, pl. 63, fig. 2. Hypotype UC 46814, Loc.B-8792, UW 20857, Loc. 1517; pl. 2, fig. 2.

Sigmomorphina schencki Cushman and Ozawa. Rau, 1948a, p. 170, pl. 30, figs. 13 & 14. Hypotype UC 46816, Loc. D-277, UW 20858, Loc. 1909; pl. 4, fig. 8.

Sigmomorphina undulata Rau, 1948a, p. 170, pl. 30, figs. 15 & 16. Hypotype UC 46815, Loc. D-276, UW 20859, Loc. 1908; pl. 4, fig. 7. This species is identical to the Porter specimens of Rau.

Siphonodosaria frizzelli Rau, 1948a, p. 171, pl. 30, fig. 10. Hypotype UC 46818, Loc. D-278, UW 20860, Loc. 1910; pl. 6, fig. 11.

Sphaeroidina variabilis d'Orbigny. Rau, 1964, p. 23, pl. 7, fig. 7. Hypotype UC 46819, Loc. B-9003, UW 20861, Loc. 1836; pl. 10, fig. 1.

Spiroloculina texana Cushman and Ellisor, 1944, p. 51, pl. 8, figs. 14 & 15. Hypotype UC 46820, Loc. B-8822, UW 20862, Loc. 1607; pl. 2, fig. 1.

Textularia sp., Hypotype UC 46821, Loc. B-8783.

Trochammina cf. T. parva Cushman and Laiming. Hypotype UC 46822, Loc. B-8807, UW 20864, Loc. 1592; pl. 2, fig. 4. The individuals assigned to this species compare favorably with the Los Sauces Creek form described by Cushman and Laiming. The Blakeley individuals are flattened.

Uvigerina auberiana d'Orbigny. Sullivan, 1962, p. 277, pl. 16, fig. 1. Hypotype UC 46823, Loc. B-8790, UW 20864, Loc. 1515; pl. 6, fig. 7.

Uvigerina cocoaensis Cushman. Cushman and Schenck, 1928, p. 312, pl. 43, figs. 17-19. Hypotype UC 46824, Loc. D-274, UW 20865, Loc. 1904; pl. 6, fig. 9.

Uvigerinella obesa Cushman *var. impolita* Cushman and Laiming, 1931, p. 111, pl. 12, fig. 11. Hypotype UC 46826, Loc. B-8842; pl. 6, fig. 10.

Vaginulinopsis cf. V. saundersi (Hanna and Hanna) subspecies *lewisensis* Beck. Hypotype UC 46827, Loc. B-8814, pl. 3, fig. 3. A single megalospheric individual appears to be similar to the subspecies from the Cowlitz Formation described by Beck, 1943, p. 598, pl. 105, figs. 3, 13.

Valvulineria araucana (d'Orbigny). Cushman, Stewart, and Stewart, 1947a, p. 20, pl. 3, fig. 1. Hypotype UC 46828, Loc. B-8986; pl. 7, fig. 4.

Valvulineria willapaensis Rau, 1951, p. 447, pl. 66, figs. 23-25. Hypotype UC 46829, Loc. B-8802, UW 20867, Loc. 1587; pl. 7, fig. 1.

Verneuilina aff. V. compressa Andrea. Hypotype UC 46830, Loc. B-8783; pl. 1, fig. 8. A few badly crushed and distorted specimens which resemble *Verneuilina compressa* Andrea in gross character and relative shape of the chambers. *Verneuilina sp.* (?) of Cushman and Hobson, 1935, p. 56, pl. 8, fig. 6, may be conspecific.

Verneuilina sp., Hypotype UC 46831, Loc. B-8783; pl. 1, fig. 9. A single specimen having a coarser textured, less compressed test and more inflated chambers than the forms referred to *Verneuilina aff. V. compressa* Andrea.

PLATE 1

1. *Bathysiphon eocenica* Cushman and Hanna 17X UC Loc. B-8783, Hypotype US 46732.

2. *Haplophragmoides trullissata* (H. B. Brady) 26X UC Loc. B-8792, Hypotype UC 46770.

3. *Haplophramoides sp.* 48X UC Loc. B-8783, Hypotype UC 46771.

4. *Pseudoclavulina communis* (d'Orbigny) 75X UC Loc. B-8797, Hypotype UC 46795.

5a, b. *Cyclammina cancellata* H. B. Brady *var. obesa* Cushman and Laiming 25X UC Loc. B-8811, Hypotype UC 46747.

6. *Cyclammina incisa* (Stache) 27X UC Loc. B-8812, Hypotype UC 46748.

7. *Cyclammina pacifica* Beck 21X UC Loc. D-281, Hypotype UC 46749.

8. *Verneuilina aff. V. compressa* Andrea 40X UC Loc. B-8783, Hypotype UC 46830.

9. *Verneuilina sp.* 40X UC Loc. B-8783, Hypotype UC 46831.

10. *Gaudryina triangularis* Cushman 34X UC Loc. B-8803, Hypotype UC 46762.

11. *Gaudryina sp.* 54X UC Loc. B-8783, Hypotype UC 46763.

12a, b. *Silicosigmoilina kleinpelli n. sp.* 31X UC Loc. B-8888, Holotype UC 46817.

13a, b. *Quinqueloculina imperialis* Hanna and Hanna 25X UC Loc. B-8795, Hypotype UC 46802.

14a, b. *Quinqueloculina minuta* Beck 46X UC Loc. B-8799, Hypotype UC 46803.

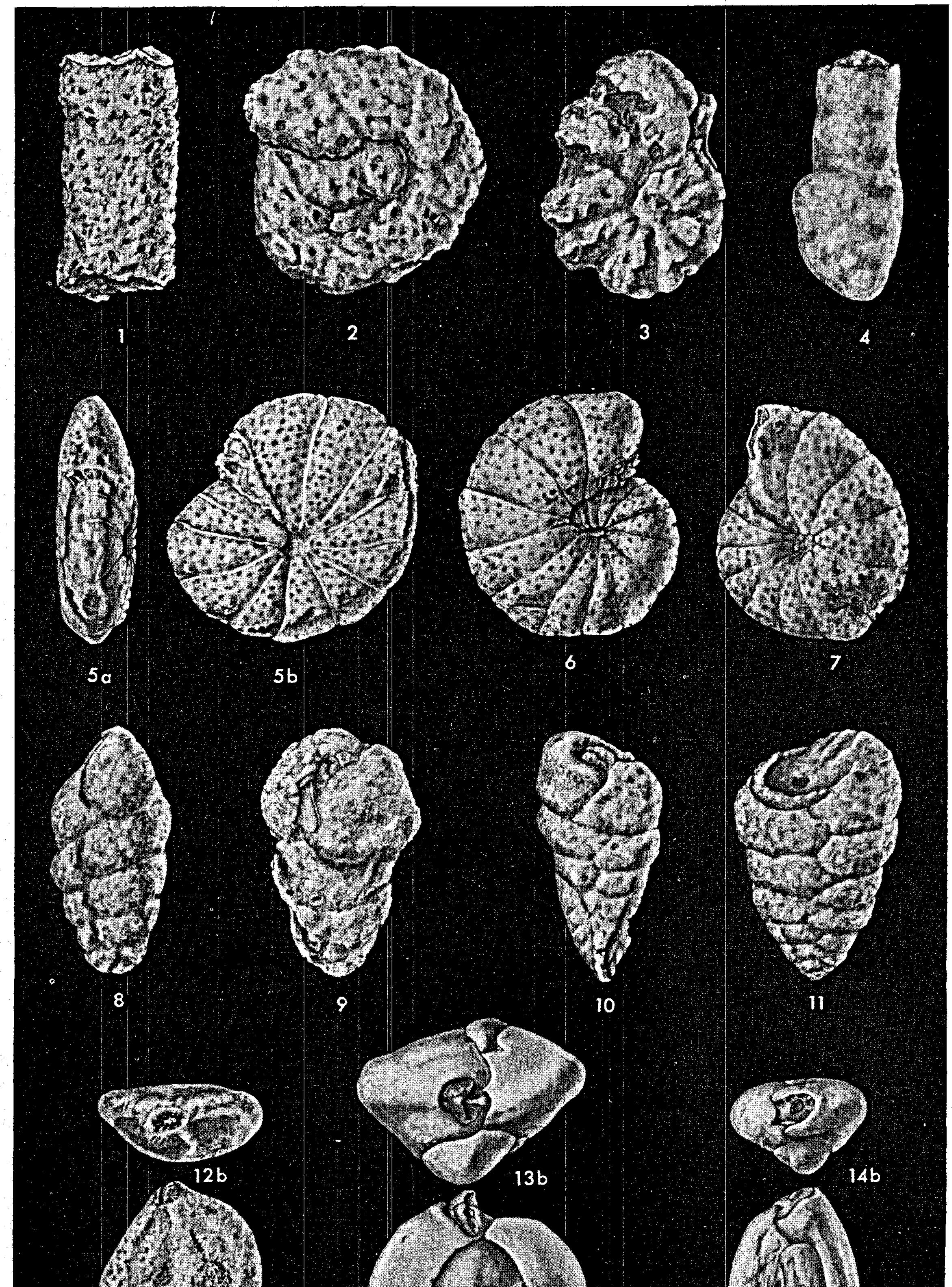

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PLATE 2

1. *Spiroloculina texana* Cushman and Ellisor 63X UC Loc. B-8822, Hypotype UC 46820.

2. *Sigmoilina tenuis* (Czjzek) 86X UC Loc B-8792, Hypotype UC 46814.

3. *Cornuspira byramensis* Cushman 33X UC Loc. D-288, Hypotype UC 46746.

4. *Trochammina cf. T. parva* Cushman and Laiming 54X UC Loc. B-8807, Hypotype UC 46822.

5a, b. *Robulus budensis* (Hantken) 24X UC Loc. D-284, Hypotype UC 46805.

6a, b. *Robulus calcar* (Linne) 54X UC Loc. B-8866 Hypotype UC 46806.

7a, b. *Robulus chehalisensis* Rau 29X UC Loc. D-286, Hypotype UC 46807.

8a, b. *Robulus inornatus* (d'Orbigny) 57X UC Loc. B-9030, Hypotype UC 46808.

9a, b. *Robulus cf. R. miocenicus* (Chapman) 35X UC Loc. B-8985, Hypotype UC 46809.

10a, b. *Robulus warmani* Barbat and von Estorff 46X UC Loc. B-8792, Hypotype UC 46810.

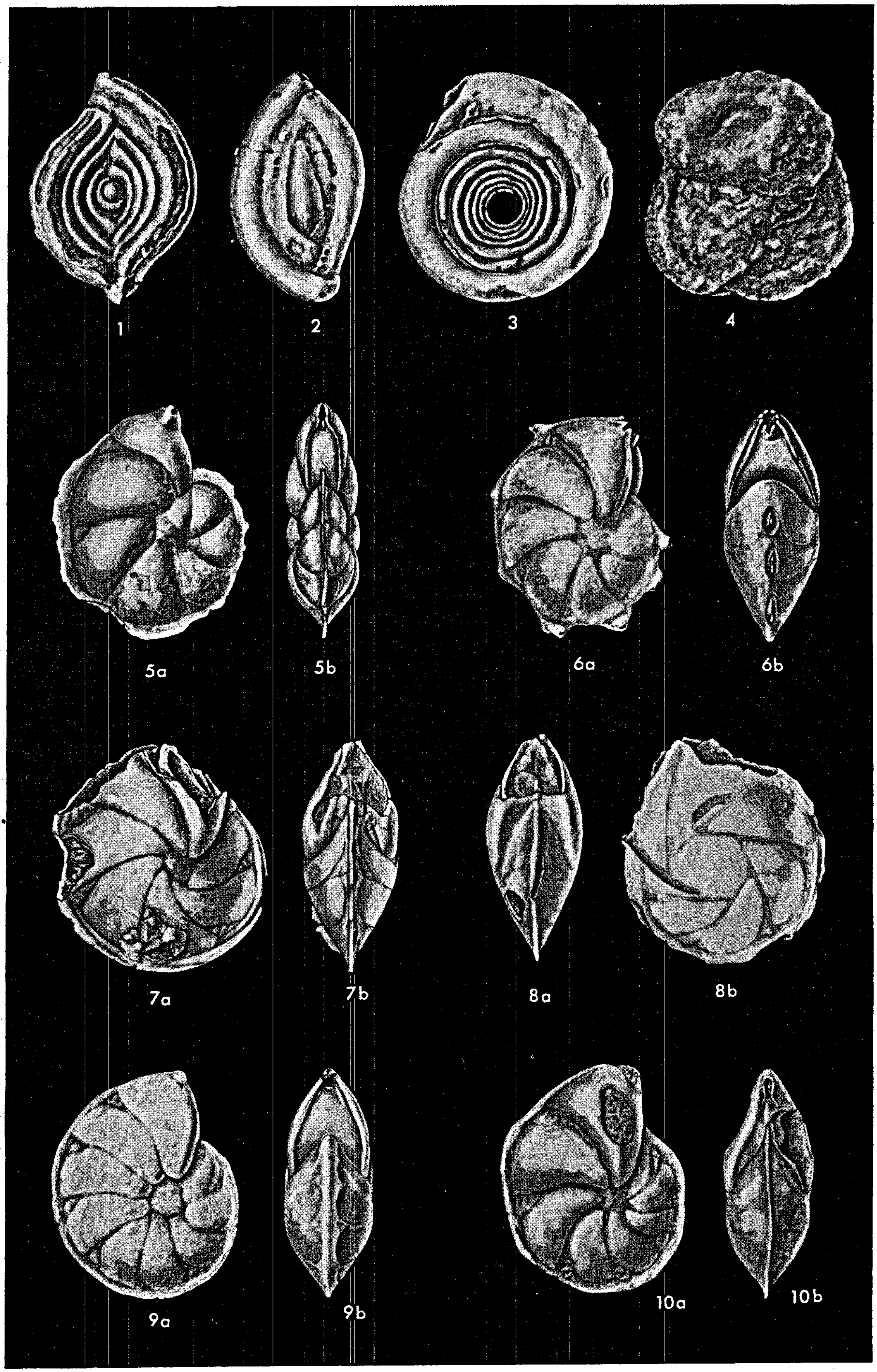
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PLATE 3

1a, b. *Lenticulina convergens* (Bornemann) 54X UC Loc. B-8929, Hypotype UC 46776.

2a, b. *Lenticulina cf. L. crassa* (d'Orbigny) 75X UC Loc. B-8935, Hypotype UC 46777.

3. *Vaginulinopsis cf. V. saundersi* (Hanna and Hanna) subspecies *lewisensis* Beck 57X UC Loc. B-8814, Hypotype UC 46827.

4. *Marginulina subbullata* Hantken 42X UC Loc. B-8865, Hypotype UC 46778.

5. *Marginulina sp.* 120X UC Loc. B-8929, Hypotype UC 46779.

6. *Robulus sp.* 46X UC Loc. B-8949, Hypotype UC 46811.

7. *Dentalina cf. D. consobrina* d'Orbigny 86X UC Loc. B-8788, Hypotype UC 46750.

8a, b. *Saracenaria schencki* Cushman and Hobson 100X UC Loc. B-8940, Hypotype UC 46812.

9. *Dentalina cf. D. pioneerensis* Kleinpell 30X UC Loc. B-8795, Hypotype UC 46752.

10. *Dentalina cf. D. quadrulata* Cushman and Laiming 86X UC Loc. B-8814, Hypotype UC 46753.

11. *Dentalina nasuta* Cushman 23X UC Loc. B-8934, Hypotype UC 46751.

12. *Nodosaria grandis* Reuss 38X UC Loc. D-276, Hypotype UC 46781.

13. *Nodosaria hamilli* Kleinpell 86X UC Loc. B-8976, Hypotype UC 46782.

14. *Nodosaria longiscata* d'Orbigny 18X UC Loc. D-285, Hypotype UC 46783.

15. *Pseudoglandulina inflata* (Bornemann) 66X UC Loc. B-8787, Hypotype UC 46796.

16. *Pseudoglandulina nallpeensis* Rau 57X UC Loc. B-9030, Hypotype UC 46797.

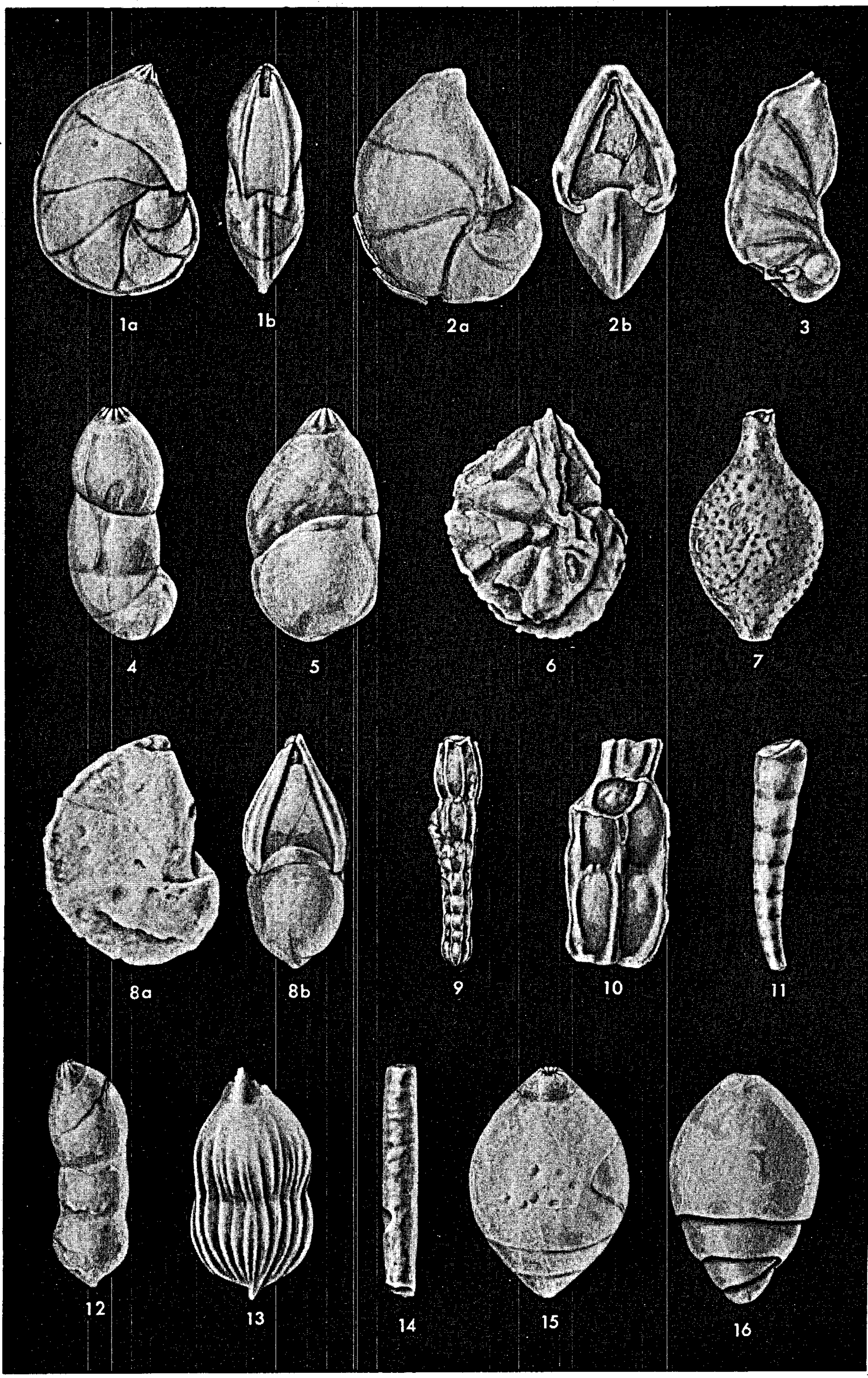
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PLATE 4

1. *Lagena acuticosta* Reuss 150X UC Loc B-8796. Hypotype UC 46772.

2. *Lagena cf. L. laevis* (Montagu) 109X UC Loc. B-8944, Hypotype UC 46773.

3. *Lagena strumosa* Reuss 100X UC Loc. B-8800, Hypotype UC 46774.

4. *Lagena cf. L. substriata* Williamson 92X UC Loc. B-8788, Hypotype UC 46775.

5. *Polymorphina sp.* 34X UC Loc. B-8815, Hypotype UC 46794.

6. *Pseudopolymorphina sp.* 38X UC Loc. B-8942, Hypotype UC 46799.

7a,b,c. *Sigmomorphina undulata* Rau 38X UC Loc. D-276, Hypotype UC 46815.

8a,b,c. *Sigmomorphina schencki* Cushman and Ozawa 54X UC Loc. D-277, Hypotype UC 46816.

9. *Sigmoidina cf. S. pacifica* Cushman and Ozawa 27X UC Loc. B-8786, Hypotype UC 46813.

10. *Guttulina frankei* Cushman and Ozawa 27X UC Loc. B-8795, Hypotype UC 46766.

11. *Guttulina irregularis* (d'Orbigny) 43X UC Loc. D-281, Hypotype UC 46767.

12a, b. *Elphidium minutum* (Reuss) 66X UC Loc. B-8845, Hypotype UC 46754.

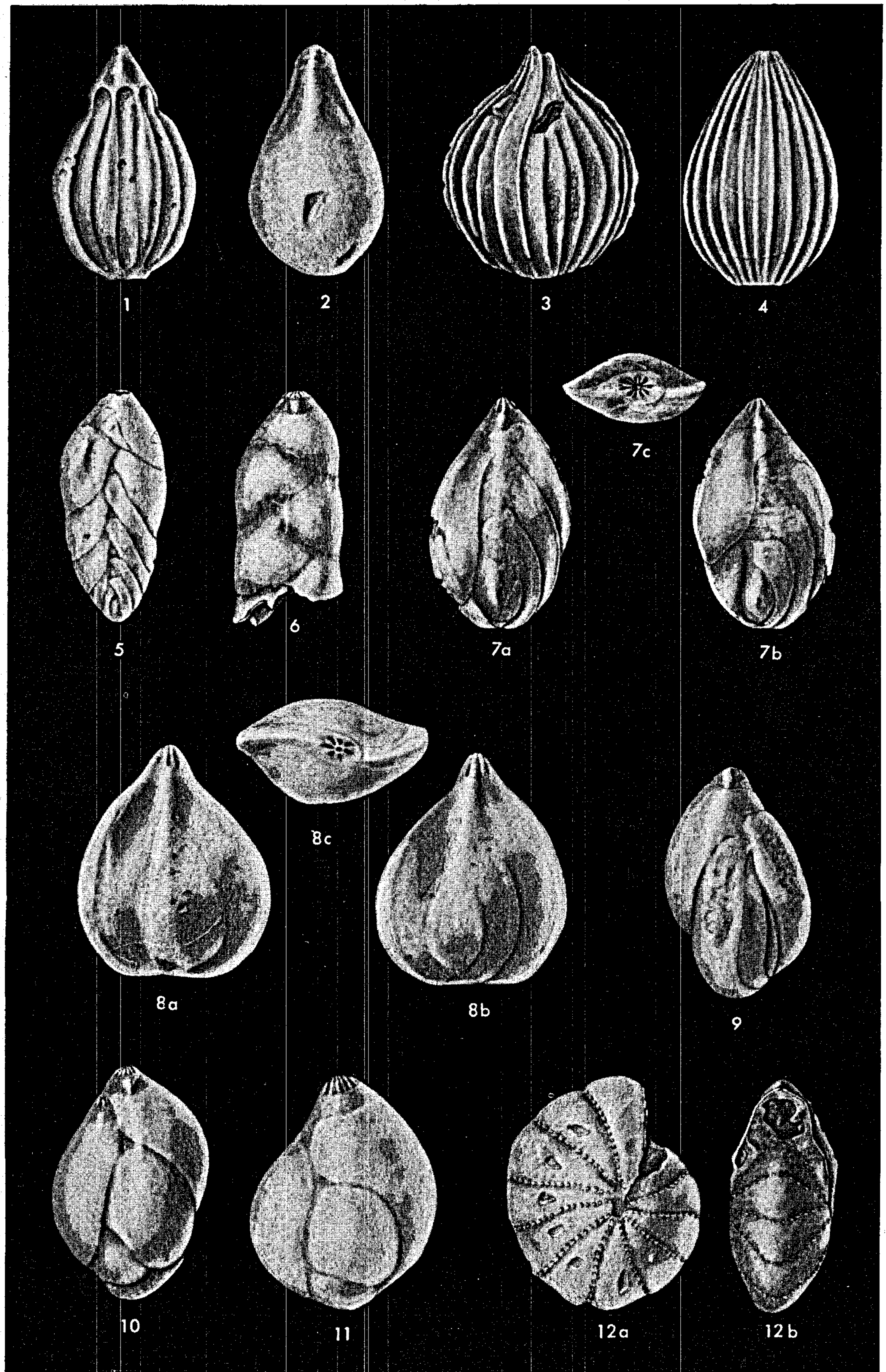
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PLATE 5

1a, b. *Nonion cf. N. affinis* (Reuss) 100X UC Loc. B-8858, Hypotype UC 46784.

2a, b. *Nonion blakeleyensis n. sp.* 86X UC Loc. B-8792, Holotype UC 46785.

3a, b. *Nonion blakeleyensis n. sp.* 86X UC Loc. B-8792, Paratype UC 46832.

4a, b. *Nonion incisum* (Cushman) *var. kernensis* Kleinpell, 75X UC Loc. B-8820, Hypotype UC 46787.

5a, b. *Nonion incisum* (Cushman) 86X UC Loc. B-8820, Hypotype UC 46786.

6a, b. *Nonion pacificum* (Cushman) 66X UC Loc. B-8846, Hypotype UC 46788.

7a, b. *Nonion tuberculatum* (d'Orbigny) 100X UC Loc. B-8792, Hypotype UC 46789.

8. *Nodogenerina sanctaecrucis* Kleinpell 75X UC Loc. B-8866, Hypotype UC 46780.

9. *Plectofrondicularia cf. P. californica* Cushman and Stewart 66X UC Loc. B-8965, Hypotype UC 46790.

10. *Plectofrondicularia miocenica* Cushman *var. directa* Cushman and Laiming 54X UC Loc. B-8818, Hypotype UC 46791.

11. *Plectofrondicularia packardi var. packardi* Cushman and Schenck 75X UC Loc. D-274, Hypotype UC 46792.

12. *Plectofrondicularia vaughani* Cushman 86X UC Loc. B-8866, Hypotype UC 46793.

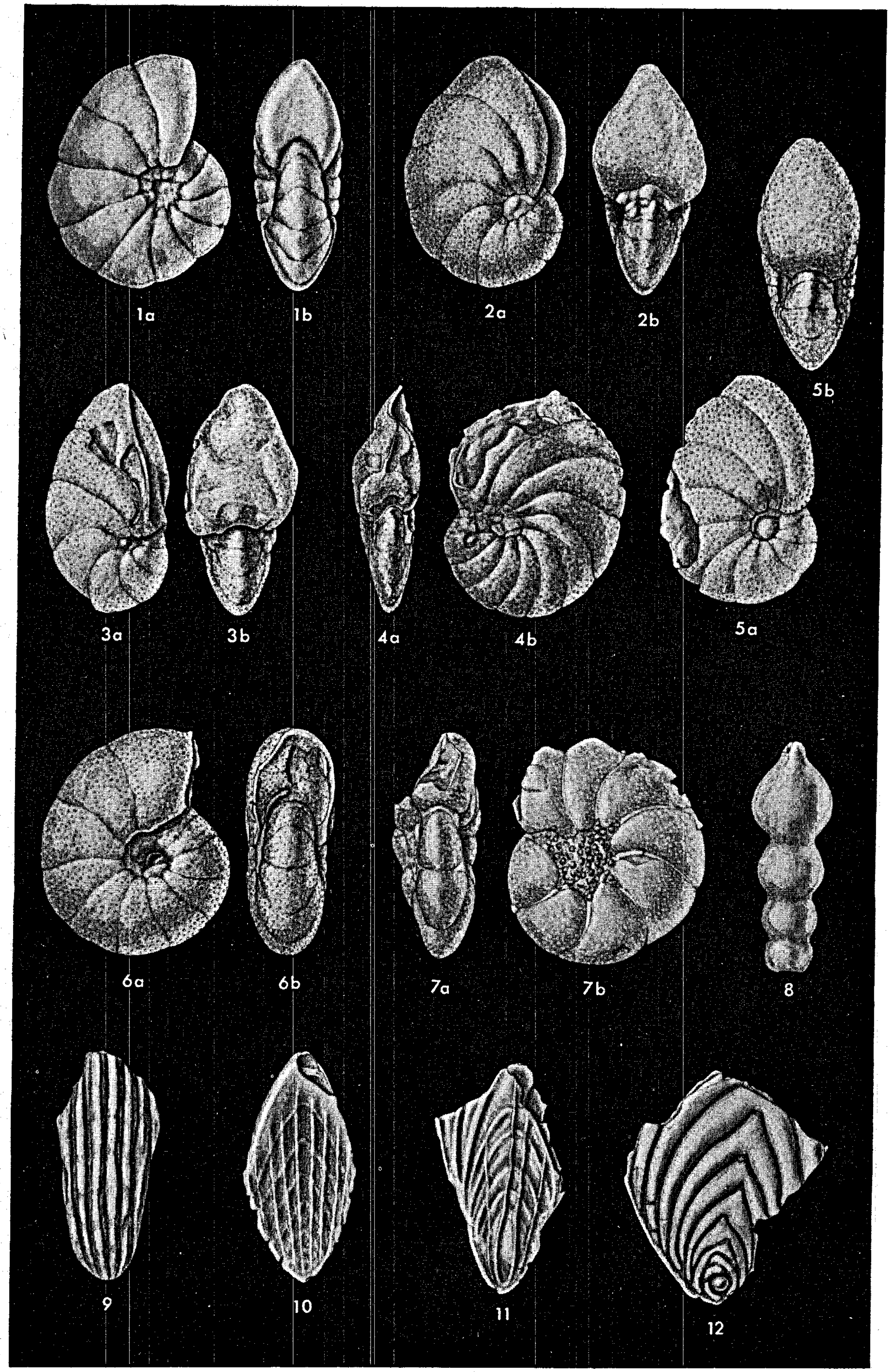
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PLATE 6

1. *Buliminella bassendorfensis* Cushman and Parker 86X UC Loc. B-8827, UC Hypotype 46737.

2. *Bulimina alligata* Cushman and Laiming 80X UC Loc. B-8785, Hypotype UC 46734.

3a,b,c. *Bulimina blakeleyensis n. sp.* 150X UC Loc. B-8827, Hylotype UC 46735.

4a, b. *Robertina cf. R. declivis* 120X UC Loc. B-8800, Hypotype UC 46804.

5a,b,c. *Uvigerina gallowayi* Cushman *var. blakeleyensis n. var.* 60X UC Loc. B-8854, Holotype UC 46825.

6. *Bulimina ovata* d'Orbigny 70X UC Loc. B-8804, Hypotype UC 46736.

7. *Uvigerina auberiana* d'Orbigny 75X UC Loc. B-8790, Hypotype UC 46823.

8. *Entosolenia sp.* 75X UC Loc. B-8789, Hypotype UC 46755.

9. *Uvigerina cocoaensis* Cushman 75X UC Loc. D-274, Hypotype UC 46824.

10. *Uvigerinella obesa* Cushman *var. impolita* Cushman and Laiming 70X UC Loc. B-8842, Hypotype UC 46826.

11. *Siphonodosaria frizzelli* Rau 66X UC Loc. D-278, Hypotype UC 46818

12. *Bolivina marginata* Cushman *var. adelaidana* Cushman and Kleinpell 60X UC Loc. B-8818, Hypotype UC 46733

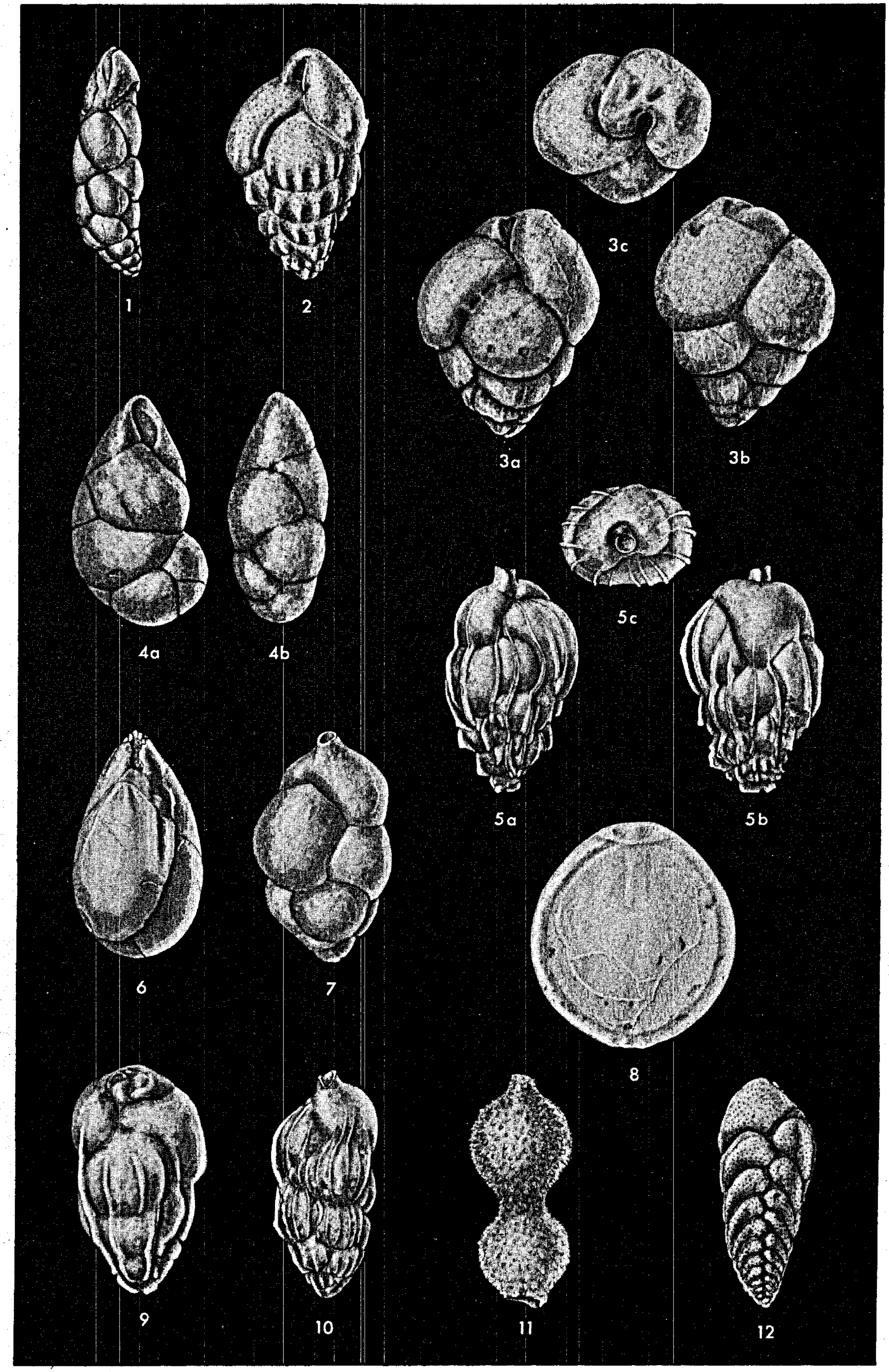
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PLATE 7

1a,b,c. *Valvulineria willapaensis* Rau 50X UC Loc. B-8802, Hypotype UC 46829.

2a,b,c. *Gyroidina condoni* (Cushman and Schenck) 100X UC Loc. B-8843, Hypotype UC 46768.

3a,b,c. *Gyroidina orbicularis* d'Orbigny *var. planata* Cushman 66X UC Loc. B-8795, Hypotype UC 46769.

4a,b,c *Valvulineria araucana* (d'Orbigny) 86X UC Loc. B-8986, Hypotype UC 46828.

5a,b,c. *Eponides healdi* Stewart and Stewart 100X UC Loc. B-8812, Hypotype UC 46759

6a,b,c. *Eponides umbonatus* (Reuss) 86X UC Loc. D-288, Hypotype UC 46761.

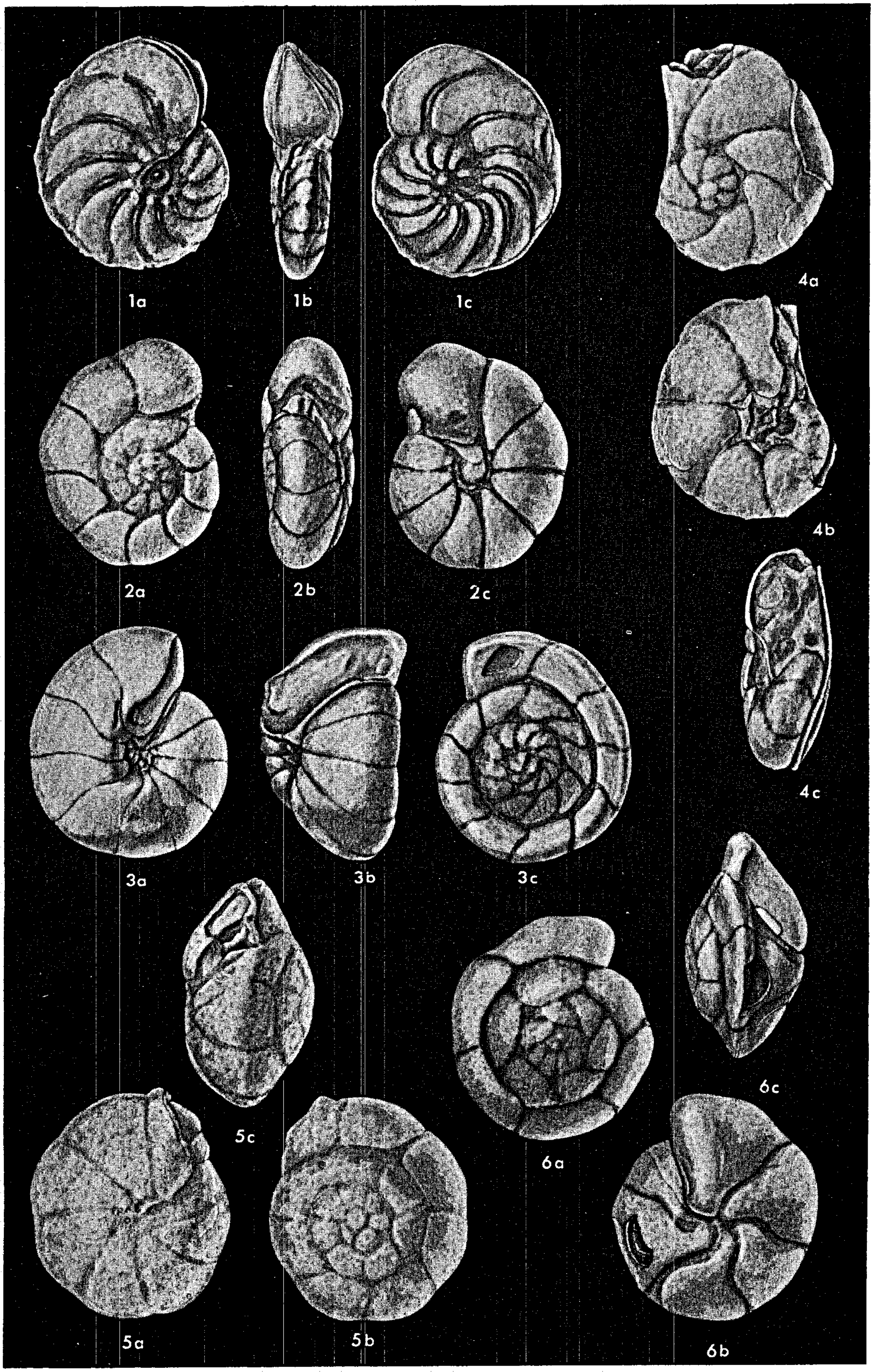
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PLATE 8

1a,b,c. *Eponides gaviotaensis* Wilson 57X UC Loc. B-8812, Hypotype UC 46758.

2a,b,c. *Eponides mansfieldi* Cushman *var. oregonensis* Cushman, Stewart and Stewart 75X UC Loc. B-8842, Hypotype UC 46760.

3a,b,c. *Epistomina eocenica* Cushman and Hanna 46X UC Loc. D-285, Hypotype UC 46756.

4a,b,c. *Epistomina ramonensis* Cushman and Kleinpell 31X UC Loc. B-8866, Hypotype UC 46757.

5a,b,c. *Ceratobulimina washburnei* Cushman and Schenck 60X UC Loc. D-280, Hypotype UC 46743.

6a,b,c. *Pseudoparrella parva* (Cushman and Laiming) 92X UC Loc. B-8865, Hypotype UC 46798.

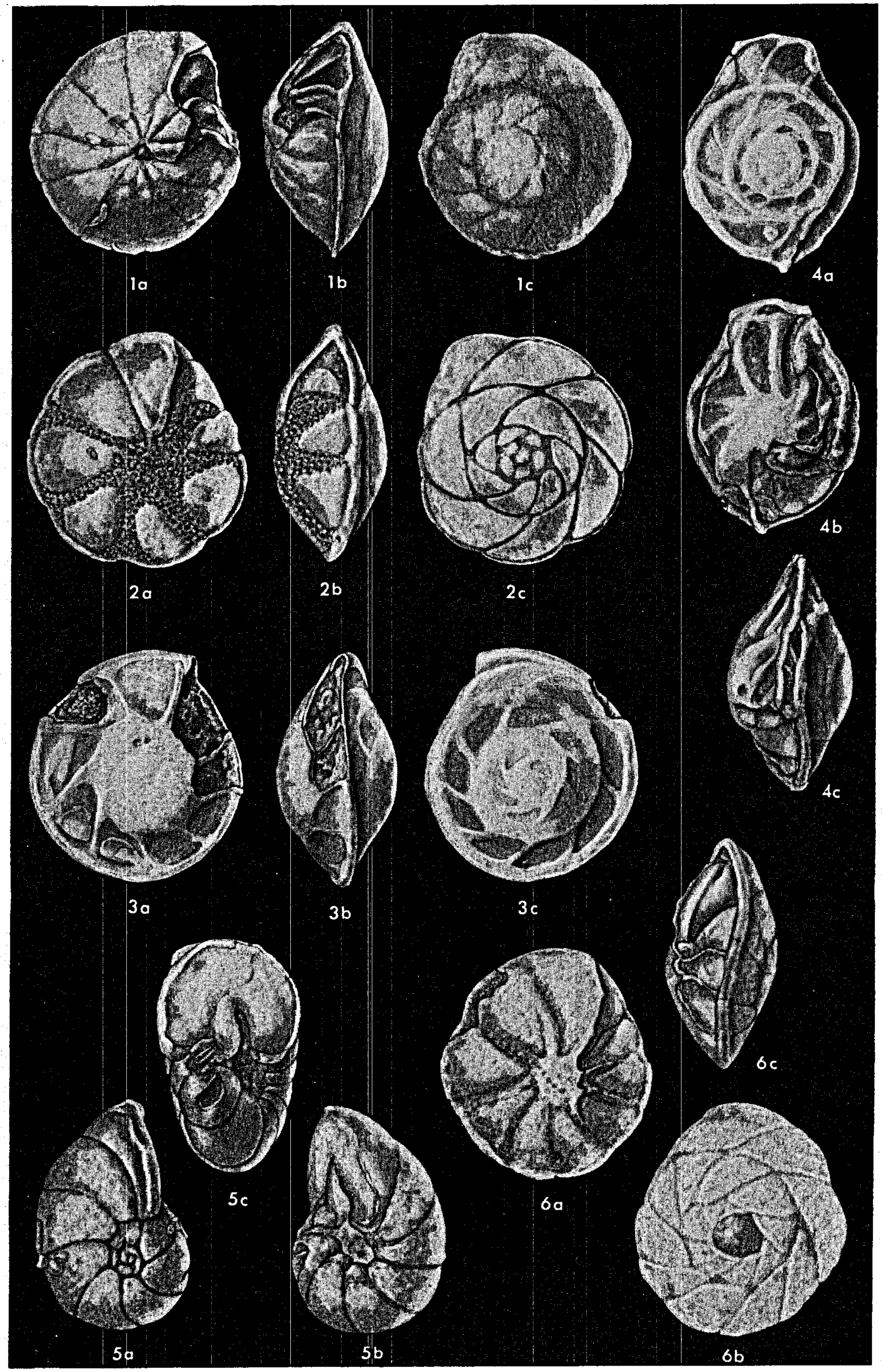
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PLATE 9

1 a, b. *Cassidulina galvinensis* Cushman and Frizzell 75X UC Loc. B-8800, Hypotype UC 46738.

2 a, b. *Cassidulina modeloensis* Rankin 86X UC Loc. B-8795, Hypotype UC 46739.

3 a, b. *Cassidulina cf. C. punctata* Reuss 92X UC Loc. D-283, Hypotype UC 46740.

4 a, b. *Cassidulina subglobosa* H. B. Brady 109X UC Loc. B-8814, Hypotype UC 46741.

5 a, b. *Cassidulinoides sp.* 134X UC Loc. B-8907, Hypotype UC 46742.

6. *Allomorphina cf. A. macrostoma* Karrer 75X UC Loc. B-8807, Hypotype UC 46730.

7 a, b. *Pullenia cf. P. salisburyi* Stewart and Stewart 55X UC Loc. D-285, Hypotype UC 46801.

8. *Chilostomella oolina* Schwager 92X UC Loc. B-8793, Hypotype UC 46744.

9 a, b. *Pullenia quinqueloba* (Reuss) 80X UC Loc. B-8849, Hypotype UC 46800.

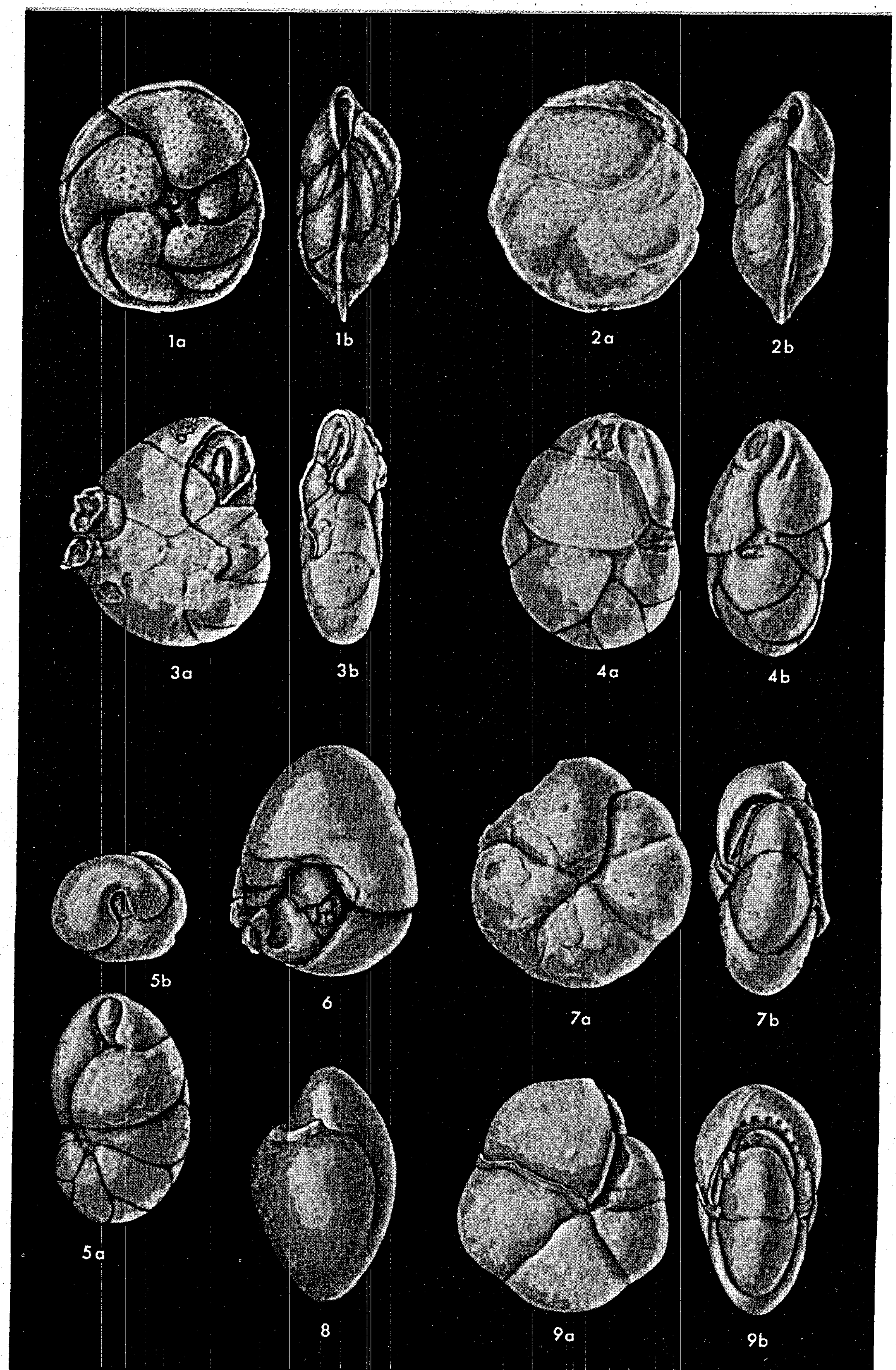
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PLATE 10

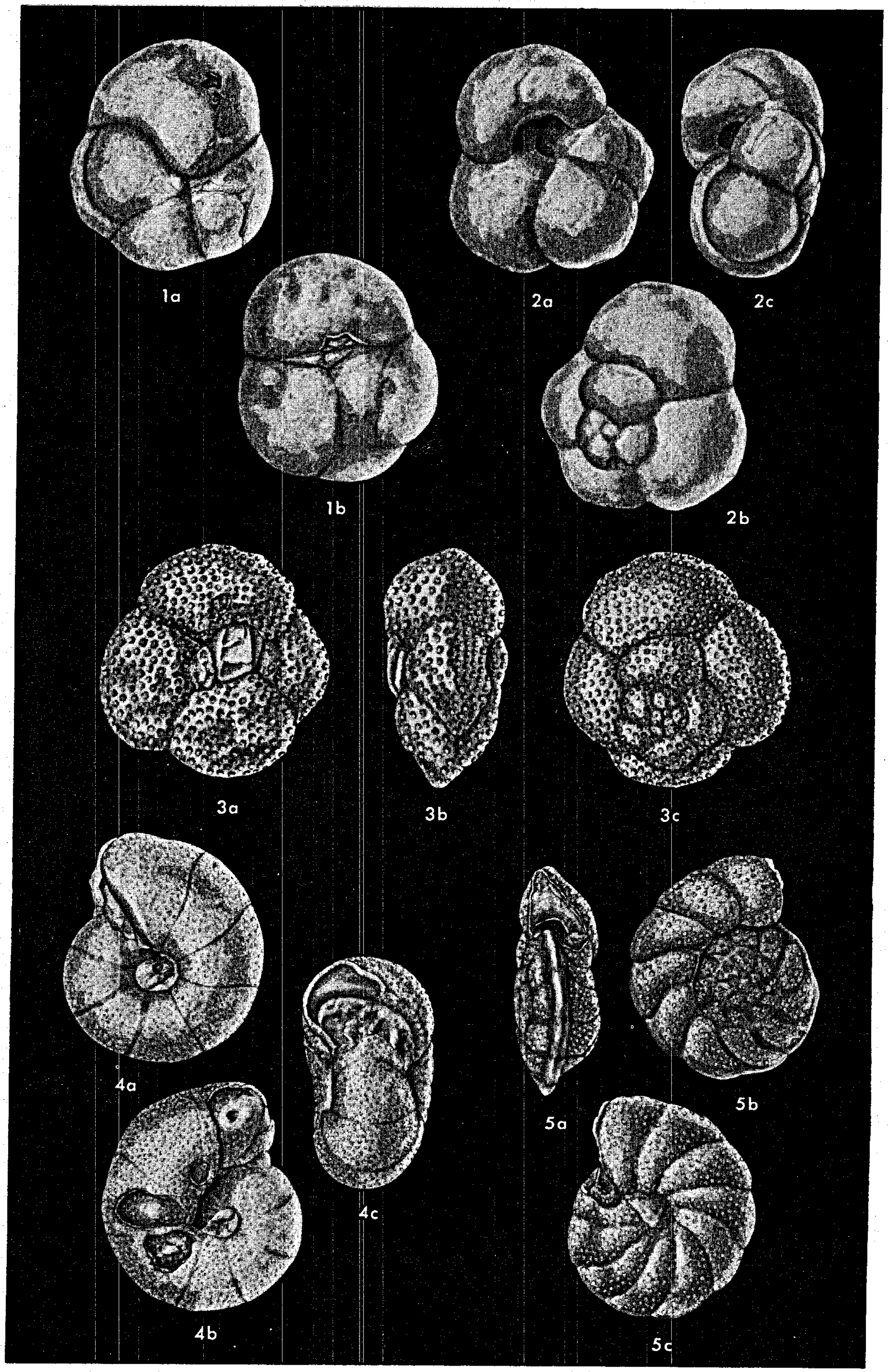
1a, b. *Sphaeroidina variabilis* Reuss 100X UC Loc. B-9003, Hypotype UC 46819.

2a,b,c. *Globigerina bulloides* d'Orbigny 93X UC Loc. B-8800, Hypotype UC 46764.

3a,b,c. *Globigerina conglomerata* Schwager 86X UC Loc. B-8803, Hypotype UC 46765.

4a,b,c. *Anomalina californiensis* Cushman and Hobson 66X UC Loc. B-8786, Hypotype UC 46731.

5a,b,c. *Cibicides elmaensis* Rau 60X UC Loc. B-8842, Hypotype UC 46745.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Middle Eocene Paleogeography of Southern California

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ABSTRACT

The onshore and offshore topography of the middle Eocene areas of the Santa Ynez, San Rafael, Topatopa and Orocopia Mountains were characterized by high relief. The offshore areas deepened from the coast to bathyal regions over a short distance. The Santa Monica Mountains and Simi Hills areas were characterized by a broad low-relief shelf environment. Paralic and coastal delta environments are suggested by middle Eocene rocks along the west side of the Peninsular Range. In the San Diego area, middle Eocene rocks indicate from east to west successive fluvial, coastal delta, and steeply inclined submarine canyon environments.

Post-Eocene right-lateral faulting in the southern California Borderland apparently has separated once contiguous strata such as the middle Eocene bathyal-fan rocks (including the Poway-like conglomerate exposed on San Nicolas, Santa Cruz and San Miguel Islands, and in the subsurface on Santa Rosa Island) from continental, shallow-marine and submarine canyon rocks in the San Diego area.

The middle Eocene mainland coast extended northwestward along the west flank of the Peninsular Range to the west Sierra Nevada. A large east-trending embayment indented this coastline toward the present site of the Orocopia Mountains. Shoal areas were also present north of the present Transverse Ranges against the emergent San Rafael high.

INTRODUCTION

Middle Eocene strata crop out over a wide area of southern California that can be informally subdivided into six regions (Fig. 1). A brief account of the middle Eocene geologic history for each of the designated six regions is given below. The middle Eocene, for purposes of this report, is considered to be equivalent to the Ulatisian Stage of Mallory (1959) and is inferred to be nearly 3 million years in duration, from approximately 46-49 m.y. B.P. Figure 2 is a correlation chart for the principal middle Eocene rock units of southern California.

Significant paleogeographic changes may have occurred in a given area during middle Eocene time, but owing to the basic limits in the precision of biostratigraphic correlation only generalized paleogeographies are reconstructed and interpolated on an interregional basis. In order to delineate the middle Eocene paleogeography of southern California from paleontologic and lithologic analyses, the following palinspastic adjustments were made: 210 km (kilometres) of right-slip along the San Andreas fault, 50 km of right-slip along the San Gabriel fault, 15 km of left-slip along the Big Pine and Santa Ynez faults, 90 km of left-slip on the Malibu Coast fault system, and 180 km of right-slip along the postulated East Santa Cruz Basin fault system.

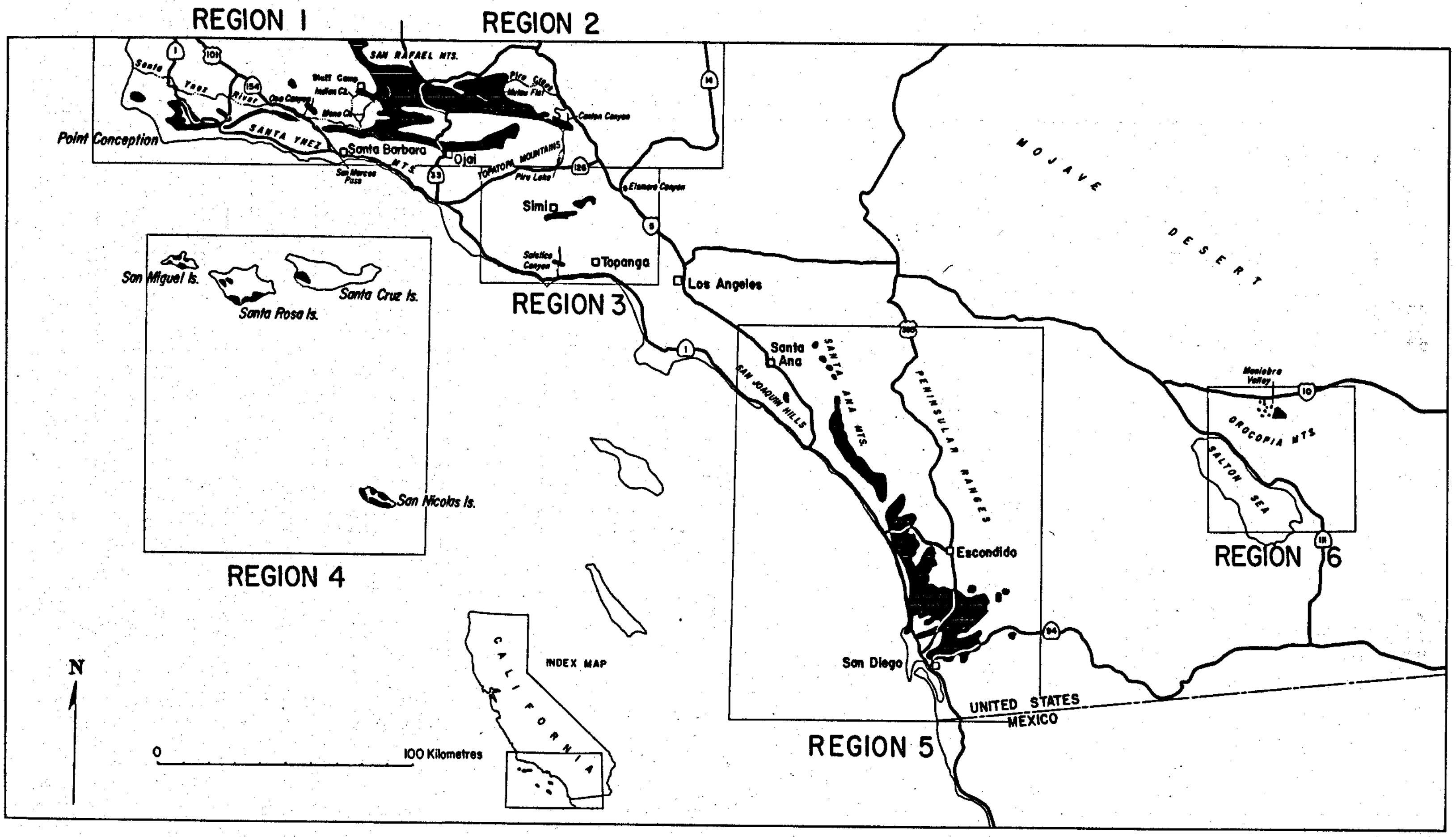

Figure 1. Six regions of basin analysis within southern California. All known outcrops of middle Eocene strata of southern California, south of the Big Pine fault, lie within these six regions.

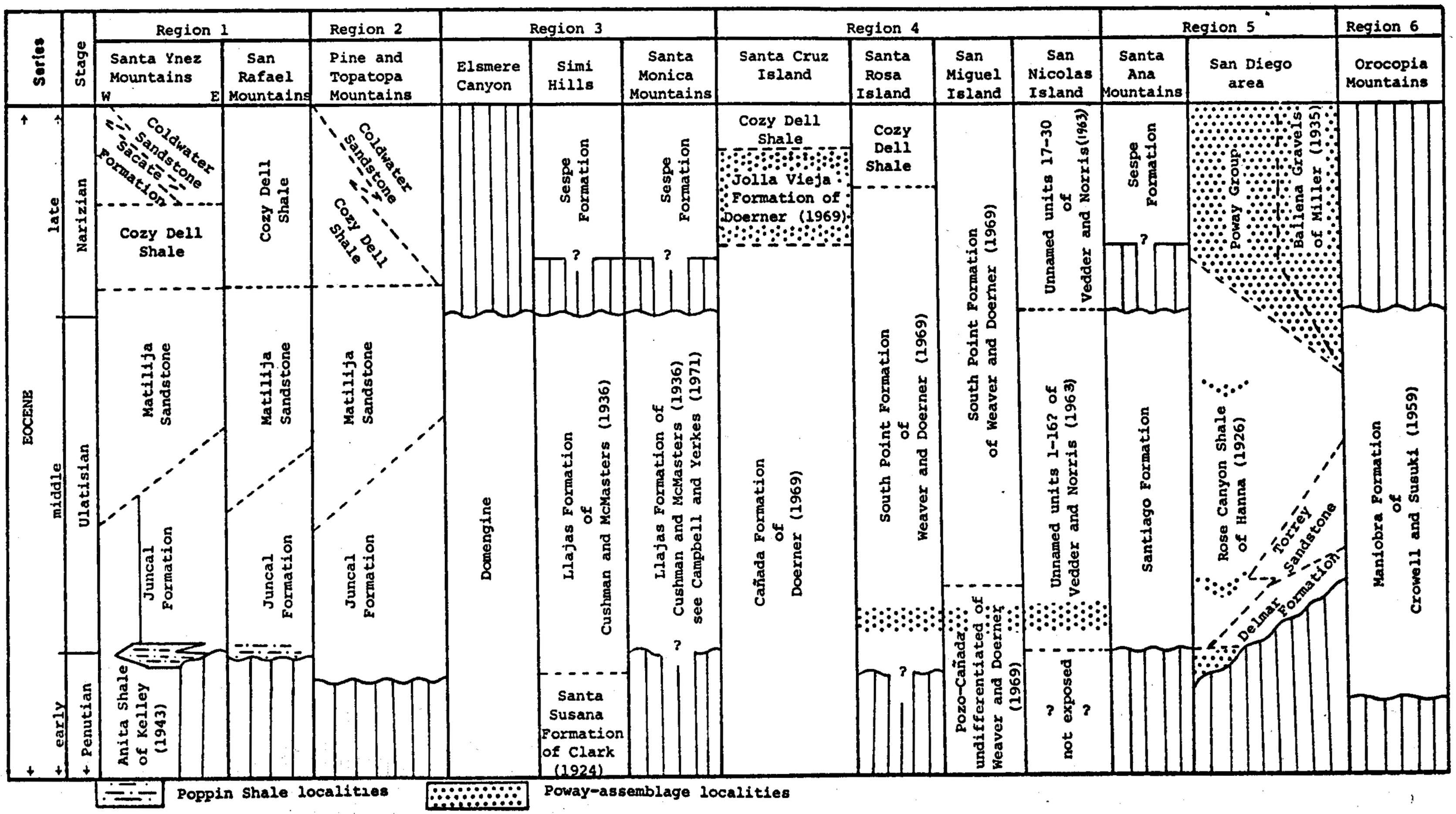

Figure 2. Correlation chart of middle Eocene strata of southern California.

BASIN ANALYSIS

Santa Ynez and southern San Rafael Mountains (region 1 of Fig. 1)

Lithology and environment of deposition. The base of the middle Eocene of the western Transverse Ranges is marked by the Poppin shale of Dibblee (1950, p. 26) which is a massive red and green mudstone in the upper part of the Anita shale as defined by Kelley (1943). In the western Santa Ynez Mountains, the Poppin shale grades upward into massive black to dark-gray mudstone and bedded siltstone of the upper part of the Anita shale which contains a few local fine-grained, thin- to medium- bedded sandstone layers. The general lack of internal structures within these strata combined with their fine-grained texture of the sediment suggests a low energy environment of deposition. The Matilija Sandstone overlies the Anita shale and is a medium- to very thick bedded fine- to medium-grained arkose and lithic arkose. Interbeds of micaceous mudstone increase in abundance up section, so that the top of the Matilija is gradational with the overlying shale and siltstone beds of the late Eocene Cozy Dell Shale.

Foraminiferal assemblages from these middle Eocene beds suggest an upper bathyal to lower neritic environment of deposition (Weaver, 1962; Weaver and Weaver, 1962; Weaver and Molander, 1964). The marine basin within this area shoaled to the north against Mesozoic granitic, Franciscan metamorphic, and Lower and Upper Cretaceous sedimentary rocks.

The middle Eocene sequence of the east Santa Ynez Mountains differs from the sequence to the west. East of the San Marcos Pass, the Juncal Formation is divided into three members: the lower member is principally a siltstone; the middle member, the Camino Cielo Sandstone of Page and others (1951), is an interbedded sandstone and siltstone sequence; and the upper member is principally siltstone with a few sandstone interbeds. The fine-grained facies of the Juncal are massive- to thin-bedded, graded units. Stauffer (1967) refers to the Juncal as a flysch sequence.

Graded bedding occurs in more than 50 percent of the beds in the Camino Cielo Sandstone Member. The sandstone is generally medium- to thick-bedded medium-grained micaceous lithic arkose. The thicker beds show evidence of amalgamation of two or more thinner sandstone beds. The graded bedding, lutite interbeds, and sole markings suggest a turbidite origin of deposition for these flyschlike beds.

The upper member is fine-grained and resembles the lower member. Paleocurrent data indicate a predominant west to southwest flow direction, with a more south to southeast trend for the upper member.

The Matilija Sandstone of the east Santa Ynez Mountains is a medium- to thick-bedded medium- to coarse-grained arkose and lithic arkose. Within its lowest part thin- to medium-bedded, graded units similar to those of the Juncal Formation are present, but most sandstone beds in the Matilija are ungraded. The overall structureless nature of the massive, often amalgamated beds in the Matilija Sandstone is characteristic of grain-flow deposits (Stauffer, 1967). In the middle part of the Matilija in the same area, channeling, erosional contacts, and both large and small-scale cross beds are present. Fossil mollusks and benthonic foraminifers indicate a shoaling condition (Link, 1971). The upper part of this formation becomes more flyschlike with lutite interbeds increasingly abundant up section. Paleocurrent data from the Matilija indicate sediment transport principally to the west and southwest (Link, 1971). The Matilija grades into the massive shale and siltstone beds of the late Eocene Cozy Dell Shale.

In the south San Rafael Mountains, north of the east Santa Ynez Mountains middle Eocene deposition began locally within the Poppin shale here occurring at the base of the Juncal Formation but the section consists principally of medium- to coarse-grained arkose and lithic arkose interbedded with thin- to medium-bedded siltstone. The flyschlike character of these rocks, the graded bedding, and abundant sedimentary structures suggest a turbidite origin. The sediment dispersal pattern was diverse, though a southwest-flowing system was dominant. Middle Eocene foraminifers from the San Rafael Mountains indicate open ocean conditions and deposition in moderate water depth equivalent to outer shelf and/or upper slope depths (Bukry, Brabb and Vedder, 1973; A. Tipton Donnelly, written commun., 1974).

Paleogeography. The distribution and lithofacies of the middle Eocene rocks of region 1 indicate that the marine environment shoaled northwestward against the emergent San Rafael high (Reed and Hollister, 1936), which was bounded on the south by an east-west-oriented basin and on the east by a northwest-oriented marine embayment. Middle Eocene rocks of the San Rafael Mountains indicate the presence of coalescing bathyal fans that prograded south and southwest. Rocks in the east Santa Ynez Mountains reflect an area of fan/delta systems prograding westward, whereas those in the west Santa Ynez Mountains reflect grain-flow deposition from the north. Figure 3 schematically represents this paleogeographic setting.

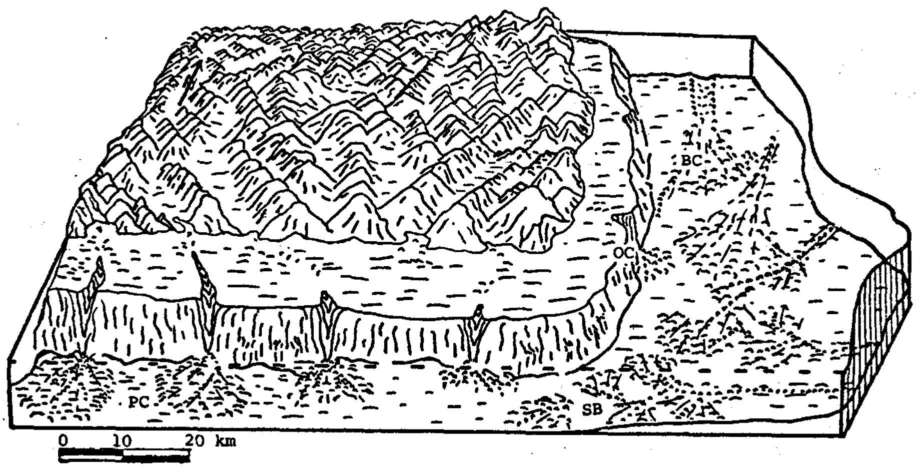

Figure 3. Middle Eocene paleogeographic reconstruction of region 1, geographic reference points are: PC = Point Conception, SB = Santa Barbara, BC = Bluff Camp, OC = Oso Canyon.

Topatopa and Pine Mountain areas (region 2 of Fig. 1)

Lithology and environment of deposition. The distribution of middle Eocene exposures in region 2 shown on figure 1 is only approximate owing to the paucity of biostratigraphic data. Within the area designated, there are three general lithofacies: principally siltstone with minor amounts of sandstone (facies 1), principally massive sandstone with minor thin- to medium-bedded sandstone and siltstone (facies 2), and massive conglomerate (facies 3).

Lithofacies 1, above, has been mapped as the Juncal Formation by Dickinson (1969), Vedder, Brown and Dibblee (1973), and Givens (1974) and as part of the Piru Formation by Kriz (1955). These strata form the oldest middle Eocene beds, and in part may be as old as early Eocene.

Stratigraphically above the oldest conglomeratic unit in the lower Piru Creek area is approximately 2,800 m (metres) of principally massive black to dark-yellowish calcareous siltstone. A lens-shaped unit of massive conglomerate that is 700 m thick is present within this siltstone. The conglomerate wedges out eastward within a short distance and is not present in Canton Canyon where the siltstone is 3,100 m thick.

Westward, in the Mutau Flat area, 5,000 m of shale, siltstone and conglomerate locally lies unconformably upon the granite basement (Schlee, 1952). The thickness of the mudstone is variable but reaches a maximum of 2,700 m (Kiessling, 1958). The fine-grained facies is increasingly coarser grained north and northwest of Mutau Flat; there, it is less massive and is interbedded with thin- to thick-bedded fine- to medium-grained arkosic sandstone. In the south part of region 2, the fine-grained facies is mapped as the Juncal Formation (Jestes, 1963), which consists of 300-500 m of shale and siltstone with interbedded thin- to thick-bedded fine- to coarse-grained arkosic sandstone. These beds are generally graded and have been interpreted to be turbidite deposits with flow in a west-southwest direction (Stauffer, 1967).

Facies 2, the massive sandstone with minor amounts of thin- to medium-bedded sandstone, overlies the fine-grained facies. The Matilija Sandstone is the most characteristic and best known formation representative of this sandstone facies. The largest outcrops of massive sandstone are in the south and northwest part of region 2. The sandstone is mostly fine- to medium-grained fair- to well-sorted thin- to massive-bedded (mostly thick-bedded) arkose. Using orientation of sedimentary structures, Jestes (1963) infers northwest, west, southwest and south transport directions.

The conglomerate, lithofacies 3, of region 2 is restricted to the east area with exposures surrounding the granitic basement complex of the Piru Creek drainage. Near Mutau Flat there are five distinct wedge-shaped conglomerate units with a maximum aggregate thickness of 1,250 m (Kiessling, 1958). The conglomerate units thin abruptly to the west and southwest and wedge out within 5 km from the granitic basement. The contact between Eocene beds and the granitic basement is at places faulted, but the separation probably is minor. There are a number of places where conglomerate rests unconformably upon this basement. At one place north of Mutau Flat, a wedge of conglomerate several hundred metres wide and about 10 m thick lies unconformably on the basement (Schlee, 1952). Just south of this locality at the northwest corner of Mutau Flat angular, 3-m-thick granitic "joint" clasts of the local basement are admixed with well rounded granitic, volcanic, and quartzitic clasts. The pebbles and cobbles of the Mutau Flat area are composed of: granite and granodiorite (30-40 percent); gneiss (10-15 percent); quartzite (10-15 percent); gray, green, and red volcanic material (20-35 percent) and sandstone (5-15 percent). Channeling and clast imbrications suggest that the material was deposited by currents flowing toward the south and southwest.

Farther to the east in the lower Piru Creek area, 1,000 m of conglomerate is in fault contact with the granitic basement (Kriz, 1947; Sage, 1973). Above this conglomerate unit in sequential order are 1,600 m of shale and siltstone, 650 m of conglomerate, 1,200 m of shale and siltstone, and 1,000 m of medium-bedded flyschlike sandstone. The conglomerate clasts are composed of granite-granodiorite (20-50 percent); gneiss (10-20 percent), quartzite (0-10 percent), and gray, green, red and purple volcanic material (40-60 percent).

A few clasts are as large as 3 m, but most range from 1 cm to 1.5 m. All clasts larger than 0.5 m are composed of granite and gneiss. The dimensional pattern of the conglomerate is unknown, although a lens shape is suggested as 4 km to the east, along strike in Canton Canyon, no conglomerate crops out. These relations suggest a high-energy environment of deposition, possibly a paleo-submarine canyon or a channel in an upper fan complex.

Paleogeography. The thick, wedge- and lens-shaped conglomerate units and the buttress unconformities near the Mutau Flat, Sespe Hot Springs, and lower Piru Creek areas indicate that the upper Piru Creek drainage area was a high-relief source terrane during the early(?) and middle Eocene (Kriz, 1947; Kiessling, 1958). The shoreline between Mutau Flat and lower Piru Creek is inferred to have trended approximately east-west on the basis of: (1) the distribution of the conglomerate facies, (2) the location and orientation of basal unconformities, and (3) inferred southward paleotransport directions.

The paleocurrent data demonstrate a general south to southwest transport direction for most of the clastic debris for this region. Paleocurrent data from the Matilija Sandstone in the southern part of this region, however, indicate west and northwest flow direction. To the south in region 3, middle Eocene rocks and fossils indicate shelf conditions without local source areas. The isopach map of Eocene strata, for the south part of region 2 (Fig. 4), shows a thick east-west trend. Elsewhere in region 2, the data indicate a source terrane to the north and northeast. It is therefore suggested that the Matilija Sandstone originated from a northeast source terrane and was dispersed to the south

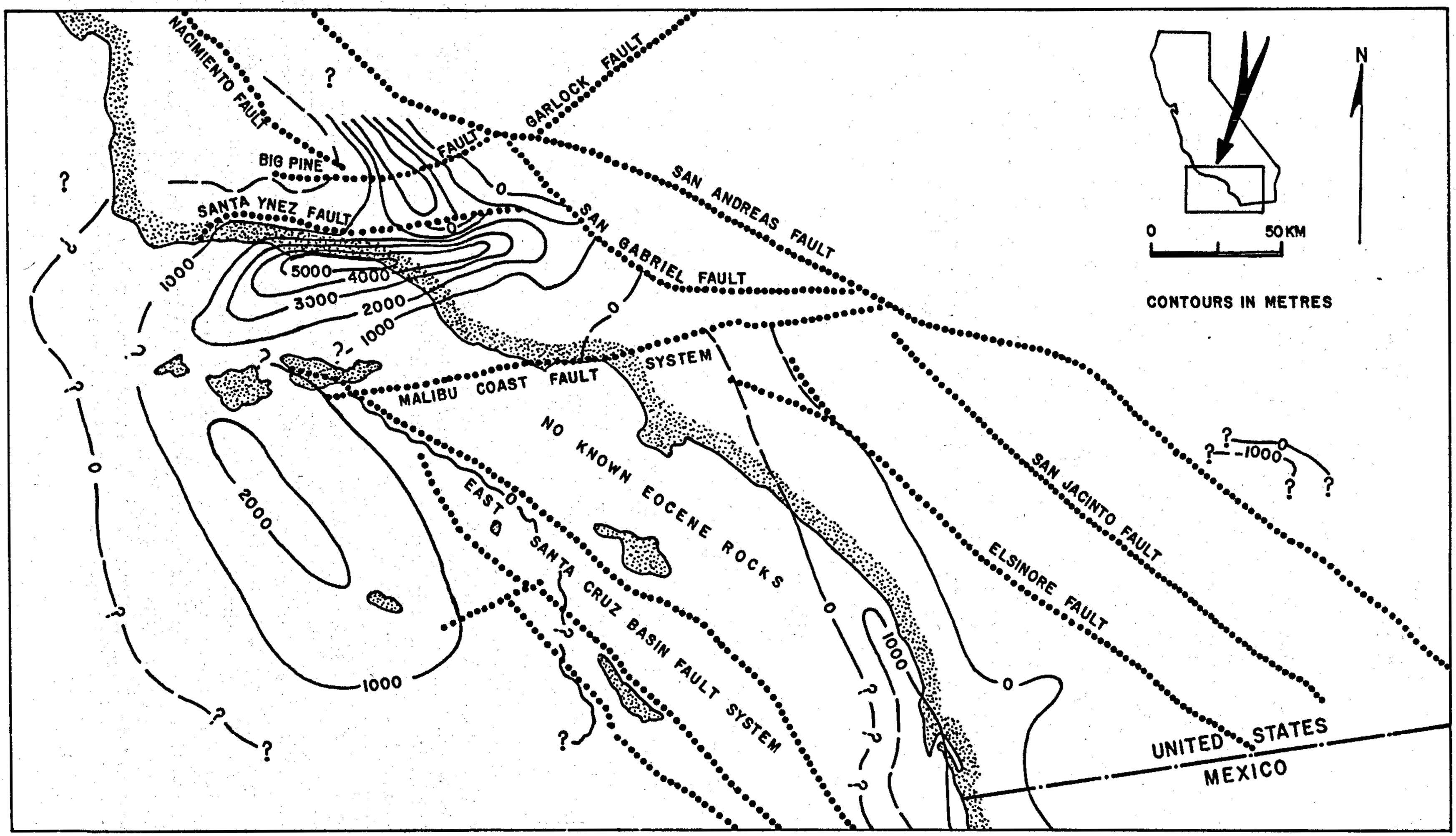

Figure 4. Isopachous map of Eocene strata in southern California. Thick isopachous lines represent shoreline pinch-outs; thin zero isopachous lines are pinch-outs due to post Eocene diastrophism, and the wavy zero isopachous line in the borderland is an inferred depositional onlap pinch-out. Data modified from Woodring and Popenoe (1945), Dibblee (1950), Weaver and others (1969), Crawford (1971), Kennedy and Moore (1971), Nagle and Parker (1971) and Parker (1971).

into an east-west-oriented basin in which flow directions were west and northwest (Fig. 5).

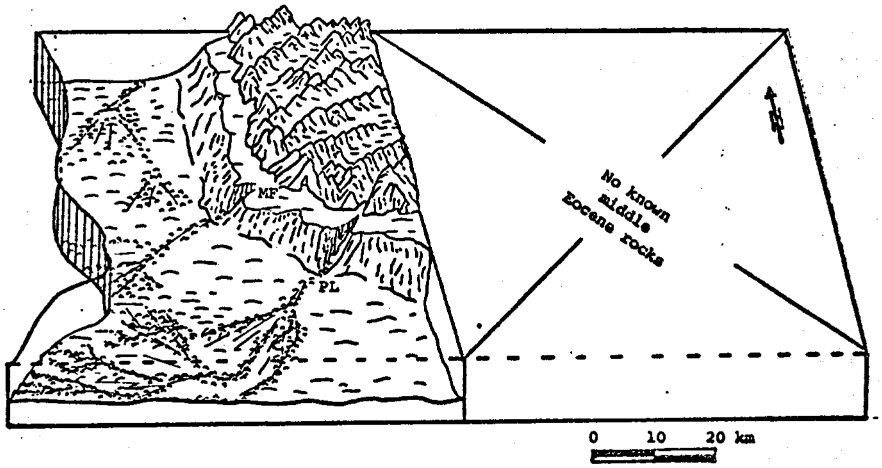

Figure 5. Middle Eocene paleogeographic reconstruction of region 2. Geographic reference points are: MF = Mutau Flats, PL = Piru Lake.

Simi Valley, Elsmere Canyon, and Santa Monica Mountains (region 3 of Fig. 1)

Lithology and environment of deposition. In the Simi Valley area stratigraphically above the lower Eocene conglomerate of the Llajas Formation of Cushman and McMasters (1936) is a mudstone that contains abundant mollusks especially of Turritella. Prominent at many horizons in the mudstone are discocyclinids indicative of tropical shelf seas. Also, numerous concretionary layers are present within the mudstone and commonly contain concentrated (transported) megafossil shell debris. The fossils in the shell debris represent upper shelf-littoral organisms. The shell fragments probably accumulated in broad depressions or channel bottoms within their habitat range. Glauconitic sandstone is also common in this interval.

The upper part of the Llajas Formation is composed of alternating mudstone and sandstone in which the sandstone crops out in beds 4-10 m thick. The sandstone is fine- to coarse-grained arkose and lithic arkose with a few lenses containing 0.5 to 1.5 cm pebbles. Bishop (1950) reports some sandstone beds to be "almost pure quartz". Large scale cross bedding is rare, but where present, it indicates flow to the west. These data suggest that the Llajas Formation was deposited in shallow marine conditions.

Very limited exposures of possible middle Eocene strata occur in Elsmere Canyon. These strata consist of medium- to coarse-grained massive arkose and lithic arkose with a basal cobble conglomerate containing anorthosite and gneissic material that is in composition similar to a conglomerate reported directly below the possibly middle Eocene shales in Continental Oil Company's Well, Phillips No. 1 (Oakeshott, 1958). This conglomerate is compositionally similar to basement rocks of the San Gabriel Mountains lying to the east (Oakeshott, 1958).

In the Santa Monica Mountains is 400 m of Eocene strata that in part may be middle Eocene in age (Yerkes, oral commun., 1974). The lowest stratum is an interbedded coarse-grained arkose and conglomerate sequence, in which clast size ranges from 0.5 to 20 cm. Granitic, gneissic, and volcanic clasts are the most abundant, with minor amounts of quartzite. The sequence is about 25 m thick in the easternmost exposure, but it thins abruptly westward.

Above the conglomerate is a sequence of thin- to medium-bedded siltstone and sandstone. The sandstone siltstone ratio is about 2:1 in the east area and decreases to about 1:1 in the west area. Near the top of the formation, a gray bioturbated siltstone and very fine grained sandstone crops out. These strata are similar to beds near the top of the Llajas Formation in Simi Valley.

The decrease in abundance of conglomerate and sandstone from east to west suggests a possible westward-flowing dispersal system. According to Yerkes (written commun., 1973), the habitats of modern analogs of the fossil genera from Eocene rocks on the Santa Monica Mountains, occupy a shallow marine environment, "low tide to about 50 fathoms".

Paleogeography. Although data that permit a paleogeographic reconstruction for region 3 are sparse, several conditions are consistent: (1) all reported fossils are shelf-inner shelf marine organisms, (2) everywhere there is evidence of a marine regression culminating in the deposition of the nonmarine Sespe Formation, the lower part of which is late Eocene in age, (3) all sediment transport directions suggest westward flow, and (4) conglomerate clasts have affinities to basement terranes to the east. Therefore, an upper shelf-coastal environment of deposition is inferred with shoaling to the east (Fig. 6). The data from region 2 suggest that the north part of region 3 may have been an area of higher energy deposition that fluctuated in depth through time (Link, 1971; Jestes, 1963). In region 3 in the Simi Hills-Santa Monica Mountains area the conditions remained shallow marine throughout the middle Eocene and gave way to nonmarine environments, advancing from the east, by late Eocene time.

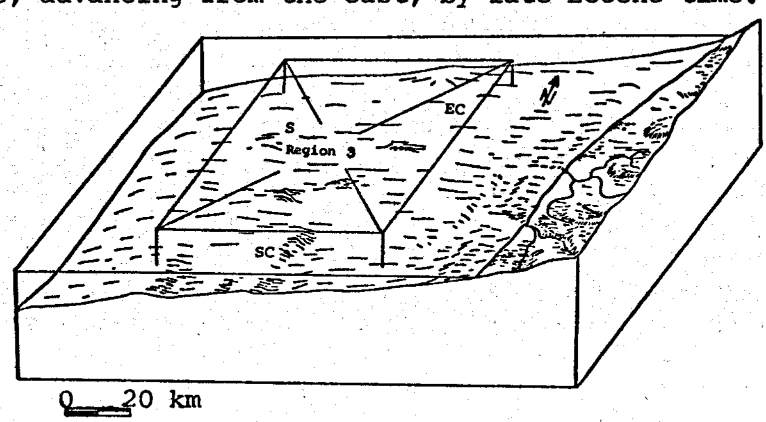

Figure 6. Paleogeographic reconstruction of region 3 inset into a large paleogeographic setting for perspective, and direction of shoaling. Geographic reference points are: EC = Elsmere Canyon, S = Simi, SC = Solistice Canyon.

Santa Cruz, Santa Rosa, San Miguel and San Nicolas Islands (region 4 of Fig. 1)

Lithology and environment of deposition. On Santa Cruz Island the middle Eocene part of the Cañada Formation of Doerner (1969) is principally shale, thin-bedded siltstone, and fine-grained sandstone, with 5- to 15-cm-thick sandy limestone beds dispersed throughout. These strata possess few current-formed sedimentary structures and are inferred to have been deposited in low-energy environments.

The low-energy condition during the middle Eocene, unique to Santa Cruz Island compared to the other islands, is broken only by the deposition of the late Eocene Jolla Vieja Formation of Doerner (1969). This formation is principally a medium-grained thick- to massive-bedded arkose with prominent lens-shaped conglomerate beds. In composition the conglomerate resembles the Stadium Conglomerate of the Poway Group in the San Diego area (Woodford and others, 1968; Kennedy and Moore, 1971; Minch, 1972). Lutite interbeds are rare though mudstone rip-ups clasts, commonly imbricated, do occur. The conglomerate beds are inferred to represent channel deposits whose axes are oriented southwest. Clast imbrications and tabular cross beds indicate flow toward the west and southwest.

Foraminifers from the Cañada Formation indicate deposition at bathyal depths. Walker and Mutti (1973) indicate that pelagic and hemipelagic shale and marl with indistinct and poorly developed laminations occur between major turbidite sequences in upper bathyal fan deposits. Deposition results from dilute suspensions (pelagic rain, nepheloid layers, dilute turbidity currents).

On Santa Rosa Island, 200 m of the South Point Formation of Weaver and Doerner (1969) consists principally of medium- to coarse-grained medium- to thick-bedded arkose and lithic arkose. Standard Oil Well, Santa Rosa No. 1, penetrated approximately 1,100 m of sandstone, near the basal part is a conglomerate composed of "red volcanic clasts."

Petrographic analysis of the feldspars and lithic fragments in samples of the sandstone indicates a bimodal source: (1) granitic batholithic and (2) silicic volcanic rocks (Erickson, 1972). The bed forms, foraminifers, and sedimentary structures indicate that this sandstone was deposited by north and northwest-moving turbidity currents, principally in channels of the upper part of a bathyal fan (Weaver and others, 1969; Erickson, 1972; Howell, 1974).

On San Miguel Island, a 15-m-thick Poway-like conglomerate (Minch, 1972; Howell, 1974) is composed of beds of pebbles and cobbles (maximum size 47 cm, mean 7 cm) that alternate with medium- to coarse-grained thick-bedded lithic arkoses. Megascopically, the suite of clasts is indistinguishable from conglomerate in the Poway Group at San Diego. Conformably above the conglomerate is 300 m of thin- to medium-bedded siltstone, in turn overlain by 120 m of medium- to massive-bedded, medium- to coarse-grained lithic arkose, similar to the South Point Formation of Santa Rosa Island (Weaver and Doerner, 1969). Sedimentary structures, fossil foraminifers, and bed forms indicate deposition principally in channels of the upper part of a bathyal fan environment by processes of turbidity currents, as well as other high-energy systems, moving to the north and northwest.

The middle Eocene strata of San Nicolas Island resemble those of San Miguel and Santa Rosa Islands. A 6 m thick Poway-like conglomerate is exposed near the base of the exposed sequence. In a stratigraphically random sequence above this are alternating beds of siltstone and thin- to massive-lithic arkosic sandstone. This flyschlike sequence contains foraminifers indicating a bathyal environment of deposition and sedimentary structures indicating flow to the south and south-southwest. These data suggest deposition from turbidity currents and associated flow processes in channels and interchannel areas of an upper fan.

Paleogeography. All the middle Eocene rocks on the islands, except Santa Cruz Island, indicate high energy turbidite environments of deposition; channelized deposits predominate and probably were associated with one or more bathyal fans. Furthermore, the inferred sediment transport directions suggest that San Miguel, Santa Rosa, and San Nicolas Islands may have been located within the same sediment dispersal area. The similar lithologies also support this hypothesis (Fig. 7). On the other hand on Santa Cruz Island, finer grained material, displaying little evidence of a high energy dispersal, suggests that this part of region 4 was peripheral to the bathyal environment during the middle Eocene time. The Jolla Vieja Formation, however, suggests that for at least part of late Eocene time the Santa Cruz Island area occupied a proximal, highly channelized, position on this bathyal fan.

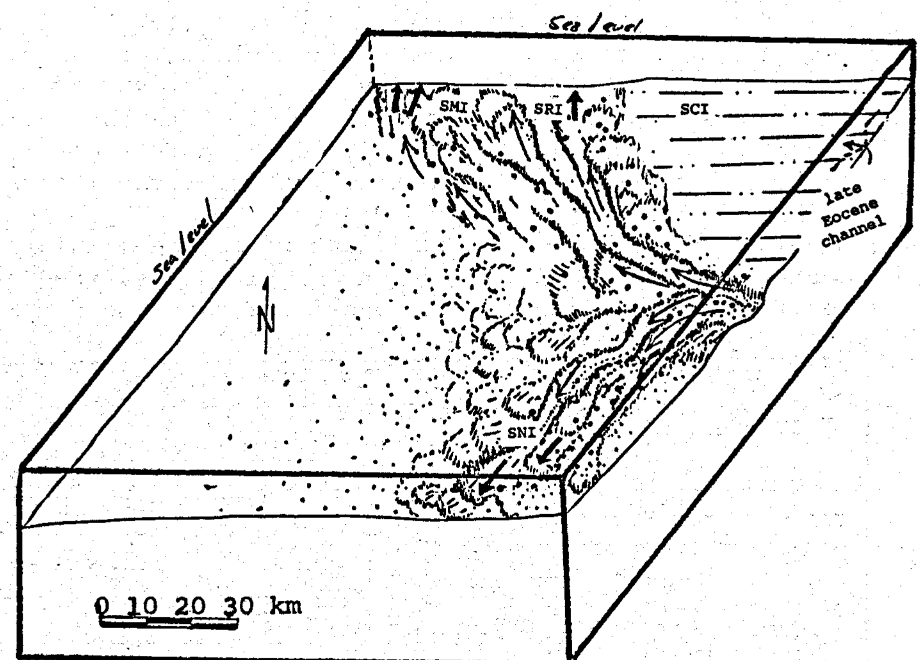

Figure 7. Middle Eocene paleogeographic reconstruction of region 4. Geographic reference points are: SMI = San Miguel Island, SRI = Santa Rosa Island, SCI = Santa Cruz Island, and SNI = San Nicolas Island.

A large area of the borderland between regions 4 and 5 appears to have no Eocene deposits (Reed and Hollister, 1936; Vedder and Norris, 1963; Weaver and others, 1969; Parker, 1971). The oldest superjacent rocks in this area are Miocene volcanic and sedimentary rocks that are inferred to be resting unconformably on schist(?) basement terrane (Parker, 1971; Vedder and others, 1974). The paleogeographic interpretation for region 4 and is fundamentally the same as that portrayed by Weaver and others (1969). There are, however, important differences involving the location of this environment relative to the other middle Eocene regions of southern California, to be discussed below.

Western Peninsular Ranges, Santa Ana Mountains to San Diego (region 5 of fig. 1)

Lithology and environment of deposition. Four principal lithofacies are present in region 5: (1) pebble and cobble conglomerate composed of red, black and gray silicic volcanic clasts with minor quartzite clasts (Ballena Gravel of Miller, 1935; Poway Group and Mount Soledad Formation of Kennedy and Moore, 1971; Minch, 1972) as well as channelized conglomerate (in the Rose Canyon Shale of Hanna, 1926); (2) gray-green and yellowish brown mudstone and sandstone (Delmar Formation); (3) principally well-sorted white sandstone (Torrey Sandstone, Santiago Formation, in part, and upper part of the Rose Canyon Shale), and (4) a intermixed mudstone, sandstone and locally conglomeratic lithofacies (Rose Canyon Shale and Santiago Formation, in part).

The lateral and superpositional relation of these lithofacies is described in Kennedy and Moore (1971) and Howell (1974) and is depicted graphically, for the San Diego area, on figure 8. This sequence is inferred to represent a major Eocene marine transgression followed by a marine regression (Reed and Hollister, 1936), with the following environments represented: fluvial (Ballena Gravel), coastal-deltaic (Conglomeration Poway Group), lagoonal (Delmar Formation), barrier bar (Torrey Sandstone), and a shelf and upper slope submarine canyon (Rose Canyon Shale). North of the San Diego area along the west flank of the Peninsular Ranges, in the Santa Ana Mountains, and in the San Joaquin Hills, the Santiago Formation is inferred to be a paralic-coastal deposit (Yerkes and others, 1965).

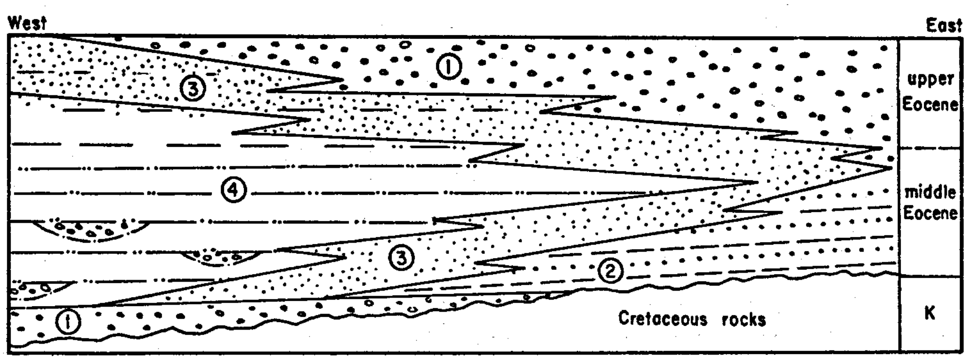

Figure 8. Diagrammatic cross section of lithofacies of region 5, San Diego area: Lithofacies 1 = conglomeratic unit; Lithofacies 2 = gray-green yellowish brown mudstone and sandstone; Lithofacies 3 = well sorted whitish-brown sandstone; and Lithofacies 4 = variable mudstone, sandstone, locally conglomeratic. Modified from Milow and Ennis (1961), Kennedy and Moore (1971), and Minch (1972).

In the San Diego area rocks inferred to be from the most eastern paleo-fluvial deposits to the westernmost shelf, upper slope, and canyon deposits, sedimentary structures indicate east to west flow. Thus the conspicuous silicic volcanic stones (Poway assemblage of Howell and others, 1974) that are so conspicuous had to originate east of the crest of the Peninsular Range. Minch (1972) and Woodford, Welday and Merriam (1968) suggest possible sources in northwest Sonora, Mexico.

Paleogeography. The paleogeography of region 5 requires that: (1) east of the San Diego coastal area a west-flowing river system that transported silicic volcanic stones across all or most of the Peninsular Range Province, (2) north of San Diego most of the Peninsular Range Province area was a topographic high; (3) the shoreline was roughly parallel to but east of the present shoreline, (4) the lower Eocene shoreline was west of the middle Eocene shoreline, which transgressed eastward, and then regressed westward in late Eocene time, (5) deltaic accumulation of sandstone was minor in the San Diego coastal area, (6) the shelf and slope gradient was steep in the San Diego area, (7) north of San Diego only shallow, coastal-marine, and nonmarine environments are represented. Figure 9 is a paleogeographic reconstruction for middle Eocene time.

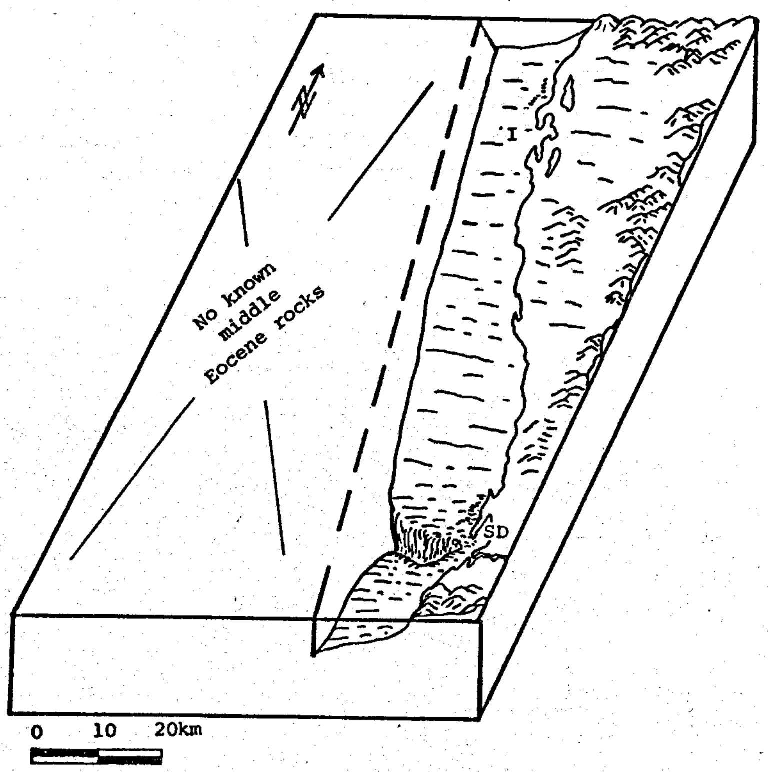

Figure 9. Middle Eocene paleogeographic reconstruction of region 5. Geographic reference points are: SD = San Diego, I = Irvine.

Orocopia Mountains (region 6 of Fig. 1)

Lithology and environment of deposition. The Maniobra Formation of Crowell and Susuki (1959) is 1,210 m thick and lies with depositional onlap on granite and quartz monzonite basement. The basal section consists mostly of conglomerate and breccia grading upward to siltstone and sandstone.

The conglomerate, with a maximum thickness of 600 m, is massive and contains beds as thick as 30 m. The clasts are composed of quartzite, granite, quartz monzonite, granodiorite, gneiss, and slightly metamorphosed siltstone (Kirkpatrick, 1958). Clasts of the local basement material, as large as 9 m, are incorporated in the basal part. Many of the larger clasts are inferred to be unabraided joint blocks. The conglomerate is inferred to represent a nearshore deposit, and the larger clasts may be remnants of collapsed sea-stacks (Crowell, oral commun., 1974).

The overlying sandstone is medium-grained, poorly sorted, angular to subangular arkose and lithic arkose. The sandstone thickens toward the west and southwest from 100 m to as much as 400 m. Interbedded with the sandstone is thin- to medium-bedded and massive buff mudstone. Fossils from the mudstone indicate shelf depths (Crowell and Susuki, 1959; Johnston, 1961).

Paleogeography. Figure 10 is a paleogeographic reconstruction for region 6. The rugged north and northeast land area is inferred from the distribution and nature of the conglomerate lenses of the Maniobra Formation. The limits of the marine environments to the southwest are unknown.

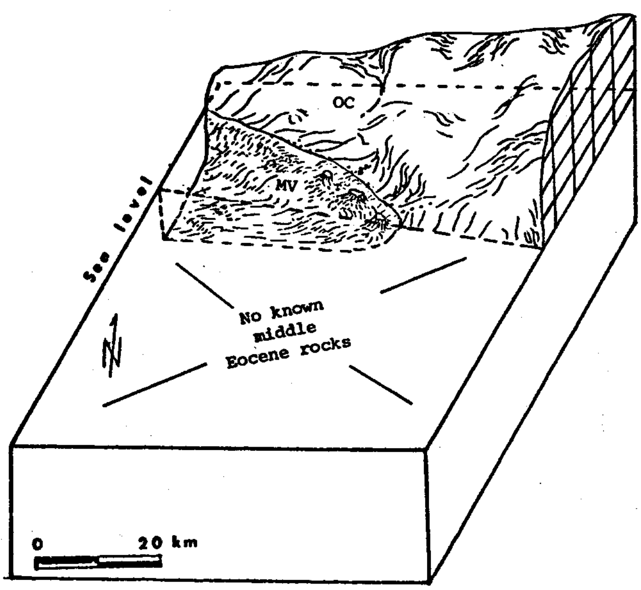

Figure 10. Middle Eocene paleogeographic reconstruction of region 6. OC = Orocopia Mountains, MV = Maniobra Valley.

SUMMARY

Figure 11 is a composite of the paleogeographic reconstructions for regions 1-6, in which each region is located in its present relative position. An unlikely paleogeographic setting would result if one attempted a reconstruction without shifting the locations of these regions.

Many lines of evidence have been offered that indicate approximately 260 km of post-middle Miocene left-slip on the San Andreas fault system (Crowell, 1962, 1973). This amount of left-slip brings together the inferred middle Eocene shorelines of region 2 (Piru Creek drainage area) and region 6 (Orocopia Mountains). Thus, it appears that by middle Eocene time, and probably early Eocene time as well, an east trending basin had developed in the area of the Neogene Ventura Basin, the east margin of which is represented by the Maniobra Formation of the Orocopia Mountains.

The configuration of Eocene strata reflected by the isopach map (Fig. 4) supports this postulated Eocene east-trending basin in the Transverse Range area. The low-energy shelf deposits of region 3 (Simi Hills and Santa Monica Mountains) are inferred to represent a southward shoaling of this basin. Thus, the coarse clastic material that flowed toward the south from the Piru Creek drainage area was deflected to the west along the trough of this basin.

Depositional environments in the western Santa Ynez and southern San Rafael Ranges indicate that a borderland was developed by middle Eocene time. Sediments being shed off this borderland flowed principally to the south. East of the borderland a northwest-trending marine embayment existed, and sediment flowing into this basin originated to the east and northeast.

Data from region 4 indicate that a channelized, bathyal, upper fan area was located east of a position about halfway between Santa Rosa and San Nicolas Islands. The Eocene strata east of the inferred bathyal fan, pinch to zero thickness, probably by depositional onlap, with the basement complex (Parker, 1971; Vedder and others, 1974). The composition of this basement rock is unknown. However, there seem to be only two distinct groups of pre-Tertiary crystalline rocks in the borderland area. The first consists of schistose rocks exposed on Santa Catalina Island. The second group includes basic plutonic, metavolcanic and metasedimentary rocks exposed on Santa Cruz Island. Neither of these two rock types are likely source terranes for the clastic constituents of the Ulatisian arkoses and in particular the stones in the Poway-like conglomerates.

It is proposed that the middle Eocene bathyal fan postulated for region 4 lay due west of the San Diego area of region 5. Such a palinspastic reconstruction brings together all the Poway-like conglomeratic suites into one paleogeographic setting. This reconstruction also results in an east-to-west sequence of fluvial, coastal-deltaic, submarine canyon and bathyal fan environments. A probable means of restoring this paleogeographic setting is to adjust palinspastically the bathyal fan part of

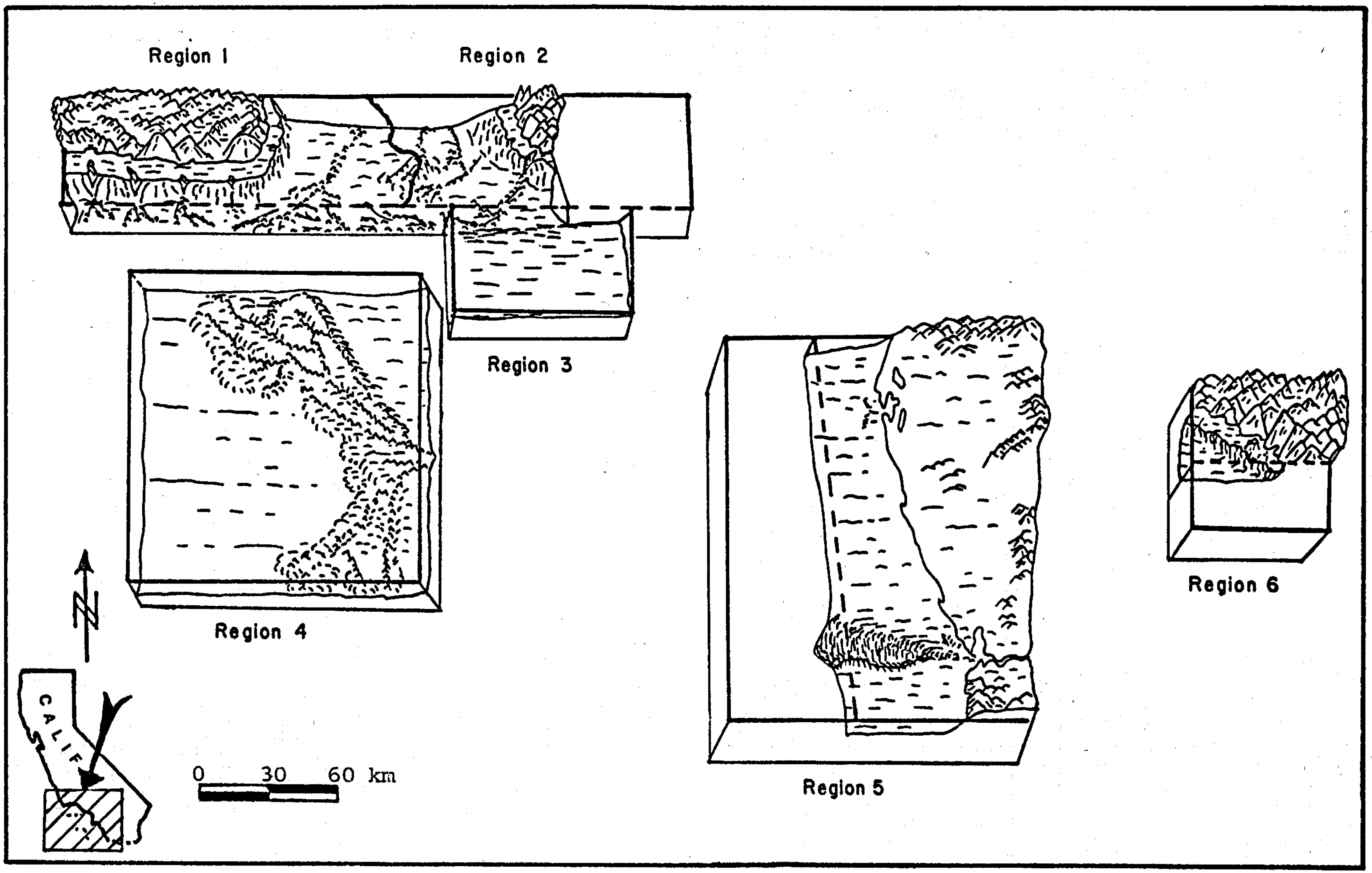

Figure 11. Composite middle Eocene paleogeographic reconstructions for regions 1-6. Each region is in its present position relative to the other regions, see figure 1.

region 4 (180 km) along the inferred northwest trending East Santa Cruz Basin fault system. Alternative hypothesis have been offered by Cole (1970) and Yeats, Cole, Marschat, and Parsley (1974).

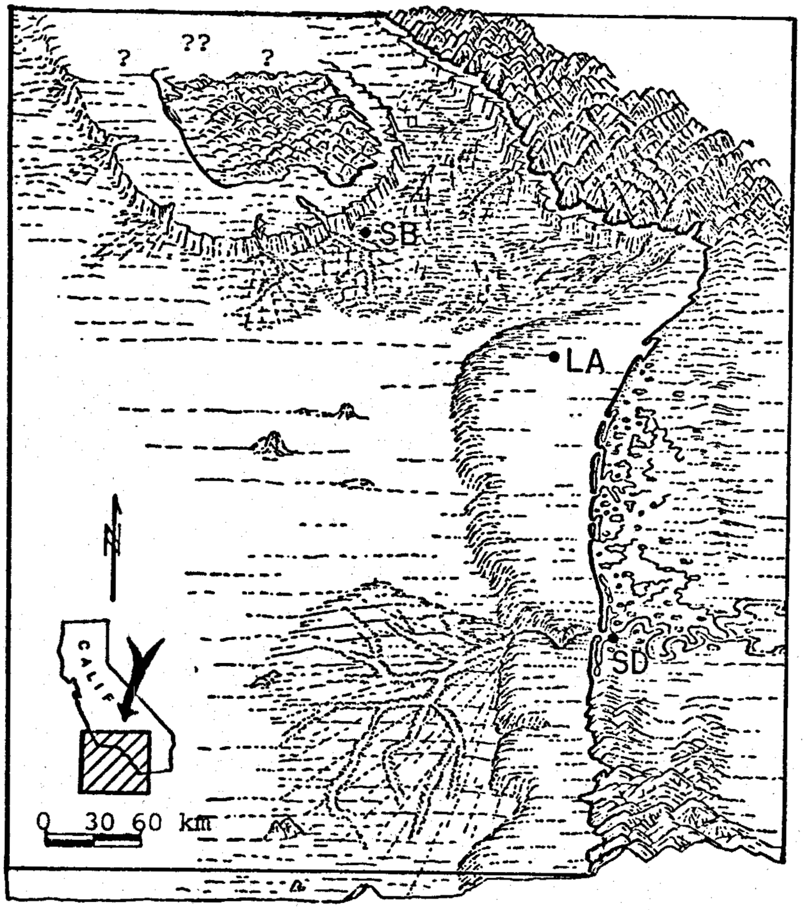

Figure 12. Middle Eocene paleogeographic reconstruction of southern California. Geographic reference points are: SB = Santa Barbara, LA = Los Angeles, and SD = San Diego.

In summary, figure 12 is an inferred middle Eocene paleogeographic setting based on basin analyses for regions 1-6 and palinspastic adjustments for: 210 km of right-slip on the San Andreas fault, 50 km of right-slip on the San Gabriel fault, 90 km of left-slip on the Malibu Coast fault system, 15 km of left-slip on the Big Pine and Santa Ynez faults, and 180 km of right-slip on the East Santa Cruz Basin fault system.

ACKNOWLEDGEMENTS

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WEST COAST ENERGY REQUIREMENTS

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Abstract.

The energy needs of California and the West Coast are met by oil (49%), natural gas (40%), hydropower (9%) and geothermal and nuclear (2%). Major consumers of this primary energy include transportation (30.5%), generation of electricity (21.6%), industry (19.1%), residential (12.3%), commercial (4.6%), military (4.3%) and misc. (7.6%).

California's present total energy demand of 6.8 quadrillion Btu should double by 1995, requiring the equivalent energy provided by 2.3 billion barrels of oil.

Energy Consumption by Type of Fuel.

Californians depend, as does the rest of the nation, on petroleum products to meet their ever increasing need for energy. Today, hydrocarbons fill 75% of our nation's energy requirements but unlike the rest of the United States, California relies on oil and natural gas to provide nearly 90% of the state's basic energy needs.

In 1920, coal furnished more than 75% of the nation's energy demand but its use has steadily declined to where today it accounts for less than 20% of our nation's requirements. Although coal is found in many California counties, the quality and quantity of this domestic fuel, limit its present (1%) and future use (0.3%) as a major energy source for the West Coast.

Hydropower never has claimed more than 5% of the nation's energy budget and furnishes only 9% of California's energy market.

Nuclear fusion and geothermal power fill approximately 2% of California's energy market but provide less than one-half percent of the nation's energy need.

Data for all curves presented with this report was obtained from public records and the references are noted with each graph. Projections of the curves are those of the author and are based on the "logical" assumption that trends are slow to change. They are not intended to indicate precise values, but rather the order of magnitude of consumption.

These projections do not include the effects of conservation measures that could be initiated in the near future. My prognosis tends to be somewhat pessimistic. Three years ago, I reported that Americans consumed 15.5 million barrels of oil per day in 1971. Since then we have experienced an energy crunch, a crisis, an oil embargo, gasless Sundays, a threat of rationing, reduced highway speeds, increased gasoline prices, reduction of military activity, a recession, new state and federal administrations, and with all that Americans consumed 16.7 million barrels of oil per day in 1974.

California Crude Oil Production.

Oil has been this country's primary source of energy since 1950,- and will undoubtly continue to be our main source of fuel for the next 25 years. The West Coast reliance on hydrocarbons date back to the early days of this century because of the then abundant crude oil in California and the obvious lack of coal on the West Coast. The state produced its first million barrel annual rate in 1895 and became a major oil producer in 1919 when production first exceeded 100 million barrels.

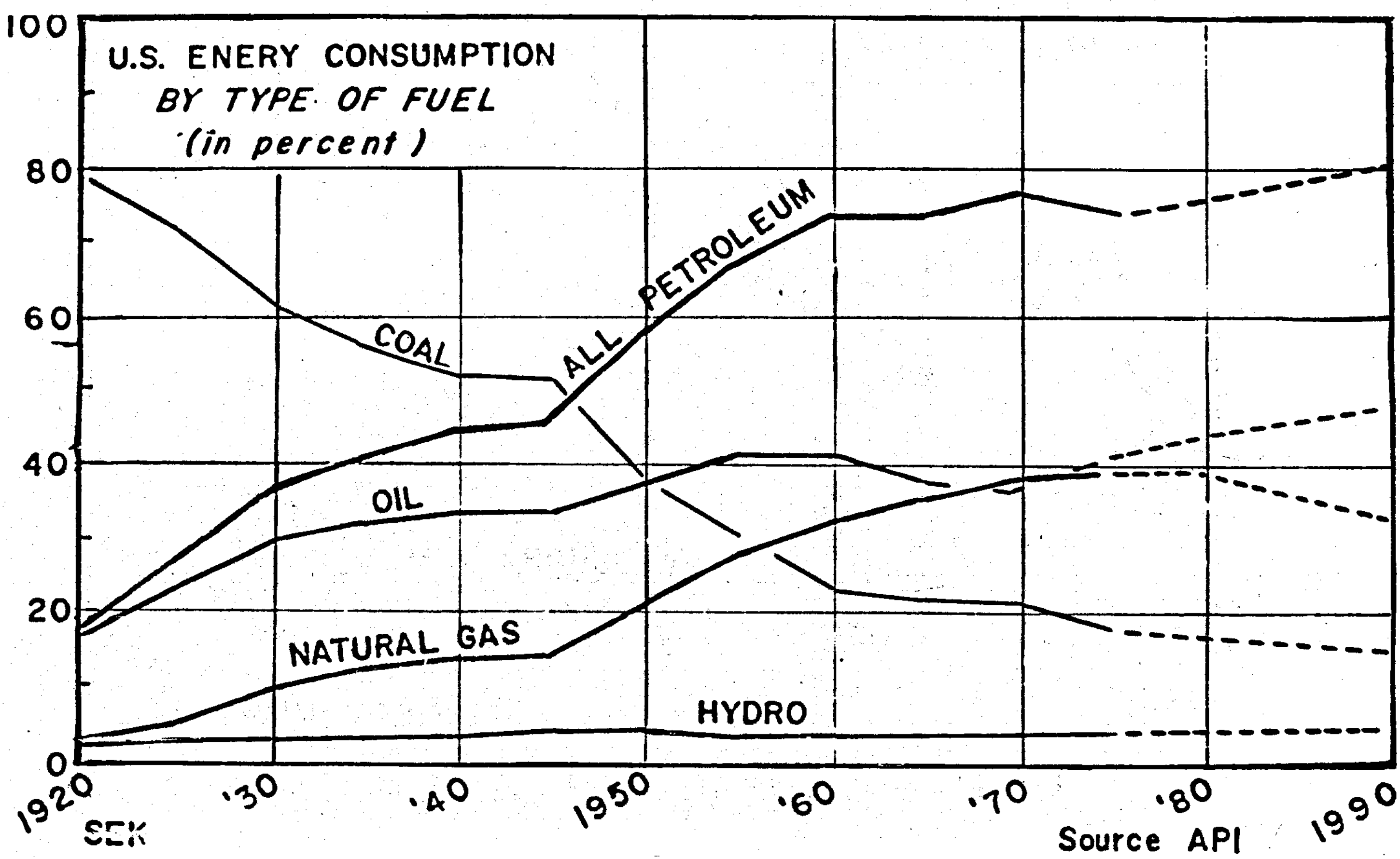

Figure 1 -- U.S. Energy Consumption by Type of Fuel

California then ranked number one among oil producing states, today it is the third largest producer, but we must import nearly a million barrels per day (951,000) to meet our own state's energy needs.

Last year, California's domestic crude oil production dipped to 307 million barrels, down ten million from 1973. California's production has declined every year since 1968 when the state's all time record production was 373 million barrels.

During 1974, West Coast refineries processed 673 million barrels of petroleum products, but the combined crude production of California and Alaska amounted to 378 million barrels or 55% of what the West consumed.

Offshore production has increased steadily from 28 million barrels in 1960 to 84 million in 1974 and now represents 27% of California's total production.

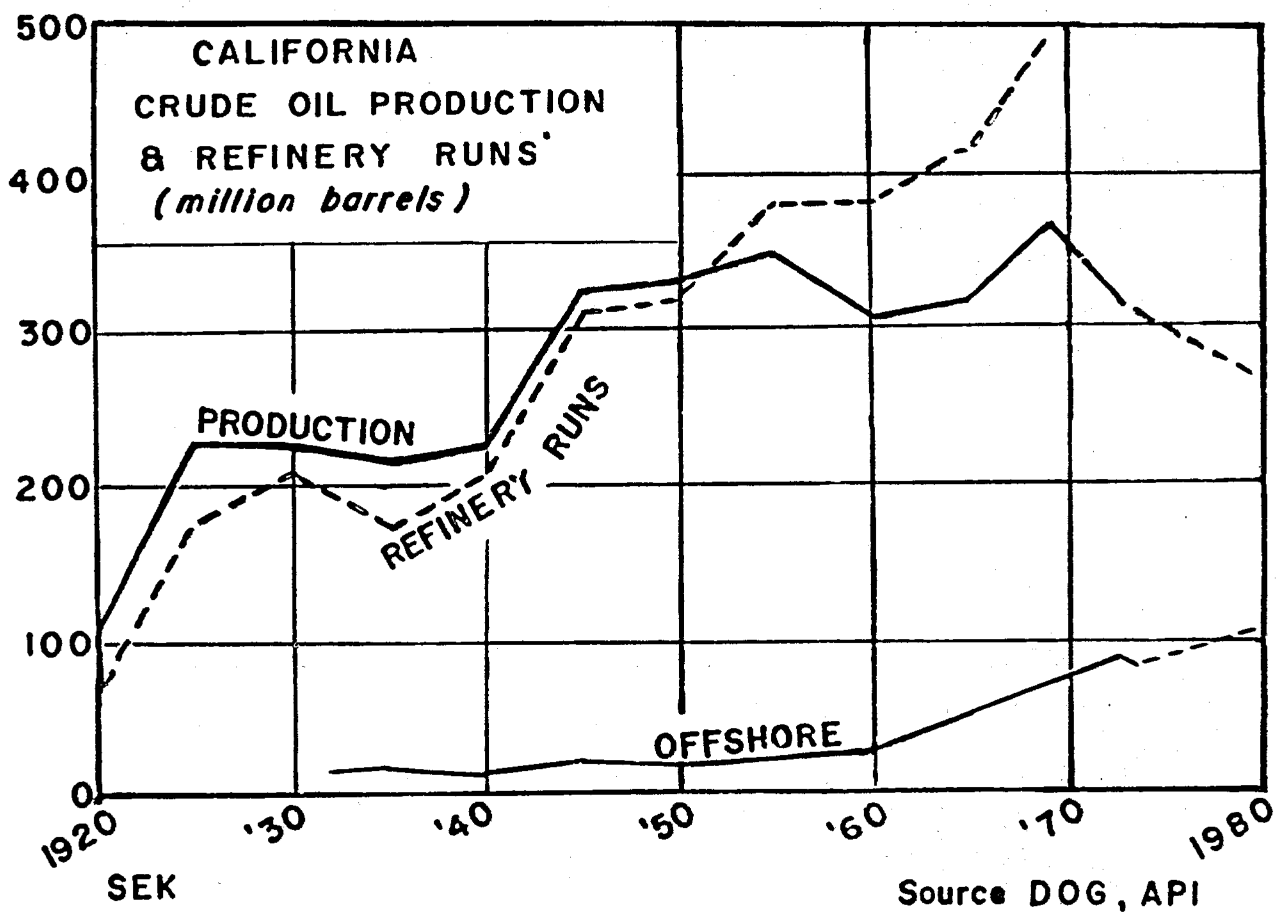

Figure 2 -- California Crude Oil Production

California Natural Gas Consumption.

The disposition of natural gas varies so rapidly that it is virtually impossible to predict its future. California has been unable to supply its gas requirements since 1947 when natural gas was first imported by pipeline from West Texas. The sixth largest gas producing state in the country will be required to import an excess of 1700 billion cubic feet of gas this year to fill the deficit created by the present demand for low cost energy.

California's natural gas marketed production has steadily declined from its peak production of 714 billion cubic feet in 1968, to last year's net withdrawal of 374 billion cubic feet. The 1974 production figures reflect a 130 billion cubic feet reduction from the previous year.

As statewide production declines, the demand for "uninterruptable" gas continues to increase. This year, Californians will consume nearly two trillion cubic feet of gas of which only 15% will be recovered from California sources. The drop in gas consumption beginning in 1970 is caused by the conversion to fuel oil by the electric utilities for electric generation. For most of the past decade nearly 90% of their fuel needs have been met with natural gas, but electric utilities have low priorities and must import low sulfur oil mostly from Alaska and Indonesia.

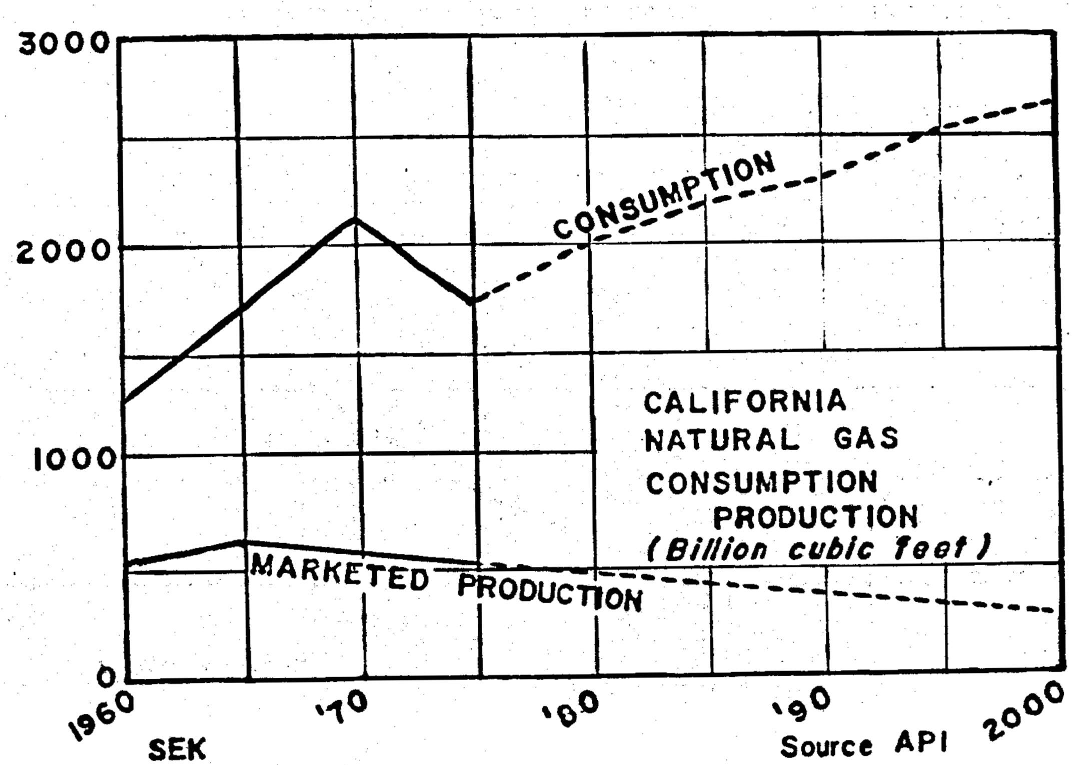

Figure 3 -- California Natural Gas Consumption

Our proved gas reserves are estimated (D.O.G.) at 5.8 trillion cubic feet If we were forced to rely solely on our domestic reserves, we would deplete our known supply in less than three years.

California Electric Energy Consumption.

California's third source of energy is hydropower and accounts for 30% of the state's electric generation capacity but less than 9% of the total primary energy consumed. Five years ago falling water generated 36% of the state's electric production, but because most of the desirable dam sites have either been developed or have been removed from development by environmental pressures, hydropower is not expected to share more than 22% of our future electric power generation. Only 9% of California's new generating capacity planned thru 1978 will be hydro generated. Approximately 20% of the electricity generated by hydropower is imported into California from Arizona and the Pacific Northwest.

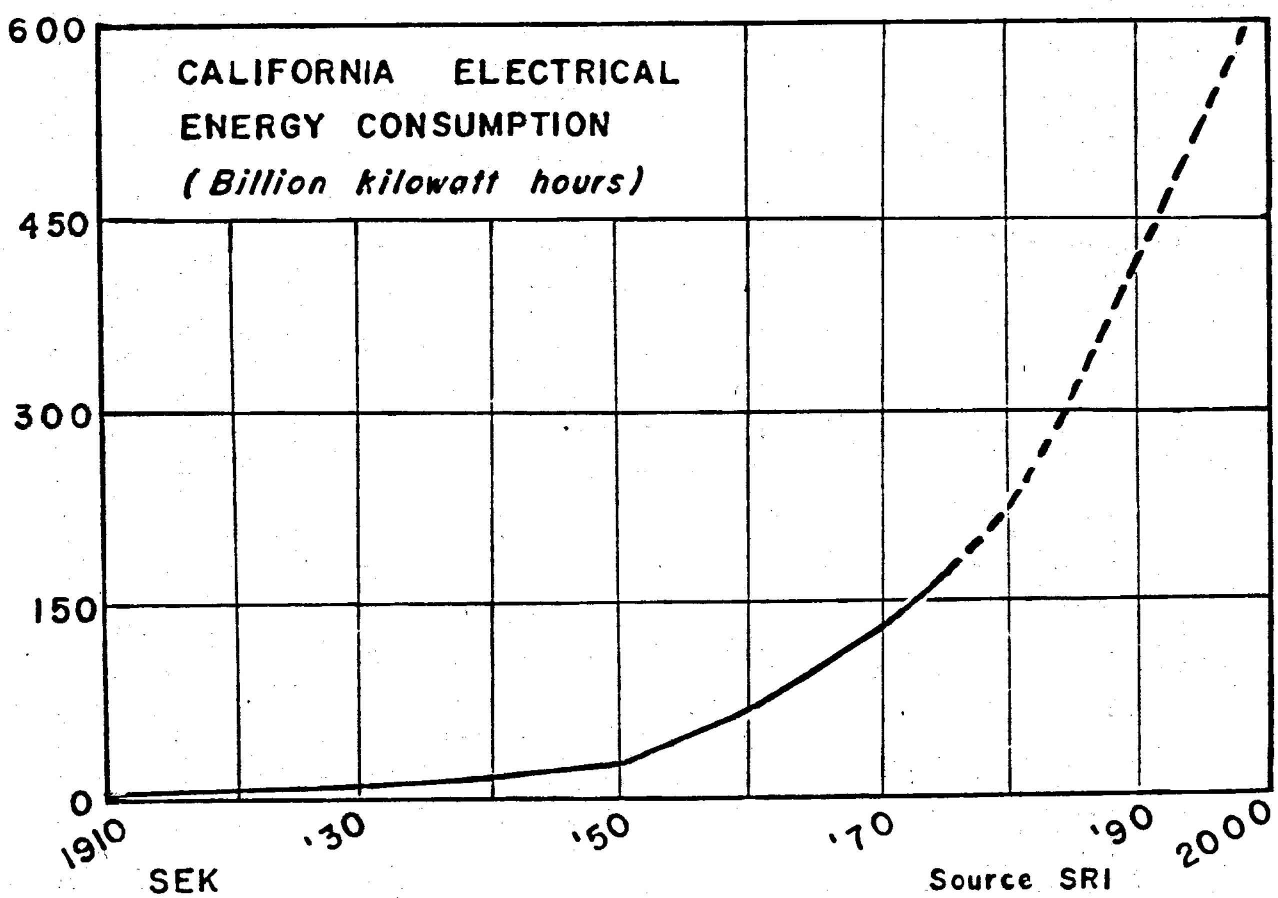

Figure 4 -- California Electrical Energy Consumption

This year's demand of 175 billion kilowatt hours of electric power is twice that consumed in this state in 1963 and amounts to an annual growth rate of 8%. If we assume a more moderate growth of 5% in our electric energy demand for the next decade, by 1985 we will use approximately 277 billion kilowatt hours of electric power or the equivalent energy procuded by 160 million barrels of oil.

<u>California Consumption of Electric Energy by Type of Producer</u>.

The demand for electric power is expected to double in the next decade as it has doubled every ten years since 1940. In the next five years, electric utilities have planned and are constructing additional resources to meet these future requirements. But even these scheduled additions rely heavily on fossil fuels. Fifty nine percent of California's new generating capacity will be fossil fuel fired; 32% nuclear fuel and 9% will be from hydro plants.

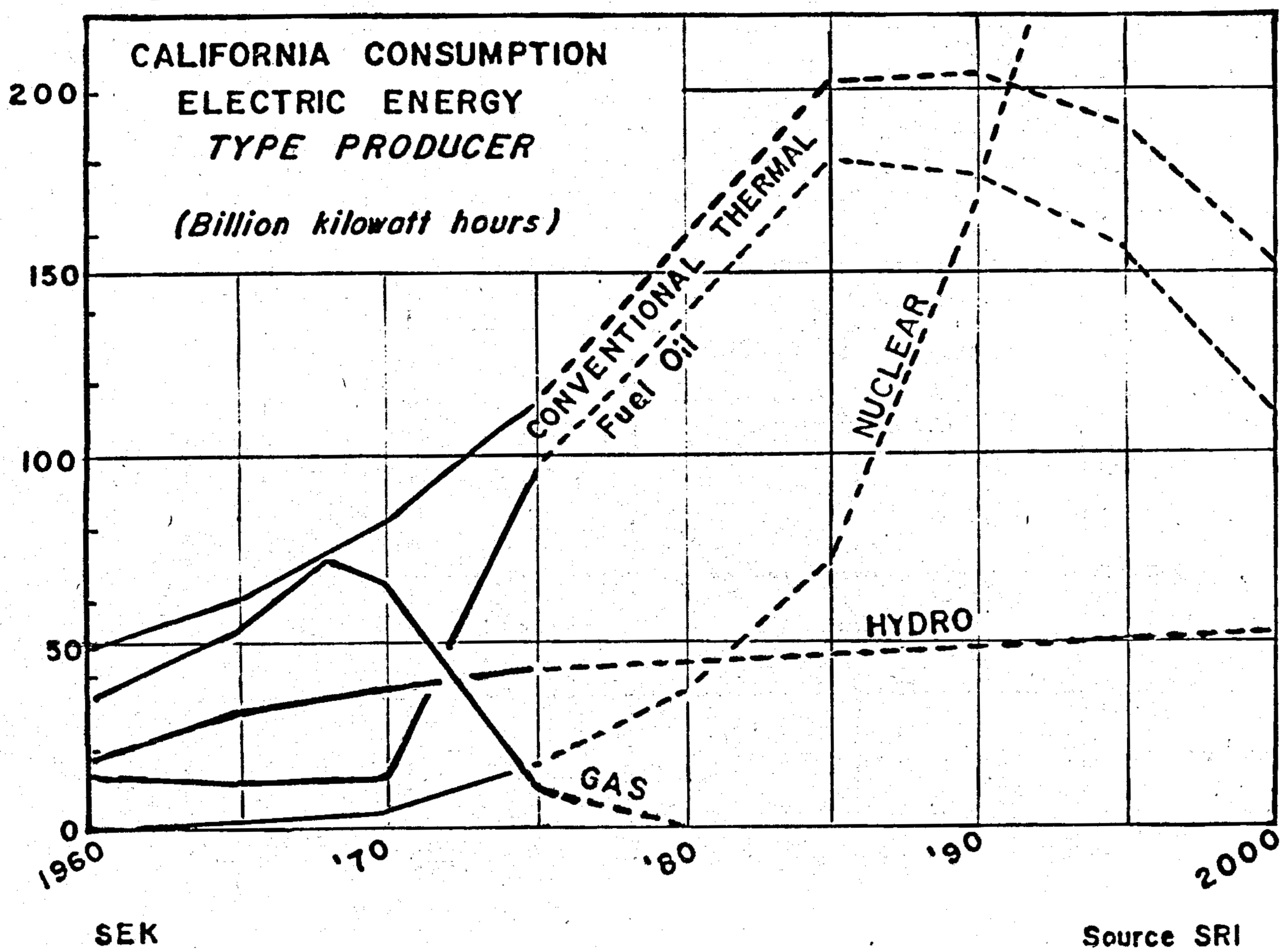

Figure 5 -- California Consumption of Electric Energy

The development of nuclear energy in California has been much slower than expected. Our first nuclear plant began operations in 1963 and now only three nuclear facilities generate electricity in California. Four more new plants or additions to existing nuclear facilities are planned for completion in the 1970's. If construction remains on schedule, California nuclear generators will develop 35 billion kilowatt hours of power and a savings of fuel oil of 60 million barrels per year in 1980.

THE ENERGY CONSUMERS

The purpose of this report is to focus attention on energy consumption on the West Coast and particularly in California. The energy consumers can be divided into six major catagories, each with their present energy requirements and future demand. These principal end use sectors are (1) transportation (2) industry (3) residential (4) commercial (5) power plants and (6) military.

Transportation.

The largest consumer of primary energy is transportation, which accounts for approximately 30% of California's energy budget. Included in this sector is highway, rail and air travel as well as marine and land shipping.

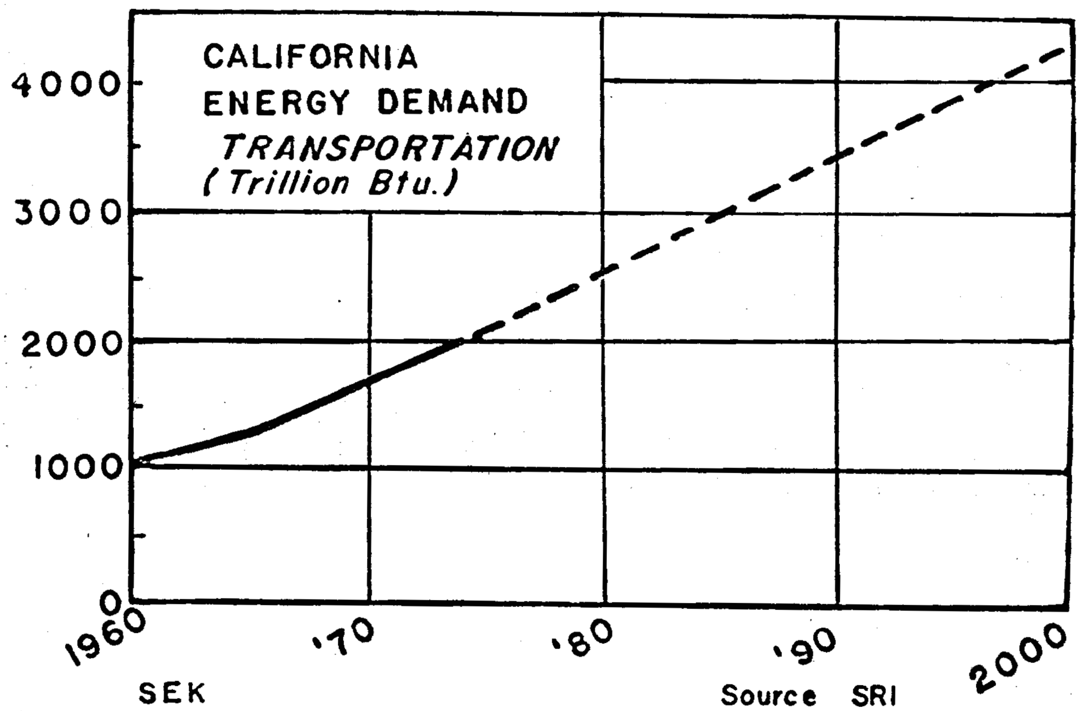

Figure 6 -- California Energy Demand Transportation

Petroleum products have always dominated this market and they will continue to do so in the future. Converting the present 2151 trillion Btu expended on transportation to barrels of oil, we now consume 370 million barrels of oil for transportation alone. (This exceeds the state domestic production by 63 million barrels.)

If the growth rate of transportation continues at its present rate of 4.6% per year and California's domestic production continues to decline as it has the past few years, we will allocate twice the amount of oil we produce just for transportation alone during the next ten years.

Gasoline Consumed.

Approximately 45% of a barrel of oil is converted into gasoline, which furnishes 70% of the energy used for transportation. The 10 billion gallon consumption of gasoline last year by Californians, amounted to 13% of national usage and was three billion gallons more than that consumed in Texas and four billion more than New York state.

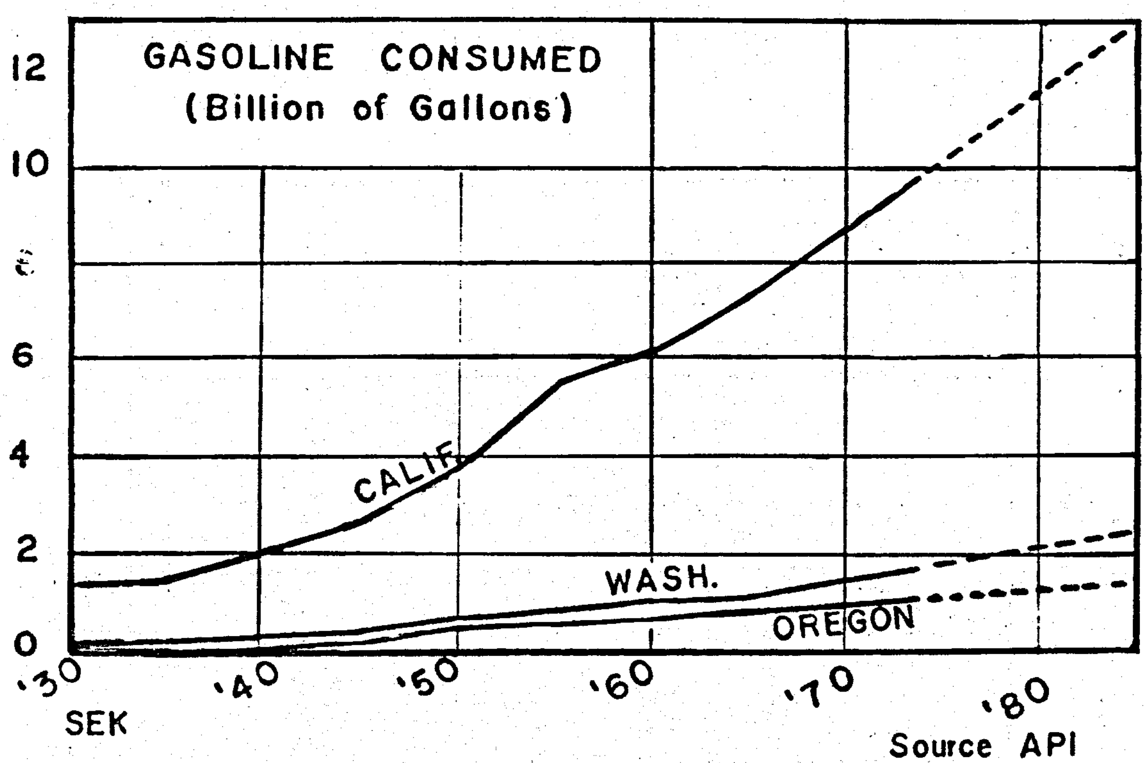

Figure 7 -- Gasoline Consumed

Twenty years ago the family car averaged 14½ miles per gallon of gasoline. With advanced automotive engineering, improved combustion and exhaust controls, the American automobile now averages 13.1 miles per gallon.

Lower maximum highway speeds and smaller cars will undoubtly improve the miles per gallon figures, but more Californians are highway bound every year.

Motor Vehicle Registration.

Californians own and drive eleven percent of the nation's vehicles. Our 13.5 million automobiles, trucks and buses are nearly double that of Texas or New York, our nearest competitors. Every year for the past ten years we have added over 340,000 cars to our overcrowded highways. California's automobile density is 80 vehicles per mile of roadway; Washington 29; Oregon 16. Each vehicle will consume an average of 740 gallons per year and the petroleum industry must make available an additional 250 million gallons of gasoline to meet this new yearly demand.

We have doubled the number of vehicles on our highways in the past 20 years and should this trend continue we could have 19 million cars crowding our streets and highways in 1985. The 17.5 million vehicles on the West Coast will consume 13 billion gallons of gasoline this year.

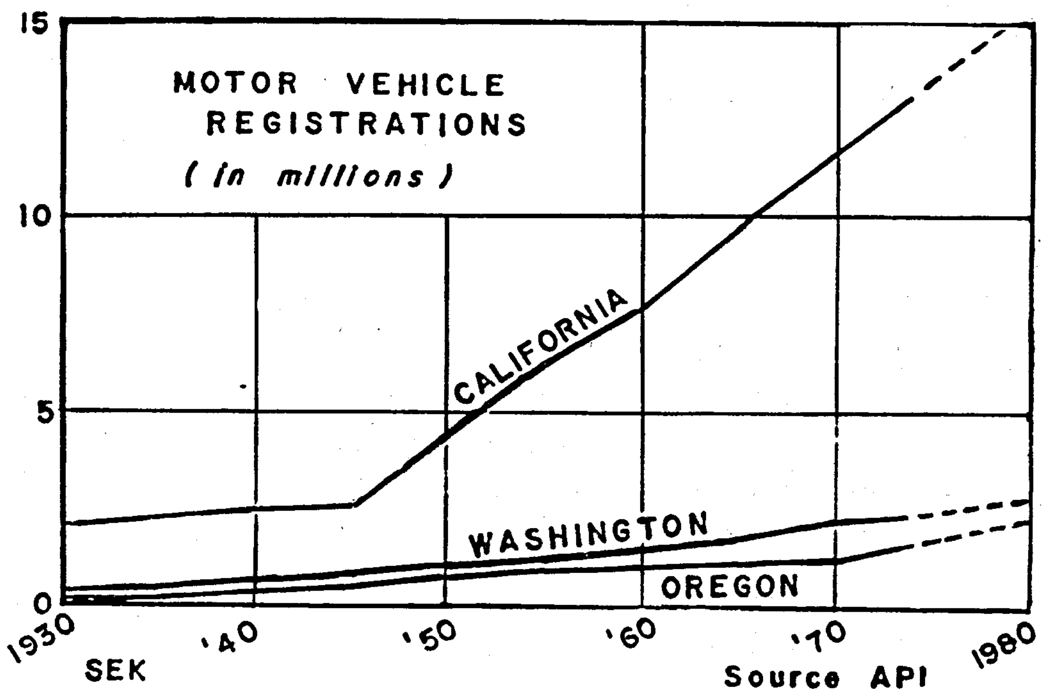

Figure 8 -- Motor Vehicle Registration

Aircraft Travel.

California is truely a state on the move, not only on the highway but in the air as well. Of the ten busiest airports in the United States, six are in California. Santa Ana airport recorded more than 632,000 aircraft take-offs and landings and was second only to the 695,000 operations at Chicago's O'Hare. Van Nuys and Long Beach airports both exceeded Los Angeles International for aircraft activity. Torrance and San Jose Municipal handle more aircraft than New York's Kennedy or La Guardia. Most of these operations are limited to general aviation as California's 109,000 licensed pilots, (Texas, our nearest competition has 52,000 pilots) based at 754 airports account for 73% of the state's ten million aircraft operations.

Not everyone pilots a plane but it appears everybody wants to fly. In 1973, fifty-four million passengers boarded or deplaned at California's ten major commercial airports, this was eight million more passengers than in 1971 and an average of nearly 3 plane trips per year for every resident in the state.

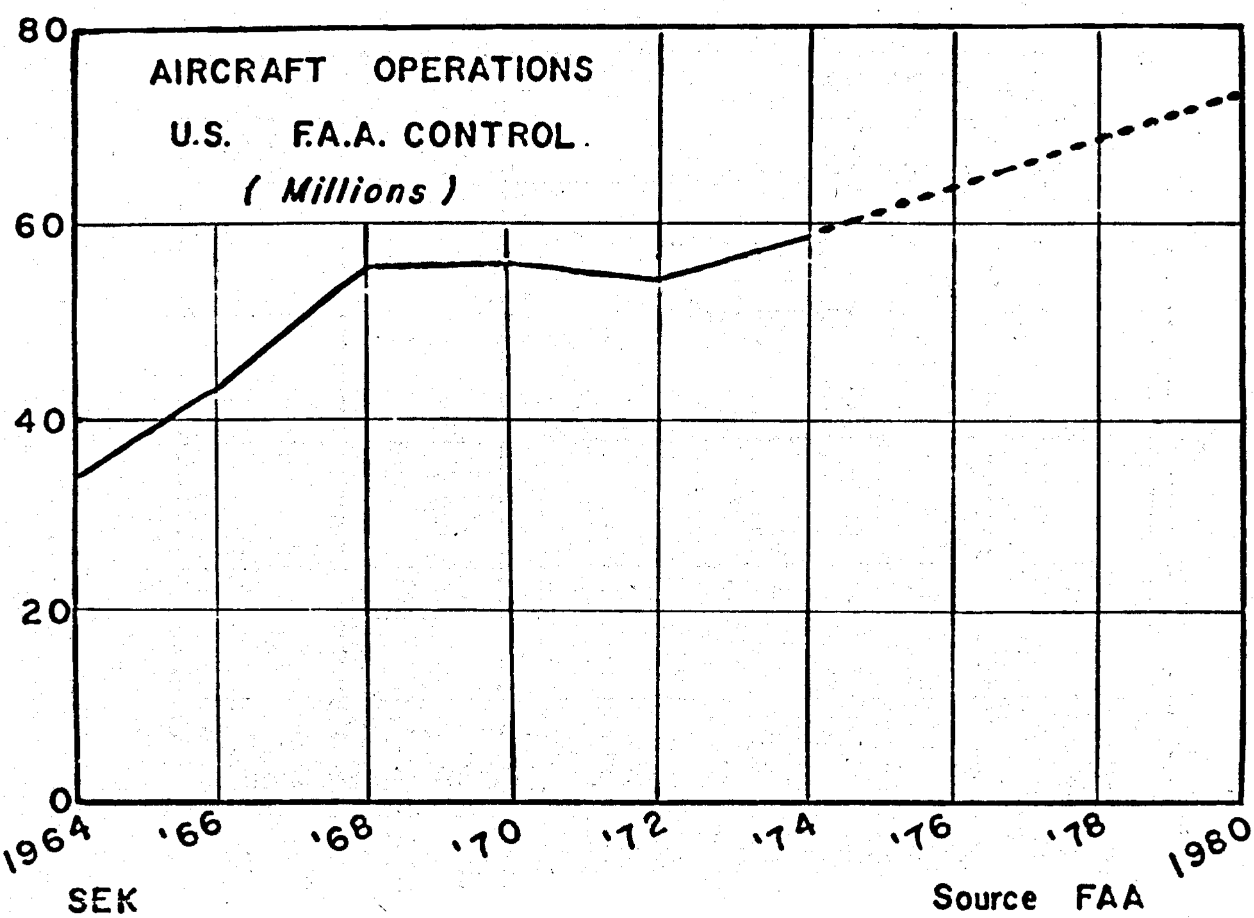

Figure 9 -- Aircraft Operations

To fill aviation's energy needs, West Coast refineries shipped 78.8 million barrels of jet fuel for commercial aviation and 2.5 million barrels (105 million gallons) of gasoline for general aviation use for West Coast consumers in 1974.

Recreation.

Californians are traveling more and seeing more. During the past twenty years, the state's population increased 60% while visitor attendance at the state parks increased nearly 400%.

West Coast states are well known for their scenic beauty and outdoor recreation facilities. California's 224 state recreation areas (state parks, reserves, historical monuments, beaches and recreation areas) will attract some 43 million visitors this year, as they have the past five years. This does not include the millions of visits to some of the most popular and beautiful federally owned parks in California.

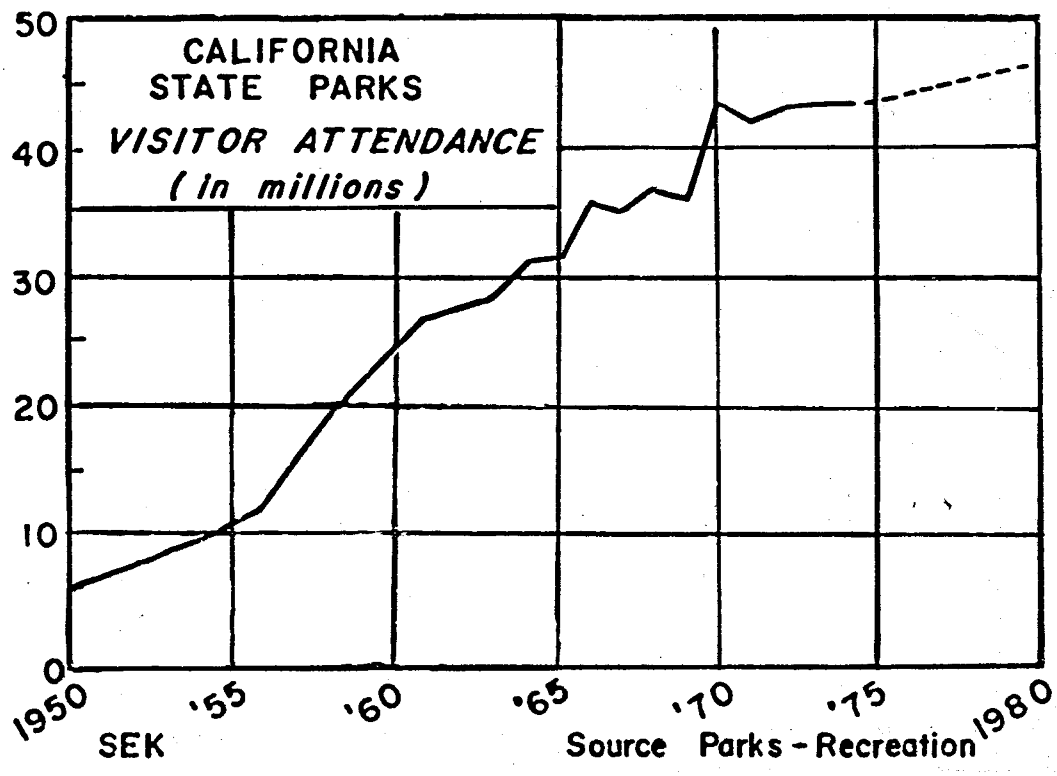

Figure 10 -- California State Parks Visitor Attendance

West Coast States have provided its citizens with 550 parks and recreation areas (California 224, Oregon 182, Washington 144), many with motor home campsite facilities. In 1973, three quarters of a million mobil homes and recreational vehicles were sold in the U.S. Records are unavailable at the present time indicating the number of recreation vehicles in the West, but anyone leaving Los Angeles on a Friday evening is soon convinced that most of the campers are in Southern California.

Industry.

California is not generally considered a highly industrialized state but 19% of our primary energy and 26% of the total energy produced is utilized by industry. All sectors of industry, large and small, are included in this catagory except power plants.

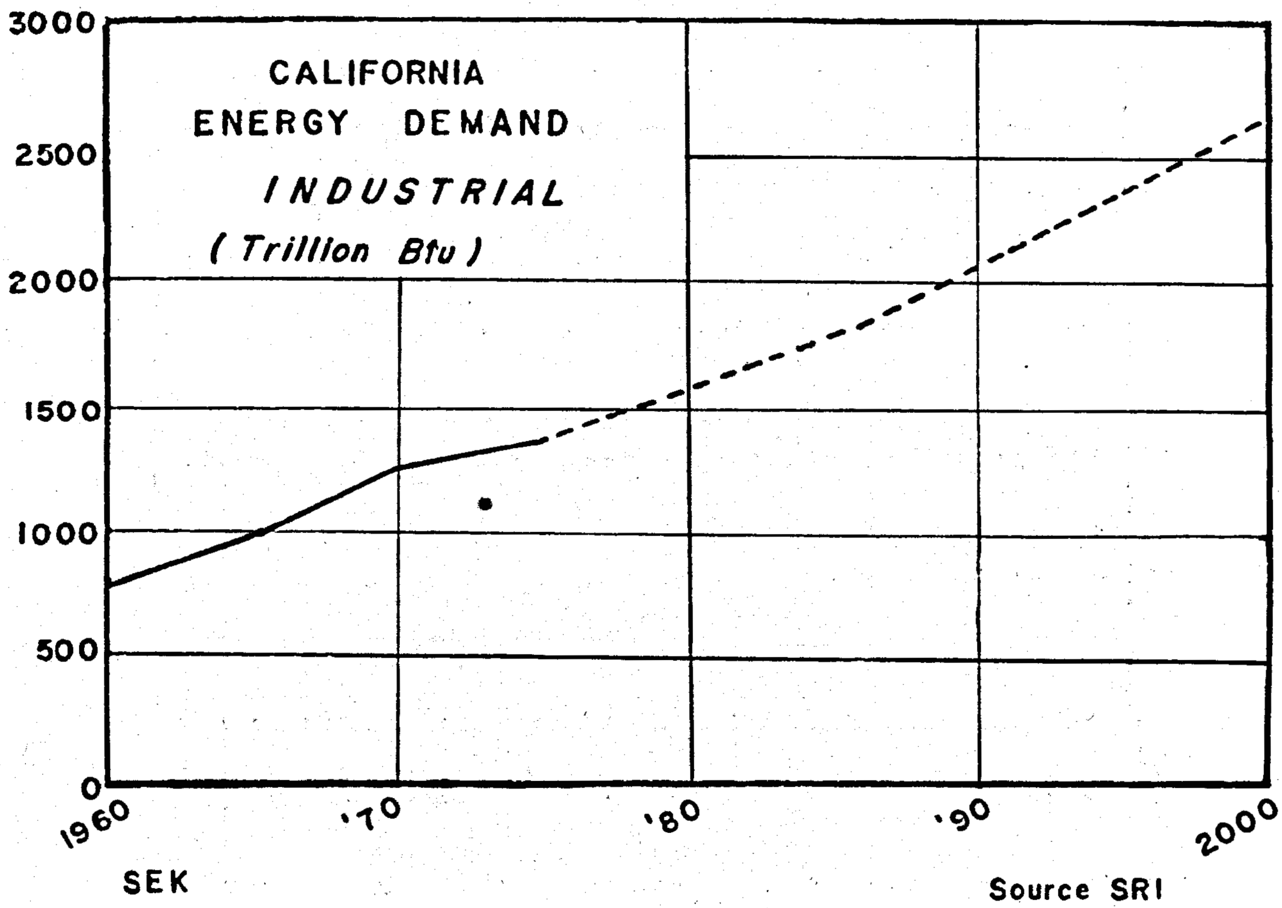

Figure 11 -- California Industrial Demand

The preferred energy source for industry is natural gas which provides 49% of its energy needs. Oil accounts for 38% and electricity 13%. As gas supplies become more limited industry will be required to rely on low sulfur fuel oil and greater dependence on imports to meet its energy requirements. California industries will consume 1390 trillion Btu of energy or the equivalent of 240 million barrels of oil. This demand should grow to 2050 trillion Btu by 1990 or the energy produced by 353 million barrels of oil.

California Agriculture.

California Agri-business is included with industry because it ranks first nationally in 55 out of 103 crop and livestock commodities. California farmers consume about 5% of the state's total energy requirements. The 30,000 acres of new land to be brought under cultivation this year will bring added demands for energy. Here too, natural gas provides the largest share (53%) of the energy market. Fetilizers, their production, distribution and application consume 15% of all the energy supplied to agriculture. Last year, California growers

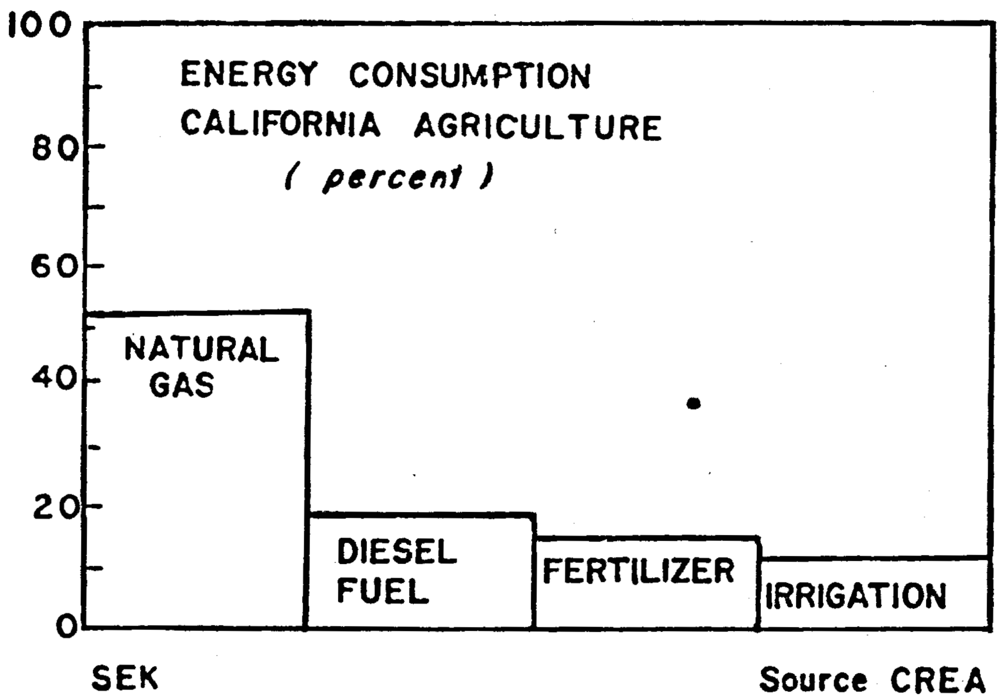

Figure 12 -- Energy Consumption California Agriculture

applied to their land, more than half a million tons of Nitrogen fertilizer produced mainly from natural gas.

Diesel fuel, the second major energy source (18%) provides frost protection, transporation and field operations. Crop irrigation, requires 14% of agriculture's energy budget or 68% of the electricity used in farming.

Population.

There is little doubt regarding the popularity of California as a place to live. California's population has tripled since 1940 and continues to grow but fortunately the rate seems to be slackening. The years 1950 to 1960 saw a yearly increase of 513,000 new residents. Four hundred and twenty three thousand persons were added each year to California's population from 1960 to 1970. Present growth rate appears to be about 250,000 per year (1.2%). Stanford Research Institute projects a state population of 27.5 million by the year 2000. The California Department of Finance sees 32.2 million people living in California by 2000. Most of the population will concentrate

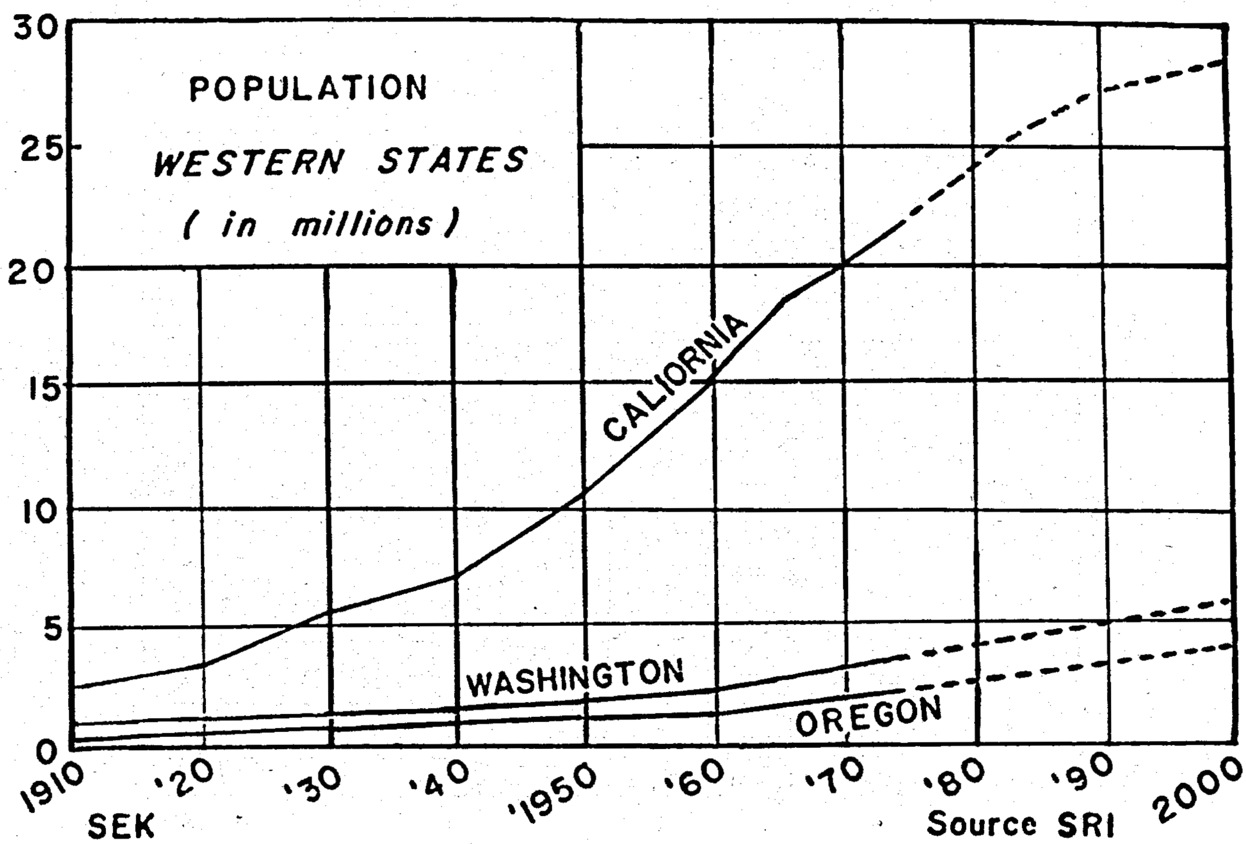

Figure 13 -- Population Western States

in urban areas. Los Angeles County has a present population density of 1729 per square mile, Orange County has 1831 and San Francisco with all its beauty and splendor crowds 15,734 residents into every square mile or 5000 more people per square mile than Hong Kong.

Residential.

The twenty one million residents of California will require 6825 trillion Btu of energy this year or a per capita need of 325 million Btu. Converting this energy appetite to barrels of oil, each Californian consumes the energy produced by 56 barrels of oil.

The residential sector requires 12% of our primary or 18.5% of our total energy resources for space heating, cooking, air conditioning, lighting, appliances and other household necessities. The lion's share of the energy burden is carried by natural gas. Despite the limitation of supply, gas furnishes 78% of the residential energy and consumers will continue to receive preferential service with non-interruptable deliveries for mostly space heating (62%), water heating (31%) and cooking (5%). The major competitor to gas is electricity, furnishing 18% of the residential energy budget. Much

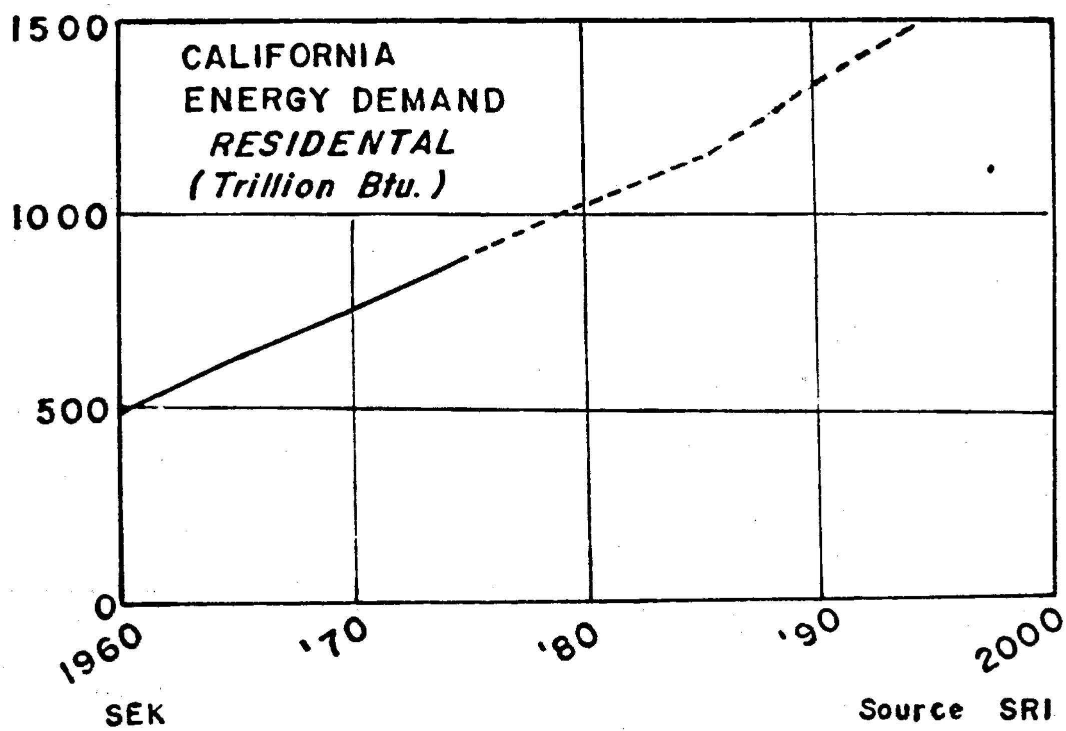

Figure 14 -- California Energy Demand

of this market can only be served by electricity. Food preparation and preservation account for 33% of the electricity used in the home, lighting 21%, space heating and cooling 14%, apparel washing and drying 10%, television 8%, water heating 7%, and other residential uses 7%.

Heating.

Space heating has never been a great concern of most Californian residents. Southern California enjoys a heating degree day index of 2000. A degree day is defined as the number of degrees that the actual temperature for the day is below the base temperature of 65^{O}F. (Example - if the average temperature on a given day is 45^{O}F, the index for the day would be 20 thus requiring the use of fuel for space heating). San Francisco's average degree day index is 2500. Portland 4300, Seattle 6000 and Spokane 8000.

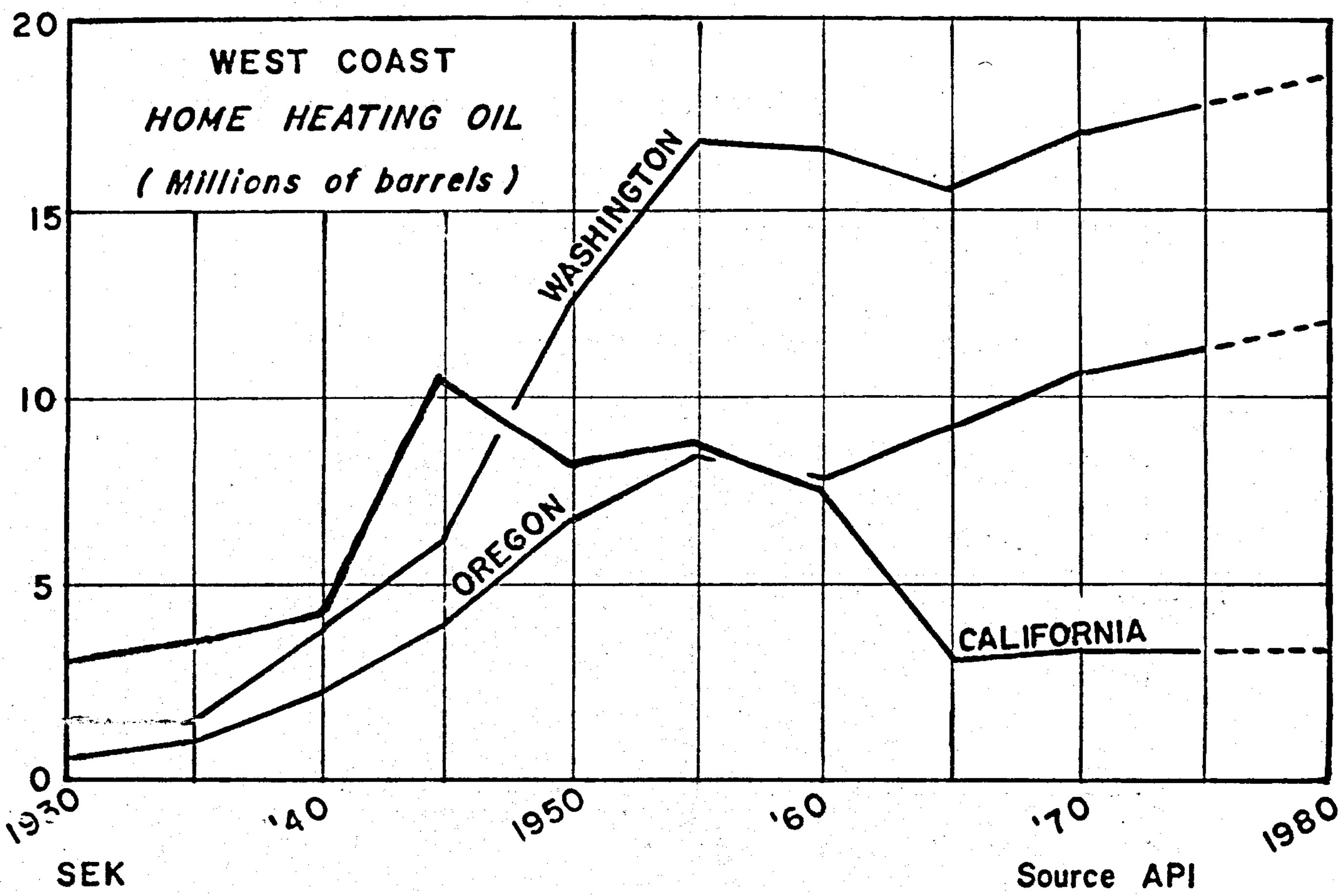

Figure 15 -- West Coast House Heating Oil

Although Washington and Oregon's population is one fourth that of California, our northern neighbors use 30 million barrels of distillate and residual oil, or eight times the heating oil consumed in California.

Our continued reliance on natural gas for space heating (2/3 of residential gas sales) rather than distillate accounts for California's low heating oil consumption.

Commercial.

One of the fastest growing markets for energy (8.7% per year 1960-71), the commercial sector consumes 4.6% of California's basic energy and 13% of the total energy. This includes hospitals, schools, office buildings, shopping malls, wholesale and retail markets.

Like the residential sector, the energy needs of the commercial market is primarily met by natural gas. Fifty-four percent of today's commercial demand of 515 trillion Btu is provided by gas while electricity meets 43% of the energy requirement and oil 3%.

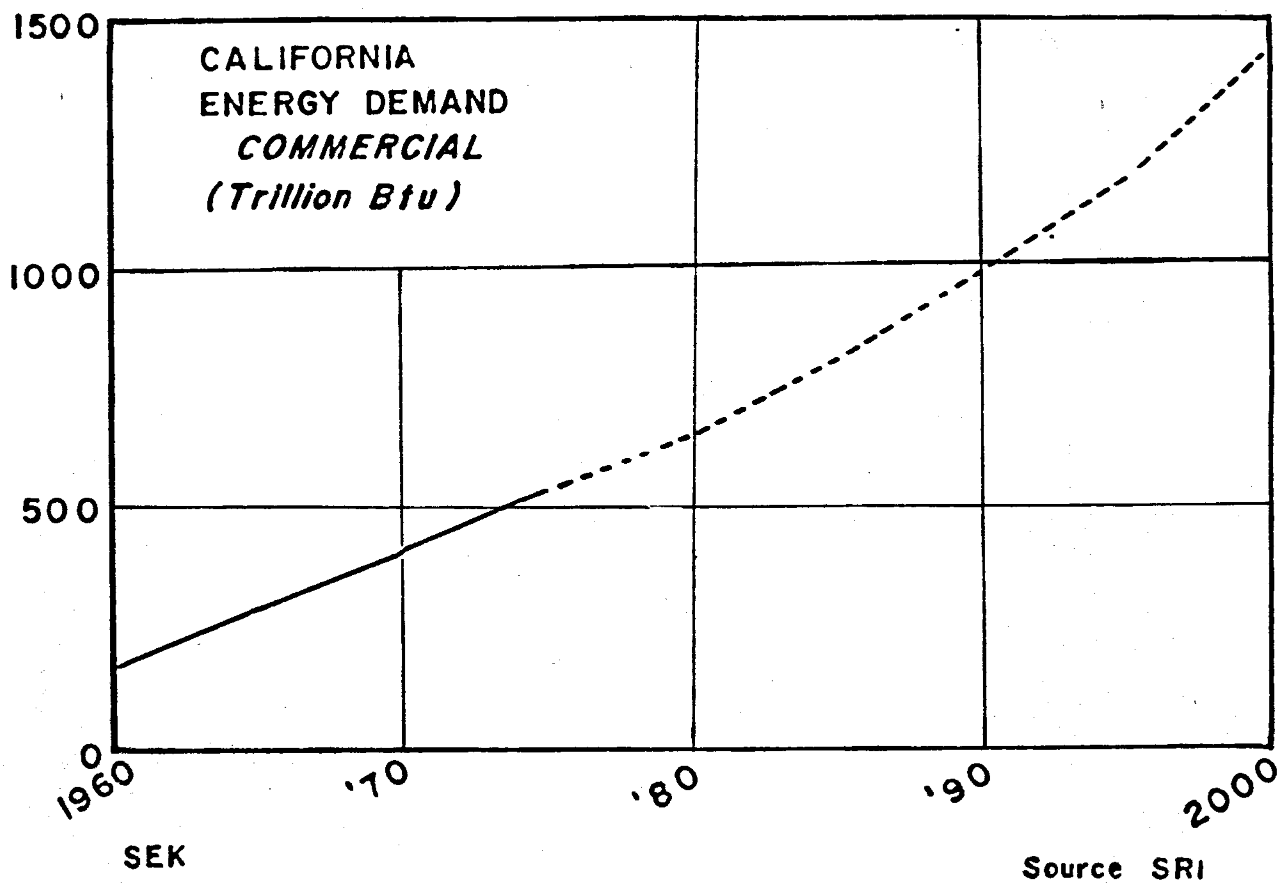

Figure 16 -- California Energy Demand Commercial

Because most commercial establishments are on a non-interruptable gas delivery, natural gas will continue to dominate the energy of this sector thru the 1970's. The growing dependence on air conditioning should boost the reliance on electricity as the major energy source by 1980. Today's commercial energy demand is equivalent to 88.6 million barrels of oil.

California Energy Demand -- Power Plants.

At present, fossil fuel plants provide 65% of California's 37,800 megawatt generating capacity. Oil now dominates the fuel used as natural gas becomes unavailable as a boiler fuel. This year California electric utilities will consume 168 million barrels of oil and 104 billion cubic feet of gas.

The California Public Utilities Commission states that "by 1975 no natural gas will be available for electric generation." Some gas will be used in gas turbine units to meet peak electric demands, but the volume consumed will drop to 21 billion cubic feet by 1976.

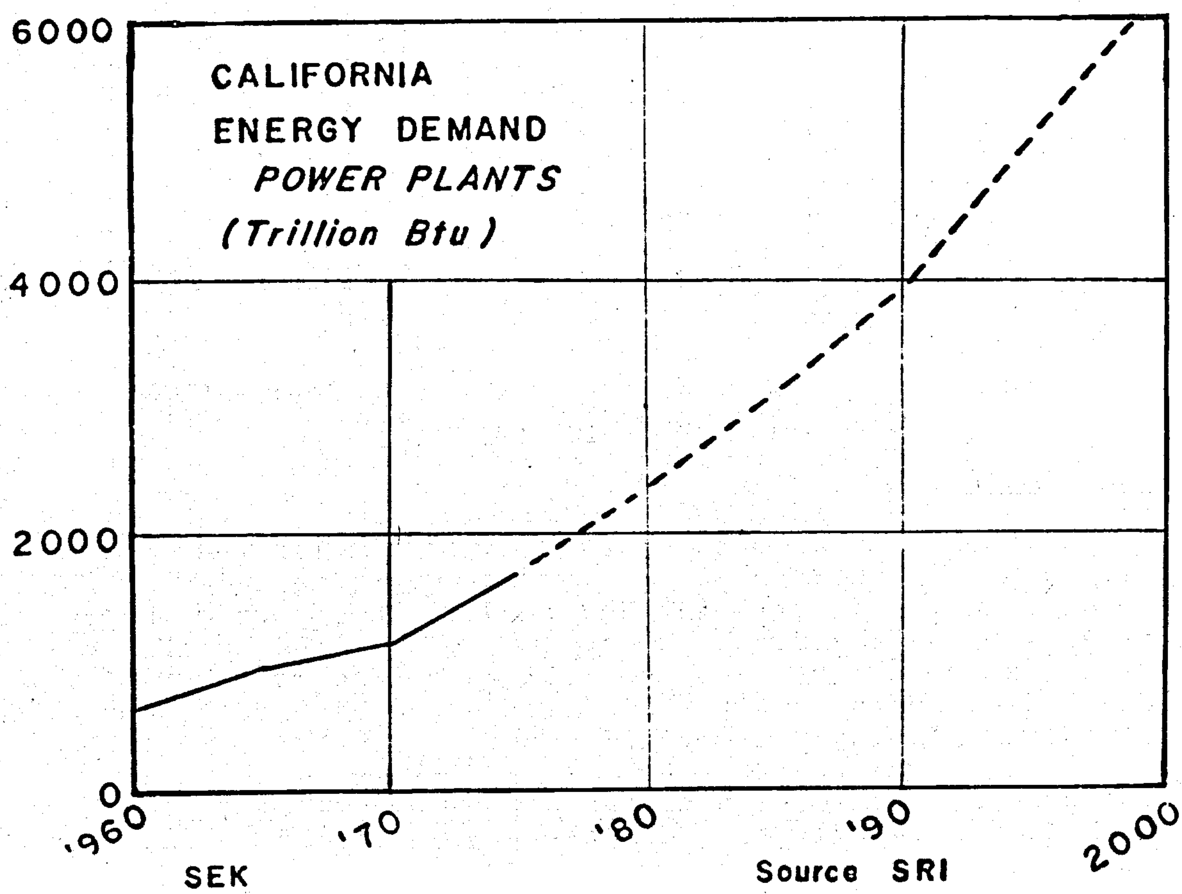

Figure 17 -- California Energy Power Plants

Military.

Since our disengagement in Viet Nam, the military sector should require less than 5% of the state's available primary energy. Military use of jet fuel, in the west amounted to less than 33 million barrels in 1973 and unless our military commitments change radically in the next few years, the West Coast drain of energy to meet military needs should remain stable at the equivalent value of 50 million barrels of oil per year.

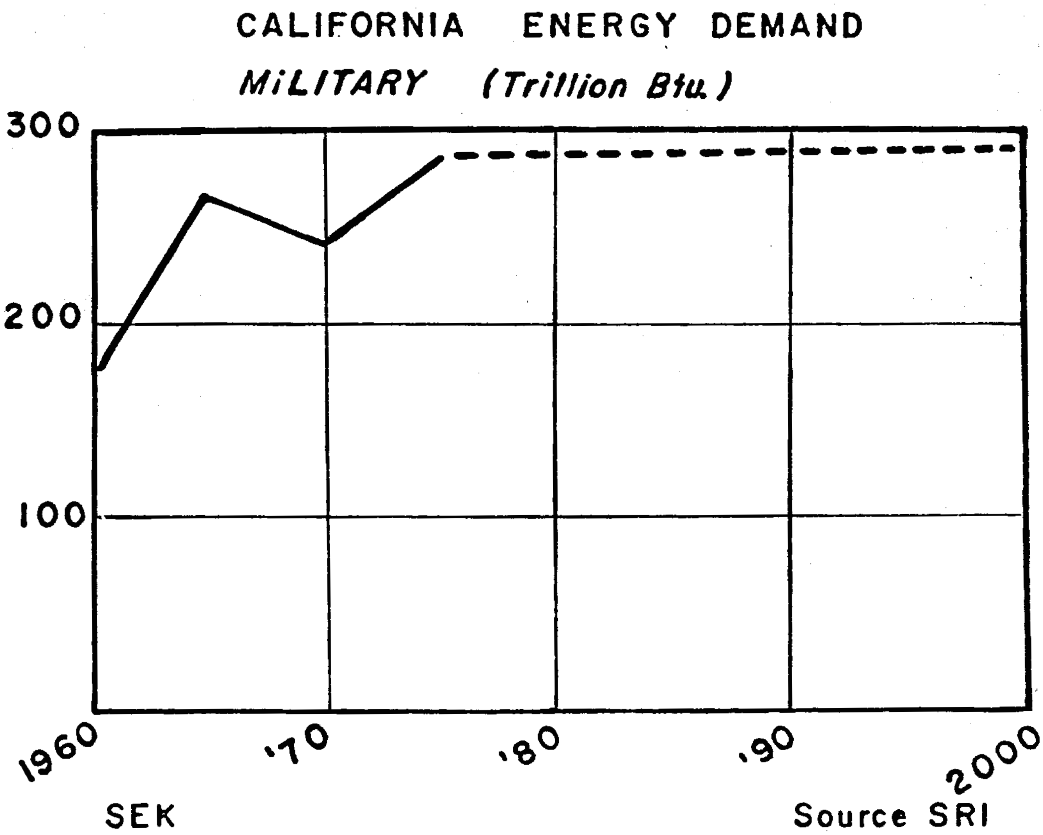

Figure 18 -- Military

Conclusion.

It seems obvious from the foregoing statistics that California is short on energy. The environmental opposition to the drilling and production of our offshore reserves, the resistance to nuclear power, the apathetic conservation efforts and the lethargic research and development of new energy sources, add pressures to our rapidly declining fossil fuel reserves.

The general public expects the petroleum geologist to work miracles and a major discovery is just that -- a miracle.

The energy problem is apparent, an indolent solution is not.

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A DETAILED GRAVITY SURVEY OF THE CRISTIANITOS FAULT ZONE, SOUTHERN ORANGE COUNTY, CALIFORNIA

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INTRODUCTION

The Cristianitos Fault is the most westerly member of a system of northwesterly trending normal faults which bounds the southeastern Los Angeles Basin, separating it from the Santa Ana Mountains. This fault system (consisting of the Cristianitos, Mission Viejo, Aliso, and subsidiary faults) is as yet poorly known; the detailed gravity survey to be discussed here is the initial phase of a longer term project to supplement the available geological information with detailed geophysical work and further geological mapping. The area of study is shown on the index map (Figure 1 on the following page), and includes portions of the San Clemente, Canada Gobernadora, and San Juan Capistrano 7-1/2' quadrangles.

Further research in this region is especially appropriate at the present time for the following reasons: (1) two recent (1975) earthquakes in the area, coupled with possible offset of Holocene sediments in a backhoe trench established across a western branch of the Cristianitos Fault (Morton and others, 1974), suggest the possibility of some seismic risk associated with this fault system; and (2) successful small-scale commercial production of petroleum from the San Clemente and Cristianitos fields, together with hot spring activity along the Aliso Fault, indicate possible further development of energy resources associated with the fault system. Since the region is becoming increasingly urbanized, an immediate assessment of the seismic risk and resource potential is crucial to effective urban planning.

GENERALIZED GEOLOGY AND SEISMICITY

Figure 2 (following the index map) is a generalized geological map of the research area, which is overlain by Bouguer anomaly contours. For purposes of comparison with these gravity values, formations with similar densities are grouped into map units, and are described below:

(1) Basement Complex (density = 2.76 gm/cm^3). The oldest rocks in the region consist of metamorphosed sedimentary and volcanic rocks

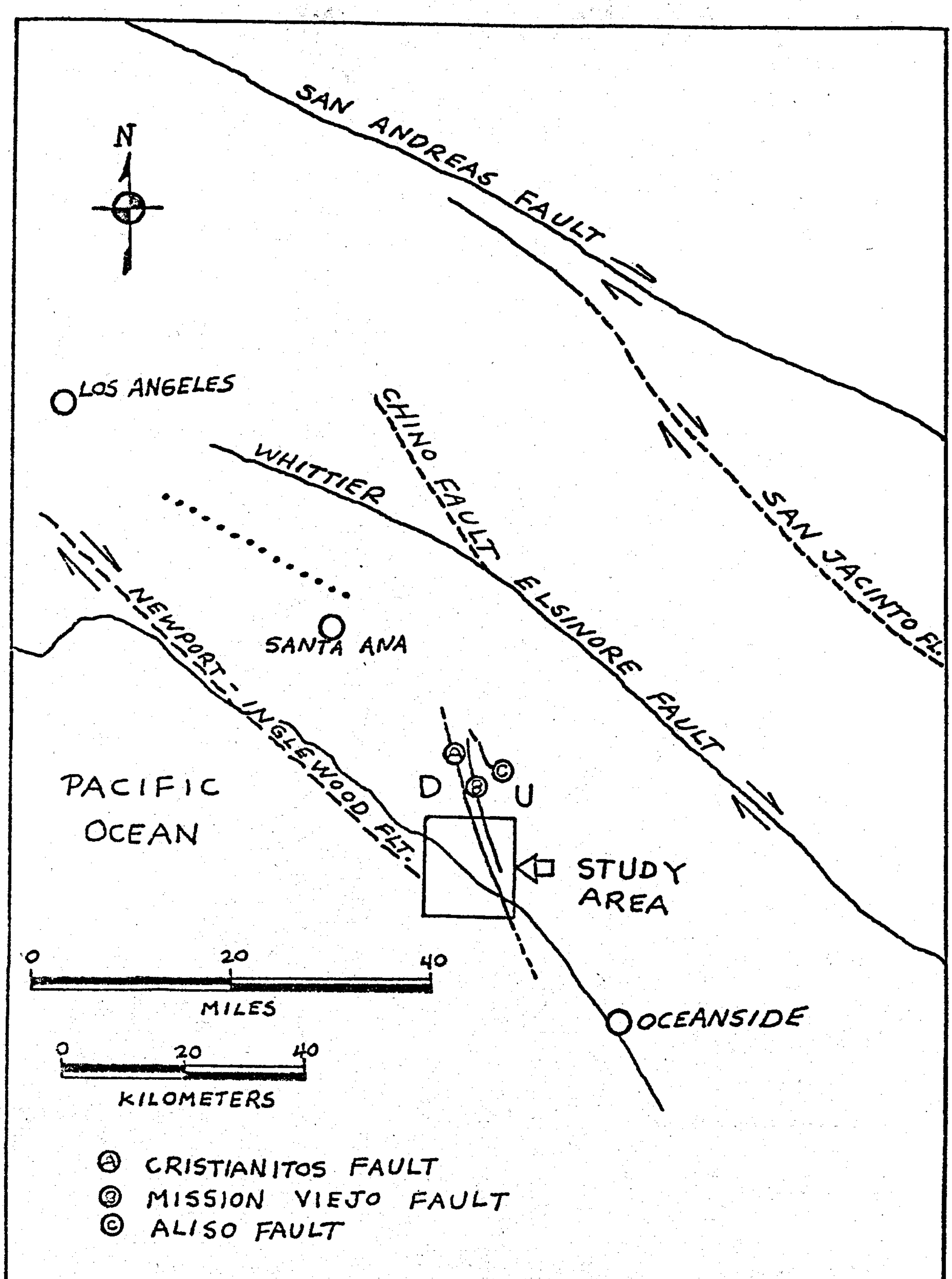
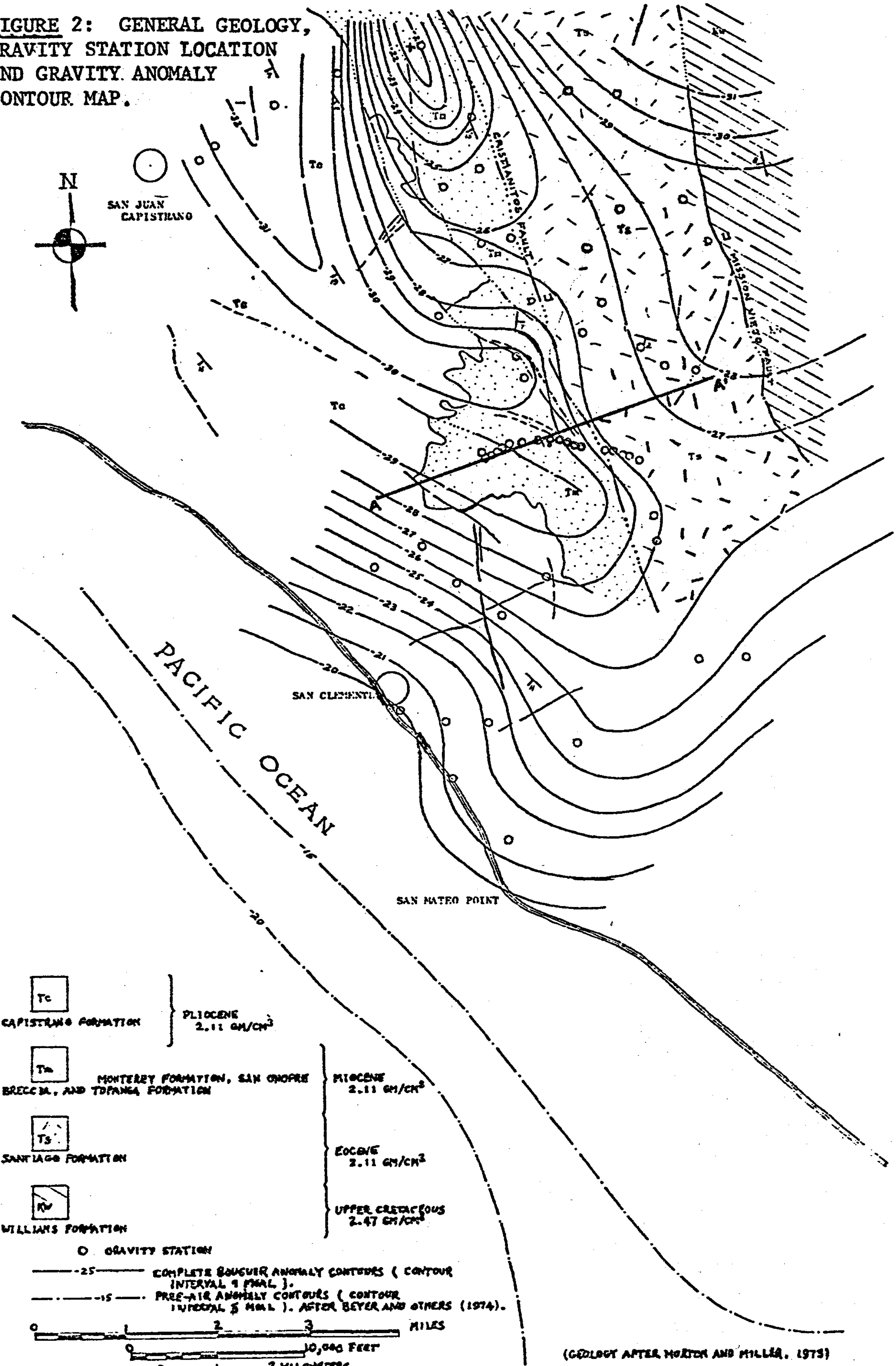


FIGURE 1: INDEX MAP

FIGURE 2: GENERAL GEOLOGY, GRAVITY STATION LOCATION AND GRAVITY ANOMALY CONTOUR MAP.



of Jurassic (?) age which have been intruded by Cretaceous gabbro and granodiorite plutons. While these rocks reportedly do not crop out in the area of the gravity survey, they form the basement for all younger rock units; recognition of their presence is crucial to the interpretation of the gravity data, since they are more dense than the overlying sedimentary rocks. Included in this complex (in order of decreasing age) are the Bedford Canyon Formation and Santiago Peak Volcanics of Jurassic (?) age, and the San Marcos Gabbro, Bonsall Tonalite, and undifferentiated granodiorites of Cretaceous age.

(2) Upper Cretaceous and Paleocene Sediments (density = 2.47 gm/cm^3). The oldest sedimentary units consist of Upper Cretaceous rocks which are exposed only to the east of the Mission Viejo Fault; these rocks unconformably overlie the basement complex, and apparently underlie Tertiary rocks throughout the field area, since wells in the San Clemente oil field encountered them at depths of 3500' to 5000' (Lang, 1972). These well-consolidated shales, sandstones, and conglomerates total a minimum thickness of 5000'; included are the nonmarine Trabuco, and marine Ladd and Williams Formations, in order of decreasing age.

The Paleocene Epoch is represented by the Silverado Formation, which consists of nonmarine to marine sandstones, siltstones and conglomerates. This unit is locally found in the field area as minor outcrops which are too small to be shown on Figure 2. However, the formation has been encountered as a 1000' thick unit in the subsurface (Ibid), and its presence has been incorporated into the calculated gravity model, to be discussed later in this paper.

(3) Younger Tertiary Sedimentary Rocks (density = 2.11 gm/cm^3). The Younger Tertiary sedimentary units range in age from Eocene through Pliocene; included are both marine and nonmarine shales, sandstones, conglomerates, and breccias, with locally interbedded minor volcanic flows. These rocks occupy the major portion of the field area, and have been further subdivided on Figure 2 into the following units: (a) Eocene rocks (Santiago Formation); (b) Miocene rocks (Topanga Formation, San Onofre Breccia, and Monterey Formation, in order of decreasing age); and (c) Pliocene rocks (Capistrano Formation). Total thickness for these Tertiary rocks ranges from approximately 3000' to 5000'. The density value of 2.11 gm/cm^3 listed above for this group of rocks is the weighted average of density values for the individual formations as reported by Dames and Moore (1971).

Not shown on Figure 2 are Quaternary alluvium, terrace, and landslide deposits. Although these rock units commonly mask the underlying geology, they are quantitatively unimportant to evaluation of gravity values except locally.

The above units have been juxtaposed by the major fault system in the area. This system trends N25°W, and consists of several normal faults dipping steeply to the west, with the eastern block typically uplifted relative to the western block. The amount of displacement on individual faults has not been adequately determined, but estimates range from 200' to 1600'; the aggregate uplift across the fault system of the Santa Ana Mountains relative to the Los Angeles Basin is approximately 7500' (Yerkes and others, 1965). Two named major members of this system (the Cristianitos and the Mission Viejo) are present in the field area; the trace of a third, the Aliso Fault, lies outside the study area approximately three kilometers northeast of the Mission Viejo Fault. Numerous subsidiary faults with the same trend occur in the area, both as onshore westerly branches of the Cristianitos Fault and offshore on the continental shelf (Morton and Miller, 1973).

Two other fault systems are represented in the immediate field area in a minor way: (1) several small faults with a N70-80°W trend, subparalleling major faults such as the Newport-Inglewood and Norwalk Faults (the more easterly part of the Aliso Fault also bends around to this orientation); and (2) two small faults with northeasterly traces.

Movement along these various faults has apparently deformed the sedimentary and basement rocks by uplift, folding, and tilting. Regionally, the strikes of sedimentary bedding planes parallel the trace of the Cristianitos Fault, while dips lie at low angles to the southwest; attitudes are often unreliable because of surficial sliding. Locally, folding has produced anticlines and synclines, and petroleum accumulation has been controlled by a combination of anticlinal and fault traps.

The seismicity of the area is poorly known. Two magnitude 3.0+ earthquakes in January 1975 could be attributed to branches of the Cristianitos Fault. From this same area, the epicenters of four instrumentally recorded small earthquakes with magnitudes less than 3.0 were located in the San Juan Capistrano Quadrangle in 1937 and 1948 (Morton and others, 1974), and a magnitude 5.5 earthquake in 1938 was centered to the northeast in Trabuco Canyon (ibid), near the intersection of the projected traces of the Norwalk and Mission Viejo Faults. Additionally, the epicenter of a poorly documented earthquake in 1929 may have been located in this area, as was that of an historical earthquake in 1769. Quaternary movement along the Cristianitos Fault is suggested by possible offsets observed in Holocene sediments which were exposed by a backhoe trench cut across the fault zone (ibid). Offshore truncation of post-Miocene isopachs implies geologically recent displacement of the fault (Vedder and others, 1974), and the senior author has observed possible offsets in landslides in the area. Thus, there is substantial evidence that members of the Cristianitos Fault system may be active.

GRAVITY SURVEY AND DATA REDUCTION

Approximately 60 gravity stations were established in the field area. Seventeen of these stations were set up in a line across the main trace of the Cristianitos Fault; their elevations were obtained by levelling. The remaining stations were occupied on points of known elevation (bench marks and useful elevations), for the purpose of establishing regional control. Locations for all stations are shown on Figure 2. All data were obtained with Lacoste and Romberg gravity meter G300 and were referred to base station #322 in Oceanside, which has an absolute gravity value of 979.5713 gals (Chapman, 1966).

Gravity data were reduced to complete Bouguer anomaly values using a density of 2.00 gm/cm^3; these Bouguer values include terrain effects which were evaluated out to a radius of 2.61 km (through Hammer zone H). The values have been contoured at a 1 milligal interval to produce a gravity map, which is shown superimposed on the generalized geological map (Figure 2). The gravity map includes marine gravity values contoured at 5 milligals which were obtained on the continental borderland of California; these marine values were tied into Chapman's land base station network (Beyer and others, 1974) and thus can be directly incorporated.

INTERPRETATION OF GRAVITY VALUES

Two definite trends can be observed in the gravity data shown on Figure 2. One is the local alignment of gravity contour lines in a northwesterly direction, paralleling the Cristianitos fault zone. The other is a more regional alignment of coastal values in the western portion of the map with the coastline and with offshore gravity data. Both trends are discussed in more detail below.

The most prominent feature of the gravity map is the elliptical 10+ milligal high associated with the Cristianitos Fault, shown on the northern part of the map. This area has been mapped as San Onofre Breccia (Morton and Miller, 1973), which is normally characterized by a relatively low density value of 2.24 gm/cm^3 (Dames and Moore, 1971). The reported geological and density data are thus in conflict with the Bouguer anomaly values, which should have yielded a gravity low rather than a high. Two explanations are capable of resolving this conflict: (1) the San Onofre Breccia is locally more dense, perhaps because of a greater ratio of large basement clasts to fine-grained matrix; or (2) the gravity high is actually underlain at least partially by basement rock. Preliminary field observations suggest that the northern part of the area mapped as San Onofre Breccia is actually an exposure of the basement complex; foliations of "clasts" apparently are oriented in one direction, and individual outcrops are too extensive to be individual clasts. Farther south, San Onofre Breccia appears to be present, and overlies basement. If this interpretation can be verified by additional geological mapping, this would be the only reported instance of San Onofre Breccia resting directly on its source area. We tentatively conclude that the faulting in the area has resulted in an uplifted basement block between the Cristianitos Fault and its western branch.

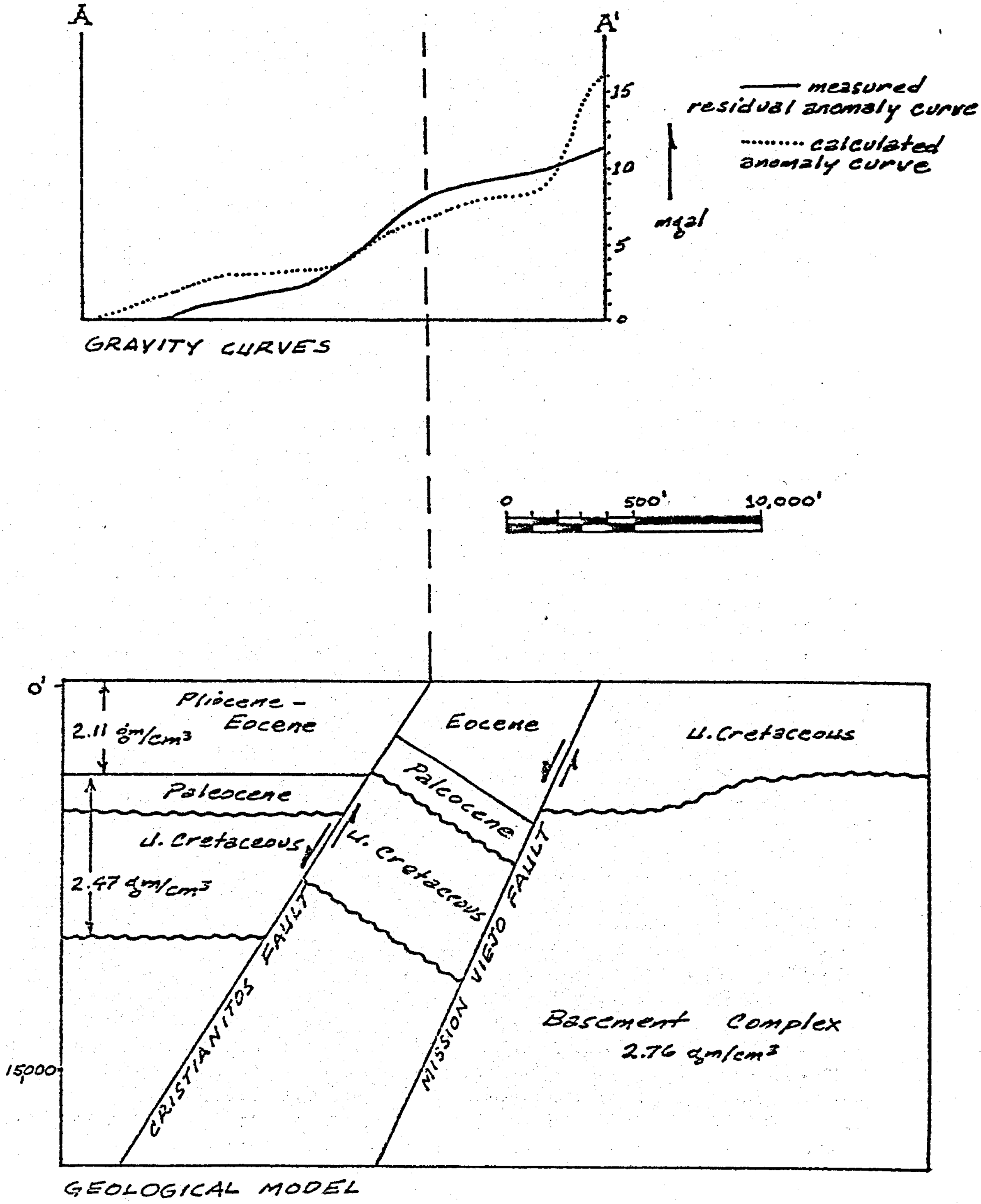
South of the gravity high, the presence of the Cristianitos Fault continues to dominate the alignment of Bouguer anomaly values. In the central part of the area, contour lines parallel the fault zone, and to the south near the coast, prominent bending of the contours indicates the continued control exerted by the fault on local geology. This effect is in our opinion also felt offshore, where the projected trace of the fault and its western branch is characterized by prominent distortion of the gravity contours, as shown on the gravity map of the California continental borderland (Beyer and others, 1974); this distortion equates to an approximate 5 milligal anomaly.

The regional northwesterly alignment of offshore free-air gravity values (ibid) is paralleled onshore in the western part of the gravity map by Bouguer values near San Clemente. This gravity trend reflects the dominant structural grain in southern California which is expressed by the orientation of several major right-lateral transcurrent fault zones (i.e., the Newport-Inglewood, San Andreas, San Jacinto, and Whittier-Elsinore; refer to the index map, Figure 1). Locally, this structural grain is expressed by several minor faults in the western part of the field area. The regional gravity gradient is largely obliterated to the east by the dominance of the more northerly Cristianitos Fault gravity trend, since the normal faulting associated with the fault has more profoundly affected the basement, thus creating significant lateral density variations. The intersection of the regional gradient with the Cristianitos trend has created a prominent gravity nose which results in a residual gravity low near San Juan Capistrano; geologically this probably reflects a thicker wedge of low density Capistrano Formation, which abuts against basement along the western branch of the Cristianitos Fault, and then swings to the southeast to end against the main trace of the fault. This marks the termination of the so-called Capistrano embayment (Lang, 1972), whose eastern margin may have been controlled by movement along the Cristianitos Fault.

A third gravity trend is defined by contours aligned in a northeasterly direction; this is developed in the southeastern part of Figure 2, and parallels several minor faults. Although we believe this trend is real, it is at present poorly defined because of sparse gravity data in the area.

Figure 3 on the following page depicts a geological cross section located along line A-A' (shown on Figure 2). This cross section served as the basis for a two-dimensional gravity model; the gravity curve derived from solution of this model is compared with the residual anomaly curve on Figure 3 above the geological cross section.

FIGURE 3 : Calculated Gravity Model



The geological model was chosen along A-A' for two reasons: (1) the location of a major paved access road subparallel to A-A' facilitated the collection of closely spaced gravity stations, to provide additional gravity control; and (2) two wells drilled in the abandoned San Clemente oil field west of the Cristianitos Fault provided subsurface geological control to a depth of 6000' - 7000', both on the dip of the fault zone (which was penetrated by the easternmost well) and on dip and thicknesses of major stratigraphic units. Subsurface density information was also readily available for the various formations present in the area (Dames and Moore, 1971).

Solution of the two-dimensional gravity model was accomplished by the method of partial infinite slabs, assuming that the fault zones and stratigraphic units in the area continue indefinitely to the northwest and southeast. The calculated model curve coincides closely with the actual residual gravity curve, as shown on Figure 3, with the discrepancy between the two averaging less than one milligal. Thus the simplified geological cross section may provide a reasonable approximation to subsurface conditions.

Several features of the model bear further elucidation:

(1) The displacement along the Cristianitos Fault as estimated on the model is over 2000', and examination of the two curves suggests that if a somewhat greater displacement were incorporated into the calculations, a closer coincidence of the two curves could be accomplished. Thus the gravity data support sizeable offset on the fault, even greater than the previously reported maximum value of 1600', which was based on geological evidence (Lang, 1972). The total vertical displacement across both the Cristianitos and Mission Viejo Faults is approximately 5000', based on the gravity model.

(2) The block east of the Cristianitos Fault appears to be rotated on the basis of subsurface data; the gravity data do not contradict this observation, and the fault thus shares a characteristic with many Basin and Range and other normal faults.

(3) The thickness of the Upper Cretaceous section totals about 5000' in the model; one well in the San Clemente oil field penetrated some 3000' of Upper Cretaceous, but did not reach basement (ibid). The gravity data thus provide an estimate of the thickness of this unit in the area.

The discrepancies between the gravity curves in Figure 3 may be due to erroneous assumptions concerning details of the geology as depicted in the cross section. Alternately, the assumption that structures extend infinitely in the third dimension is assuredly partially incorrect, based on the gravity map, and this factor may contribute to the lack of coincidence between the curves. As an example, the basement wedge postulated to exist between the branches of the Cristianitos Fault in the northern map area is nowhere found at the surface to the south along the line of the geological cross section; indeed, the basement appears to be dipping toward the south, so that its surface would be encountered there at a depth of greater than 8000'. Yet the presence of basement at or near the surface to the north will nevertheless affect the gravity values along line A-A', making them artificially high in comparison with model values.

The greatest discrepancy between the two gravity curves on Figure 3 exists at the eastern edge of the model, where the calculated curve rises 3 milligals above the residual anomaly curve. The Upper Cretaceous was assumed to thin eastward; it may not do so, or may be actually less dense than measured values.

SUMMARY REMARKS

The findings of this study can be summarized as follows:

(1) The Cristianitos Fault is a major normal fault with approximately 2000' of displacement. This fault may result from the tensional component corresponding to a north-south compression system which defines the structural grain of southern California. The strike-slip faults associated with this stress pattern (i.e., San Andreas, Newport-Inglewood) are recognized as being seismically active. Possible seismicity associated with the Cristianitos fault system is therefore consistent with this regional pattern.

(2) An unreported basement sliver may exist in the northern part of the study area. The presence of San Onofre Breccia has also been reported near this location, and hence the possibility exists that the San Onofre may be in contact with its basement rock source at this site. Further geological field mapping is needed to substantiate this hypothesis.

(3) Model calculations indicate that Upper Cretaceous strata in the subsurface of the study area may approximate a thickness of 5000'.

Further work is necessary, and planned, to resolve several questions. What is the exact relationship of the Cristianitos Fault system to the major strike-slip system of southern California? Does basement crop out in the northern portion of the research area? And what future energy sources (both petroleum and geothermal) may be associated with the Cristianitos fault system, on land and in the continental borderland?

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Telluric Mapping Over the Mesa Geothermal Anomaly, Imperial Valley, California

by

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Abstract

The telluric prospecting method employs naturally occurring AC electric fields in the earth to measure the variations in lateral electrical conductance within a sedimentary basin. It is a relatively inexpensive, rapid and deeply penetrating method of estimating electrical conductivity. Telluric measurements were made at thirty nine stations in the vicinity of the Mesa Geothermal Anomaly, Imperial Valley, California in order to evaluate the usefullness of the method as a geothermal prospecting tool. The area of investigation is characterised by thick (about 3 km) and highly conductive(resistivity on the order of 5 ohm-m) sediments. The large sediment depth and conductivity neccessitated a more sensitive(p-p noise level = 5 uV)apparatus operating at lower frequencies(.0067 hz) than is normally employed for telluric investigations. Relative ellipse areas were determined for the stations and plotted as total field and residual contour maps. These maps clearly reveal the presence of the thermal anomaly. They coincide well in geometry with the anomaly shown by shallow thermal gradient data and are consistent with temperature data from five deep wells in the area.

Introduction

It is well known that the electrical conductivity of rocks increases with rising temperature. Methods of measuring conductivity in situ have thus played an important role in the detection and evaluation of geothermal resources.

The telluric method, long used for petroleum exploration outside of America, has several potential advantages as a method of mapping conductivity variations over an area. It is capable of deep penetration (3 km in this study) and is rapid and inexpensive in its field application (A three man crew can occupy six stations per day.). The data obtained can be readily displayed in map form so areal changes in conductivity can be easily seen.

The telluric method has been well described in the literature(Berdichevskii,1960; Boissonnas and Leonarddon,1948; Yungul, Hembree, and Greenhouse, 1973). The method utilises certain frequencies of naturally occurring electric currents which have the property of flowing in more or less uniform sheets within the sedimentary layer of the earth's crust. The frequencies used are chosen to have enough depth of penetration to reach the bottom of the sedimentary section yet not be able tc induce significant current flow in the more electrically insulating crystaline rocks below.

For these frequencies it is generally accepted that if basement depth and sediment resistivity vary only gently in lateral directions, then the horizontal electric field due to these frequencies measured at one station (a field station) will be related to that at another station (a base station) by

$$E_u = AE_x + BE_y$$

(1) $$E_v = DE_x + CE_y$$ (Berdichevskii,1960)

where E_u and E_v are the horizontal components of the electric field at the field station and E_x and E_y are the components at the base station. A,B,C and D are constant parameters for each station which depend on local geology. It is easily seen that the Jacobian J = AD - BC is also a constant related to local geology.

For a horizontally layered subsurface it has been shown (Berdichevskii,1960) that to a good approximation

(2) $$J \approx \frac{S_b}{S_f}$$

where the subscripts refer to base and field stations and S is the longitudinal conductance

(3) $$S = \sum_{i=1}^{n} \frac{h_i}{\rho i} .$$

h_i and ρ_i are the thickness and resistivity of the i'th layer below the surface. The summation includes all the layers between the earth's surface and the insulating basement rocks. For a continuous variation of resistivity with depth, eq. 3 can be expressed in integral form

(4) $$S = \int_0^D \frac{dz}{\rho(z)}$$

where z is depth below the surface and D is the basement depth.

Methods of determining J from field measurements are well known (Berdichevskii,1960; Yungul,1968). As can be seen from eqs. 2 and 3, the value of J will be proportional to the square of the resistivity under a station and inversely proportional to the square of the thickness of the sediments. By measuring the value of J at many different stations we can thus prepare a map which effectively represents (but does not differentiate between) variations in conductivity and thickness of the sedimentary cover in a region. Such a map would show high values of J in areas of thin or poorly conductive sediments.

The Mesa Geothermal Anomaly

The Mesa Geothermal anomaly is located (fig. 1) in California's Imperial Valley, a deep basin filled in the most part with Cenozooic clastic sediments (Diblee,1954). The anomaly is on the order of 40 km^2 in area. Temperatures encountered in several deep geothermal test wells are on the order of 160 to 200°C at depths greater than a kilometer(U.S.B.R.,1974).

This area was chosen as the site for the telluric investigation for several reasons. Gravity and seismic data (Biehler, 1971) show that the basement depth is fairly uniform there and on the order of 3 km. The area is centrally located in the basin and it is reasonable to expect that there will not be extreme variations in the nature of the sediments within the area of investigation. The lack of extreme variations in basement depth and sediment type is an ideal condition for the identification of effects on the telluric electric field due to the the presence of the thermal anomaly.

The area has been investigated extensively by other geophysical methods, notably gravity and seismic refraction (Biehler,1971), thermal studies(Combs,1971,1972) and DC resistivity(Meidav and Furgerson,1971; Furgerson,1972). These studies provide an important framework within which the telluric data can be evaluated.

Apparatus

The telluric recording apparatus consists of a set of electrodes for sampling the earth's electric field, a sensitive two channel amplifier, a two channel filter for removal of undesired frequency components, and an X-Y recorder. Two channel recording is neccessary because, as will be explained later, the method of determining J requires knowledge of two orthogonal, horizontal components of the telluric electric field.

In this study, the three electrodes were connected in an L shaped array 0.3 km on a side with a 90° angle at the apex. The potential difference between each of the outer electrodes and the center electrode was measured to obtain the two electric field components. The recording instruments were located near

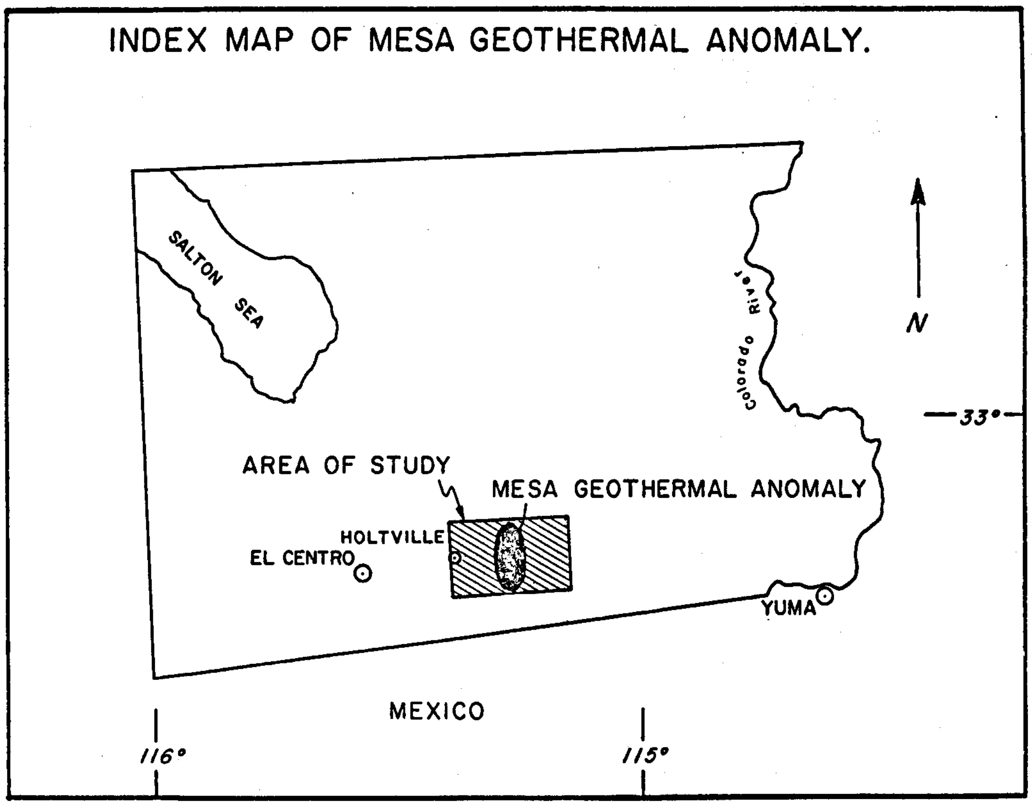

Figure 1: Index map to the Mesa Geothermal Anomaly, Imperial Valley, California

the apical electrode and the two outer electrodes were connected by means of insulated wires.

Two properties of the Imperial Valley influenced the design of the apparatus. The sediments there are quite conductive (resistivities on the order of five to ten ohm-meters in the test area) and quite thick (on the order of three kilometers). These conditions cause the signal level there to be exceptionally small. Typical signal levels were ten to fifty microvolts, varying from day to day with the state of excitation of the geomagnetic field.

A second effect of local conditions was decreased depth of penetration of the natural electromagnetic field due to the low resistivity of the sediments. This effect was compensated for by observing lower frequencies than usual for telluric prospecting methods. The filters used in this study had a peak response at .0067 hz (equivalent to a period of 150 sec). Meaningful data could not be collected for periods shorter than 30 sec because for these higher frequencies it was impossible to correlate the records between field and base stations.

Because of the low signal levels encountered in the measurements, it was neccessary to reduce instrument noise to a minimum. Since modern solid state amplifiers have a very low internal noise level, the electrodes which connect the apparatus to the ground are the major source of instrument noise. Several different types of electrode were tested for use in the project and it was found that the quietest were silver-silver chloride electrodes. These had an internal peak to peak noise level of less than 5 uV as compared to about 25 uV for a pair of copper-copper sulphate porous pot electrodes. Electrode noise levels were tested by immersing various types of electrodes in solutions which duplicated their electrolytes and measuring their noise output with the same apparatus used for making the measurements of telluric voltages in the field. The physical construction of the electrodes actually used in the field is shown in fig. 2.

The amplifiers used in the study were two stage devices utilising operational amplifiers (fig. 3). The first stage was an Analog Devices AD 504M operational amplifier connected in the noninverting configuration with a gain of 100. This was AC coupled to a second stage of gain 10. The AC coupling network had the effect of removing signals with periods longer than 1,200 sec and was for the purpose of removing the effect of electrode drift. The pure DC component of the electrode potential was removed by a biasing network in the first stage input. The second stage amplifier was a National Semiconducters LM 308H connected in the noninverting configuration. The complete amplifiers had noise levels between 1 and 2 uV in the frequency band of interest. DC imput impedence was larger than one megohm.

Undesired frequency components of the telluric field and cultural noise were removed by means of active filters(fig. 4). The peak response of the filters was at a period of 150 sec (.0067 hz) with attenuation proportional to the square of the frequency away from the peak (fig. 5). A sharp cutoff was especially neccessary for the high frequency end of the filter curve in order to strongly reject frequencies with periods in the range 1 to 30 sec. These frequencies often were observed with amplitudes larger than the frequencies of interest and had to be strongly attenuated in order to obtain useful data.

Method of Determining J

The J values for this study have been determined by the "vectorgram" method of Yungul(1968). In this method the two components of the horizontal electric field are amplified, filtered and fed into the two channels of an X-Y recorder. The pen of the recorder will then trace out a plot of the variations of the electric field with time. If this recording is made for a period of several minutes, the record will appear as a series of loops made by the pen recrossing its path several times in a more or less random manner. Since, within a given structural basin, the electric field is quite coherent, a vectorgram produced in this way at a field station will be very similar to one produced simultaneously at the base station. Yungul has shown that the ratio of areas of corresponding loops on simultaneous field and base vectorgrams is equal to J. In actual practice there is a considerable amount of variation in J values obtained in single measurements and data from about ten different pairs of loops should be averaged to obtain the J value at a particular station.

As a measure of the reliability of the mean J values, the standard deviation of the mean, S_m, was calculated at each station. This is a measure of the deviations of the means of many separate samples arond the true mean of the population being sampled (in this case the true value of J). If a number of sample means were determined, S_m would be the standard deviation of the population of sample means. It is given by

$$(5) \qquad S_m = \frac{S}{\sqrt{N}}$$

where S_m is the standard deviation of the mean, S is the standard deviation of the individual determinations of J at a station, and N is the number of individual determinations of J at a station. S is given by

(6) $$S = \frac{1}{N-1} \left(\sum_{i=1}^{n} (Ji - \bar{J})^2 \right)^{\frac{1}{2}}$$

where the J_i are determinations of J from different single pairs of loops and $\bar{J}$ is the mean J determined at a station.

At most stations S_m was found to be about 5 or 10% of the mean J value. Over 68% of the sample means should lie within $\pm S_m$ of the true mean at a station (Bevington,1969). The statistical parameters for the individual stations are given in Table 1.

Table 1: Statistical Parameters of Telluric Stations.

Stations are listed according to increasing $\bar{J}$ and with the northernmost station first where values of $\bar{J}$ are duplicated.

Mean Value of J Measurements, $\bar{J}$	Standard Deviation of J Measurements, S	Standard Deviation of Mean, S_m	Standard Deviation of Mean as % of mean	Number of Measurements, N
.44	.166	.062	14.2	7
.47	.130	.039	8.3	11
.49	.181	.050	10.3	13
.52	.099	.033	6.4	9
.52	.148	.034	6.7	18
.55	.124	.039	7.1	10
.56	.164	.054	9.7	9
.58	.103	.034	5.9	9
.58	.251	.094	16.4	7
.50	.182	.064	10.7	8
.64	.160	.048	7.6	11
.64	.109	.025	3.9	19
.65	.302	.101	15.6	9
.73	.163	.062	8.4	7
.74	.162	.049	6.6	11
.74	.132	.042	5.6	10
.77	.176	.059	7.7	9
.80	.151	.062	7.7	6
.81	.129	.049	6.0	7
.85	.304	.087	10.3	12
.85	.299	.100	11.8	9
.86	.103	.030	3.5	12
.88	.329	.125	14.1	7
.89	.239	.084	9.4	8
.92	.276	.104	11.4	9

Table 1: Continued:

Mean Value of J Measurements	Standard Deviation of J Measurements	Standard Deviation of Mean	Standard Deviation of Mean (% of mean)	Number of Measurements
.92	.200	.070	7.7	8
.95	.204	.062	6.5	11
.96	.241	.098	10.2	6
.97	.265	084	8.6	10
1.03	118	.042	4.0	8
1.12	.234	.074	6.6	10
1.13	.291	.092	8.1	10
1.14	.402	.142	12.4	8
1.16	.275	.104	8.9	7
1.24	.167	.056	4.5	10
1.32	.428	.135	10.3	10
1.46	.446	.141	9.7	10
1.72	.530	.168	9.8	10
2.01	.142	.045	2.2	10

Interpretation

Two maps have been prepared from the data. The first shows the measured values of J at the various stations. The second is a residual map. The residual map was prepared by least squares fitting of a planar regional to the raw J data and subtraction of the regional value at each data point. Both maps have a contour interval of 0.2. Contouring was done automatically on an IBM 360-50 computer. The value given by the contours at any given point represents a weighted least squares fit to all the data (either total field or residual, depending on which map) under the following weighting function.

(7)
$$W = \left(\frac{r_o - r}{r + \delta}\right)^2 \quad r < r_o$$
$$W = 0 \quad r > r_o$$
$$r_o = 20\text{km} \qquad \delta = .15\text{km}$$

r = distance from map point to field data point

The regional variation in J can be seen in the total field map (fig. 6) as a tendency for J values to decrease from southeast to northwest. This decrease in J value to the northwest is probably the result of a decrease in ground water resistivity due to increasing salinity in that direction (Meidav and Furgerson, 1971).

The most striking feature on the residual map (fig. 7) is a large negative J anomaly coinciding in position with the Mesa Geothermal Anomaly. Comparison of the J contours with the shallow thermal gradient data in fig. 7 shows a strong agreement in the position and shape of the anomaly shown by the two data types with the low J values corresponding to high thermal gradient values. This is well illustrated by the similarity in shape between the 8^{o}F/100ft thermal gradient contour and the -.2 J contour over the western and northern portions of the anomaly.

An interesting exception to this correspondence is seen in the soutneastern corner of the anomaly. Here at a single point is seen a high residual J anomaly of +.38 in a place where the high thermal gradient value would predict a negative residual J. This high value has been verified by repeating the field measurement. Such a large increase in J over surrounding values is indicative of a substantial amount of resistive material in the subsurface. The fact that this material does not produce a visible effect at adjacent stations one mile distant indicates that it is at shallow depth, probably a few thousand feet or less. This body is most reasonably explained either by the presence of steam (which has a much higher electrical resistivity than water) or by filling of the pore spaces in the sediments by hydrothermally deposited minerals. Since none of the wells drilled over the Mesa Anomaly have encountered steam and the anomalous resistive body is located over a mile to the east of the hottest part of the anomaly (as judged by thermal gradient data)the resistive body appears most likely to represent mineral precipitation within the shallow part of the sedimentary column.

The U.S. Bureau of Reclamation has drilled five deep geothermal test wells over the Mesa Anomaly which have encountered temperatures in excess of 160^{o}C (U.S.B.R.,1974). All five of these wells are closely spaced around the central low in residual telluric anomaly which is illustrated in Fig. 7. This supports the hypothesis that high temperatures at depth tend to occurr near places with large negative residual J values in this area. If anything, one would expect the correlation with deep well temperatures to be better than the correlation with shallow thermal gradient data because of the large depth penetration characteristic of the telluric method.

Conclusions

On the basis of this test project, the telluric prospecting method appears to show promise as a reconaissance tool for geothermal investigations in sedimentary basins. The main advantages of the method are that it can be applied rapidly in the field by a small crew; the apparatus is inexpensive; and it can sample the entire sedimentary sequence, even to great depth.

In this study the telluric method has located a known geothermal anomaly and shown a geometry for it which is consistent with that shown by available thermal data.

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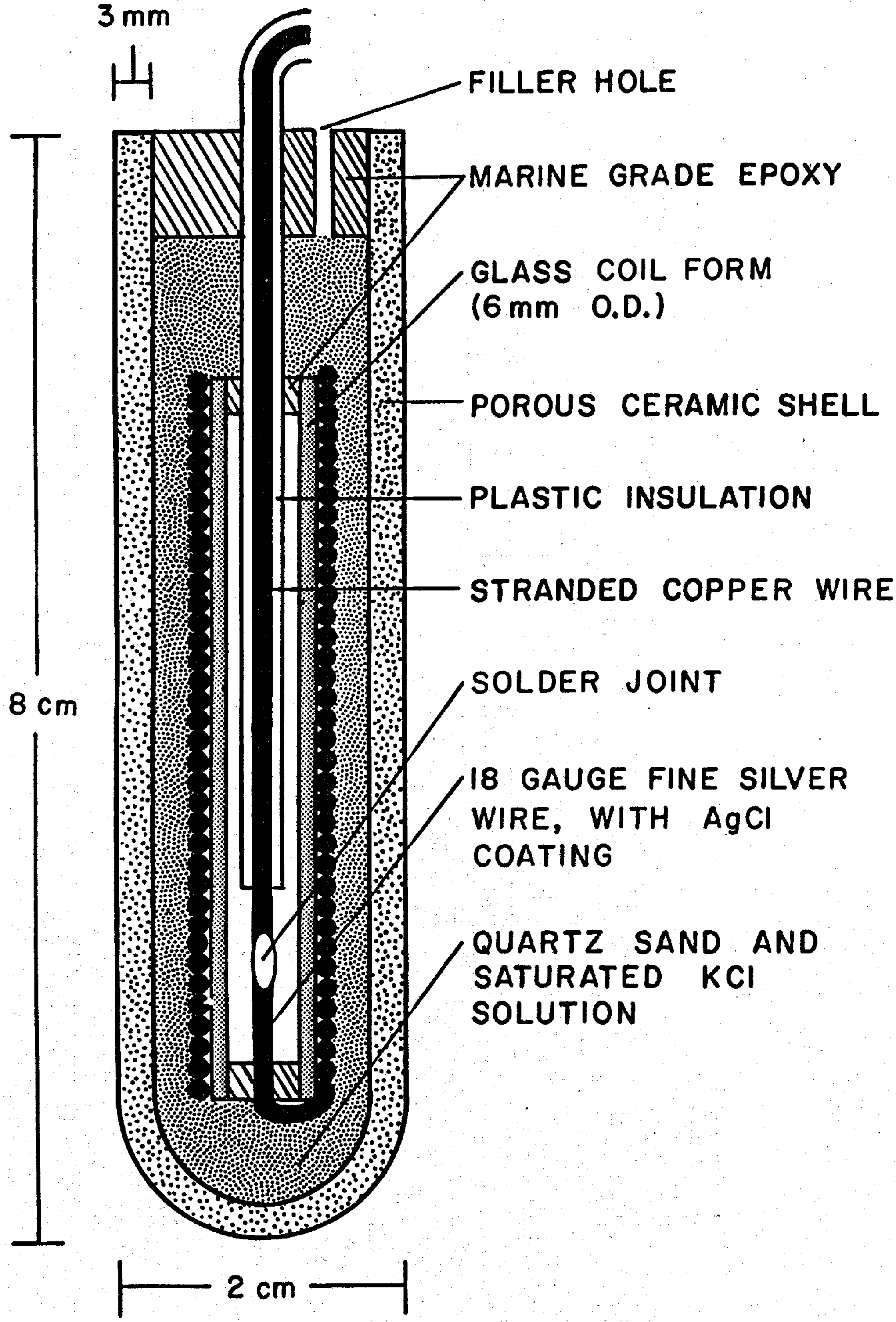

Figure 2:Construction details of field model silver-silver chloride electrode.

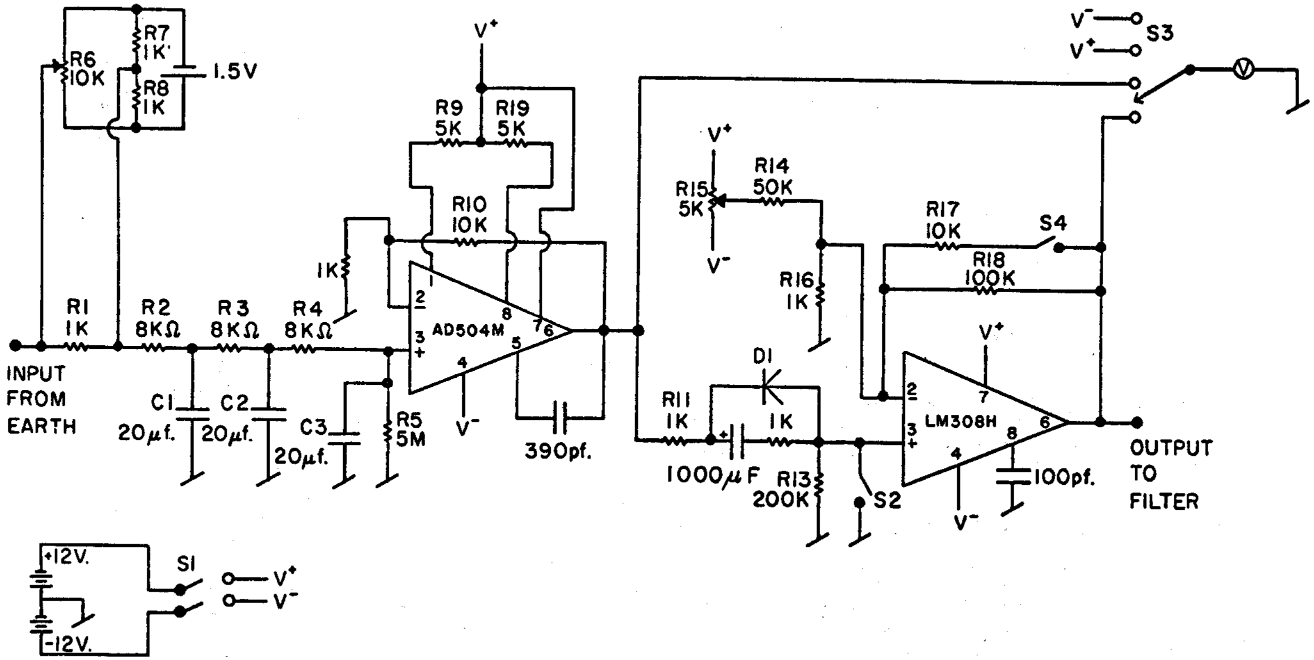

Figure 3: Schematic of single channel of telluric voltage amplifier used in this study. Gain is switchable by means of S4 from 1,000 to 10,000. DC input impedence is greater than one megohm. All resistors are 1% metal film. C1,C2 and C3 are mylar capacitors.

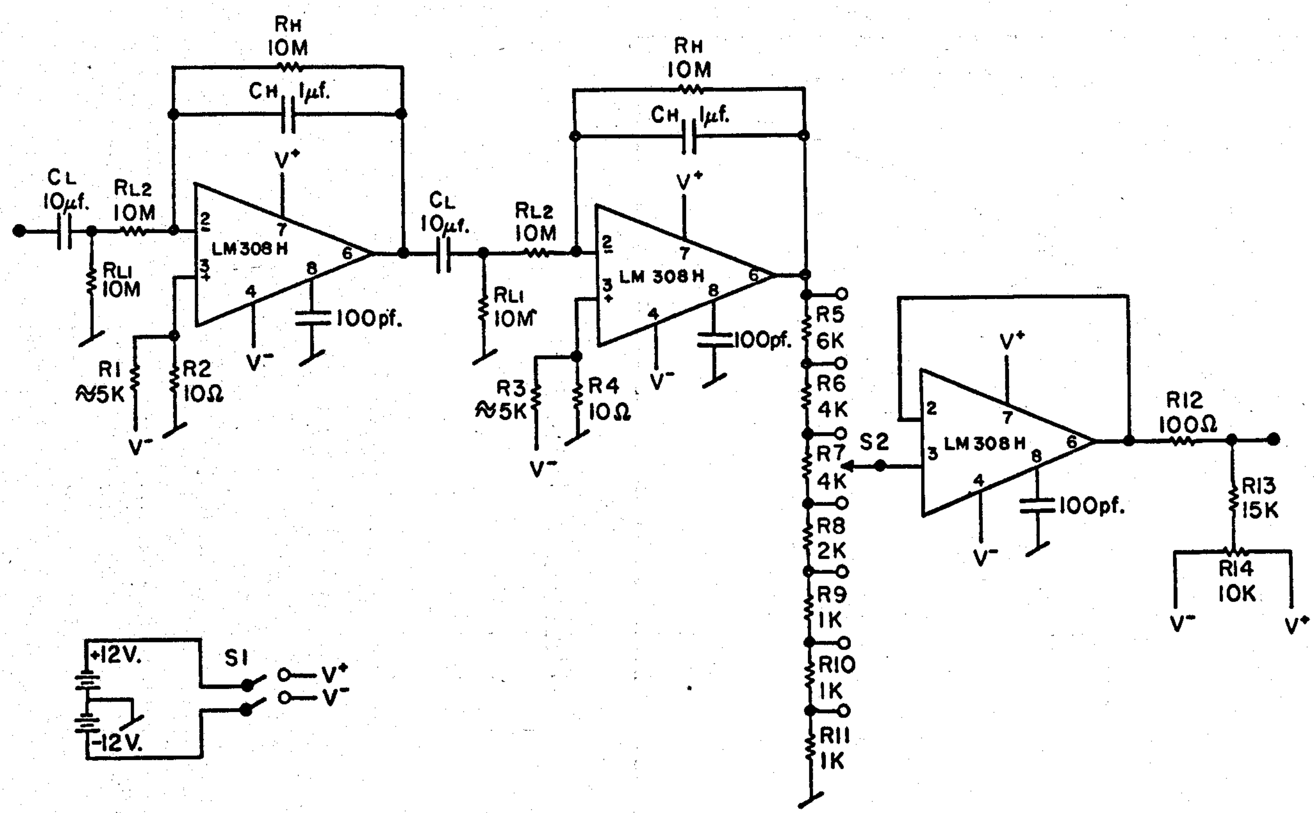

Figure 4: Schematic of single channel of band pass filter used in this study. Pass band centers on frequencies with periods of 150 sec (See fig. 5). All resistors are 1% metal film. All capacitors except the 100 pf compensators are 1% mylar.

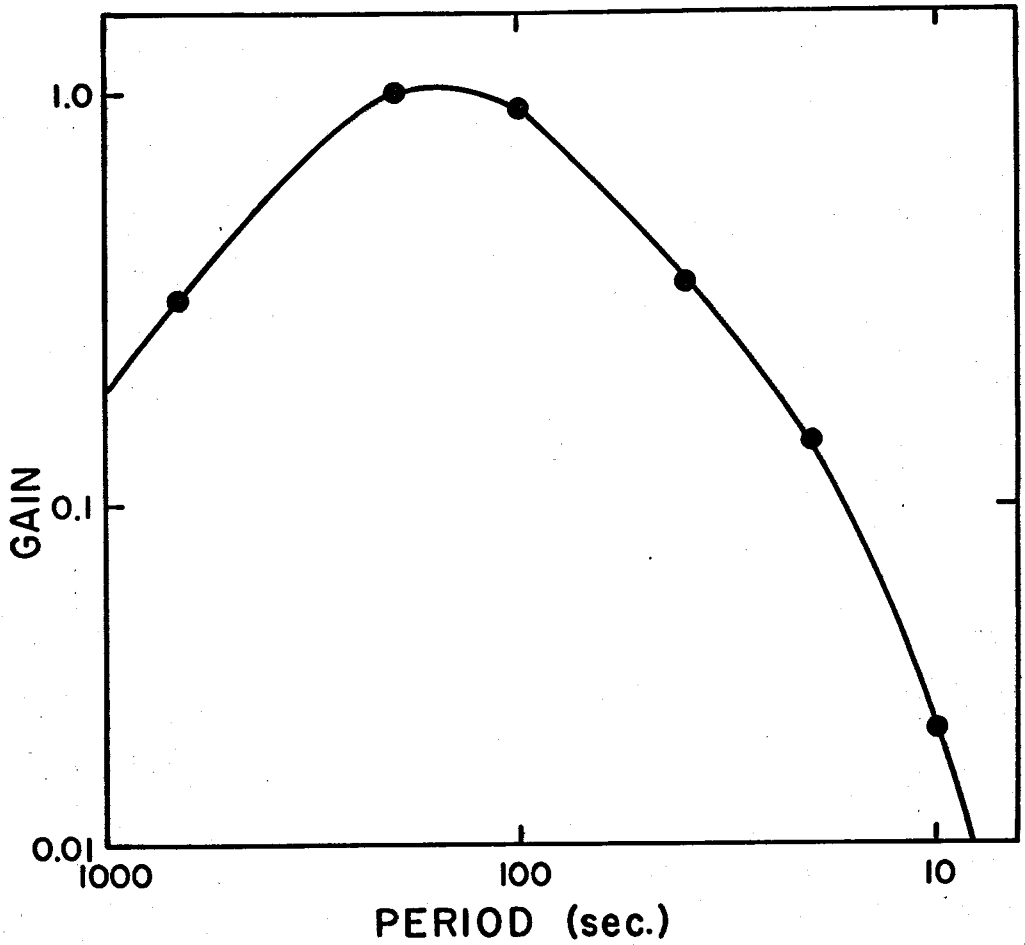

Figure 5: Response curve of band pass filters used in this study. Data points represent laboratory measurements of response.

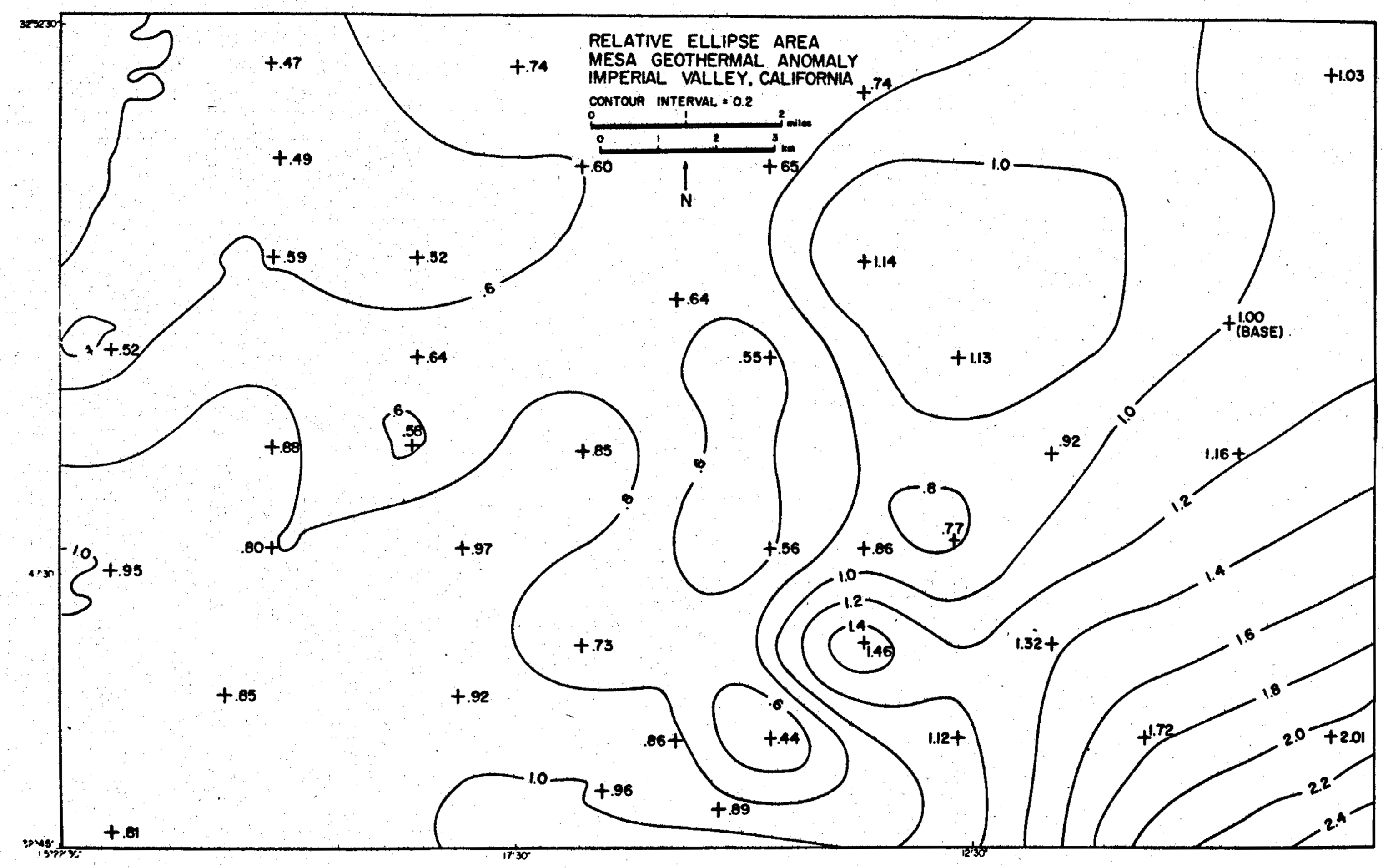

Figure 6: Relative ellipse area (J) over the Mesa Geothermal Anomaly. The two negative closures of the .6 contour near the center of the map coincide in position with the thermal anomaly. The regional effect is seen as a southeast to northwest decrease in J.

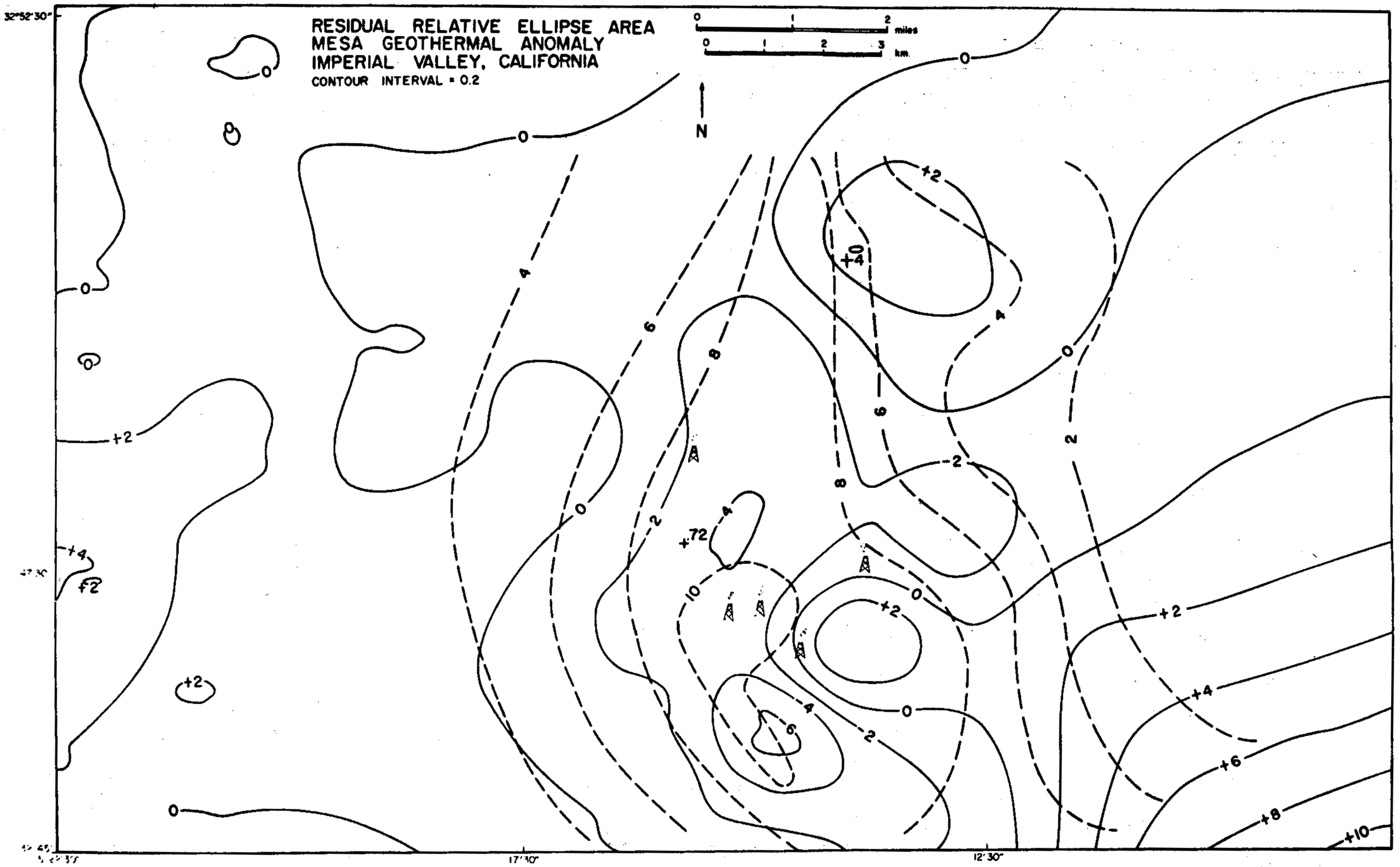

Figure 7: Residual map of relative ellipse area (J) and thermal gradient (after Combs, 1971) over the Mesa Geothermal Anomaly. Contour interval for J is .2; for thermal gradient 2 ^{o}F/100ft. The well symbols represent the five hot wells.

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THE MICROFAUNA OF THE TYPE SECTION OF THE KEASEY FORMATION OF NORTHWESTERN OREGON

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Abstract

The term Keasey has unfortunately been used in a lithostratigraphic and time stratigraphic sense. In either case the formation has been inadequately sampled and studied. The abundant and diverse microfauna present permits biostratigraphic and paleoecological study of this formation with relation to other West Coast formations. Biostratigraphically the type section of the Keasey Formation is Narizian to Refugian in age. The Refugian section represents the basal Refugian and lower Refugian zones of California and the Sigmomorphina schencki zone of Washington. Paleoecologically, the formation represents the outer shelf-upper slope region.

Introduction

The lower Tertiary strata of Northwestern Oregon and Southwestern Washington is composed of a complex of nearly continuous marine sedimentary and volcanic sequences. The abundant megafossil assemblages have been frequently studied but the microfaunas of these formations have received little attention except for an occasional published paper and by micropaleontology classes from local Universities. Several of these formations are cited by Schenck and Kleinpell (1936) in the definition of the Refugian Stage of California, as time equivalents of the type but representing a different facies of the stage. Among the microfossiliferous formations cited are the Lincoln Creek Formation (Lincoln and Keasey Formations) of Washington and the Keasey and Bastendorff Formations of Oregon. The Lincoln Creek Formation has been extensively studied by Rau (1948, 1951, 1958, 1966, and 1967) and it was from this formation that Rau (1958, 1966) proposed a zonation for the Washington Refugian Stage. The Bastendorff Formation is covered by another paper in this volume (A. T. Donnelly).

The Keasey Formation of Oregon, although it contains abundant microfossils, has been largely ignored. Yet this fauna is essential to the understanding of the mid-latitude zonation of the Refugian Stage and represents a facies different from those present in either the Bastendorff or the Lincoln Creek Formations.

Previous Work

The name Keasey Shale was first applied by Schenck (1927) to the sandy shales underlying the sandstone at Pittsburg Bluff, Columbia County Oregon. Megafauna, typical of this formation, can be found along the railroad near Keasey Station, Rock Creek drainage. An age of lower Oligocene was suggested on the basis of this megafauna as well as possible correlation with the Bastendorff and Moody Shale Formations of Oregon.

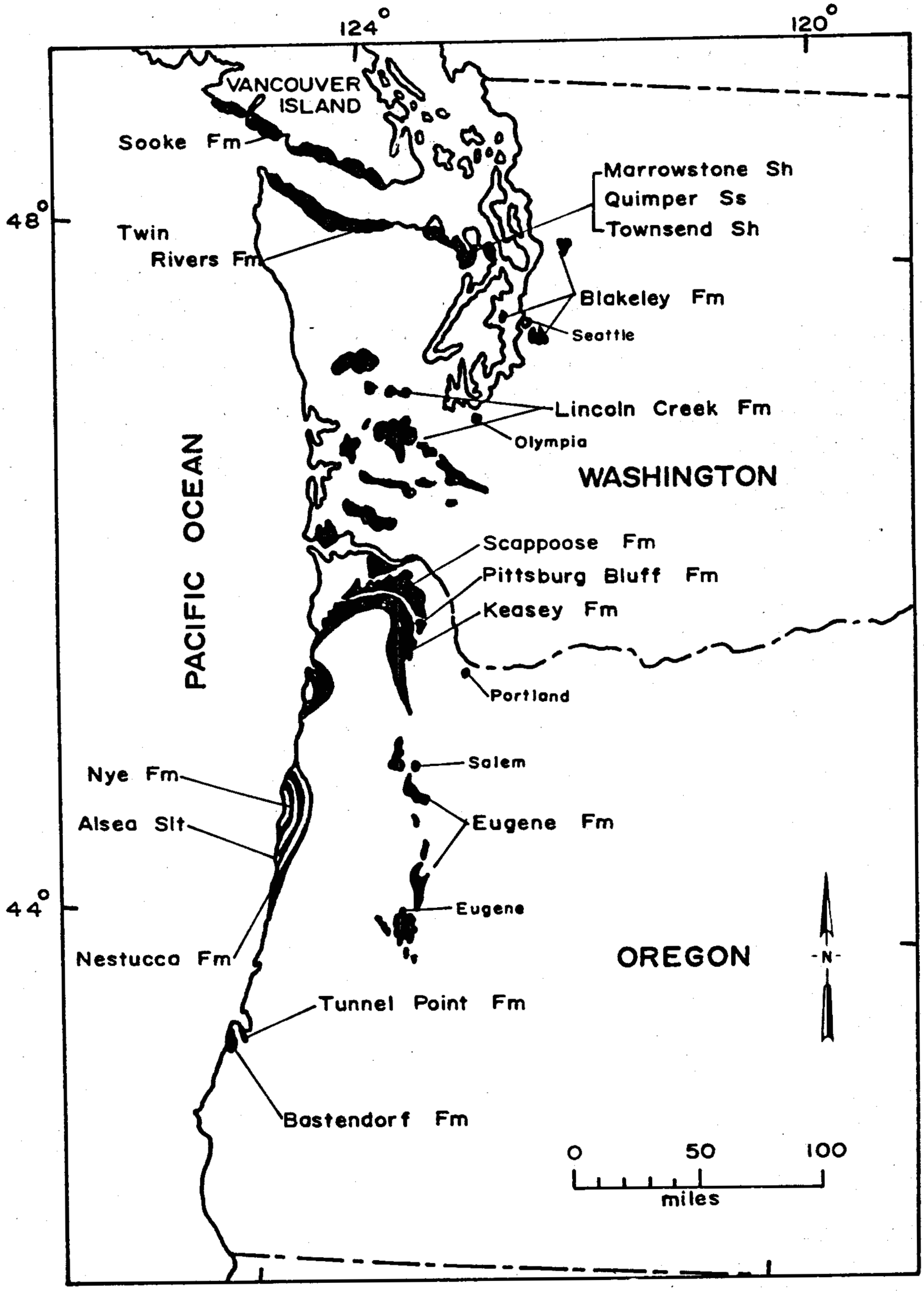

FIGURE 1 - DISTRIBUTION OF MIDDLE TERTIARY FORMATIONS IN WASHINGTON AND OREGON. AFTER HICKMAN (1969)

The following year, Schenck (1928) published a more extensive review of the Oligocene of Oregon. In his discussion he described the Keasey Shale lithologically as "sandy tuffaceous, bluish fossiliferous shale" and cited the outcrops along the banks of Rock Creek, near Keasey (Universuty of California locality UC 4194; Stanford University locality N.P. 3,N. P. 4; and California Academy of Science locality C.A.S. 162) as being the most characteristic of this strata. Molluscan, foraminiferal and stratigraphic relations continued to suggest an Oligocene age for this formation. The similarity of the megafauna with an assemblage in Western Washington along the Willapa River suggests a correlation.

Cushman and Schenck (1928) studied the foraminiferal samples from the Keasey Formation and some from the Bastendorff Shale (locality UC A-94) and decided that the correlation made by Schenck (1927) between these two formations and the Oligocene strata was valid. Weaver (1942) and Weaver et.al. (1944) further described the megafauna and supported these correlations. Weaver et. al. (1944) also implied that the Keasey Formation correlated with the lower Refugian, Uvigerina cocoaensis foraminiferal zone of California.

Mapping of Northwestern Oregon was undertaken in 1945 by a U.S.G.S. group (Warren, Norsbirath, and Grivetti, 1945). This map is the most accurate done on the area and has been little modified since publication. The following year, Warren and Norsbirath (1946) elaborated on the earlier mapping and divided the Keasey Formation into three lithologic members. Deacon (1953) attempted a revision which is generally not accepted. He introduced the terms "Nehalem" for parts of the lower member of the Keasey Formation, and "Rocky Point"for the underlying Cowlitz Formation. Van Atta (1971) made a very careful study of the sedimentary petrology of the area and was able to refine the contact between the Cowlitz and the Keasey Formations only very slightly from that described by Warren and Norsbirath (1946).

Stratigraphy

The Keasey Formation of this study outcrops in the northwestern corner of Oregon. Exposures of the formation can be seen along the rivers and creeks which drain the region, the logging roads, railroads, and highways, and in the quarries. The heavy cover of vegetation and high rainfall, alter the exposures rapidly making geologic work difficult.

The relationship between the Keasey Formation and the underlying Cowlitz Formation and Goble Volcanics in this area is poorly understood, and has been considered both conformable and unconformable. The Cowlitz Formation consists of conglomerate, arkose, and siltstone which interfingers with the pillow basalts, basaltic flows and breccias of the Goble Volcanics (Beaulieu, 1971, and Niem and Van Atta, 1973). The upper limit of the Cowlitz Formation is marked by massive mudstones and siltstones where as the lower Keasey Formation contains siltier, more stratified sediments (Van Atta, 1971). Occassionally the contact is marked by a pebbly tuffaceous mudstone. The Cowlitz and Goble Volcanics are considered late Eocene (Narizian microfaunal stage) in age.

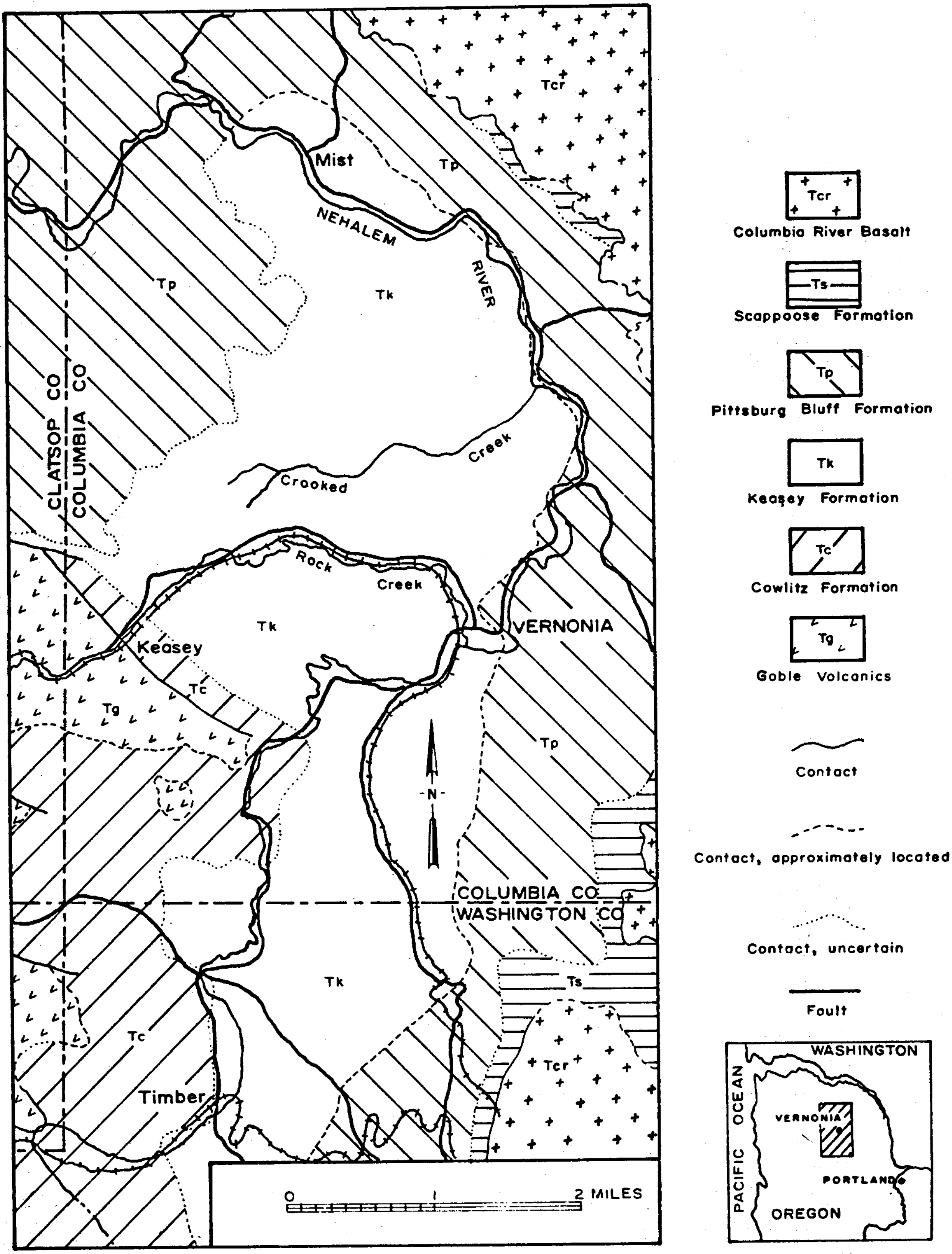

FIGURE 2.- UPPER NEHALEM RIVER, NORTHWESTERN OREGON

Overlying the Keasey Formation in this area is the Pittsburg Bluff Formation. The finely laminated arkose, glauconitic sandstone, siltstone, mudstone, and conglomerate of this formation conformably overlie the Keasey. The Pittsburg Bluff Formation has been considered middle Oligocene in age.

The Keasey Formation can be divided into three lithologic members following the work of Warren and Norsbirath (1946) and Van Atta (1971). These three members can be described as: 1) a lower dark gray glauconitic tuffaceous mudstone which interfingers with a volcanic sandstone, 2) a middle massive tuffaceous siltstone, and 3) a sequence of concretionary tuffaceous siltstone and mudstone beds.

The type section of the Keasey Formation along Rock Creek consists primarily of the lower member and a part of the middle member is poorly exposed. Both the middle and upper members are best exposed along the Sunset Highway (Wolf Creek Highway) to the south, however the lower member and the Keasey-Cowlitz contact are not exposed.

Age

The microfauna of the type section of the Keasey Formation has previously only been described by Schenck (1928) and Cushman and Schenck (1928) from three samples. Therefore samples were collected along Rock Creek in the summer of 1973 in an attempt to more accurately describe the fauna.

The base of the Keasey Formation along this section is marked by a pebbly tuffaceous sandstone which is barren of microfossils (KAM 1002). The fauna from KAM 1003 to KAM 1008 contains some species characteristic of Mallory's (1959) Narizian Stage. Among these species are Bulimina corrugata, Bulimina microcostata, Lenticulina welchi, and Uvigerina garzaensis. Thus indicating that this basal Keasey Formation is Narizian in age.

Some of the Refugian species which have been found to first appear below the stage boundary are present within this interval. For example Cibicides hodgei (KAM 1010), Bulimina sculptilis lacinata (KAM 1008), Plectofrondicularia packardi packardi (KAM 1003), and Valvulineria tumeyensis (KAM 1013).

The Narizian species are gone from the assemblage in KAM 1016 but included in the assemblage are species typical of the Refugian Stage of Schenck and Kleinpell (1936) and Sigmomorphina schencki zone of Rau (1958, 1966). This assemblage marks the first appearance of Cibicides elmaensis, Cibicides haydoni, Ceratobulimina washburnei, and Guttulina problema.

This assemblage continues up through KAM 1038 and also adds other species which are indicative of the Sigmomorphina schencki zone. Among these species are Cibicides pseudoungerianus evolutus, Dentalina dusenburyi, Guttulina frankei, Guttulina hantkeni, Guttulina irregularis, Nonion halkyardi, Sigmomorphina schencki, Quinqueloculina imperialis, and Quinqueloculina weaveri. Absent from this assemblage is Uvigerina atwilli and Uvigerina cocoaensis. Both of these species are very characteristic

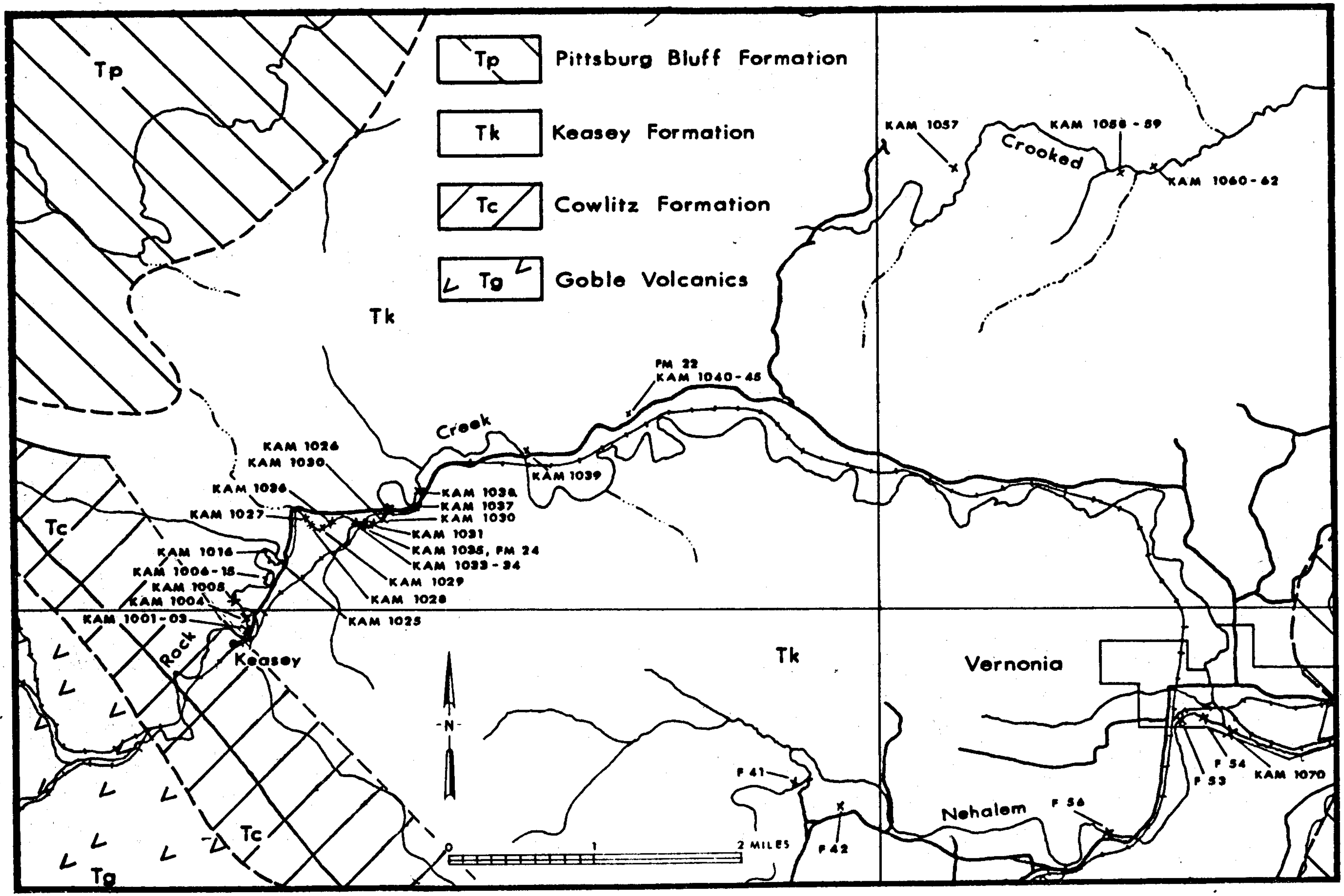

FIGURE 3 SAMPLE LOCALITIES, ROCK CREEK SECTION

ROCK CREEK SECTION

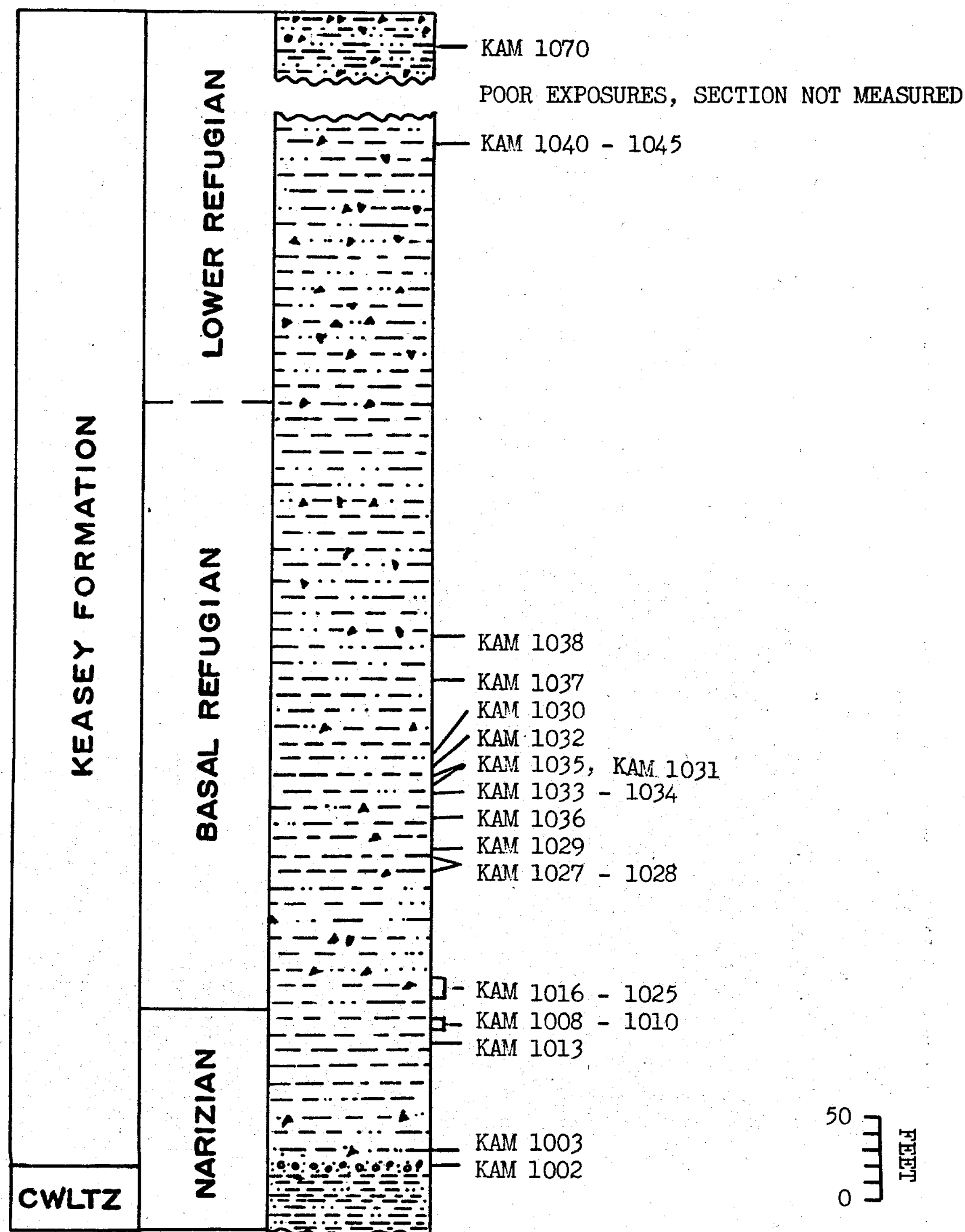

FIGURE 4

of the lower Refugian, Uvigerina cocoaensis zone (Kleinpell and Weaver, 1963), to which Rau correlated the Sigmomorphina schencki zone. It is, therefore suggested that this interval of strata correlates with a "basal" Refugian zone as suggested by Tipton et. al. (1973,1974). This zone would lack the Uvigerina atwilli and Uvigerina cocoaensis, but contain Bulimina sculptilis lacinata, Valvulineria tumeyensis, and Plectofrondicularia packardi packardi. Unpublished work in the Gaviota Formation of California suggests that this basal Refugian would also be characterized by the last appearance of Eggerella subconica. This species is present in the Keasey Formation furthering the implication that this strata represents the basal Refugian.

Section above locality KAM 1038 becomes difficult to sample because of poor exposure. Assemblages in KAM 1043 and KAM 1070 both contain Uvigerina cocoaensis and Eponides gaviotaensis which are present in the Uvigerina cocoaensis zone of California and the Sigmomorphina schencki zone of Washington. With the exception of these species most of the other characteristic lower Refugian species have disappeared, however none of the upper Refugian species are present.

The poor exposures suggest that in order to biostratigraphically describe the fauna of the middle and upper members of the Keasey Formation samples will have to be taken from along other sections. Based on lithology the middle and upper members are best exposed along the Sunset Highway to the south. Preliminary work there (samples KAM 104-107 and B0060-68, not check listed in this paper) indicate that the fauna present is characteristic of the Sigmomorphina schencki zone and the lower Refugian Stage, Uvigerina cocoaensis zone. Important species present in these samples include:

Ceratobulimina washburnei
Cibicides pseudoungerianus evolutus
Eponides gaviotaensis
Guttulina irregularis
Guttulina problema
Plectofrondicularia packardi packardi
Pseudoglandulina inflata
Quinqueloculina imperialis
Quinqueloculina weaveri
Uvigerina atwilli
Uvigerina cocoaensis

Paleoecology

The Narizian section of the Keasey Formation along Rock Creek suggests that the fauna represents an environment probably bathyal in depth. Bulimina corrugata has been compared to Bulimina rostrata in modern faunas where it represents water depths of bathyal to abyssal (Mallory, 1959). Valvulineria tumeyensis which resembles Eponides pygmaea of the modern faunas is considered to represent cold, bathyal conditions. Also the Bulimina microcostata present in these Narizian assemblages is indicative of bathyal depths.

The Refugian strata along Rock Creek contains a mixture of species which are representative of cold, deep water and some species which repre-

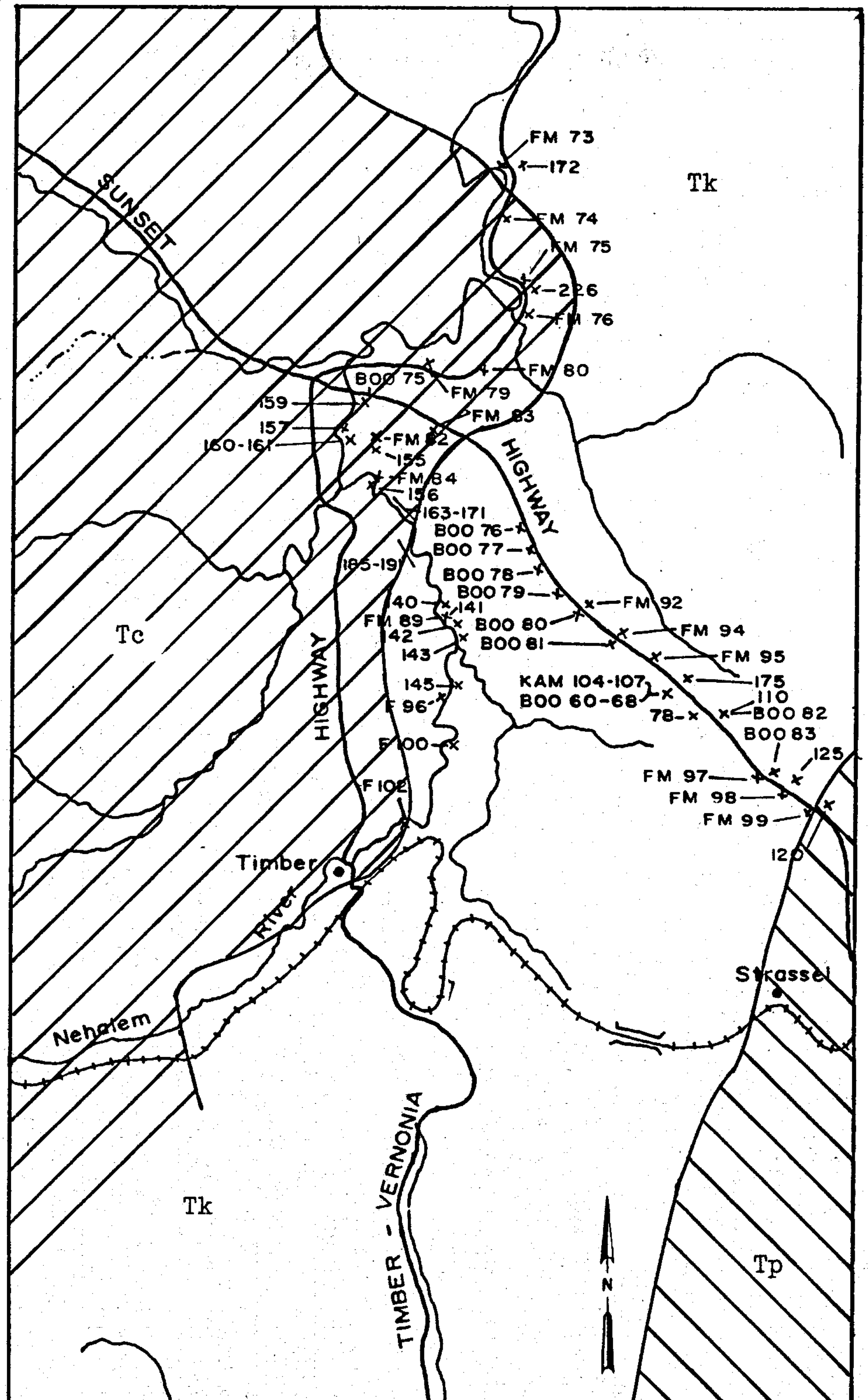

FIGURE 5 SAMPLE LOCATIONS, SUNSET HIGHWAY

SPECIES \ LOCATION	KAM 1003	KAM 1013	KAM 1010	KAM 1009	KAM 1008	KAM 1016	KAM 1017	KAM 1019	KAM 1020	KAM 1021	KAM 1022	KAM 1023	KAM 1025	KAM 1027	KAM 1028	KAM 1029	KAM 1036	KAM 1034
Anomalina coalingensis																		
Astrolocus sp.		X	/															
Asterigerina sp.														?				
Bathysiphon eocenicus					●					X		X	X	X		■		
Bathysiphon spp.					/												X	
Bolivina kleinpelli		X	●															
Bolivina spp.		/	/															
Bulimina corrugata			■															
Bulimina microcostata		X	■	●														
Bulimina cf. B. ovata						X												
Bulimina pyrula		X											X			/		
Bulimina sculptilis lacinata																		
Bulimina spp.	X																	
Cassidulina globosa	X	■	■		●	■	■	■	■	X	■		■	X	X	■		■
Ceratobulimina washburnei						/	X	X	●		/		/					X
Chilostomella cylinderoides																/	/	
?Chilostomella sp.																		
Cibicides cushmani																		
Cibicides elmaensis	?					X	●	●	■	■	X		/	/	■	X	X	
Cibicides haydoni						■	●	●	■	■	■		■	■		■	■	■
Cibicides hodgei			/		X	X		X		■	X			■		■	X	X
Cibicides pseudoungerianus											X					X		
evolutus																		
Cibicides spp.																		
Cyclammina clarki ?																		
Cyclammina pacifica			■		■						/					X	●	●
Cyclammina sp.						/			/									
Dentalina catenula		X																
Dentalina communis			X		X		/		X									
Dentalina consobrina		/						/			X		X		●	X		
Dentalina cf. D. consobrina													X	/				
Dentalina dusenburyi														X				
Dentalina spp.						/					X							
Dorothia principensis ?											X							
Eggerella subconica		●			●	/			X		/							
Ellipsonodosaria sp.			/															
Eponides duprei																		
Eponides cf. E. ellisorae																		
Eponides gaviotaensis														/	X			
Eponides sp.	?																	
Fursenkoina bramletti		/	●						X		X					X		
Globigerina spp.		/						/	/							X		
Globobulimina pacifica	■		●		X	●		■	X	■	■			X		■	■	■
Guttulina frankei									X	X			/	X	X	X		
Guttulina hantkeni														?				
Guttulina irregularis							/		X					X		X	X	
Guttulina problema						X	/		/	X			X		X			
Guttulina sp.							/			/					/			
Gyroidina condoni																		

■ Abundant ● Common X Few / Rare

SPECIES \ LOCATION	KAM 1003	KAM 1013	KAM 1010	KAM 1009	KAM 1008	KAM 1016	KAM 1017	KAM 1019	KAM 1020	KAM 1021	KAM 1022	KAM 1023	KAM 1025	KAM 1027	KAM 1028	KAM 1029	KAM 1036	KAM 1034
Gyroidina orbicularis octocamerata																		
Gyroidina orbicularis planata																		
Gyroidina soldanii	X	X	X		/	X		X	X	X	X		X			/	X	/
Gyroidina sp.																		
Hoeglundina eocenica						/	X	X	X	X	X							
Haplophragmoides spp.	X			/														X
Hastigerina micra															/			
Karreriella washingtonensis						X	X	/	X	/				X	/	X		
Lagena becki							/			/			/	/			/	/
Lagena cf. L. substriata								/										
Lagena vulgaris							/		/									/
Lenticulina austriaca																		
Lenticulina chehalinensis						X	X	X	X					●		●	X	/
Lenticulina crassa																		
Lenticulina cultratus																		
Lenticulina inornatus														●		X	X	
Lenticulina kincaidi						X			X									
Lenticulina limbosus hockleyensis							X	/			X					/	X	
Lenticulina lincolnensis																X		
Lenticulina sp. A						X	X		●					X	X	●	X	
Lenticulina spp.	●		/		/	X			/					/			X	X
Lenticulina texana									/									
Lenticulina welchi		●	■		■													
Marginulina alazaensis																	/	
Marginulina exima								X						/				
Marginulina cf. M. exima																/		
Marginulina sp.									X						X			/
Marginulinopsis sp.																		
Nodogenerina adolphina			X															
Nodogenerina advena					X													
Nodosaria arundinea				X												X		
Nodosaria pyrula		X			X				/				X	X	X	X	X	
Nodosaria cf. N. pyrula												X						
Nodosaria sp.																		
Nonion halkyardi															/	X		X
Nonion umbilicatulus							●	/	■	■	■		■	X	X	●		/
Nonionella applini	■	■			X		X	X		X	X		●					
Nonionella cf. N. jacksonensis		X	X				●											
Nonionella sp.										/						/		
Planularia cf. P. markleyana																/		
Plectofrondicularia oregonensis		X																
Plectofrondicularia packardi multilineata							X		X					X				
Plectofrondicularia packardi packardi	X		X			X	●	X	X	■	X		X	X	X	●	●	X
Plectofrondicularia packardi spinata																		
Plectofrondicularia sp.																		
Plectofrondicularia vaughani																		

SPECIES \ LOCATION	KAM 1003	KAM 1013	KAM 1010	KAM 1009	KAM 1008	KAM 1016	KAM 1017	KAM 1019	KAM 1020	KAM 1021	KAM 1022	KAM 1023	KAM 1025	KAM 1027	KAM 1028	KAM 1029	KAM 1036	KAM 1034
Pseudoglandulina inflata							●	X	X	■	X		X		■	■	●	●
Pseudoglandulina nallpeensis														X				
Pullenia salisburyi			X		X		/	X					/	/	X	X	/	
Quinqueloculina imperialis						X					/		/		X			X
Quinqueloculina sp.										X								
Quinqueloculina weaveri							/	X	X									
Reophax pilifer																		
Sigmomorphina schencki						/												
Soiroloculina texana		X	X		X													
Textularia cf. T. adalta					X													
Trochammina sp.					/						/						/	
Uvigerina cocoaensis																		
Uvigerina garazaensis		X	●	X	■													
Valvulineria araucana					X													
Valvulineria jacksonensis welcomensis		X	X		X													
Valvulineria tumeyensis																		

SPECIES \ LOCATION	KAM 1033	KAM 1035	KAM 1031	KAM 1032	KAM 1030	KAM 1037	KAM 1038	KAM 1043	KAM 1070		C & S							
Anomalina coalingensis											P							
Astrolocus sp.																		
Asterigerina sp.			?															
Bathysiphon eocenicus		/					X											
Bathysiphon spp.	/																	
Bolivina kleinpelli																		
Bolivina spp.																		
Bulimina corrugata																		
Bulimina microcostata					?													
Bulimina cf. B. ovata																		
Bulimina pyrula			/		/			/										
Bulimina sculptilis lacinata						■					P							
Bulimina spp.																		
Cassidulina globosa	X	X	●	/	■						P							
Ceratobulimina washburnei	●	X	X								P							
Chilostomella cylinderoides			/															
?Chilostomella sp.					/													
Cibicides cushmani																		
Cibicides elmaensis	X			/	●	/		/										
Cibicides haydoni	■	■	■	X	■	X					P							
Cibicides hodgei	X	X	X	/	X						P							
Cibicides pseudoungerianus evolutus																		
Cibicides spp.																		
Cyclammina clarki ?											P							
Cyclammina pacifica		/	X	X			X											
Cyclammina sp.	X							X										
Dentulina catenula																		
Dentalina communis	/										P							
Dentalina consobrina	X	X	/	X	X	X					P							
Dentalina cf. D. consobrina																		
Dentalina dusenburyi					/													
Dentalina spp.					/													
Dorothia principensis																		
Eggerella subconica																		
Ellipsonodosaria sp.																		
Eponides duprei											P							
Eponides cf. E. ellisorae					/													
Eponides gaviotaensis					/				X									
Eponides sp.																		
Fursenkoina bramletti																		
Globigerina spp.											P							
Globobulimina pacifica	■		■	X	●													
Guttulina frankei			X	/		/		/										
Guttulina hantkeni																		
Guttulina irregularis	X			/	/	/		X			P							
Guttulina problema			/								P							
Guttulina sp.																		
Gyroidina condoni											P							

C & S Cushman and Scheck (1928)

SPECIES \ LOCATION	KAM 1033	KAM 1035	KAM 1031	KAM 1032	KAM 1030	KAM 1037	KAM 1038	KAM 1043	KAM 1070		C & S
Gyroidina orbicularis octocamerata									/		P
Gyroidina orbicularis planata								X			
Gyroidina soldanii	X			X							
Gyroidina sp.											
Hoeglundina eocenica		●					●	X	/		P
Haplophragmoides spp.											
Hastigerina micra					/						
Karrerella washingtonensis											
Lagena becki					X						P
Lagena cf. L. substriata											
Lagena vulgaris											
Lenticulina austriaca											P
Lenticulina chehalinensis											
Lenticulina crassa											P
Lenticulina cultratus											P
Lenticulina inornatus											P
Lenticulina kincaidi											
Lenticulina limbosus hockleyensis	/	/	/		/	/			/		
Lenticulina lincolnensis											
Lenticulina sp. A	X				X						
Lenticulina spp.						/	X	/			
Lenticulina texana											
Lenticulina welchi											
Marginulina alazaensis											
Marginulina exima	/										
Marginulina cf. M. exima											
Marginulina sp.											
Marginulinopsis sp.											
Nodogenerina adolphina											P
Nodogenerina advena											
Nodosaria arundinea							/				
Nodosaria pyrula		/				/					P
Nodosaria cf. N. pyrula											
Nodosaria sp.							X				
Nonion halkyardi											
Nonion umbilicatulus	X	●	■			/		X	/		P
Nonionella applini		X	/								
Nonionella cf. N. jacksonensis											
Nonionella sp.											
Planularia cf. P. markleyana											
Plectofrondicularia oregonensis											
Plectofrondicularia packardi multilineata		X									
Plectofrondicularia packardi packardi	X	X	X	X	X	X			X		P
Plectofrondicularia packardi spinata											P
Plectofrondicularia sp.											
Plectofrondicularia vaughani					X						

SPECIES \ LOCATION	KAM 1033	KAM 1035	KAM 1031	KAM 1032	KAM 1030	KAM 1037	KAM 1038	KAM 1043	KAM 1070		C & S
Pseudoglandulina inflata	X	X	■	X	■	X		X			
Pseudoglandulina nallpeensis			X								
Pullenia salisburyi	X										
Quinqueloculina imperialis			X	/							P
Quinqueloculina sp.											
Quinqueloculina weaveri											
Reophax pilifer							X				
Sigmomorphina schencki		X									
Spiroloculina texana											
Textularia cf. T. adalta											
Trochammina sp.											
Uvigerina cocoaensis								■	X		
Uvigerina garzaensis											
Valvulineria araucana											
Valvulineria jacksonensis welcomensis											
Valvulineria tumeyensis											

sentative of medium water depths. The cold deep water species include the Gyroidinas, Cassidulinas, and Nonion umbilicatulus (=Melonis pompiloides). Included in the medium depth species are the Plectofrondicularias, Uvigerinas, Lenticulinas, and Eponides (Smith, 1971). It is suggested that these assemblages represent an outer shelf - upper slope (outer neretic-upper bathyal) environment. The cold, deep water species present are responding to cold water and not depth.

Summary

The type section of the Keasey Formation is abundantly microfossiliferous. The microfauna indicates that the Narizian Stage is present in the very lowest part of the section. This is followed by strata representative of a basal Refugian zone which has not yet been well described in California. The rest of this section is represented by strata of lower Refugian age, Uvigerina cocoaensis zone of California and the Sigmomorphina schencki zone of Washington.

The Keasey Formation was initially deposited at bathyal depths but depths of outer neretic to upper bathyal persisted throughout most of the formation's deposition in the Rock Creek section. The faunas were influenced by the presence of cold water and could, therefore, exist in shallower water depths.

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DIAPIRIC INTRUSIONS AND BASIN FORMATION IN THE CONTINENTAL BORDERLAND

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Abstract

The Sierra Vizcaino in the Vizcaino Peninsula, Baja California is an example of an elongated arch produced by cold ultramafic diapiric intrusions which may be common in the continental borderland.

The basement rock consists of schists, ultra-mafic and mafic rocks (187 my.) which were intruded by lower Cretaceous tonalites (123-154 my.). These basement rocks were emplaced as a diapir into middle and upper Cretaceous Valle rocks as relatively cold bodies accompanied by hydro-thermal eminations. The ultra-mafic intrusions did not metamorphose the Valle beyond a few tens of meters from the contact. That metamorphism consists almost entirely of silicification of the Valle rocks within a few meters of the contacts accompanied by faulting. The intrusions continued in stages through Miocene and Pliocene time forming deep basins marginal to the ridge.

This tectonic style may explain the presence of highs in the continental borderland which did not appear to be shedding sediments prior to Miocene time. Such highs may well have thick Miocene basins marginal to their axes. These relationships if not clearly understood may lead to the assumption that the highs are entirely Cretaceous features when in fact they probably had their greatest development in the Cenozoic. We must also be aware of the fact that geologically old basement may be tectonically young basement.

Introduction

The Sierra Vizcaino occupy the western and northwestern portions of the Vizcaino Desert (Fig. 1). They consist of a core of meta-sedimentary and intrusive rocks which form the most rugged peaks of the mountain mass. This core is flanked on both sides by a foothill belt of steeply dipping Mesozoic sedimentary rocks. Near the coast the range is flanked on both sides by moderately thick Miocene and Pliocene basins. Numerous fault valleys sub-parallel the range.

The basement complex consists of metamorphic rocks with basic and ultrabasic intrusives. The dominant rock types are hornblende schist, hornblende gneiss, hornblendites, tonalite and gabbro. Fault zones contain hornblendite, diabase, serpentine and serpentinized peridotite. Near the coast this body represents a large basic-ultrabasic diapiric intrusion.

Older schists and basic intrusives of the basement complex yield dates of 187 to 167 my. Tonalite plutons yield dates of 154 to 123 my. The emplacement of the basic-ultrabasic diapirs followed the emplacement of the tonalite plutons.

Evolution of the Vizcaino Arch

The intrusion and accompanying arching of the Sierra Vizcaino probably began early in Valle time as evidenced by thinning of the lower Valle over the arch (Fig. 2). This highland could not have been very high at any time, as there are no significant sediments shed off of it. Uplift and erosion occurred sporadically in the area throughout middle Valle time forming angular unconformities between the lower Valle shales and the middle Valle conglomerates.

After deposition of the Valle conglomerates, the ultramafic rocks of the Sierra Vizcaino forcefully penetrated through lower Valle rocks arching them into a broad faulted anticline (Fig. 3). There is no known Paleocene or Eocene sediments within the range. During the Miocene the Sierra Vizcaino continued to be elevated by the diapiric intrusions. This depressed the range flanks and allowed the deposition of the only deep water marine Miocene (Tortugas Formation) in the Vizcaino, which occupies two troughs north and south of the main ultramafic diapir: one near Bahia Tortugas and one near Asuncion (Fig. 4).

In the Pliocene, as in the Miocene, the Sierra Vizcaino continued to rise, causing the deposition of thick sections of Almejas Formation (Pliocene) on both sides of the range

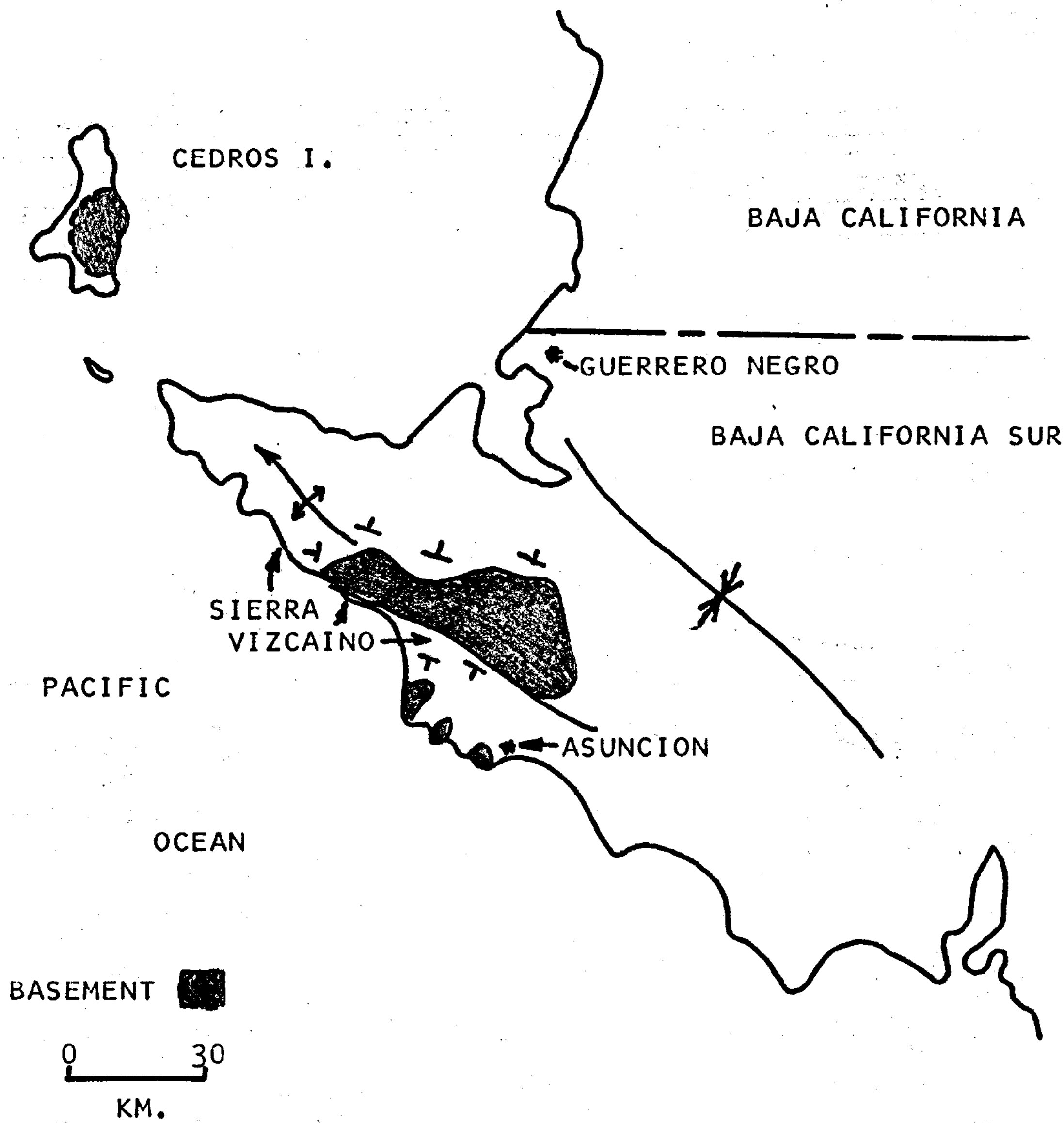

FIGURE 1 - LOCATION MAP

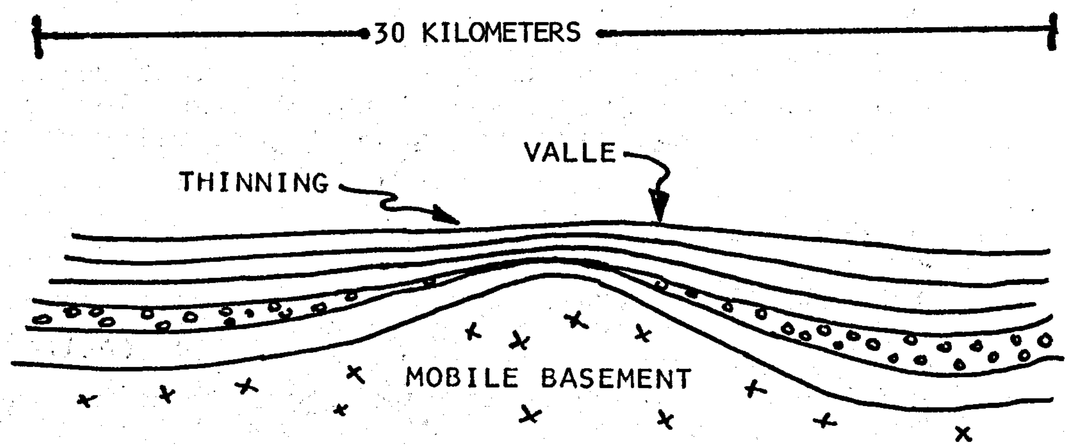

FIGURE 2 - VALLE ARCHING

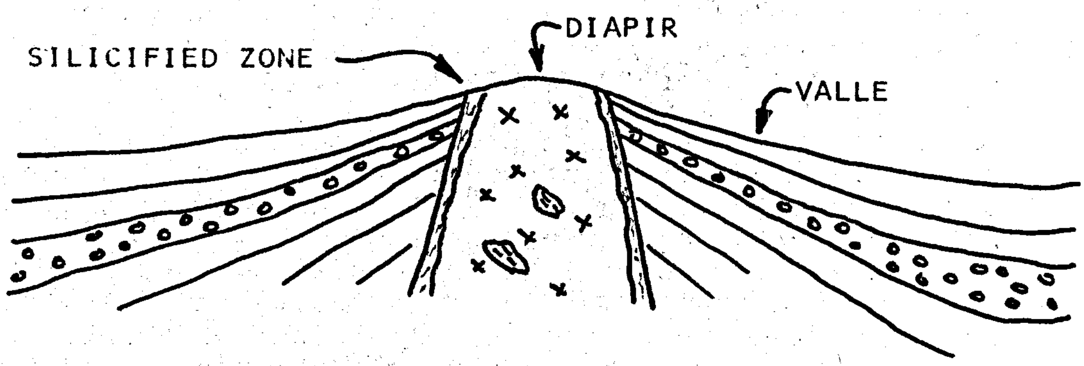

FIGURE 3 - POST VALLE - PRE-MIOCENE DIAPIR

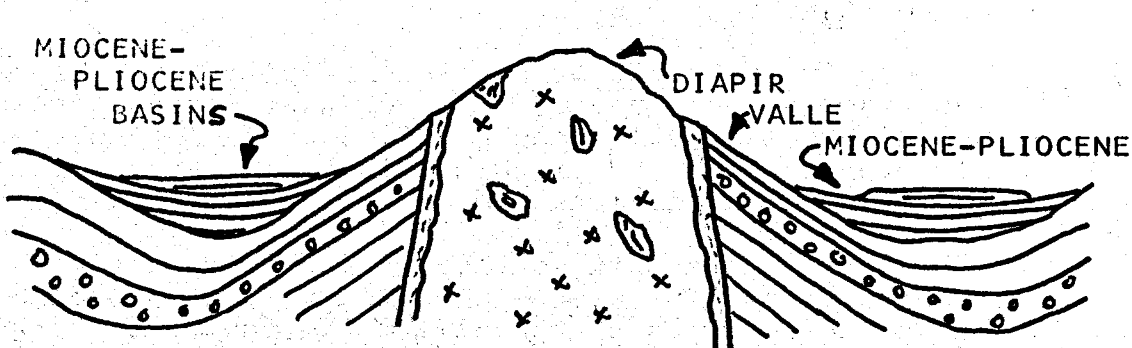

FIGURE 4 - MIOCENE-PLIOCENE ARCHING

in positions corresponding to the Miocene basins. The Sierra Vizcaino appears to be rising today, as remnants of Plio-Pleistocene sediments are found at high elevations in the range while the flanking pediments are being dissected.

Intrusive Relationships

The contacts between the basement complex and the enclosing Cretaceous Valle Formation are clearly seen in numerous places in the Sierra Vizcaino particularly on the road to Puerto Nuevo which crosses the core of the range. This contact usually consists of up to 30 meters of well-silicified Valle Formation rocks. These rocks appear to be largely "indurated" and usually do not exhibit any real signs of metamorphism. Locally the shales are altered to red and green splintery shales while the sandstones are totally silicified. This "silicified" zone is usually in fault contact with unaffected Valle rocks. There are often numerous shear surfaces parallel to the bedding, and the rock may be contorted as though it were deformed between the fault zone and the intrusion (Fig. 5).

These diapiric bodies probably formed below the sea floor as layered differentiates. At a later time they were intruded dynamically upward raising the roof as they penetrated producing peripheral faults. The mobilizing hot water caused hydrothermal alteration within and near these fractures with the formation of magnesite and chlorite. Locally sulfide mineralization also occurs within these zones. This alteration and mineralization has produced a light-grey to white weathered surface on the diapir.

Other Possible Diaperic Intrusions

There are a number of possible diapiric intrusions in the continental borderland. Between the Sierra Vizcaino and Asuncion several small basement highs probably represent smaller versions of the Vizcaino Diapir. They separate small Miocene basins on the flanks of a large Miocene basin.

Margarita Island in southern Baja California has similar basement and contains well silicified Cretaceous rocks which could be the remnants of the silicified contact. Margarita is flanked by a deep basin on its landward side (geophysical evidence). Cedros Island contains similar type basement and has a Miocene basin associated with it. Catalina Island also contains such basement and shows evidence of having been a high without shedding sediments. It also has deep water Miocene rocks on its flanks. Several of the offshore banks are possible diaperic intrusive highs.

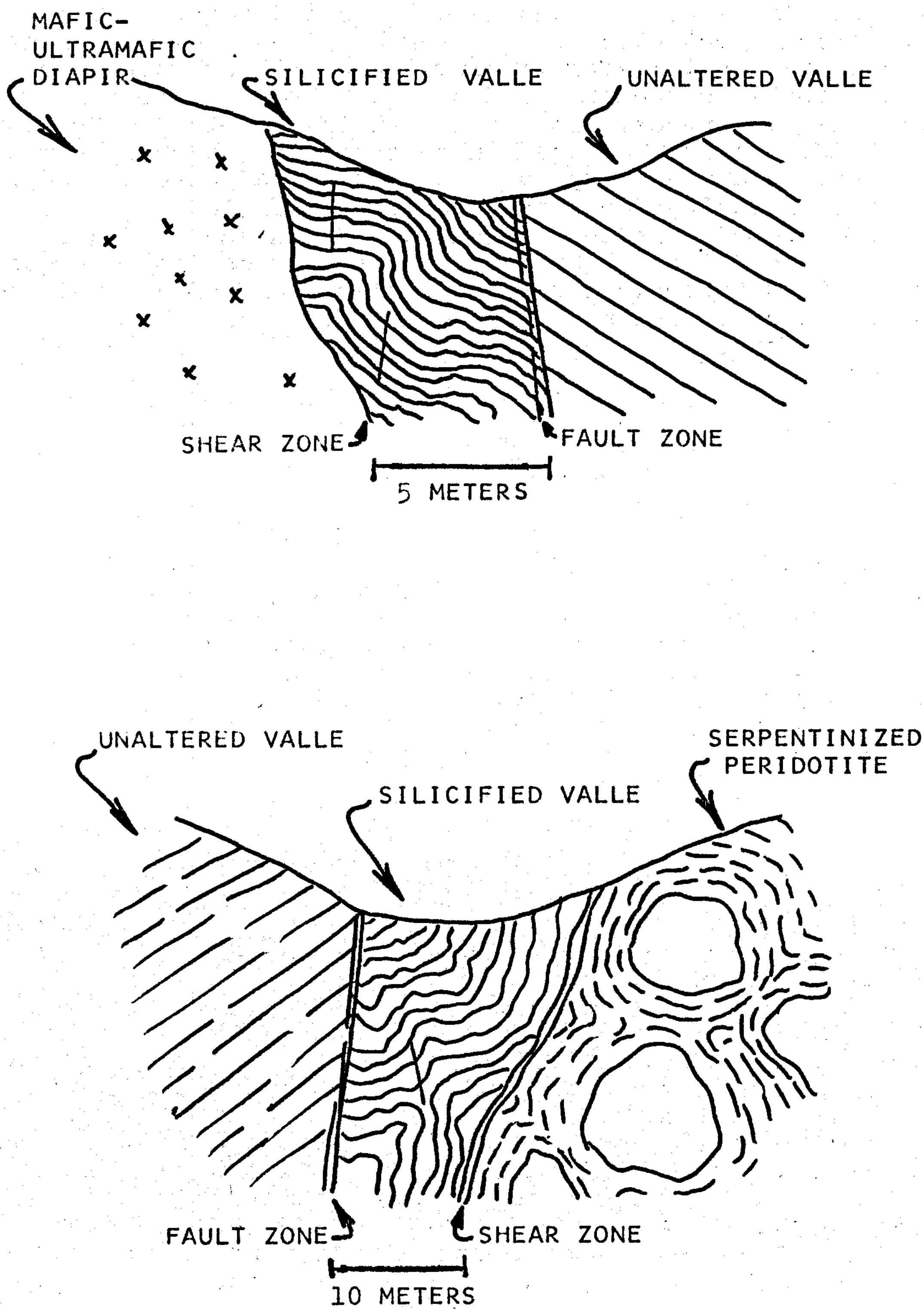

FIGURE 5 - DETAILED SECTIONS OF DIAPIR CONTACTS

Summary

The Sierra Vizcaino appears to be a diapiric intrusion of older basement into younger marine sedimentary rocks. As such it leads to a vastly different interpretation of borderland tectonics in that a geologically old basement can be responsible for forming the overlying structures by intrusion into them instead of the structures forming by draping over preexisting highs. This mobilized ultrabasic rock may not be expressed in outcrops in the upper parts of a diapir. Instead exposures consist of a suite of older rocks, including contorted and altered sediments, which are bounded by a fault zone which is in turn surrounded by younger rocks and/or basin sediments. These cold intrusions and active tectonic highs would allow for the accumulation of oil against and near the contacts.

Stratigraphy, sedimentology and offset along the San Andreas fault of Eocene to lower Miocene strata of the northern Santa Lucia Range and the San Emigdio Mountains, Coast Ranges, central California

By

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ABSTRACT

Our studies of Eocene to lower Miocene strata in the Coast Ranges of central California suggest that the sequence west of the San Andreas fault in the northern Santa Lucia Range was deposited contiguously with a sequence east of the San Andreas fault in the San Emigdio and western Tehachapi Mountains. The sequences record a similar geologic history and are characterized by nearly identical stratigraphic relations and rock types and inferred paleogeographic frameworks, sedimentary environments, and sedimentary processes. Paleogeographic reconstruction suggests that these sequences have been offset approximately 190-200 miles (305-320 km) by post-early Miocene right-lateral offset along the San Andreas fault.

The Eocene to lower Miocene sequence in the northern Santa Lucia Range consists in ascending order of (1) the Junipero Sandstone of Thorup (1941), (2) the Lucia Mudstone of Dickinson (1965), (3) The Rocks Sandstone of Thorup (1941), (4) the Church Creek Formation, (5) the Berry Formation, and (6) the Vaqueros Formation. More than 5,000 feet (1,525 m) of conglomerate, sandstone, siltstone, mudstone, and shale accumulated in this depositional area commencing in "Capay" (early Eocene) time with deposition of the basal, shallow-marine, transgressive Junipero Sandstone. The sequence rests unconformably on Mesozoic granitic basement rocks except to the southwest, where it rests on strata of Paleocene and Late Cretaceous age. In general it thins and shoals toward the southeast; paleocurrent directions, thickness, and stratigraphic relations in the exposed sections indicate that sediments were transported northwestward into the basin. The sedimentary rocks were deposited primarily in shallow to deep marine environments with the exception of the Berry Formation, a nonmarine conglomerate and sandstone of Oligocene(?) age that interfingers northwestward with marine strata of the Church Creek and Vaqueros Formations.

The Eocene to lower Miocene stratigraphic sequence in the San Emigdio and western Tehachapi Mountains consists in ascending order of (1) The Tejon Formation, subdivided into (a) the Uvas Conglomerate Member, (b) the Liveoak Shale Member, (c) the Metralla Sandstone Member, and (d) the Reed Canyon Siltstone Member; (2) the San Emigdio Formation; (3) the Pleito Formation; (4) the Tecuya Formation; and (5) the Temblor

Formation. More than 5,000 feet (1,525 m) of conglomerate, sandstone, siltstone, mudstone, and shale accumulated in this depositional area, generally referred to as the southern San Joaquin basin, commencing in "Capay" (early Eocene) time with deposition of the basal, shallow-marine, transgressive Uvas Conglomerate Member in the western end of the basin. The sequence rests unconformably on Mesozoic gabbroic rocks in the west and on granitic rocks in the east. In general, it thins and shoals to the east and southeast; paleocurrent directions, thickness, and stratigraphic relations in the exposed sections indicate that sediments were transported westward and northwestward into the basin. The sedimentary rocks were deposited primarily in shallow to deep marine environments with the exception of the Tecuya Formation, a nonmarine conglomerate and sandstone of latest Eocene(?) to early Miocene age that contains volcanic rocks in the east and partly overlays and partly interfingers westward with marine strata of the San Emigdio, Pleito, and Temblor Formations.

We conclude that the following stratigraphic units from the two depositional areas are lithologically similar and were deposited by similar processes in similar environments during approximately similar time intervals: (1) the Junipero Sandstone and Uvas Conglomerate Member, basal shallow-marine transgressive deposits; (2) the Lucia Mudstone and Liveoak Shale Member, outer neritic to abyssal hemipelagic deposits; (3) The Rocks Sandstone and Metralla Sandstone Member, shallow and deep marine deposits, the former a submarine fan complex that grades southeastward into a shallow marine sandstone sequence, and the latter a thinly bedded turbidite sequence that grades eastward into a shallow marine sandstone sequence and westward into deep-marine shale; (4) the Church Creek Formation and Reed Canyon Siltstone Member, San Emigdio Formation, and possibly part of the Pleito Formation, shallow to deep marine deposits, (5) the Berry Formation and Tecuya Formation, nonmarine deposits, and (6) the Vaqueros Formation and part of the Pleito Formation and the Temblor Formation, mostly shallow marine deposits.

The reconstructed depositional area is inferred to have extended southward as a narrowing linear basin from the San Emigdio Mountains area across the present trace of the San Andreas fault and through the Gabilan Range area into the northern Santa Lucia Range area. We infer that most of the sequence originally deposited in the northern Gabilan Range area was subsequently eroded off; however, a depositional remnant of these strata is present at the northern end of the Gabilan Range near San Juan Bautista, where lower Eocene to Miocene siltstone and fine-grained sandstone deposited at shallow marine to bathyal depths, nonmarine red beds, and volcanic rocks are exposed.

INTRODUCTION

The San Andreas fault (fig. 1), a major right-lateral fault in California, has juxtaposed tectonic blocks underlain by contrasting basement complexes that have different stratigraphic and structural histories. In central and northern California, the San Andreas forms the eastern boundary of the Salinian block, a long, narrow tectonic sliver underlain by Mesozoic granitic crust. East and west of the

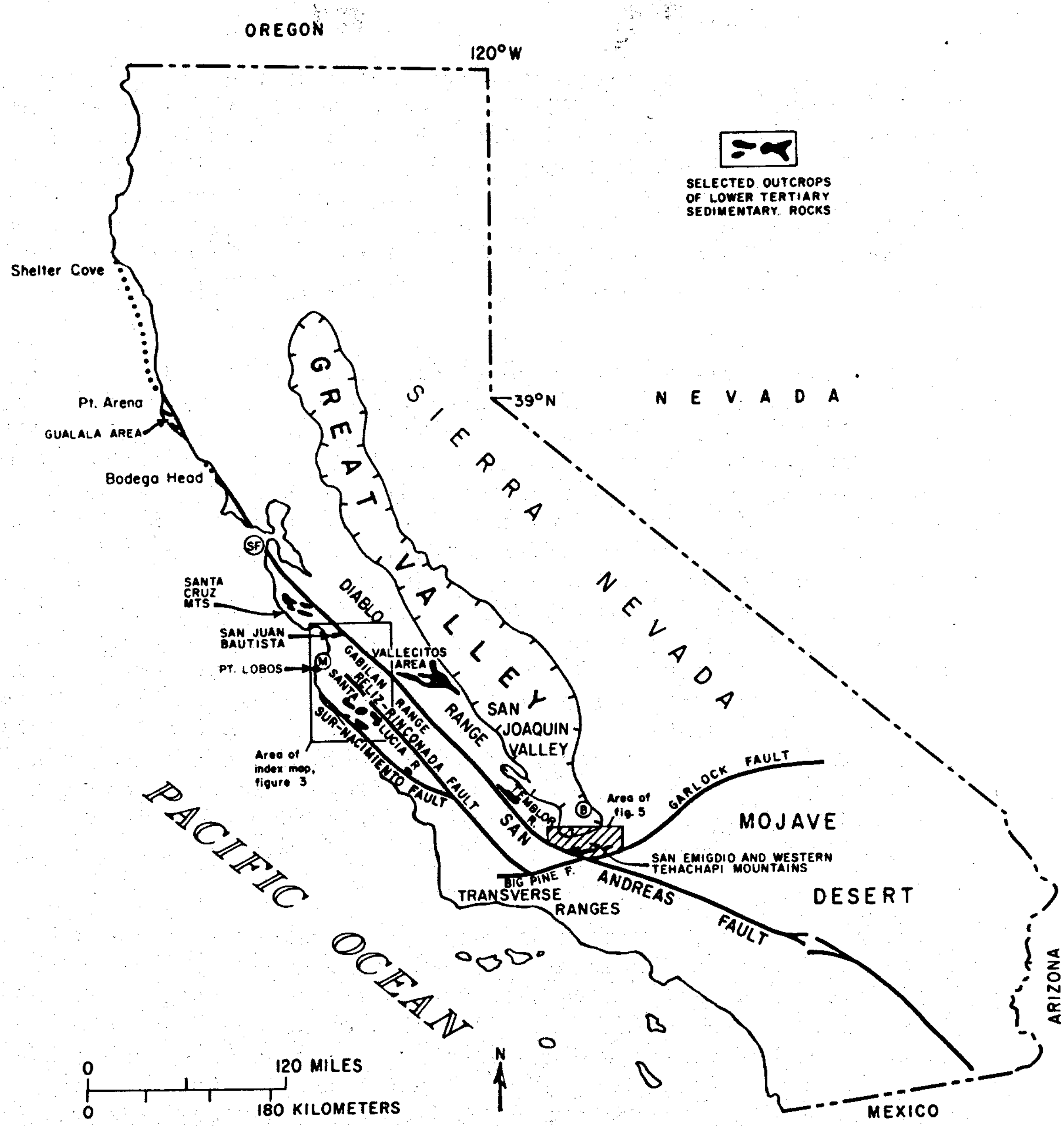


Figure 1. Index map of California showing location of study areas, selected outcrops of lower Tertiary rocks, and the San Andreas and other faults. SF=San Francisco, M=Monterey, B=Bakersfield.

Salinian block, the Franciscan assemblage, thought to represent subducted Mesozoic oceanic crust and sediments, forms the basement complex. Late Cretaceous and Cenozoic sedimentary and volcanic strata deposited unconformably on the two basement complexes have been offset by major right-lateral movement along the San Andreas fault.

The history of the San Andreas fault has been the subject of many studies since Hill and Dibblee (1953) suggested that cumulative offset along it might amount to hundreds of miles. Numerous studies have shown that Holocene to lower Miocene strata in central and northern

California are offset by progressively greater distances along the fault to a maximum of about 190-200 miles (305-320 km) (Dibblee, 1966; Dickinson and Grantz, 1968; Addicott, 1968; Turner and others, 1970; Huffman, 1972; Dickinson and others, 1972; Mathews, 1973). Other studies have indicated that Mesozoic basement rocks and Late Cretaceous strata in central and northern California are offset greater distances, on the order of 325-450 miles (525-725 km) (Dibblee, 1966; Wentworth, 1968; Hill and Hobson, 1968; Colburn, 1969; Ross, 1970; Ross and others, 1973).

This paper forms part of a continuing study by the U.S. Geological Survey to determine offsets of Paleocene, Eocene, and Oligocene strata along the San Andreas fault in central and northern California. Offsets of lower Tertiary strata amounting to about 190-200 miles (305-320 km) have been suggested from comparative studies of the Gualala and Vallecitos areas (Nilsen and others, 1974), the San Juan Bautista and San Emigdio Mountains areas (Clarke and Nilsen, 1973), and the Santa Cruz Mountains and Temblor Range areas (Clarke and Nilsen, 1973) (fig. 1). These suggested offsets along the San Andreas fault support the inference that a proto-San Andreas fault, subparallel to the modern San Andreas fault, was responsible for right-lateral offsets of 135-260 miles (220-420 km) during Late Cretaceous to possibly early Paleocene time (Suppe, 1970; Kistler and others, 1973; Clarke and Nilsen, 1973). Regional analyses of early Tertiary paleogeography, tectonics, and sedimentation for central and northern California in relation to the history and influence of the San Andreas fault have recently been compiled by Nilsen and Clarke (1975) and Clarke, Howell, and Nilsen (this volume).

The purpose of this paper is to compare the stratigraphy and sedimentology of Eocene to lower Miocene sedimentary and volcanic rocks of the northern Santa Lucia Range with those of the San Emigdio and western Tehachapi Mountains (figs. 1, 2). The northern Santa Lucia Range is located in the west-central part of the Salinian block about 25 miles (40 km) southwest of the San Andreas fault. The San Emigdio and western Tehachapi Mountains are located east of the San Andreas fault and form the southwestern extension of the Sierra Nevada province. The sequences are very similar and provide data for additional determinations of offsets along the San Andreas fault. In addition, a sequence of Eocene to lower Miocene strata at the northern end of the Gabilan Range adjacent to and west of the San Andreas fault (fig. 2), although not studied in detail by us, provides additional data to support the offsets suggested herein and to strengthen our inferences about lower Tertiary paleogeography.

NORTHERN SANTA LUCIA RANGE

Introduction

The northwest-trending northern Santa Lucia Range is underlain by a pre-Tertiary granitic and metamorphic crystalline basement complex (fig. 3). Cretaceous and Cenozoic strata rest unconformably on the basement complex and are exposed in down-faulted homoclines and as

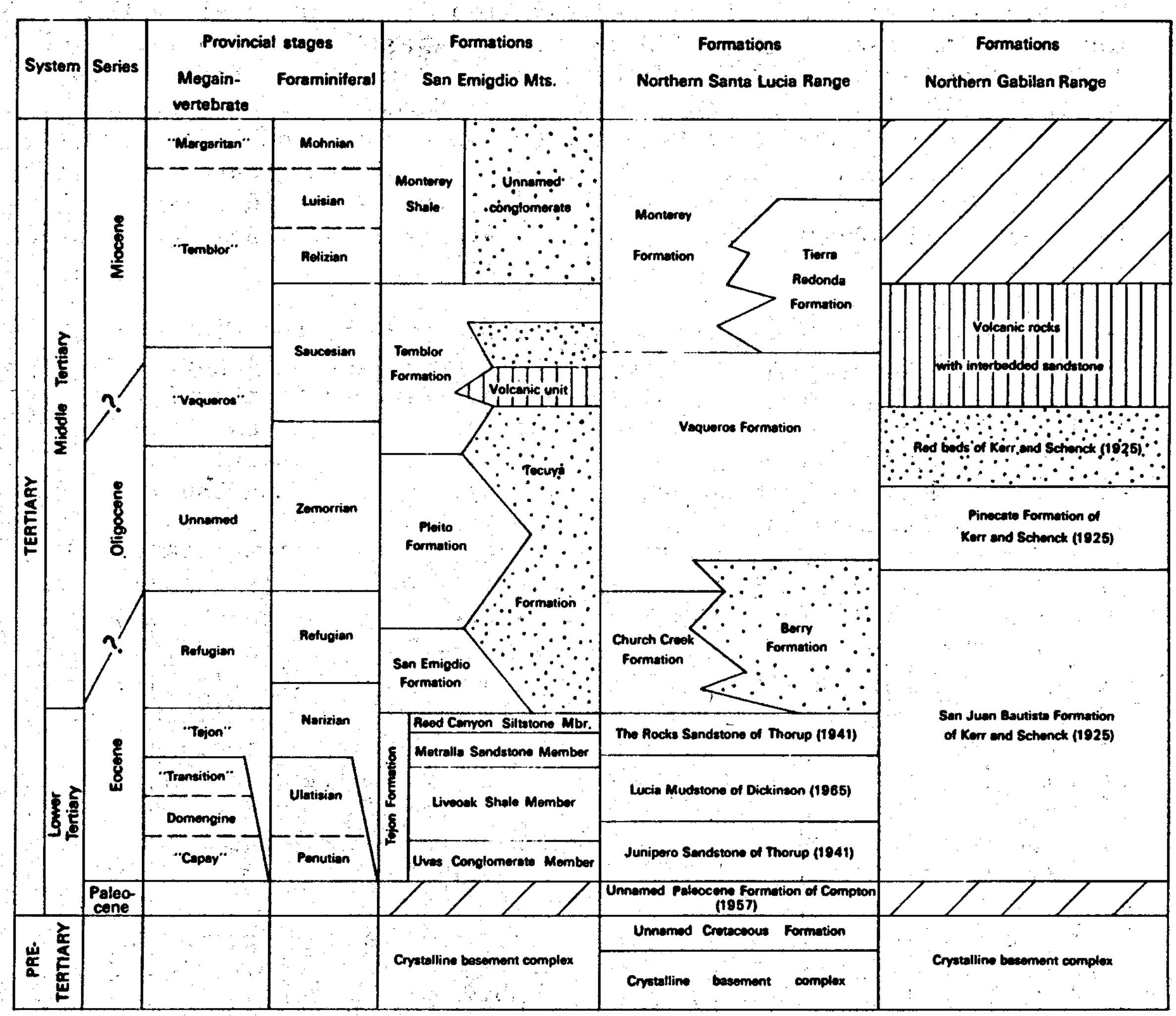


Figure 2. Lower and middle Tertiary formations exposed in the San Emigdio and western Tehachapi Mountains, northern Santa Lucia Range, and northern Gabilan Range. Foraminiferal stages from Kleinpell (1938) and Mallory (1959); megainvertebrate stages from Weaver and others (1944) and Addicott (1972). Sources of data include Nilsen and others (1973) for San Emigdio and western Tehachapi Mountains, Dickinson (1965), Brabb, Bukry and Pierce (1971), and Durham (1974) for northern Santa Lucia Range, and Clark and Reitman (1973) for northern Gabilan Range. Stippled units are nonmarine; vertically lined units are volcanic; inclined lines indicate absence of strata. The reader should note that in the text of this paper we use the following age assignments for provincial stages: Penutian=early Eocene, Ulatisian=middle Eocene, Narizian=late Eocene, Refugian and Zemorrian=Oligocene, and Saucesian=early Miocene.

erosional remnants adjacent to major reverse faults of Pliocene and Pleistocene age (Dickinson, 1965). The strata are generally tilted toward the northeast and minor folding is present locally. The ages, formation names, and stratigraphic relations of the lower and middle

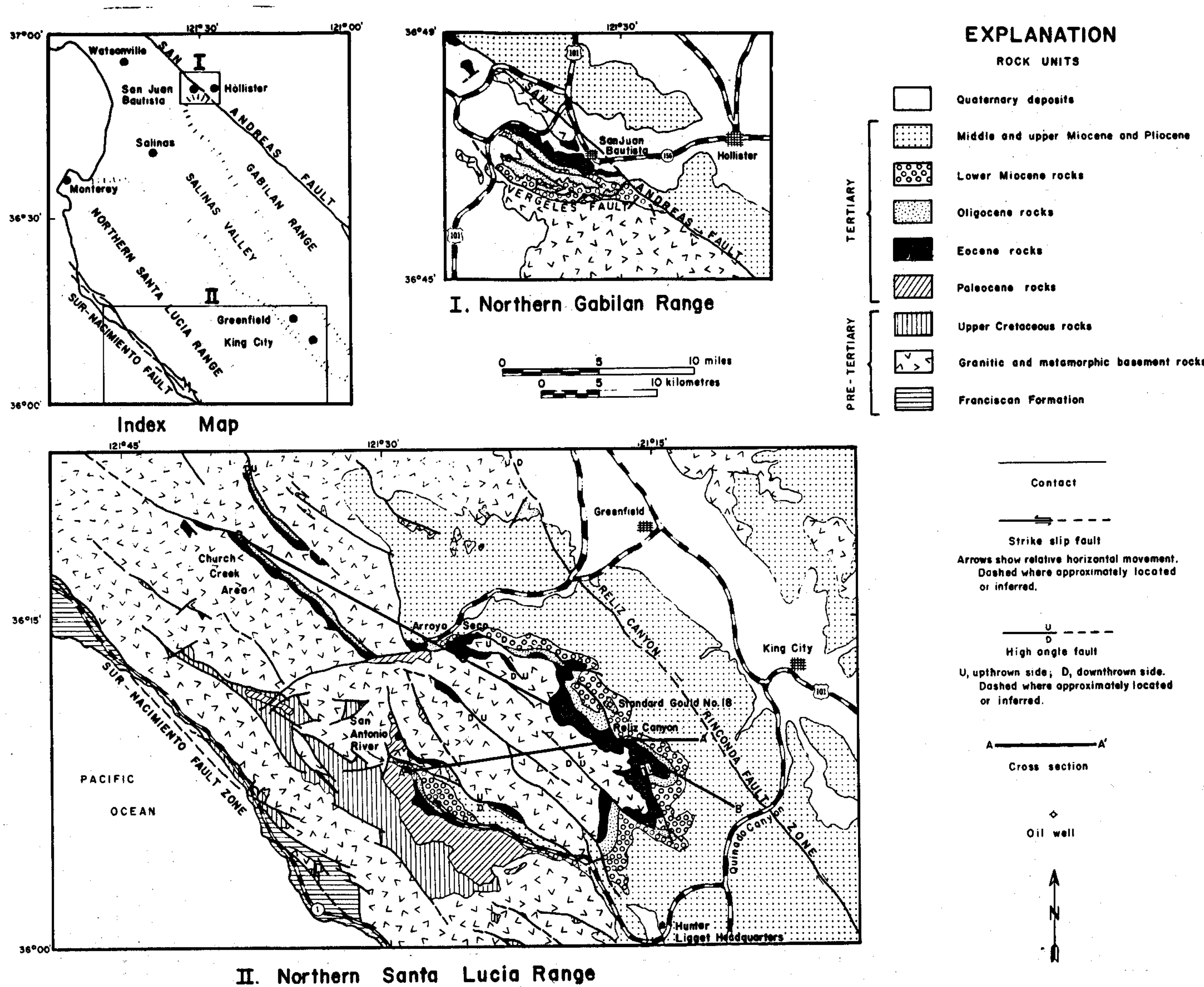


Figure 3. Simplified geologic maps of parts of the northern Gabilan Range(I) and northern Santa Lucia Range(II). Map I modified from Jennings and Strand (1958) and Clark and Reitman (1973); Map II modified from Jennings and Strand (1958) and Dibblee (1971). Note: rocks shown as Eocene on Map I represent the San Juan Bautista Formation of Kerr and Schenck (1925), which also includes Refugian strata that are considered in this report to be Oligocene (fig. 2).

Tertiary sequence are shown in figures 2 and 4.

The Sur-Nacimiento fault in the western part of the range is the western boundary of the Salinian block; it is thought to be primarily a reverse fault that forms the contact between Franciscan basement rocks to the west and granitic and metamorphic basement rocks to the east (Page, 1970). The northern end of the Reliz-Rinconada fault system of Dibblee (1972) is present along the eastern margin of the range; this right-lateral fault extends northward into the Salinian block several hundred miles from the Transverse Ranges to the south, dying out in the vicinity of the northern Santa Lucia Range. Dibblee (1972) suggested as much as 40 miles (64 km) of post-early Tertiary offset along the fault in the central and southern Santa Lucia Range area.

The basement complex consists of (1) high-grade metamorphic rocks of the Sur Series of Trask (1926, p. 134), schist, quartzite, marble and calc-silicate rocks thought to be metamorphosed miogeosynclinal sedimentary rocks of Paleozoic age on the basis of fossils found in similar rocks in the northern Gabilan Range (Bowen and Gray, 1959), and subordinate metavolcanic rocks of the amphibolite and locally granulite facies (Dickinson, 1965); and (2) plutonic rocks that are primarily quartz monzonite to quartz diorite, but range in composition from peridotite to granite (Compton, 1966).

Previous work

Hamlin (1904, p. 14) proposed the name "Vaquero Sandstone" for strata in Los Vaqueros Valley resting on crystalline basement rocks and underlain by the Monterey Formation. Later workers (Anderson and Martin, 1914; Wiedey, 1929; Kleinpell, 1930; Loel and Corey, 1932; Schenck, 1936; Eaton and others, 1941; Thorup, 1941; Taliaferro, 1943) demonstrated that the Vaqueros Formation was a mappable unit ranging in age from early Eocene to early Miocene. Thorup (1943) redefined the type Vaqueros Formation, in the Vaqueros Canyon area, dividing it in ascending order into five new formations, the Junipero Sandstone, Lucia Shale, The Rocks Sandstone, Berry Conglomerate, and the Vaqueros Formation. Dickinson (1959, 1965) recognized the same stratigraphic units in the Church Creek area northwest of Vaqueros Canyon, noting that the Berry Conglomerate interfingered with the Church Creek Formation and modifying the name Lucia Shale to Lucia Mudstone. Subsequent studies (Wardle, 1957; Dickinson 1959, 1965; Masters, 1962; Waters, 1963; Durham, 1963, 1974; and Brabb and others, 1971) further defined the ages and characteristics of these units.

Durham (1963, 1974) grouped the stratigraphically lowest units (Junipero Sandstone of Thorup (1941), Lucia Mudstone of Dickinson (1965), and The Rocks Sandstone of Thorup (1941)) as unnamed members of the Reliz Canyon Formation, noting that the upper and lower arenaceous members are indistinguishable where the middle pelitic member is absent. Durham (1974) also reintroduced the name Berry Formation (Bramlette and Daviess, 1944) for the Berry Conglomerate (Thorup, 1943). In this paper, the formation names of Thorup (1941), as modified by Dickinson (1965), Bramlette and Daviess (1944), and in part by Durham (1974), are

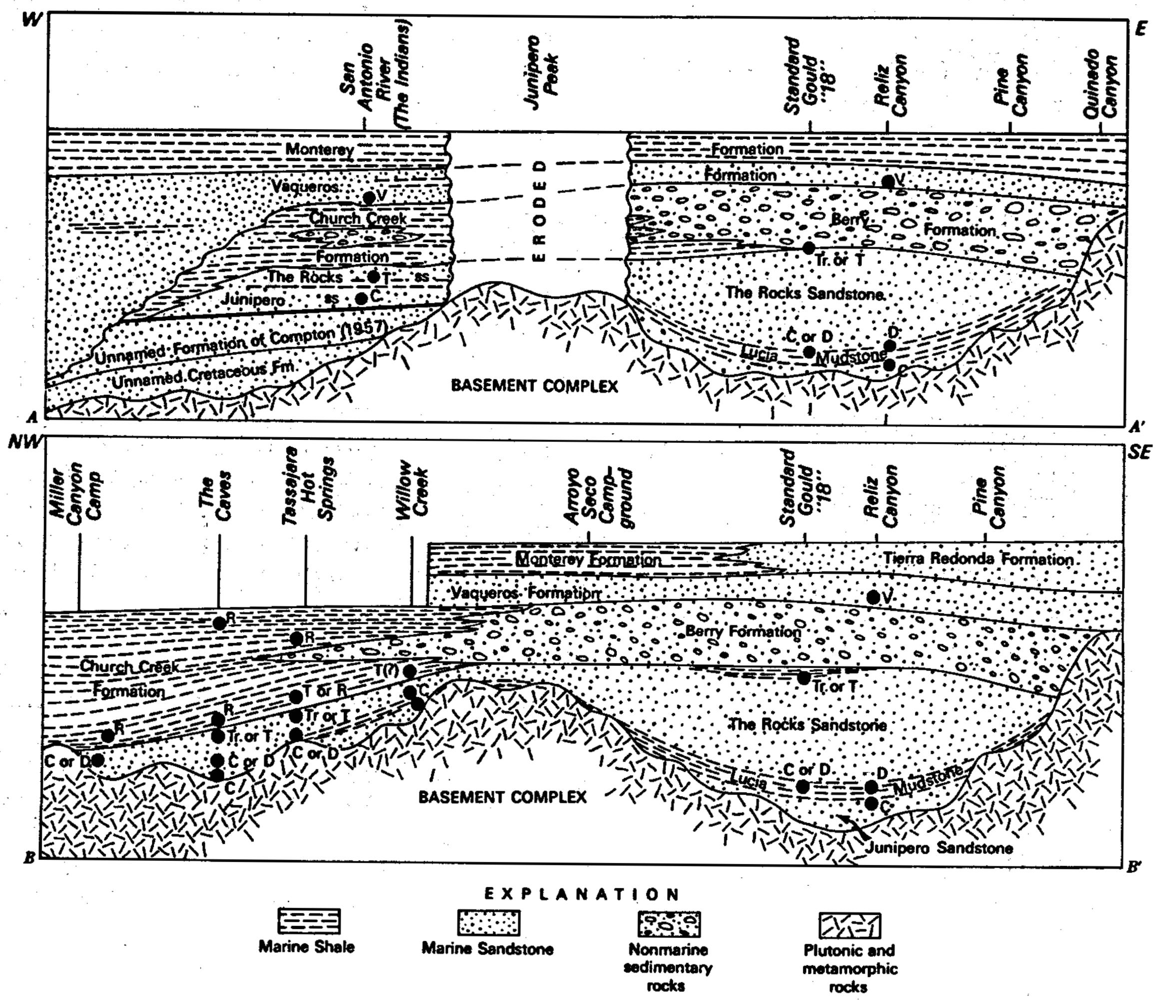


Figure 4. General lithofacies and geologic relations of the lower and middle Tertiary stratigraphic units of the northern Santa Lucia Range. Unconformities are indicated by wavy lines. Dots with letters indicate critical megainvertebrate collections and stage assignment, partly from published sources cited in text: C, "Capay Stage"; D, "Domengine Stage"; Tr, "Transition Stage"; Tj, "Tejon Stage"; R, "Refugian Stage"; V, "Vaqueros Stage." Not drawn to scale nor with reference to time lines. See Figure 3 for location and orientation of cross-section lines. Note: Monterey Formation is present in the northwestern part of the study area, but not in contact with Church Creek Formation.

used: Junipero Sandstone, Lucia Mudstone, The Rocks Sandstone, Berry Formation, Church Creek Formation, and Vaqueros Formation.

Stratigraphy and sedimentology

General

Strata overlying the basement rocks range in age from Late Cretaceous to Quaternary, consist mostly of clastic marine sedimentary rocks, and are about 25,000 feet (7,620 m) thick. The pre-middle Miocene rocks are divisible into two continuous sequences that are bounded by unconformities and whose basal beds rest locally upon basement rocks.

The older unnamed Late Cretaceous and Paleocene sequence is more than 10,000 feet (3,050 m) thick and rests unconformably on basement rocks along the western flank of the northern Santa Lucia Range (fig. 3). The Paleocene strata consist of basal shallow-marine sandstone and conglomerate overlain by mudstone and siltstone deposited in deeper marine and possibly locally in nonmarine environments (Compton, 1957; Dickinson. 1959).

The younger Penutian to Saucesian sequence is more than 5,000 feet (1,525 m) thick (fig. 2) and rests unconformably upon either basement rocks or the Cretaceous and Paleocene sequence. It includes the Junipero Sandstone of Thorup (1941), the Lucia Mudstone of Dickinson (1965), The Rocks Sandstone of Thorup (1941), the Berry Formation, the Church Creek Formation, and the Vaqueros Formation. These units were deposited in marine environments at bathyal, neritic, and littoral depths except for the Berry Formation, which was deposited primarily under nonmarine conditions.

Overlying younger strata, more than 10,000 feet (3,050 m) thick and middle Miocene to Quaternary in age, include the Tierra Redonda Formation, Monterey Formation, Pancho Rico Formation, and Paso Robles Formation (Durham, 1974).

Junipero Sandstone of Thorup (1941)

The Junipero Sandstone at its type locality in Reliz Canyon rests unconformably on basement, forming the base of the Eocene to lower Miocene sequence. To the southwest in The San Antonio River area it rests unconformably(?) on the Paleocene and Cretaceous strata. Because the basal contact is topographically irregular, the Junipero is thicker in areas that were topographic lows and thinner or locally absent in areas that were topographic highs at the time of deposition. It is thickest to the southwest, where it is as thick as 500 feet (150 m) or more. The Junipero includes boulder conglomerate containing clasts derived from the local basement complex, cobbly and pebbly sandstone containing quartzitic and volcanic clasts derived from either more distant sources or reworked older conglomerates, and thin intercalations of mudstone and siltstone. Compositionally the sandstones are arkosic and locally contain abundant heavy minerals; texturally they are moderately well sorted and contain subangular to rounded grains. Common sedimentary features are massive bedding, cross bedding, parallel lamination, and bioturbation.

Locally abundant fossils of "reefoid" algae, mollusks, and orbitoid foraminifers indicate deposition in shallow, aerated marine waters during Penutian time (Dickinson, 1965, p. 33). The Junipero is a basal transgressive unit deposited in nearshore, high-energy conditions that grades upward into thinly bedded, finer grained strata deposited in deeper marine conditions.

Lucia Mudstone of Dickinson (1965)

The Lucia Mudstone at its type locality in the Reliz Canyon area consists of 300-500 feet (90-150 m) of thin-bedded, greenish-gray mudstone that contains interbeds of locally thick and massive sandstone and maroon mudstone in its upper part. It ranges from 0 to 500 feet (0-150 m) or more in thickness and rests conformably on the Junipero Sandstone or unconformably on basement rocks where the Junipero is locally absent. It pinches out southeastward, where the underlying Junipero Sandstone and the overlying The Rocks Sandstone merge.

Abundant and dominantly pelagic foraminifers suggest free connections with the open ocean (Wardle, 1957; Dickinson, 1965), deposition at outer neritic to bathyal depths, a Penutian age for the lower part (Wardle, 1957) and a Ulatisian age for the upper part in Reliz Canyon. The poorly-sorted, bioturbated mudstone was probably deposited slowly in a generally deep and quiet marine environment with sporadic deposition locally of thin- to thick-bedded turbidites.

The Rocks Sandstone of Thorup (1941)

The Rocks Sandstone at its type locality in Reliz Canyon consists of 2,000 feet (610 m) or more of thick-bedded to massive sandstone that conformably overlies the Lucia Mudstone and is conformably overlain by the nonmarine Berry Formation. To the northwest in the Church Creek area it is overlain conformably by the marine Church Creek Formation and to the southeast it onlaps the Lucia Mudstone, locally resting unconformably on basement rocks or conformably on the Junipero Sandstone. It varies in thickness from 400 to 2,000 feet (120-610 m) or more, and consists of lens-shaped sandstone bodies that form prominent hogbacks and flatirons and contain minor amounts of conglomerate and thin silty sandstone and mudstone interbeds.

A meager fauna includes orbitoid foraminifers from sandstone in the lower part, ubiquitous plant debris, and benthonic and pelagic foraminifers from mudstone in the upper part (Masters, 1962; Dickinson, 1965) that indicate a Ulatisian and Narizian age and deposition primarily at outer neritic and bathyal depths at a depositional site connected to the open ocean. It is older to the southeast in the Reliz Canyon area and younger to the northwest in the Church Creek area.

The Rocks Sandstone is arkosic and contains subangular detritus that includes volcanic and quartzitic clasts; the grain size coarsens and bed and section thickness increase toward the southeast. Common sedimentary structures and features include channeling at the base of beds, dish structures, mudstone rip-up clasts, groove, flute, and load casts, small- to large- scale cross-bedding, parallel lamination, convolute lamination, disturbed bedding, and imbricated pebbles and mudstone clasts.

The Rocks Sandstone is inferred to have been deposited as a submarine fan in moderately deep marine conditions. Sedimentary structures suggest deposition by turbidity currents, fluidized sediment flows, and grain flows. Paleocurrent, thickness, and stratigraphic data indicate transport of sediments toward the northwest.

Church Creek Formation

The Church Creek Formation at its type locality along Church Creek consists of 1,250-1,500 feet (380-455 m) of interbedded marine gray mudstone, brown siltstone, and sandstone with minor amounts of phosphate. In general, it conformably overlies The Rocks Sandstone and is overlain conformably by the Vaqueros Formation. Scattered and poorly exposed outcrops elsewhere indicate that it varies laterally in lithology and thickness, interfingering southeastward with the nonmarine Berry Formation in the Church Creek and San Antonio River areas, and possibly in subsurface (Standard Gould 18) near Reliz Canyon.

Abundant foraminiferal and nannoplankton faunules indicate an early Narizian(?) to Refugian age, deposition at outer neritic to bathyal depths, and free connections to the open ocean (Dickinson, 1959, 1965; Masters, 1962; Waters, 1963; Brabb and others, 1971). A shallow-marine algal, molluscan, foraminiferal, and coral fauna is present in the San Antonio River area. These faunas data indicate that it is time- transgressive, being slightly older to the southeast and younger to the northwest (Masters, 1962; Waters, 1963; Dickinson, 1965).

Shallow- to deep-marine mudstone, sandstone, and siltstone of the Church Creek Formation were deposited at outer neritic to bathyal depths. A shallow marine fauna and interfingering with the nonmarine Berry Formation indicate shallow marine deposition in the San Antonio River area. Variable lithologies, thicknesses, and sedimentary features probably reflect deposition in basin floor, slope and shelf environments.

Berry Formation

The Berry Formation at its type locality in Reliz Canyon consists of interbedded conglomerate, sandstone, and mudstone that rest conformably on The Rocks Sandstone and are overlain conformably by and locally interfinger with the Vaqueros Formation (fig. 2). Where present in the east and south it rests unconformably on either underlying lower Tertiary units or the basement complex. Over basement rocks, it consists of a basal conglomerate that grades upward into a cross-bedded white sandstone that is in turn overlain by and interbedded with red to yellow mudstone. In the west, northwest, and southwest, it interfingers with the Church Creek Formation. It is 600-1,500 feet (185-465 m) thick.

Although no fossils have been found, an Oligocene(?) age has been assigned to it (Durham, 1974) because of its conformable position below the Vaqueros Formation and above The Rocks Sandstone, and its lateral interfingering with the Church Creek Formation. It probably ranges at least from Refugian to early Zemorrian in age.

Sandstone and conglomerate of the Berry Formation consist of angular to well-rounded local basement complex clasts and well-rounded quartzite and volcanic clasts. Thorup (1943, p. 465) suggested that these well-rounded clasts were reworked from pre-Eocene conglomerates. The basal conglomerate is generally poorly sorted, whereas the finer-grained white sandstones are moderately to well-sorted and contain abundant cross-beds. Common sedimentary structures include small- to large-scale cross-bedding, climbing ripples, current ripple markings, parallel laminations, large channels, imbricated pebbles, and trace fossils. Abrupt vertical and lateral variations in bedding thickness and maximum clast size are typical.

The Berry was deposited primarily under terrestrial conditions, probably in alluvial fan, fluvial, dune, floodplain, and lagoonal environments. The poorly sorted, red-brown, basal sandstone and conglomerate interval suggests mud-flow and debris-flow deposits on alluvial fans; the well-sorted, white cross-bedded sandstones suggest fluvial, dune, and possibly beach environments; and the interbedded white cross-bedded sandstones and the red to yellow mudstones suggest a flood plain or lagoonal environment. The interfingering relationship of the Berry with the Church Creek and the Vaqueros Formations suggests in part transitional marine environments.

Vaqueros Formation

The Vaqueros Formation at its type locality near Vaqueros Creek consists of 2,000 feet (610 m) of highly fossiliferous white to gray, cross-bedded sandstone and siltstone that is in gradational contact with the underlying Berry Formation and overlying Monterey Formation. It is as thick as 2,500 feet (765 m) or more and has been locally subdivided informally into six members (Thorup, 1941, 1943). Abundant molluscan and foraminiferal faunas from the Vaqueros Formation belong to the "Vaqueros" provincial megainvertebrate stage and Zemorrian and lower Saucesian foraminiferal stages (Thorup, 1941, 1943). Numerous molluscan and echinoid biostromes can be traced for miles. Sedimentary features include various types of cross-bedding, accretionary channels, lag gravels, climbing ripples, current ripple markings, parallel laminations, and trace fossils. The Vaqueros Formation was deposited in a high-energy, shallow-marine environment, probably during a renewed transgression over the Berry Formation.

Younger units

The lower Eocene to lower Miocene sequence is overlain conformably by the shallow marine Tierra Redonda Formation of middle Miocene age and the Monterey Formation of middle and late Miocene age. The Monterey is a marine siliceous shale that contains calcareous mudstone and shale, chert, procelanite, sandstone, dolomite, and some volcanic rocks, and was deposited at neritic to abyssal depths (Durham, 1974).

Paleogeography

The Eocene to lower Miocene sequence in the northern Santa Lucia Range was deposited within the Salinian block at neritic to bathyal depths, with some nonmarine sedimentation. Deposition commenced during a major transgression from west-northwest to east-southeast from Penutian to Bulitian and possibly Narizian time (fig. 2). During this transgression, the shallow-marine Junipero Sandstone was deposited on a topographically irregular basement complex, followed by deposition of the Lucia Mudstone in deeper marine conditions. The sea retreated westward during Bulitian to Refugian time, resulting in deposition of the regressive The Rocks Sandstone and the Berry and Church Creek Formations. The Rocks Sandstone submarine-fan complex was covered by the northwestward-prograding nonmarine Berry and marine Church Creek Formations. During Oligocene and early Miocene time, the widespread shallow-marine transgressive Vaqueros Formation was deposited.

Approximately north-south trending slopes and shorelines are indicated by paleocurrent, thickness, petrographic, and stratigraphic studies of the Eocene to lower Miocene sequence in the northern Santa Lucia Range. The source areas were located to the east and southeast and were composed of granitic and metamorphic rocks and probably minor amounts of sedimentary rocks. Volcanic and metasedimentary clasts may have been derived from the reworking of Cretaceous and Paleocene conglomeratic rocks. Paleocurrent patterns generally indicate sediment transport toward the northwest. Proximity to the source area at the southeastern end of the depositional area is indicated by (1) southeastward thinning of the Eocene units, (2) southeastward pinching out locally of the Lucia Mudstone, resulting in the Junipero and The Rocks Sandstone resting on one another, (3) the presence to the southeast of the nonmarine Berry Formation resting unconformably on basement rocks and older sedimentary units, and (4) the southeastward interfingering of the marine Church Creek into the nonmarine Berry Formation.

SAN EMIGDIO AND WESTERN TEHACHAPI MOUNTAINS

Introduction

The lower and middle Tertiary stratigraphic units exposed along the north flank of the San Emigdio and western Tehachapi Mountains were deposited along the southern margin of what is generally referred to as the San Joaquin basin. The units form a sequence of sedimentary and local volcanic rocks that is moderately thick and complete (fig. 2). The strata dip northward off a pre-Tertiary crystalline basement complex, have been folded and faulted along a series of south-dipping thrust faults, and form a prominent northeast-plunging syncline in the Devils Kitchen area (fig. 5). The sequence thickens westward from a few hundred to many thousands of feet, with some units extending northwestward

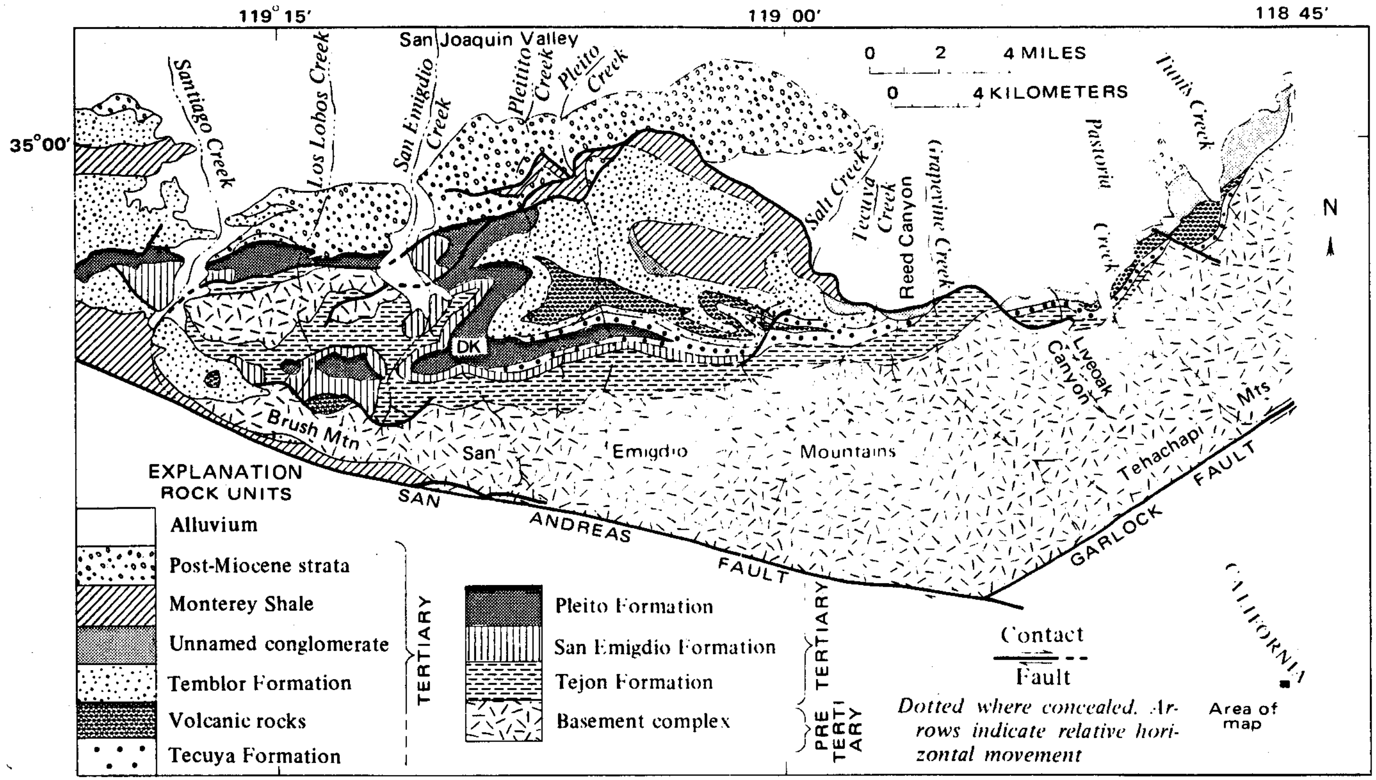


Figure 5. Simplified geologic map of the San Emigdio and western Tehachapi Mountains (from Nilsen and others, 1973). Modified from Smith (1964) and Jennings and Strand (1969). DK, Devils Kitchen area, location of Devils Kitchen syncline.

into the Temblor Range. The ages, formation names, and stratigraphic relations are shown in figures 2 and 6.

The sequence is unconformably overlain by primarily nonmarine late Cenozoic sedimentary rocks and rests unconformably on pre-Tertiary plutonic and metamorphic crystalline basement rocks that are primarily granitic, except in the Los Lobos Canyon area, where mafic and ultramafic igneous and metamorphic rocks are present. Ross (1970, 1972) inferred that the non-granitic rocks are a fragment of Mesozoic oceanic crust.

Previous work

The reader is referred to the listing of previous work by Nilsen and others (1973, p. H4-H7) for a summary. The lithologies, stratigraphic relations, thicknesses, ages, and depositional environments of the lower and middle Tertiary stratigraphic units are also summarized in Nilsen and others (1973). The upper Tertiary and Quaternary stratigraphic units are described by Hoots (1930), McGill (1951), and Dibblee (1961). The stratigraphy and sedimentology of the Eocene Tejon Formation, with emphasis on paleogeography, are summarized by Nilsen (1973). The distribution of Tertiary and underlying basement rocks is shown by Dibblee and Nilsen (1973). Subsurface stratigraphy is described by Tipton (1971), Tipton and others (1973, 1974), Clarke (1973), and Weber (1973).

Stratigraphy and sedimentology

General

Tertiary sedimentation began with the marine Tejon Formation of Eocene age, which was deposited across most of the study area. Overlying the Tejon Formation in the western part of the area is a sequence of conformable marine units, in ascending order, the San Emigdio, Pleito, and Temblor Formations. The Pleito and Temblor Formations interfinger eastward into the nonmarine Tecuya Formation and the San Emigdio Formation pinches out eastward between the Tecuya and Tejon Formations. The Tecuya Formation conformably overlies the Tejon Formation in the eastern part of the area. Sedimentary facies in the central part of the area define an oscillating late Eocene, Oligocene, and early Miocene shoreline. The Miocene Monterey Shale conformably overlies the Temblor Formation in the western and central parts of the area and intertongues eastward into unnamed nonmarine conglomerate that unconformably overlies the Tecuya Formation.

Tejon Formation

The Tejon Formation records a major eastward transgression during early, middle and possibly late Eocene time followed by a westward regression in late Eocene time. It thickens westward from zero near Tunis Creek to more than 4,000 feet (1,210 m) near Pleito Creek in the central part of the San Emigdio Mountains; westward from there it thins to about 1,000 feet (305 m) near Santiago Creek, where it is unconformably trun-

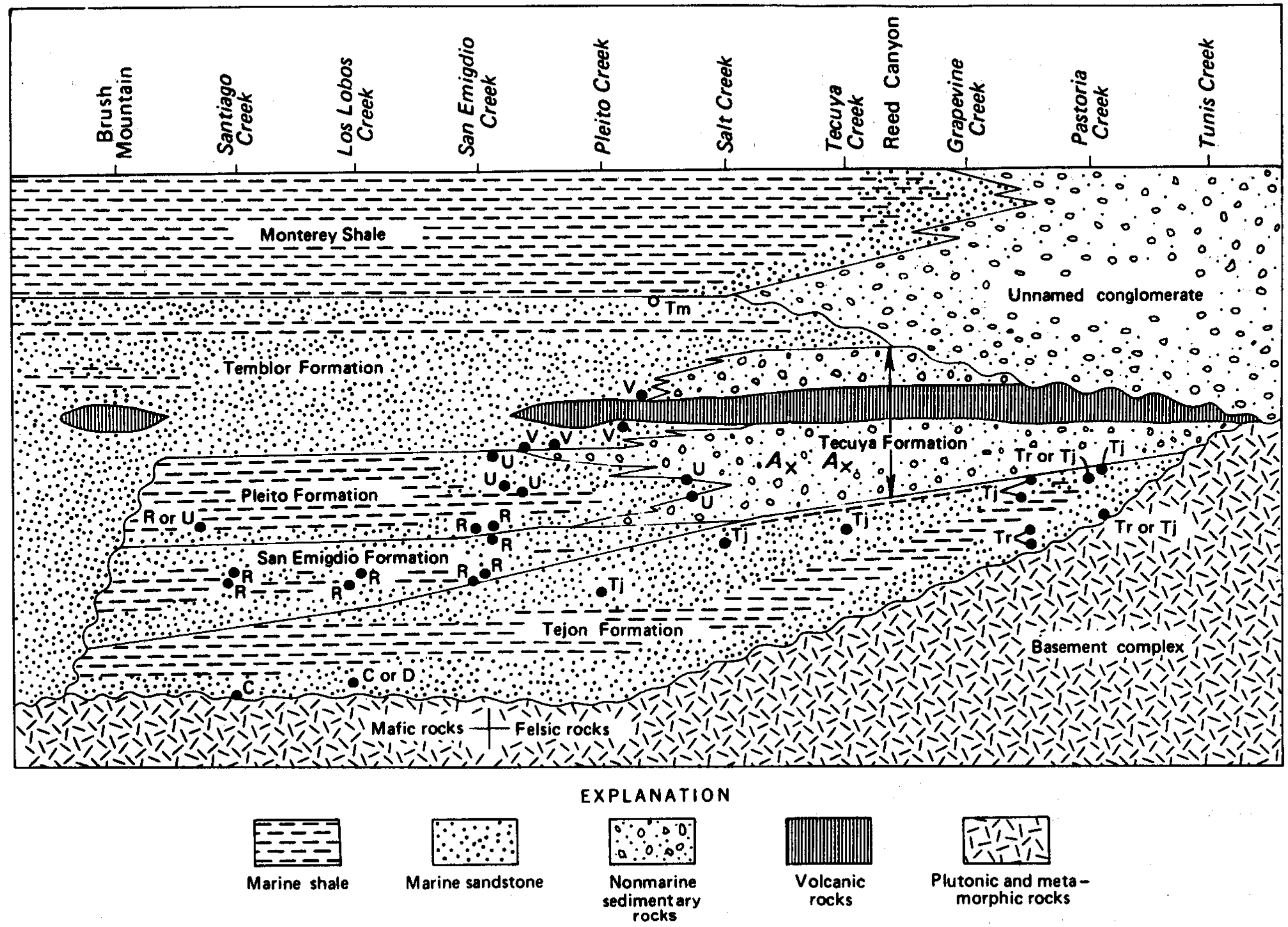


Figure 6. General lithofacies and geologic relations of the lower and middle Tertiary stratigraphic units of the San Emigdio and western Tehachapi Mountains (from Nilsen and others, 1973). Unconformities are indicated by wavy lines. Dots with letters indicate critical megainvertebrate collections and stage assignment: C, "Capay Stage"; D, "Domengine Stage"; Tr, "Transition Stage"; Tj, "Tejon Stage"; R, "Refugian Stage"; U, unnamed stage (Addicott, 1972); V, "Vaqueros Stage"; Tm, "Temblor Stage." Occurrences of early Arikareen mammals in the Tecuya Formation (Stock, 1920, 1932) are indicated by X^A. Not drawn to scale nor with reference to time lines.

cated by the Temblor Formation on Brush Mountain (fig. 6). Marks (1943) subdivided the Tejon Formation in the Grapevine Canyon area into four members, which were subsequently extended throughout the outcrop area by Nilsen (1973). The members, in ascending order, are the Uvas Conglomerate Member, the Liveoak Shale Member, the Metralla Sandstone Member, and the Reed Canyon Siltstone Member.

The Uvas Conglomerate Member is a basal conglomerate and sandstone that rests unconformably on the basement complex. Because the basal contact is topographically irregular, the Uvas is thicker in areas that were topographic lows and thinner or locally absent in areas that were topographic highs at the time of deposition. Its maximum thickness is about 400 feet (120 m). It includes boulder conglomerate containing clasts derived from the local basement complex, pebble and cobble conglomerate containg quartzitic and volcanic clasts probably derived mostly from more distant sources, breccia containing fragments derived by in situ weathering of the basement complex, and thin- to thick-bedded sandstone containing minor amounts of shale. Locally abundant fossils of mollusks and orbitoid foraminifers indicate deposition at depths of less than 15 fathoms in nearshore environments with bare rock commonly exposed as shoals or reefs; sedimentary structures, grain-size distributions, and textures suggest a high-energy environment of deposition. Trace fossils are common locally as long vertically-oriented cylindrical burrows and medium- to large-scale cross-strata, flat-strata, and current ripple markings are common. Paleocurrents indicate transport of sediments toward the west-northwest. The Uvas records in outcrop an eastward marine transgression that spanned most of the Eocene Epoch. It grades upward into shale of the overlying Liveoak Shale Member except at the eastern end of the area, where it merges with and is overlain directly by the Metralla Sandstone Member.

The Liveoak Shale Member is a bioturbated shale and mudstone that contains some interstratified siltstone in most areas, and sandstone in its upper and lower parts where it grades into the coarser grained members of the Tejon Formation. It is as thick as 2,000 feet (610 m) in the Pleito Creek area; eastward it pinches out between the Uvas and Metralla Members. Foraminifers are common and indicate a Ulatisian and Narizian (middle and late Eocene) age, deposition at lower bathyal to abyssal depths to the west and bathyal to shallow marine depths to the east, and free access to the open ocean.

The Metralla Sandstone Member increases in thickness westward from a few hundred feet near Pastoria Creek to about 2,000 feet (610 m) near Pleito Creek; further west it thins to form a turbidite sequence that interfingers with siltstone and shale of the Liveoak Shale Member near San Emigdio Canyon. The Metralla is conformably overlain by the Tecuya Formation in the eastern, Reed Canyon Siltstone Member in the central, and San Emigdio Formation in the western parts of the area. It consists of a shallow marine, megafossil-rich, conglomeratic sandstone characterized by cross bedding and ripple markings in the east and a deeper marine, microfossil-rich, finer grained sandstone characterized by graded bedding, Bouma sequences and sole markings in the west. Paleocurrents indicate westward transport of sediments in both shallow and deep marine facies. Megafaunas and microfaunas indicate a late Eocene age, with the unit younger to the west, suggesting a late Eocene westward regression.

The Reed Canyon Siltstone Member is less than 200 feet (60 m) thick and consists of bioturbated fine-grained sandstone, siltstone, and silty shale containing abundant carbonaceous material. West of Reed Canyon it is a thin, very poorly exposed fine-grained unit that overlies the Metralla Sandstone Member and near Salt Creek may grade laterally into the middle shale unit of the overlying San Emigdio Formation or persist westward as a thin unit below the San Emigdio Formation. Foraminifers suggest a Narizian age. It locally contains mollusks indicative of shallow marine sedimentation, and is inferred to probably represent lagoonal sedimentation behind barrier bars.

San Emigdio Formation

The San Emigdio Formation forms a sequence of marine sandstone and shale about 1,000 feet (305 m) thick in the Devils Kitchen area, where it is divisible into three units, a lower unfossiliferous sandstone that is locally conglomeratic, a middle shale, and an upper fossiliferous sandstone that also is locally conglomeratic. To the east it thins to a locally fossiliferous sandstone that pinches out between the Tejon and Tecuya Formations near Salt Creek. To the west it thickens to a locally fossiliferous conglomeratic sandstone that is interbedded with siltstone and shale.

Foraminiferal faunas indicate a Narizian age for the middle shale unit in San Emigdio Canyon and deposition at upper bathyal or outermost shelf depths (DeLise, 1967). Molluscan faunas from the upper sandstone unit indicate a Refugian age and deposition at inner shelf depths. The San Emigdio Formation was deposited west or offshore from the nonmarine Tecuya Formation and may grade laterally into it as well as pinch out beneath it. In the San Emigdio Canyon area it apparently records a minor eastward or southward transgression followed by a regression. Both outcrop relations and subsurface thickness and facies changes suggest derivation of sediments from the south and southeast (Nilsen and others, 1973; Tipton and others, 1973, 1974).

Pleito Formation

The Pleito Formation is about 2,300 feet (700 m) of marine sandstone and shale in its type section near San Emigdio Creek. It conformably overlies the San Emigdio Formation, interfingers eastward into nonmarine beds of the Tecuya Formation, and underlies the Temblor Formation. In the San Emigdio Canyon area it is divisible into three units, a lower massive fossiliferous sandstone containing a thin basal conglomerate, a middle shale unit, and an upper locally conglomeratic fossiliferous sandstone.

Mollusks from the lower part of the Pleito indicate a Refugian age, foraminifers from the middle and upper parts a Zemorrian age, and mollusks from the top part a late Oligocene age (unnamed provincial megainvertebrate stage of Addicott, 1972). The megafauna indicate deposition of the coarse-grained units in shallow marine environments and the microfauna indicate deposition of the fine-grained units at middle to lower bathyal depths. The changing depths probably coincide with migrations of the shoreline caused by minor transgressions and regressions, and are defined by the interfingering contact of the Pleito and Tecuya Formations. Both outcrop relations and subsurface thickness and facies changes suggest derivation of sediments from the south and southeast (Nilsen and others, 1973; Tipton and others, 1973, 1974).

Tecuya Formation

The Tecuya Formation is about 2,350 feet (715 m) thick near Tecuya Canyon, where it consists of three units, both the upper and lower of interbedded red, green, gray, and brown mudstone, siltstone, sandstone, and pebble and cobble conglomerate, and the middle of basalt and andesite with minor amounts of dacite. A basal granitic breccia present in the canyon west of Tecuya Canyon is considered to be of sedimentary origin. The Tecuya rests unconformably on basement rocks east of Tunis Creek, conformably on the Metralla Sandstone or Reed Canyon Siltstone Members of the Tejon Formation between Tunis Creek and Salt Creek, and conformably on the San Emigdio Formation west of Salt Creek. To the east, it is truncated with angular unconformity by an unnamed conglomerate of Miocene age; to the west, it interfingers with shallow marine sandstone of the Pleito and Temblor Formations. The volcanic unit pinches out westward into the marine Temblor Formation just east of San Emigdio Canyon.

Vertebrate fossils from the Tecuya Formation indicate an Oligocene to early Miocene age, but stratigraphic relations suggest that its basal part may be as old as late Eocene (Nilsen and others, 1973). It is inferred to have been deposited as a complex series of coalesced alluvial fans on a coastal plain by streams draining source areas to the east and southeast. It is a regressive unit that prograded westward and northwestward as the late Eocene and Oligocene shoreline retreated and it intertongues westward in outcrop and northwestward in subsurface with marine strata. The volcanic rocks were probably extruded from nearby fissures or vents.

Temblor Formation

The Temblor Formation is a thick marine sandstone and shale unit that can be traced southeastward into the San Emigdio Mountains from the Temblor Range. In the west it conformably overlies the Pleito Formation and is conformably overlain by the Monterey Shale. Eastward, it conformably overlies and intertongues with the upper part of the Tecuya Formation and is unconformably overlain by unnamed Miocene nonmarine conglomerate. The Temblor thins eastward from about 5,500 feet (1,675 m) west of Santiago Creek to about 2,000 feet (610 m) near Salt Creek; southward toward Brush Mountain, it thins to 1,000 feet (305 m) or less, becomes very coarse-grained, unconformably overlaps the San Emigdio and Tejon Formations onto the basement complex, and contains several local lenses of dacite.

Mollusks indicate a "Vaqueros" and "Temblor" age and foraminifers a late Zemorrian to late Saucesian age. Sparse sedimentologic data suggest general shallow marine and local deep marine deposition during an eastward transgression; local oscillations of the shoreline are indicated by interfingering with the Tecuya Formation. The Temblor was apparently derived from source areas located to the south and southeast.

Younger units

The Monterey Shale, a thin-bedded siliceous and semi-siliceous shale of middle and late Miocene age, conformably overlies the Temblor Formation (Dibblee, 1961). An unnamed arkosic nonmarine conglomerate of probable Miocene age truncates the lower and middle Tertiary sequence from Salt Creek eastward to Tunis Creek, where it rests directly on granitic basement rocks. This conglomerate probably intertongues northward and westward with marine Miocene formations such as the Monterey Shale.

Paleogeography

The lower and middle Tertiary sedimentary rocks of the San Emigdio and western Tehachapi Mountains record a series of marine transgressions and regressions across a shelf area that are defined by interfingering eastward of shallow marine sandstone and deeper marine shale with nonmarine strata. This depositional cycle began with a marine transgression in early Eocene time and continued until at least middle Miocene time. Uplift took place at least locally during late Oligocene or early Miocene time in the Brush Mountain area, where the Temblor Formation truncates older strata with angular unconformity. Extensive eruptions of dacite and basalt flows covered the eastern terrestrial area and flowed partly out onto the marine shelf during late Oligocene and early Miocene time. Post-middle Miocene tectonism and thrust faulting uplifted the lower and middle Tertiary strata along the east-west trending structural orientation of the present mountain range.

Paleocurrents and facies relations suggest derivation of sediments mostly from the east and southeast during the Eocene and from the south and southeast during the Oligocene and Miocene. Source areas were located to the east, southeast, and south, and contained primarily granitic, quartzitic, and porphyritic volcanic rocks. The boundary between mafic and felsic basement terranes near San Emigdio Canyon corresponded during the late Eocene to a physical change from a shallow marine shelf in the east to a submarine slope and deep marine floor in the west. This paleogeography is expressed as a lateral facies change in the Metralla Sandstone Member of the Tejon Formation.

Subsurface data from wells drilled for oil to the north indicate that (1) the submarine slope and shelf edge trended approximately N 70° E, suggesting that turbidites of the Metralla were derived from the southeast (Weber, 1973); and (2) fine-grained Oligocene sedimentary rocks in subsurface to the northwest beneath the southwestern San Joaquin Valley were deposited in deeper environments than coeval strata in the San Emigdio Mountains, suggesting that source areas were located to the south in the direction of Santiago and San Emigdio Creeks (Tipton, 1971; Tipton and others, 1973, 1974).

The area of early Eocene to early Miocene sedimentation consisted of a relatively narrow marine shelf bounded on the east and southeast by a coastal plain on which fluviatile sediments and volcanic rocks were deposited. The area northwest of the shelf was characterized by a submarine slope and deep-sea floor, where muds and some fine-grained turbidites were deposited.

NORTHERN GABILAN RANGE

The Gabilan Range is separated from the northern Santa Lucia Range by the Salinas Valley, and is bounded on the east by the San Andreas fault (fig. 1). It is underlain mostly by granitic basement rocks, although mafic and ultramafic basement rocks are present locally at Logan Quarry (Ross, 1970, 1972). Lower and middle Tertiary strata are present north of the Vergeles fault (figs. 2, 3), where they rest unconformably on the granitic and mafic basement complex. They consist in ascending order of (1) the marine San Juan Bautista Formation of Kerr and Schenck (1925), Penutian or Ulatisian to early Zemorrian in age, 1,800-5,000+ feet (550-1,525 m) thick, a poorly bedded fine-grained sandstone and siltstone; (2) the marine Pinecate Formation of Kerr and Schenck (1925), Zemorrian in age, 650-1,100+ feet (200-335 m) thick, a massive arkosic sandstone with a few interbeds of pebble and boulder conglomerate; (3) nonmarine red beds of Kerr and Schenck (1925), thought to be Zemorrian and early Saucesian in age on the basis of stratigraphic relationships, 0-1,200 feet (0-365 m) thick, pebble and boulder breccia and conglomerate with some interbedded arkosic sandstone; and (4) an unnamed volcanic unit, thought to be Saucesian in age (dated by Turner, 1968, as 21.6$\pm$0.7 m.y.), 1,000-1,400 feet (305-425 m) thick, dacitic and andesitic flows and agglomerate with interbeds of arkosic sandstone (Kerr and Schenck, 1925; Allen, 1946; Castro, 1967; Waters, 1968; Addicott, 1968; Turner, 1968; Clark and Reitman, 1973).

The lower 600 feet (185 m) of the San Juan Bautista Formation of Kerr and Schenck (1925) consists of foraminiferal siltstone deposited at bathyal depths (Castro, 1967; Waters, 1968). The upper part of the unit, which is sandier, contains mollusks and foraminifers indicative of shallow marine deposition, but may also have been deposited partly in terrestrial conditions (Clark and Reitman, 1973, p. 8). Conglomeratic beds in the Pinecate Formation and red beds of Kerr and Schenck (1925) are inferred to have been deposited along a shoreline or as alluvial fanglomerates (Allen, 1946; Clark and Reitman, 1973).

SAN ANDREAS FAULT OFFSETS

Background

The north- to northeast-trending Eocene to early Miocene paleogeographic elements and depositional facies in the southern San Joaquin basin are truncated by the modern San Andreas fault. The presumed southern continuation of this basin has probably been displaced by right-slip along the San Andreas fault. The north- to northwest-trending Eocene to early Miocene paleogeographic elements and depositional patterns of the northern Santa Lucia area cannot be easily traced northward because of lack of outcrops. The Eocene to lower Miocene sequence in the northern Gabilan Range is truncated by the San Andreas fault to the north and cannot be easily traced southward because of lack of outcrops. Previous reconstructions for the basement rocks and lower and middle Tertiary strata of these areas along the San Andreas fault are summarized below.

Offsets of basement rocks

Ross (1970) concluded that mafic basement rocks in Logan Quarry at the north end of the Gabilan Range (fig. 3) are offset about 200 miles (320 km) from mafic basement rocks near Los Lobos Canyon in the western San Emigdio Mountains (fig. 5). Wentworth (1968), Ross (1970), and Ross and others (1973) suggested that mafic conglomerates of Late Cretaceous age in the Gualala area (fig. 1) are offset 350 miles (565 km) from their postulated source area of mafic basement rocks in the western San Emigdio Mountains.

Offsets of Eocene strata

Hill and Dibblee (1953) and Dibblee (1966) suggested that the Butano Sandstone in the Santa Cruz Mountains (fig. 1) might be offset 225 miles (360 km) from the Tejon Formation in the San Emigdio Mountains. Clarke and Nilsen (1972, 1973) concluded that the Butano Sandstone is offset about 190 miles (305 km) from the Point of Rocks Sandstone in the Temblor Range and suggested that Eocene strata in the northern Gabilan Range are offset the same amount from the Tejon Formation in the western San Emigdio Mountains (fig. 1).

Offsets of Oligocene strata

Hill and Dibblee (1953) and Dibblee (1966) suggested that Oligocene shoreline in the northern Santa Lucia and Gabilan Ranges is offset about 175 miles (280 km) from a shoreline of similar age in the San Emigdio Mountains. Addicott (1968), based on additional data, concluded that the northeast-trending Oligocene shoreline and depositional basin preserved in the northern Santa Lucia and Gabilan Ranges are offset 190-200 miles (305-320 km) from the same shoreline and basin in the San Emigdio Mountains. Addicott also inferred that the Oligocene northern Santa Lucia depositional area originally extended in unbroken fashion across the Salinas Valley and the northern Gabilan Range areas to the San Andreas fault. Allen (1946) and Clark and Reitman (1973), on the other hand, concluded that uplift had taken place during Oligocene time on the south side of the Vergeles fault, resulting in deposition of nonmarine and shallow marine sediments along an east-west trending shoreline in the San Juan Bautista area to the north (fig. 3). The same offset of about 180-200 miles (290-320 km) results from reconstructions based on the northeast-trending shoreline of Addicott (1968) and the east-west-trending shoreline of Allen (1946) and Clark and Reitman (1973).

Offsets of lower Miocene strata

Hill and Dibblee (1953), Bazely (1961), Dibblee (1966), and Addicott (1967, 1968) suggested that marine, nonmarine and volcanic rocks of the northern Gabilan Range and San Emigdio Mountains are offset 175 miles (280 km) along the San Andreas fault. Radiometric dating and detailed petrographic studies by Turner (1968, 1969) indicate that lower Miocene dacitic volcanic rocks (about 22 m.y.) in the northern Gabilan Range are offset about 190 miles (305 km) from similar rocks in the western San Emigdio Mountains.

Summary

Previous workers have suggested that basement rocks and Eocene to lower Miocene strata in the northern Gabilan Range are offset right-laterally about 190 miles (305 km) from similar rocks in the San Emigdio Mountains. From Eocene to early Miocene time the northern Santa Lucia and northern Gabilan Range depositional areas formed a single interconnected depositional area that connected northward with the southern San Joaquin basin to form a continuous, southward-narrowing depositional area. The depositional area within the Salinian block is underlain by granitic crust whereas in the western part of the southern San Joaquin basin it is underlain by Mesozoic oceanic crust. This reconstruction strengthens the conclusion that Eocene to lower Miocene strata are offset by the same amount in central California.

PALEOGEOGRAPHIC RECONSTRUCTIONS

Eocene paleogeography

A major eastward transgression of the sea commenced during early Eocene time, resulting in deposition of the Uvas Conglomerate Member and Junipero Sandstone, both discontinuous basal conglomerate and sandstone units that are younger toward the east. As the shoreline migrated east-, southeast-, and possibly southward in middle Eocene time, shale and mudstone of the Liveoak Shale Member and the Lucia Mudstone of Dickinson (1965) were deposited offshore in deeper water to the west and northwest.

The transgression reached its maximum extent during middle or possibly early late Eocene time, and was followed by a major regression in the late Eocene that extended into the Oligocene. During the regression, the shallow to deep marine Metralla Sandstone Member and shallow marine Reed Canyon Siltstone Members were deposited in the San Emigdio Mountains area and the moderately deep submarine fan complex of The Rocks Sandstone of Thorup (1941) was deposited in the northern Santa Lucia depositional area (fig. 7).

The transitional zone between mafic basement rocks to the west and felsic basement rocks to the east in the San Emigdio Mountains formed a west-facing slope in the late Eocene that separated a shallow marine shelf to the east from a deep marine area to the west. Because of this feature, the coarse-grained shallow marine facies of the Metralla

Sandstone Member east of San Emigdio Canyon grades laterally westward in outcrop into a fine-grained, thin-bedded turbidite facies that in turn pinches out into the Liveoak Shale Member at the west end of the San Emigdio Mountains; the Liveoak in this area was deposited at lower bathyal to abyssal depths and is late Eocene in age (fig. 6).

The Reed Canyon Siltstone Member may have been deposited in lagoons behind barrier bars during the regression across the eastern shelf area. No clearly defined late Eocene shelf sequence can be recognized in the northern Santa Lucia Range, although The Rocks Sandstone may possibly have been deposited in shallow marine conditions toward the southeast. The lack of lower Tertiary shelf deposits may be characteristic of sedimentary basins located within the northern continental borderland (Salinian block), and may be due to the postulated extensional pull-apart origin of the basins, which yielded deep, areally restricted basins adjacent to actively uplifting, areally restricted source areas (Nilsen and Clarke, 1975).

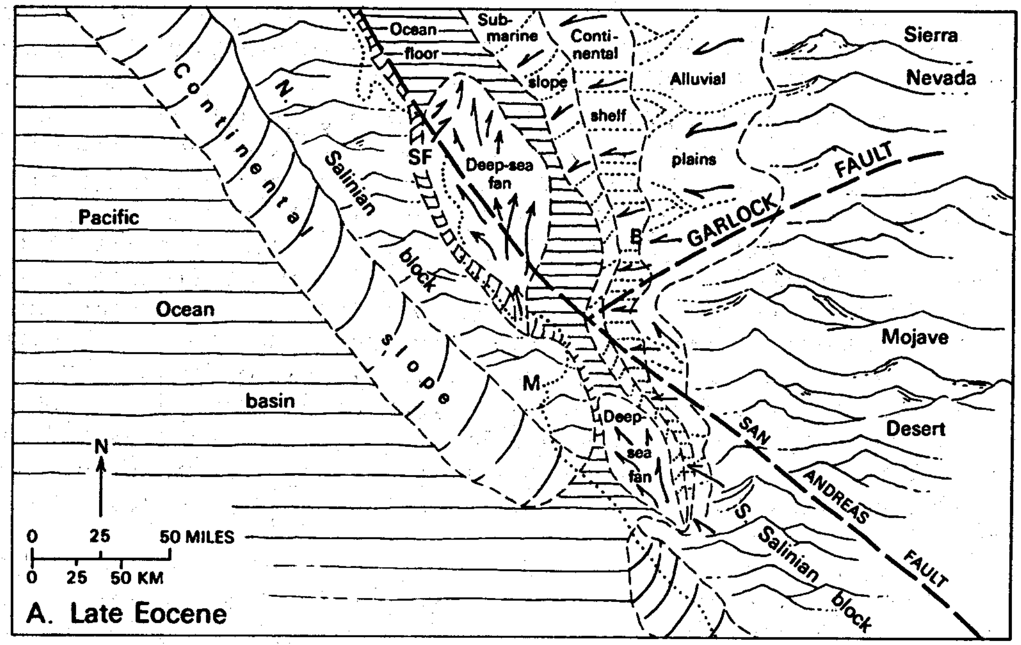
In the northern Gabilan Range, the Eocene sequence rests unconformably on basement rocks and was deposited during the same time interval as the San Emigdio and northern Santa Lucia Range sequences. A basal conglomerate or sandstone unit has not been described from this area, but we suspect that one may be present that is thin or only locally present and would be equivalent to the Uvas Conglomerate Member and the Junipero Sandstone. Siltstone of Ulatisian and Narizian and possibly Penutian age, deposited at bathyal depths, comprises most of this sequence. The sequence is inferred to be coeval with and deposited contiguously with the Liveoak Shale Member in the western San Emigdio Mountains and correlative with and originally continuous with the Lucia Mudstone in the northern Santa Lucia Range.

The inferred regional Eocene paleogeography, based on restoring about 190-200 miles (305-320 km) of right-lateral slip along the San Andreas, is shown in Figure 7A. The Salinian block extended farther north, probably as a series of tectonically active islands that supplied sediment to the Butano-Point of Rocks deep-sea fan in the western San Joaquin basin (Clarke and Nilsen, 1973). However, the main source areas for the Eocene sedimentary rocks of the eastern and southern San Joaquin basin and the northern Gabilan and Santa Lucia Range areas were located to the east and south in the granitic basement rocks of the Sierra Nevada, Mojave Desert, and southern Salinian block areas (fig. 7A).

Oligocene paleogeography

The westward regression begun in late Eocene time continued during Oligocene time in both the southern San Joaquin and northern Santa Lucia areas, with extensive deposition of the nonmarine Tecuya and Berry Formations. The nonmarine deposits prograded westward and northwestward, interfingering with shallow to deep marine deposits of the San Emigdio and Pleito Formations of the San Emigdio Mountains and the Church Creek and lower Vaqueros Formations of the northern Santa Lucia Range.

Marine Oligocene strata of the northern Gabilan Range, which include



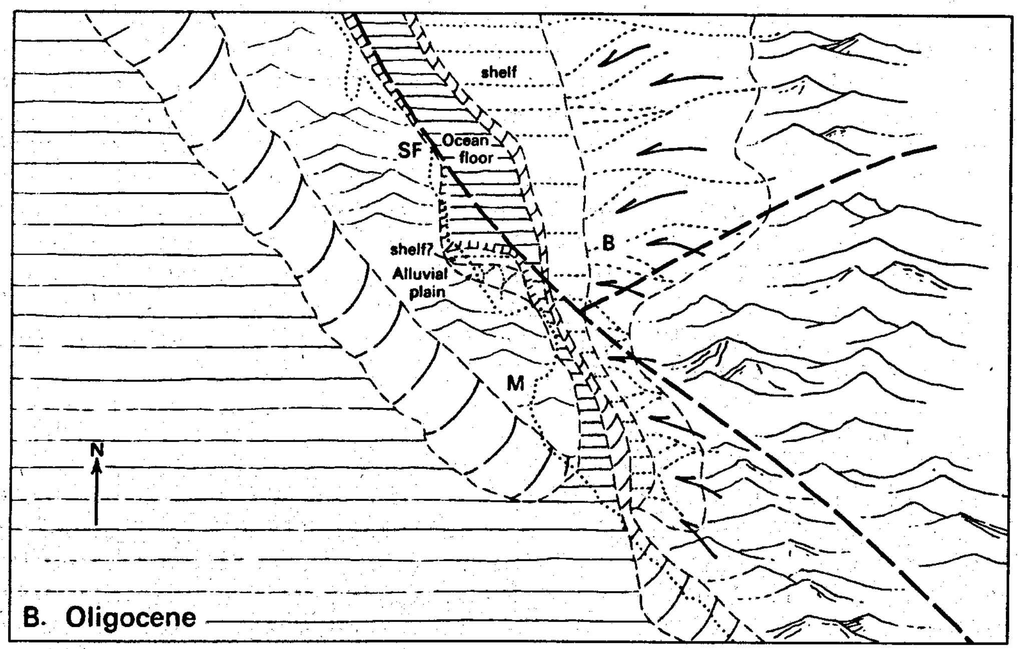


Figure 7. Generalized late Eocene (A) and Oligocene (B) regional paleogeographic maps of central California based on restoration of about 190-200 miles (305-320 km) of post-Eocene right-lateral offset along the San Andreas fault. Arrows indicate directions of sediment transport. In Map A, the larger deep-sea fan in the northern part comprises the Butano Sandstone of the Santa Cruz Mountains and the Point of Rocks Sandstone of the Temblor Ranges, as restored by Clarke and Nilsen (1973); the smaller deep-sea fan to the south represents The Rocks Sandstone. Modern coastline (dotted line), trace of modern Garlock and San Andreas faults, and San Francisco (SF), Monterey (M), and Bakersfield (B) shown for reference.

the uppermost part of the San Juan Bautista Formation and Pinecate Formation, were deposited at shallow marine depths, and document a gradual shoaling of this depositional area from early Eocene to Oligocene time. In apparently late Zemorrian and Saucesian time, nonmarine sediments (red beds of Kerr and Schenck, 1925) were deposited over the shallow marine deposits of earlier Oligocene age. Little data have been published regarding the source area and direction of transport of these red beds, although Allen (1946) and Clark and Reitman (1973) inferred derivation from the south, across the Vergeles fault (fig. 3). Deposits at the base of these red beds appear to be younger than those at the bases of the nonmarine Berry and Tecuya Formations, which may possibly be as old as late Eocene. Based on the regional paleogeographic framework, we suggest that the red beds represent the northwesternmost extent of nonmarine deposition during the maximum late Oligocene regression, that they are related to the Tecuya and Berry Formations, and that they were derived from source areas to the east and southeast, as suggested in part by Addicott (1968).

The regional Oligocene paleogeography is shown in Figure 7B. Source areas were primarily the Sierra Nevada, Mojave Desert, and southern Salinian block areas. To the north, in the area of the Santa Cruz Mountains, uplift of a large island area apparently resulted in local deposition of nonmarine sediments and widespread deposition of shallow- to deep-marine sandstones (Cummings and others, 1962; Clark, 1968; Clark and Reitman, 1973). We conclude that the southern San Joaquin basin during the Oligocene continued to extend in unbroken fashion across the northern Gabilan Range southward into the northern Santa Lucia Range area; however, nonmarine and nearshore sedimentation predominated during the Oligocene in the southward-narrowing trough, as opposed to shelf and deep-marine sedimentation during the Eocene. The pattern of broad regional uplift, regression, and widespread deposition of nonmarine sediments toward the close of Eocene time and during the Oligocene is characteristic of many parts of California.

Early Miocene paleogeography

Major paleogeographic changes took place during early Miocene time. Extensive coeval volcanic rocks that Turner (1968) determined to be identical and offset about 190 miles (305 km) were extruded in the San Emigdio, Tehachapi, and northern Gabilan Range areas. In the San Emigdio and Tehachapi Mountains, the nonmarine Tecuya Formation interfingers westward with extensive shallow marine deposits of the Temblor Formation and in the northern Gabilan Range, shallow marine arkosic sandstone is interbedded with volcanic rocks (Castro, 1967). Volcanic rocks are not abundant in the lower Miocene sequence of the northern Santa Lucia Range, which consists primarily of shallow marine deposits of the Vaqueros Formation and possibly some nonmarine deposits, if the upper beds of the Berry Formation are as young as early Miocene.

Lower Miocene shelf, slope, and abyssal deposits have not been carefully delineated in any of the three study areas, so that the regional paleogeography is not well-defined. It is complicated by the angular unconformity at the base of the Temblor Formation near Brush

Mountain in the western San Emigdio Mountains and local unconformities at the base of the Berry and Vaqueros Formations in the northern Santa Lucia area (figs. 4, 5, 6). Uplift near Brush Mountain may have shed sediments westward into the area of the northern Gabilan Range, and could possibly be related to the initiation of the modern San Andreas fault and right-lateral slip along it. Other source areas to the east, southeast, and possibly south remained the same as those that were present during Eocene and Oligocene time. During this interval of renewed tectonic activity that probably extended into middle Miocene time, Eocene, Oligocene and lower Miocene strata may have been stripped from much of the central and northern Gabilan Range and possibly parts of the Santa Lucia Range. Older sedimentary rocks and granitic basement rocks in the Gabilan Range may have been an important source area for the Temblor Formation and younger strata in the western San Emigdio Mountains, as suggested in part by Nilsen, Dibblee, and Addicott (1973, p. H20).

SUMMARY AND CONCLUSIONS

We conclude that the stratigraphic, sedimentologic, and paleontologic characteristics of Eocene to lower Miocene rocks in the northern Santa Lucia Range, northern Gabilan Range, and San Emigdio Mountains and western Techachapi Mountains are compatible with 190-200 miles (305-320 km) of right-lateral offset along the San Andreas fault. However, little or no post-Eocene right-lateral offset is apparent between the northern Santa Lucia and northern Gabilan Ranges based on our comparison of these strata.

We suggest that the Eocene to early Miocene southern San Joaquin basin originally extended southward in narrowing fashion across the trace of the modern San Andreas fault into the areas of the present northern Gabilan Range and northern Santa Lucia Range. If so, this elongate basin or trough extended across the central part of the Salinian block, separating it into a southern part apparently attached to the western Mojave Desert area and a northern continental borderland part consisting probably of islands. The continuous San Joaquin-northern Gabilan-northern Santa Lucia depositional area was later displaced and offset by post-early Miocene displacements along the San Andreas fault.

The suggested offsets support a general history of movement of the San Andreas fault derived from other studies that consists of (1) 135-260 miles (220-420 km) of pre-late Paleocene right-lateral offset along a proto-San Andreas fault that may possibly have been located in the present Salinas Valley, (2) no major right-lateral displacements from late Paleocene to early Miocene time, and (3) 190-200 miles (305-320 km) of right-lateral offset from post-early Miocene time to the present along the modern San Andreas fault (fig. 8). A major angular unconformity and outcrops of volcanic rocks near Brush Mountain in the western San Emigdio Mountains and thick sedimentary and volcanic rocks in the northern Gabilan Range may be related to the initial movements along and creation of the modern San Andreas fault during early or middle Miocene time.

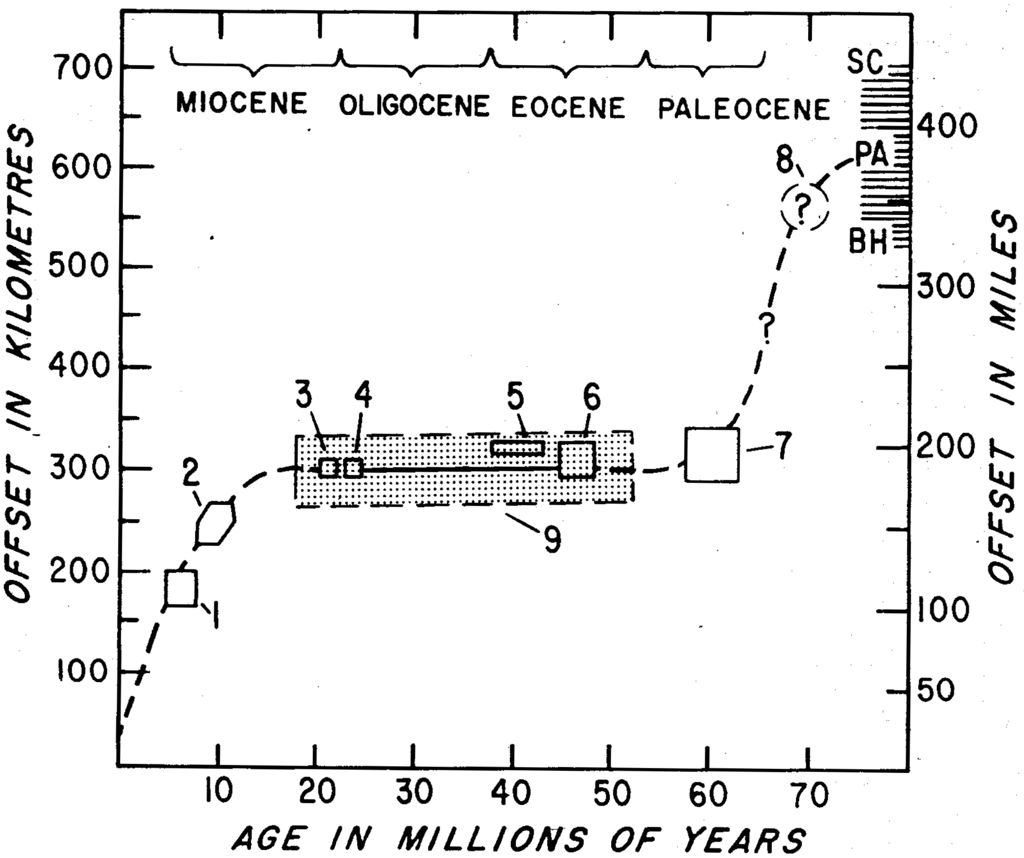


Figure 8. Inferred history of offset along the San Andreas fault in central and northern California. Data points include (1) Dickinson and others (1972); (2) Huffman (1972); (3) Turner and others (1970); (4) Turner and others (1970); (5) Addicott (1968); (6) Clarke and Nilsen (1973); (7) Nilsen and others (1974); (8) Ross and others (1973); and (9) this paper (cross-hatched area). Size of box indicates inferred general accuracy of tie. Locations of Bodega Head (BH), Point Arena (PA), and Shelter Cove (SC) shown on figure 1. Age estimates of time boundaries from Berggren (1972).

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PALEOGENE PALEOSOLS AND PALEOCLIMATES, SOUTHWESTERN CALIFORNIA

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ABSTRACT

The Eocene rocks of the San Diego area (La Jolla and Poway Groups) rest unconformably on Upper Cretaceous sedimentary rocks (Rosario Group), on mid-Cretaceous granitic rocks and on pre-batholithic metavolcanic rocks. The gently rolling terrane beneath the unconformity has been severely weathered to a lateritic paleosol.

The laterite developed on the metavolcanic rocks is typically hematite-enriched and brick red. Paleosol exposures are fairly common but typically they are thin erosional remnants. The paleosol developed on granodiorite tends to be grayish-white. South of the U.S. border are outcrops where the remaining A horizon is over 40 feet thick. The A horizon here is two-thirds kaolinite and one-third residual quartz grains. Age of the paleosol is possibly latest Cretaceous but it probably ranges well into the Paleocene. The formation of the pre-Eocene lateritic paleosol required a humid tropical climate probably accompanied by lush vegetation, an environment which we interpret to be similar to that dominant within 20 degrees of the modern equator. Annual rainfall probably exceeded 50 inches.

In marked contrast some of the nonmarine Middle to Upper Eocene rock units (Friars Formation and Mission Valley Formation) contain widespread aggradational paleosols characterized by well-developed caliches. The presence of these caliches in the Middle to Upper Eocene rock units implies a marked change to a semi-arid climate and accompanying savanna- or steppe-type of vegetational cover. Annual rainfall probably was less than 25 inches and seasonal to give alternate periods of precipitation and evaporative pumping necessary for soluble salts (chiefly calcite) to become concentrated in the upper portion of the soil profile.

Neither of the Paleogene paleosols is compatible with the modern climate which is temperate, arid, and with an annual rainfall of about 10 inches. Some possible explanations for the markedly different climates indicated by the paleosols include movement of the continent (or part of the continent) with respect to the earth's climatic belts or possibly markedly different sizes of climatic belts in the Paleogene Period.

INTRODUCTION

The nature of the residual soil formed by weathering is dependent on the parent rock, the topography, the duration of exposure, and, most importantly, the climate or conditions of weathering. Given enough time to produce a mature soil profile, the mineralogy, thickness, and degree of development of the various soil horizons are in harmony with the prevailing climatic conditions.

Soils, in large part, provide the sediment, both chemical and detrital, which ultimately are transported and deposited to make up the stratigraphic record. In some places, soil profiles themselves are preserved in the stratigraphic record, and are then referred to as paleosols. Since the ancient soils developed in response to the climatic conditions prevailing at that time, the study and classification of paleosols, and comparisons with the distribution of modern analogs and the climates under which they develop, can yield useful information regarding climates of the past.

In the Paleogene succession of San Diego and vicinity, two distinctively different paleosols form a part of the stratigraphic record. It is the purpose of this paper to briefly outline the distribution and character of these paleosols, to compare them with modern soils, and to indicate their implications regarding Paleogene climates of southwestern California.

PALEOGENE RECORD

The Paleogene stratal record is sparse in southwestern California and adjacent Baja California. There are no Paleocene or Oligocent rocks and only roughly 1,000 feet of Middle and Upper Eocene rocks. The latter rest unconformably on a pre-Eocene terrane consisting of pre-batholithic Upper Jurassic metavolcanic rocks, Cretaceous batholithic rocks, and a narrow belt of post-batholithic Upper Cretaceous sedimentary rocks. The pre-Eocene terrane had a topographic relief in excess of 2,000 feet and was severely weathered prior to deposition of the Eocene rocks (Peterson and Nordstrom, 1970; Peterson, 1971; Peterson and Abbott, 1973; Flynn, 1970). The severely weathered erosion surface and its lateritic paleosols are of probable Late Cretaceous, Paleocene, and Early Eocene age and are the first of the paleosols to be discussed in this paper.

The Eocene sedimentary succession is subdivided into two markedly contrasting groups of rocks (Kennedy and Moore, 1971). The lower and westernmost rock unit is the La Jolla Group, a succession dominated by an assemblage of marine, barrier bar, lagoonal, and clastic rock units. The uppermost formation in the La Jolla Group, the Friars Formation, is the only rock unit which is predominantly of nonmarine origin. The upper and easternmost rock unit is the Poway Group which is predominantly of fluvial and deltaic origin. In stratigraphic order, it consists of the Stadium Conglomerate, the Mission Valley Formation, and the Pomerado Conglomerate (Kennedy and Moore, 1971; Peterson and Kennedy, 1974). Within the nonmarine portions of the Friars and Mission Valley Formations are a number of thin, scattered, but fairly widespread caliche horizons (Hanna, 1926; Pierce, 1974). These constitute the second type of paleosol in the Paleogene stratal record.

PRE-EOCENE PALEOSOL

The pre-Eocene paleosol is well developed and widely distributed in southwestern California and adjacent Baja California. It is highly variable in thickness and character from place to place, but lies beneath the Eocene succession and involves all pre-Eocene rock units to varying degrees. One of the difficulties in studying the pre-Eocene paleosol is that it underwent erosion prior to and during deposition of the Eocene rocks. Thus the profile is only partially preserved and to varying degrees. In rare areas nearly the entire profile is preserved, whereas in most areas only the lower or C horizon is preserved. For paleoclimatic interpretations, of course, the A and B portions of the profile are the most critical, and the first to disappear under conditions of erosion.

The pre-batholithic rocks consist of a complex assemblage of andesitic volcanic, volcaniclastic and related sedimentary rocks along with numerous small plutons associated with this assemblage. In several places, particularly in cut slopes in some of the newer residential districts of San Diego and vicinity, the upper part of the pre-Eocene paleosol is well developed on the volcanic rocks and is well exposed, at least for the moment. Good exposures of the paleosol crop out in the Rancho Penasquitos development immediately south of Black Mountain. Another exposure is along the western to southwestern flank of Del Cerro near San Diego State University. Other localities are abundant, but the exposures are not good. Typically the clay-rich paleosol is overlain by the very poorly sorted clastics and clay-rich strata of the Friars Formation and the contact between the two is hard to pick without almost perfect exposure.

At localities where the paleosol is well developed on the volcanic rocks, exposures are typically brick red. The paleosol is dominated by residual hematite, clay minerals, and small chips of relatively unweathered parent rock. This residual cap grades downward into the same fine ferruginous material containing spheroidal boulders of the relatively unweathered parent volcanic rock, which is apparently well down within the C horizon.

In other places, the paleosol is developed on the granitic batholithic rocks. Here it typically consists of grus or saprolite altered to varying degrees depending on which part of the paleosol is preserved and exposed. If fully preserved, the top portion of the paleosol consists of a mixture of quartz, clay minerals, iron oxides, and little else. The paleosol is difficult to distinguish from the basal beds of the overlying Friars Formation which consists of detritus derived from the paleosol (Peterson, 1971). Good exposures of the paleosol occur north of San Diego around the communities of Rancho Bernardo and Poway. Additional exposures occur in El Cajon Valley near Santee and Lakeside, and along the eastern edge of Fletcher Hills.

The best exposure of the pre-Eocene paleosol located to date occurs south of Tijuana near Rancho Delicias. Here the paleosol is developed on granodiorite. The total profile exceeds 100 feet in thickness. The lower portion grades from unaltered granodiorite to spheroidal boulders of granodiorite separated by grus to progressively more weathered grus horizons in the C profile. The A profile at this locality is roughly 50 feet thick and consists entirely of kaolinite, quartz, and minor amounts of iron oxide. It is severely depleted in all soluble compounds (Abbott et al., 1973). There is no evidence of a zone of accumulation. It is overlain by Middle Eocene marine sedimentary rocks (Flynn, 1970).

The abundance of kaolinite in the A horizon, the total thickness of the profile, and the absence of a B horizon all indicate that the pre-Eocene paleosol is a laterite or very close to being a laterite. Although hydroxides of iron and aluminum, characteristic of many laterites, have not been detected, all the other characteristics fit.

LATE EOCENE CALICHE

Two of the Middle to Late Eocene nonmarine rock units, the Friars and Mission Valley Formations, are characterized by containing fairly widespread caliches. A caliche, as we are using the term here, is a secondary accumulation chiefly composed of calcium carbonate and thought to have formed in the B horizon of a pedocal soil profile. It is typically whitish and highly friable with calcium carbonate making up about three quarters of the caliche.

Caliches have been noted in the Late Eocene rock units in the past (Hanna, 1926; Emery, 1945), however, some question has been raised regarding their age of formation. Some of them appear to be a modern development as they conform with the topography (Emery, 1945; Pierce, 1974), however, an additional explanation is required regarding this observation. The Late Eocene rock units are characterized by an abundance of expansive montmorillonitic clays. With wetting and drying these clays provide an ideal mechanism for downslope transportation or creep. Thus, for example, in many places the Stadium or Pomerado Conglomerate crops out at the crest of a hill, drapes over the edge, and covers the slopes of the hill all the way to the bottom with a veneer of conglomeratic debris. In some places this veneer exceeds 10 feet thick and without exposures in artificial cuts can be very misleading. The same phenomena works with the caliches. Where they crop out, they likewise drape down the sides of the hill and conform to the modern topography. However, this is not where the caliches formed, but rather they owe their position to downslope mass movement. They are modern in a sense, but are derived from Eocene formations. For the purpose of our Paleogene paleoclimatic interpretation we are ignoring this type of caliche.

Caliches are apparently not forming in the vicinity of San Diego at the present time. Of all the sedimentary rock units in San Diego, only the nonmarine Eocene formations contain caliches in any abundance. If caliche formation were a modern phenomenon, most rock units presumably would be affected.

An additional line of evidence indicates that the caliches are of Late Eocene age. Where deep artificial cuts have been produced in the Fraiars and especially the Mission Valley Formation, the caliches can be observed to follow the Eocene stratification. Good examples of this type of caliche can be found in the Mission Valley Formation in the Rancho Penasquitos development north of San Diego, and in Tierrasanta, College Heights, San Carlos, and Fletcher Hills in San Diego (Pierce, 1974).

Several different types of caliche occur within the Mission Valley Formation. One type is typically white and friable, but locally may be well indurated. It is observed in artificial cuts where it follows the stratification of the formation. Typically this type of caliche ranges in thickness from a few inches to a foot or more and generally it occurs as multiple layers following one another. This type of caliche is particularly characteristic of the Rancho Penasquitos and Tierrasanta localities.

A second type of caliche is nodular. The nodules range in size from a fraction of an inch to several inches long and are generally well indurated. The caliche nodules are usually white but locally vary to red, brown, or green depending on the color of the surrounding rocks. In some places the nodular caliche occurs along with the bedded friable caliche.

A third type of calcium carbonate accumulation is found in some of the sandier portions of the Mission Valley Formation. It ranges from caliche to a calcite-cemented sandstone in which clastic materials make up about 50 percent of the sample.

The caliches in the Friars and Mission Valley Formations are interpreted as having formed in B horizons in a series of soil profiles developed during deposition of those Late Eocene formations. The profiles of the pre-Eocene paleosols developed on an erosion surface, but the Late Eocene caliches developed during aggradation. After the sand and finer clastic materials were deposited, a soil profile was formed or partially formed. The profile development was interrupted by further deposition and another profile was developed on the later deposits. The end result is multiple layers of caliche developed to varying degrees and running parallel to the stratification of the host formation.

PALEOCLIMATIC IMPLICATIONS

The development of the pre-Eocene lateritic paleosol implies that a warm, humid, tropical climate existed during its formation. Modern laterites are predominantly located within 20 degrees of the equator in the western hemisphere, within 15 degrees of the equator in Africa, and mostly within 30 degrees of the equator in the Asia-Indonesia-Australia region (McNeil, 1964). We interpret the Late Cretaceous-Paleocene-Early Eocene paleoclimate to be similar to that of the modern equatorial belt. Rainfall probably exceeded 50 inches per year and the average annual temperature was probably in the vicinity of 20-25° centigrade (Maignien, 1966). A lush rainforest type of vegetation probably predominated.

The humid tropical paleoclimate indicated by the lateritic paleosol differs markedly from the present San Diego climate. At present the climate is mild, temperate, and with about 10 inches of rainfall per year. The vegetation is characterized by grass and sparse chaparral. A lateritic soil profile could not form under the present climatic conditions. Between the Early Eocene and the present, the climate must have undergone a dramatic change.

The reasons for the climatic change are problematical. One might immediately speculate that if a humid tropical climate prevailed, then perhaps the San Diego area might have been in the humid tropical belt at that time. The simple reconstruction of removing the Gulf of California opening is sufficient to put San Diego 150-175 miles to the south - closer to the area of modern laterite formation, but not near enough. Furthermore, paleomagnetic latitudes indicate that the San Diego area has not changed latitudes significantly and, if anything, was farther north (Teissere and Beck, 1973).

A second possibility is that the present climatic belts were not characteristic of conditions in the Eocene. Perhaps, for example, the equatorial humid tropical climatic belt was greatly expanded to the point where San Diego and vicinity were within it. An additional possibility includes a worldwide climate of considerably warmer and more humid conditions due to a difference in the position of the continents and resulting differences in early Tertiary oceanic currents (Frakes and Kemp, 1972). We cannot say what the reasons are from evidence in the San Diego area; it is clear, however, that a humid tropical climate quite unlike that of today prevailed in Late Cretaceous and Early Paleogene time.

Assuming that the caliches present in the Late Eocene rock units are indeed Late Eocene in age, then they imply a climate different than that prevalent in the earlier Paleogene record. Caliches form in areas having at least semi-arid climates. Water from rainfall soaks into the ground but not to the water table. Evaporation at the surface draws the water back to the surface, but the soluble salts are precipitated in the B horizon. The extent of caliche development might depend upon topography, soil permeability, amount of time, and so forth, but it probably would not form in climates where the annual rainfall exceeded 25 inches (Steel, 1974), and it would seem a necessity that evaporation exceeded precipitation.

We thus interpret the Late Eocenepaleoclimate as semi-arid with an annual rainfall of less than 25 inches. In this climate the vegetational cover would probably be considerably less than that indicated by the earlier paleosol. We expect that the vegetation would be more like the modern savanna or steppe regions with grass or other sparse vegetation and scattered drought resistant trees and shrubs predominating. Rainfull would probably be markedly seasonal. Although we visualize the Late Eocene climate to be semi-arid, we do not interpret it to be as arid as the present climate. Thus it might in part indicate at least a portion of the transition from the humid tropical climate of the earlier Paleogene to the arid climate of the present.

A major change in Early Tertiary climates was likewise noted by Frakes and Kemp (1972), who deduced climatic conditions from assumed positions of continents and resulting oceanic circulation patterns in the Eocene and Oligocene. It is interesting to note that they called for a change from widespread humid tropical conditions more characteristic of the Eocene to cooler and drier conditions in the Oligocene. Our local observations likewise suggest such a change except indicate that the change took place during Late Eocene time.

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FORAMINIFERA AND BIOSTRATIGRAPHY OF THE ALSEA FORMATION OF WESTERN OREGON

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ABSTRACT

The Alsea Formation, of tuffaceous siltstone and sandstone, ranges in thickness from 50 to 1100 meters and forms an arcuate outcrop pattern on the central Oregon coast. Parts of both the Refugian Stage of Schenck and Kleinpell (1936) and the Zemorrian Stage of Kleinpell (1938) are represented in the formation. Although the boundary between these stages is gradational, it is fairly well defined in the type section at Alsea Bay. A limited number of foraminiferal species suggest that a lower part of the Refugian Stage may be represented in the lower part of the Alsea Formation. Upper Zemorrian Foraminifera occur in the upper part of the Alsea Formation, as well as in the overlying Yaquina Formation. Based on the biostratigraphic framework of Kleinpell and Weaver (1963), the Alsea Formation falls entirely within the Pacific coast Oligocene, with the possible exception that the lowest part of the formation may be within the uppermost part of the Eocene.

Foraminifera of the Alsea Formation suggest a particularly good correlation with the Cassidulina galvinensis and Pseudoglandulina inflata zones of the Lincoln Creek Formation of southwest Washington, the entire known part of the type Blakeley Formation of the Puget Sound area, and the middle and upper parts of the Twin Rivers Formation of the northern Olympic Peninsula, Washington.

Outer shelf to, occasionally, upper slope depositional environments are inferred by the Foraminifera of the Refugian part of the Alsea Formation. Relatively shallow conditions, possibly inner sublittoral depths, are suggested for a short period during lowermost Zemorrian deposition. Shelf conditions continued through the remaining part of the Zemorrian, at times probably reaching outer sublittoral depths. Shoaling conditions are suggested locally in the uppermost part of the Alsea Formation, particularly in the Yaquina River area where littoral depths probably prevailed throughout the deposition of much of the overlying Yaquina Formation.

INTRODUCTION

The recently named Alsea Formation (Snavely and others, 1975) forms the lower part of a marine Oligocene sedimentary sequence that crops out in a westward-dipping arcuate outcrop belt on the central Oregon coast (fig. 1). The type section has been designated as exposures along both the north and south sides of Alsea Bay. A reference section has also been designated as outcrops and roadcuts along a part of the north side of the Yaquina River. Although the formation is thinner in the latter area, contact relations both at the top and bottom of the formation are best seen in the Yaquina River section.

The tuffaceous siltstone and sandstone now designated as the Alsea Formation are an upper part of the Toledo Formation of Harrison and Eaton of 1920. In several recent reports and geologic maps by Snavely and others (1969), Snavely and others (1972 a,b), and MacLeod and Snavely (1973), tuffaceous siltstone and sandstone of early and middle Oligocene age have been mapped for more than 65 kilometers along the west side of the central Oregon Coast Range and informally referred to as "siltstone of Alsea." These strata are now formally regarded by the U.S. Geological Survey as part of the Alsea Formation.

In the Yaquina River section and throughout most of its area of outcrop, the massive- to thick-bedded tuffaceous siltstone and sandstone of the Alsea Formation conformably overlie thin-bedded siltstone of the Nestucca Formation of late Eocene age. Although the contact is usually gradational within a few meters, in places it is sharply defined. The Alsea Formation is overlain conformably by a predominantly sandstone sequence, the Yaquina Formation of late Oligocene and early Miocene age.

The Alsea Formation ranges from 50 to 1100 meters in thickness and shows an inverse thickness relation to the overlying Yaquina Formation (fig. 1)—a result from lateral gradation of the coarse clastic deltaic sedimentary rocks of the lower part of the Yaquina Formation with deeper water siltstone of the Alsea Formation.

The Alsea Formation typically consists of massive- to medium-bedded tuffaceous siltstone and very fine-grain sandstone. Calcareous concretions and nodules occur in many outcrops. Mollusks are well preserved in parts of the formation and Foraminifera are particularly abundant and diverse.

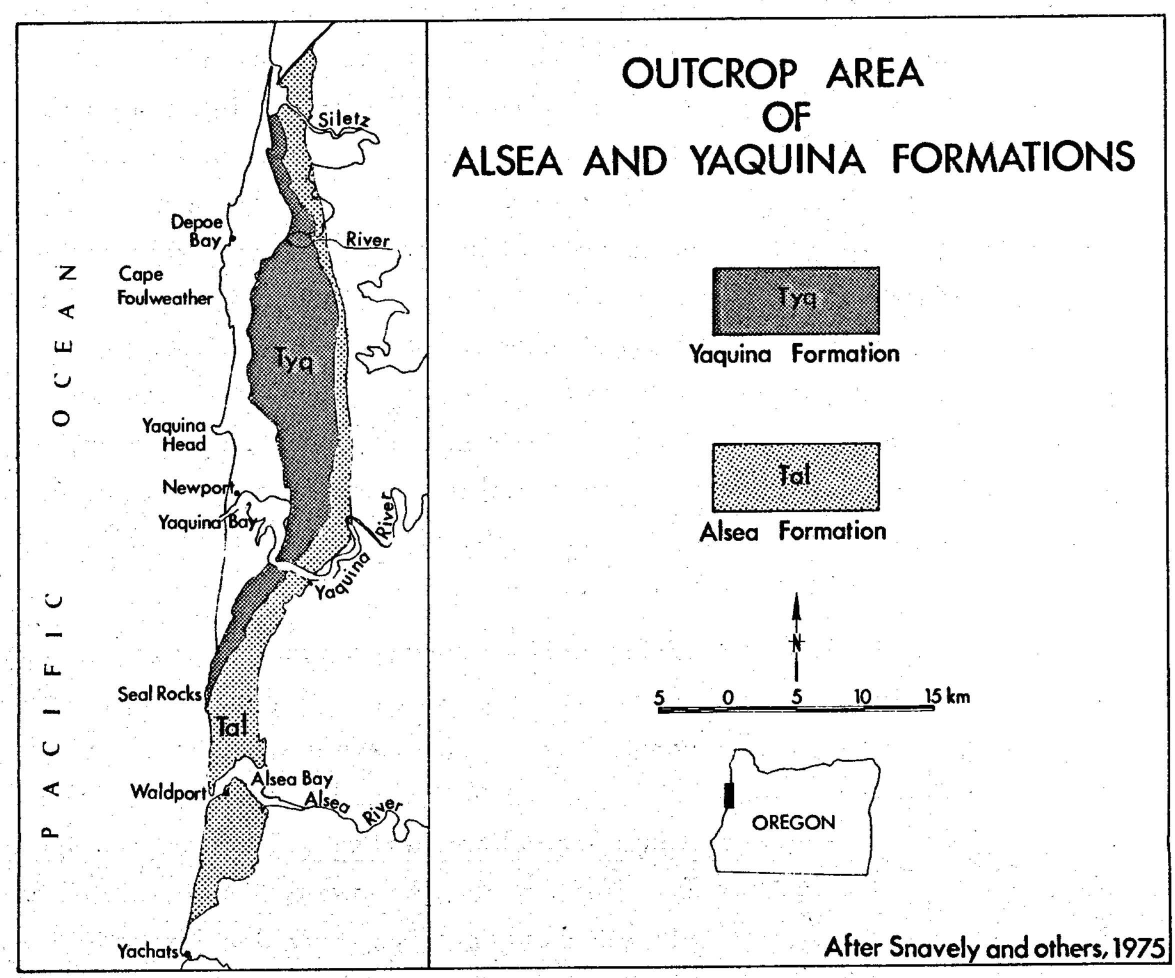
OUTCROP AREA
OF
ALSEA AND YAQUINA FORMATIONS
Tyq
Yaquina Formation
Tal
Alsea Formation
N
5 0 5 10 15 km
OREGON
After Snavely and others, 1975
P A C I F I C O C E A N
Siletz
River
Depoe Bay
Cape Foulweather
Tyq
Yaquina Head
Newport
Yaquina Bay
Yaquina River
Seal Rocks
Tal
Waldport
Alsea Bay
Alsea River
Yachats

FIGURE 1

BIOSTRATIGRAPHY

Evidence for the position of the Alsea Formation in the Pacific coast biostratigraphic framework is corroborated by both the Foraminifera and Mollusca. Foraminifera from the formation are referable to both the Refugian Stage of Schenck and Kleinpell of 1936, and the Zemorrian Stage of Kleinpell, 1938. Although nowhere is the boundary between the Refugian and Zemorrian parts of the sequence known to be a precise horizon, it can be most accurately located in the section at Alsea Bay (fig. 2). There, it is placed within an unexposed part of the section that has been calculated to represent about 25 meters of thickness. This concealed interval lies some 25 meters stratigraphically below a 20-meter-thick concretionary sandstone bed that is exposed some 80 meters below the top of the section on the north side of the Bay. Of the many typical Refugian species that dominate the lower part of the formation, those listed on the lower part of figure 2 make their highest occurrence at or immediately below this covered interval. Furthermore, of the typical Zemorrian forms that constitute the fauna of the upper part of the formation, those listed on the upper part of figure 2 make their lowest occurrence at or just above this interval. Although some characteristic Refugian forms do occur above and some Zemorrian forms below, the most noticeable break between typical Refugian and Zemorrian assemblages occurs at this interval.

Neither the base of the Refugian Stage nor the top of the Zemorrian Stage are represented in the Alsea Formation in either the Alsea Bay section or the Yaquina River section. However, the formation may extend down into the lower part of the Refugian Stage because a few species commonly known in that part of the stage, for example, Uvigerina cocoaensis, and Vaginulinopsis saundersi, do occur in the lower part of the formation at Alsea Bay. Furthermore, the lower 400 meters of the formation in the Alsea Bay section has yielded only poorly preserved and essentially nondiagnostic assemblages.

The uppermost part of the Zemorrian Stage, as known in the Pacific Northwest, is represented in the superjacent Yaquina Formation. However, the occurrence in the Alsea Formation of such forms as Cassidulinoides californiensis, Bolivina advena, Uvigerinella obesa impolita, and Planulina cushmani suggests that the Alsea Formation may also extend up into an upper part of the Zemorrian Stage.

The generally accepted biostratigraphic framework used by Kleinpell and Weaver, 1963, places the lower part of the Refugian Stage in an uppermost part of the Pacific coast Eocene sequence, whereas the upper part of the Refugian Stage and

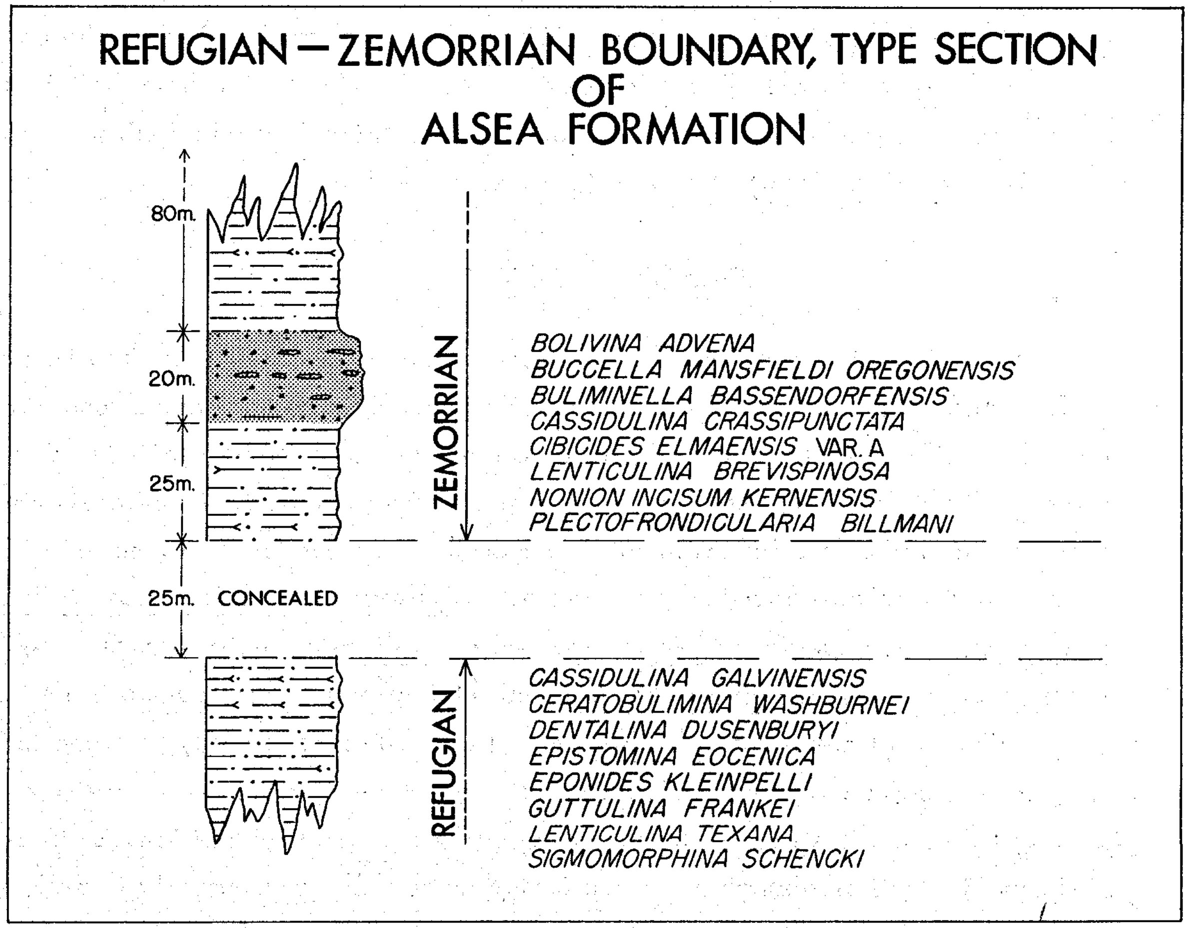
REFUGIAN — ZEMORRIAN BOUNDARY, TYPE SECTION OF ALSEA FORMATION
80m.
20m.
25m.
25m. CONCEALED
ZEMORRIAN
BOLIVINA ADVENA
BUCCELLA MANSFIELDI OREGONENSIS
BULIMINELLA BASSENDORFENSIS
CASSIDULINA CRASSIPUNCTATA
CIBICIDES ELMAENSIS VAR. A
LENTICULINA BREVISPINOSA
NONION INCISUM KERNENSIS
PLECTOFRONDICULARIA BILLMANI
REFUGIAN
CASSIDULINA GALVINENSIS
CERATOBULIMINA WASHBURNEI
DENTALINA DUSENBURYI
EPISTOMINA EOCENICA
EPONIDES KLEINPELLI
GUTTULINA FRANKEI
LENTICULINA TEXANA
SIGMOMORPHINA SCHENCKI

FIGURE 2

all of the Zemorrian Stage is referred to the Oligocene. On this basis, the Alsea Formation is entirely within the Oligocene, with the possible exception that the lowest part of the formation may be in the uppermost part of the Eocene.

Foraminifera of the Alsea Formation compare well and therefore suggest correlation of the formation with formations of other areas of the Pacific Northwest. Faunas displaying the greatest similarity are those from the Lincoln Creek Formation of southwest Washington, particularly those from the Cassidulina galvinensis and Pseudoglandulina inflata zones of Rau, 1966 and 1958. Assemblages from the entire section of the type Blakeley Formation of the Puget Sound area and from the middle and upper part of the Twin Rivers Formation of the northern Olympic Peninsula (Rau, 1964) also compare well with those of the Alsea Formation.

PALEOECOLOGY

Paleoecologic conditions inferred from the Foraminifera of the Alsea Formation are dominantly those of a shelf environment, but vary from perhaps uppermost bathyal to possibly littoral depths with water temperatures varying from cool to cold, particularly for the shallow depths suggested in certain parts of the formation. Moderately deep water is suggested by the faunas of the lower or Refugian part of the formation. The persistent and in places abundant occurrences of Epistomina eocenica, Cassidulina galvinensis, various species of Lenticulina, varied Polymorphids, a species of Alabamina, Uvigerina cocoaensis, Cibicides elmaensis and Plectofrondicularia packardi are among those significant elements that together suggest outer shelf to possibly, at times at least, upper slope environments of deposition. The characteristically robust size of the Foraminifera in this part of the formation suggests optimum conditions for their development where an abundance of nutrients was available. Unusually large Foraminifera are typical of many of the assemblages of the Refugian Stage in the Pacific Northwest from west-central Oregon to at least as far north as southern Vancouver Island, and suggest that a similar shelf environment extended throughout these areas during the Refugian time.

Shelf conditions probably continued throughout much of the Zemorrian deposition. Evidence of a short period of particularly shallow conditions, possibly inner sublittoral depths, is suggested in deposits of the lower Zemorrian. There, some of the deeper water forms that were common in the lower part of the formation are absent and a large Elphidum similar to E. californicum appears common, along with a diversity of

Lenticulina and other Lagenids. However the occurrences together throughout most of the Zemorrian part of the section of such forms as Cassidulina crassipunctata, Virgulina bramlettei, Gyroidina orbicularis planata, Bolivina marginata adelaidana, Buliminella bassendorfensis, and Nonion incisum kernensis suggests that shelf conditions continued to prevail, though probably somewhat shallower than during Refugian times, possibly inner sublittoral but occasionally extending down to outer sublittoral depths.

Shoaling probably took place locally during the deposition of the uppermost part of the Alsea Formation, particularly in the Yaquina River area as marked by the first occurrence of Nonionella miocenica, Nonion cf. N. costiferum, Elphidium minutum, and a small species of Bolivina, together with the common occurrence again of an Elphidium similar to E. californicum.

Shoaling conditions persisted throughout the overlying and interfingering Yaquina Formation where littoral and some inner sublittoral depths are inferred by a dominance in the foraminiferal fauna of a large Elphidium, similar to E. cf. californicum, Nonion incisum kernensis, and Buccella mansfieldi oregonensis.

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Upper Cretaceous and Paleocene Sedimentation and Tectonic Implications, Simi Hills, Ventura County, California.

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ABSTRACT

Upper Cretaceous and Paleocene strata in the Simi Hills are separated by a slight disconformity yet were deposited in the following diverse environments: 1) gravel, sand and silt of the Upper Cretaceous "Chico" Formation were deposited from north-northwesterly flowing turbidity currents on a submarine fan complex; 2) cobble, sand, silt and clay of the Paleocene Simi Conglomerate, Las Virgenes Sandstone and "Martinez" Marine Member were successively deposited in a southwesterly flowing alluvial system, in a lagoonal complex, and in a transgressive marine environment.

Comparison of a northwest trending, distinctive, Paleocene pisolitic claystone in the Simi Hills and Santa Ana Mountains suggest approximately 60 kilometers of left-slip on the Malibu Coast-Santa Monica fault system.

Other workers have noted that source area rocks for Upper Cretaceous strata in the Simi Hills are presently not exposed in a southerly direction from these strata. Paleocene geography suggest that the southerly outcrops of the Upper Cretaceous source terrain would have also been displaced approximately 60 kilometers by left-slip on the Malibu Coast-Santa Monica fault system.

INTRODUCTION

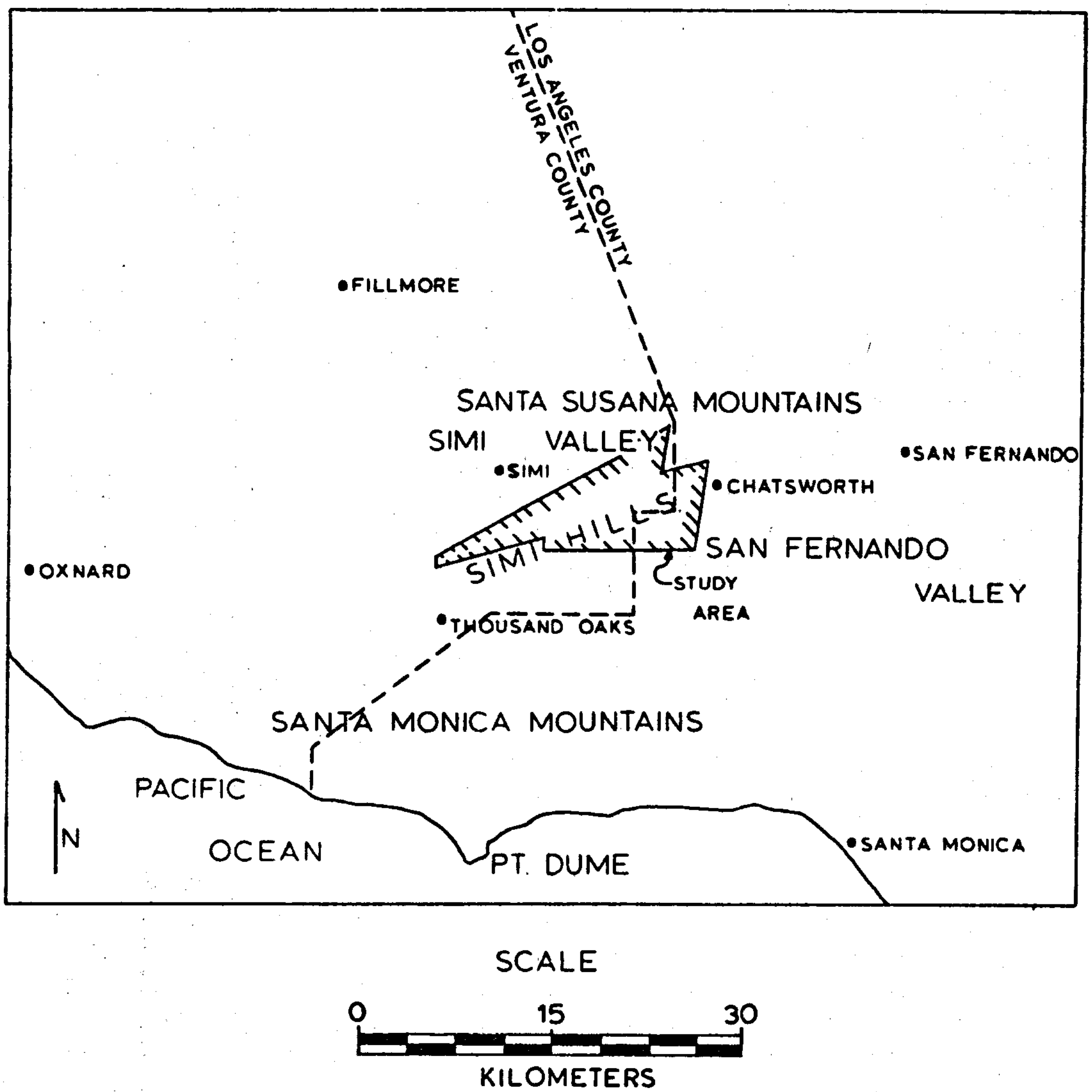
Detailed studies of the Upper Cretaceous "Chico" Formation, in the eastern Simi Hills, and the Paleocene "Martinez" Formation of the western Santa Susana Mountains and the Simi Hills were undertaken in spring of 1971 and fall of 1972 (Fig. 1). Results of these studies have aided in interpretation of sedimentation trends between rock strata that are separated by only a slightly disconformable contact. Further interpretation of Paleocene geography of the Los Angeles region has given a clue as to post-Paleocene movement on several major southern California fault systems. Subsequent left-slip movement of probable source terrain formerly directly south-southeast of Upper Cretaceous strata of the eastern Simi Hills is also suggested by Paleocene geography.

LITHOSTRATIGRAPHY

Upper Cretaceous Strata

Upper Cretaceous strata, as exposed in the eastern portion of the Simi Hills comprise interbedded sandstone, siltstone, and subordinate pebble conglomerate (Fig. 2). These strata have been subdivided into a lower, fossiliferous sandstone and siltstone member; a middle, sparsely fossiliferous, highly resistant sandstone and siltstone member; and an upper, sparsely fossiliferous, weakly resistant sandstone and siltstone

FIGURE 1.
Location map of study area.



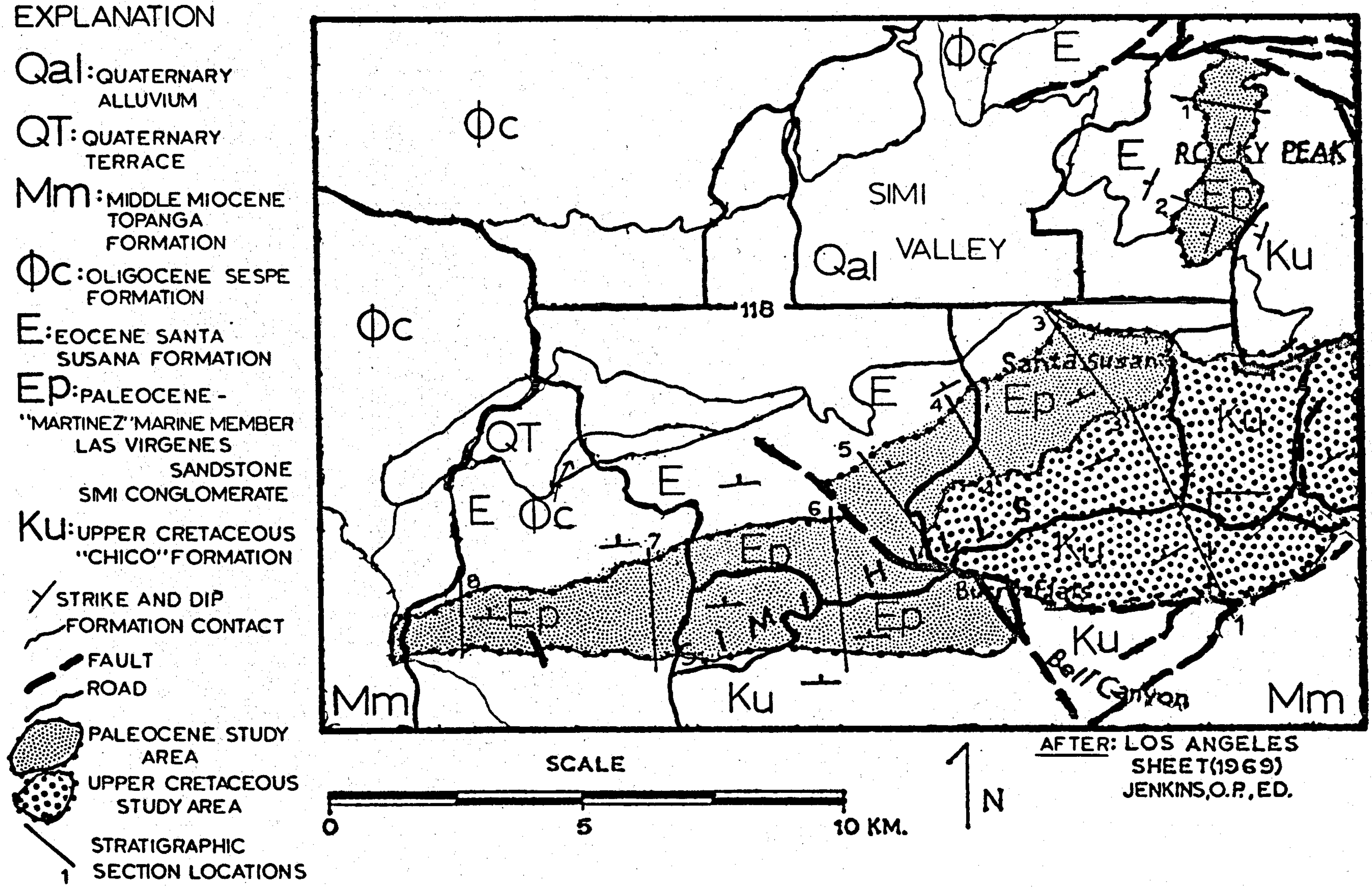


FIGURE 2.
Geologic map of study area.

member (Fig. 3). Age of these strata, based on foraminiferal data, is considered to be late Campanian to early Maastrichtian (?) (Almgren, 1973).

The lower member comprises dark-gray siltstone, medium-grained, moderately sorted, calcareous, light-brown sandstone and fossiliferous, coarse-grained, calcareous, light-brown sandstone. The fossiliferous sandstone form highly resistant "reef-life" beds consisting of <u>in-situ</u> relatively shallow water mollusks (Popenoe, 1973).

The middle member is separated from the lower member by a fault, hence, vertical continuity between the two sequences is not possible. The middle member comprise the following interbedded lithologies: A) thick-bedded, medium-to very coarse-grained, poorly sorted, buff sandstone, with subordinate pebble conglomerate, and thin-bedded light-gray siltstone; and B) thick-bedded, light-gray siltstone with subordinate thin-bedded, fine-to medium-grained, moderately sorted, buff sandstone.

The first of the above mentioned lithologies contain the following features: 1) Complete Bouma (1962) sequences consisting of a Graded Bedding interval 0.5 centimeters to 225.0 centimeters thick, a Lower Parallel-Lamination interval 0.3 centimeters to 59.0 centimeters thick, a Contorted Bedding and Micro-Cross-Lamination (less than 5 centimeters high) interval 0.5 centimeters to 17.0 centimeters thick, an Upper Parallel-Lamination interval 0.3 to 5.0 centimeters thick, and a Pelagic interval (siltstone) 0.8 centimeters to 15.0 centimeters thick. The above thicknesses are quite variable as are the bedding units within the Upper Cretaceous strata. 2) Incomplete Bouma sequences consisting of successive, thick, Graded Bedding and Lower Parallel-Lamination intervals separated by a thin Pelagic interval or successive amalgamated Graded Bedding and Lower Parallel-Lamination intervals. 3) Channel-shaped concentrations of pebble conglomerate interspersed within the thick Graded Bedding intervals. 4) Abraded thick-shelled mollusk fragments within the pebble conglomerate concentrations. 5) Bathyal depth foraminifera within the Pelagic intervals (Almgren, 1973). 6) Sedimentary structures consisting of sole markings, rip-ups, flame structures, slump folds, pebble imbrication, micro-cross-laminations, channels, and large-scale cross-bedding (greater than 25 centimeters high). 7) Lateral continuity of some of the thick-bedded sandstone units for nearly 1200 meters along strike.

The second distinct lithologic unit within the middle member has the following characteristics: 1) Thick-bedded (30 meters) siltstone sequences with subordinate thin (2 centimeters to 10 centimeters) sandstone beds. 2) The sandstone beds contain ripples and small-scale cross-bedding (less than 5 centimeters high). The cross-bedding is rare yet it is of a different origin than the above mentioned micro-cross-laminations since it is not found within Bouma sequences.

The middle and upper members are gradational and contain similar sedimentary features as described for the middle member. The upper member does contain a higher proportion of siltstone and forms correspondingly

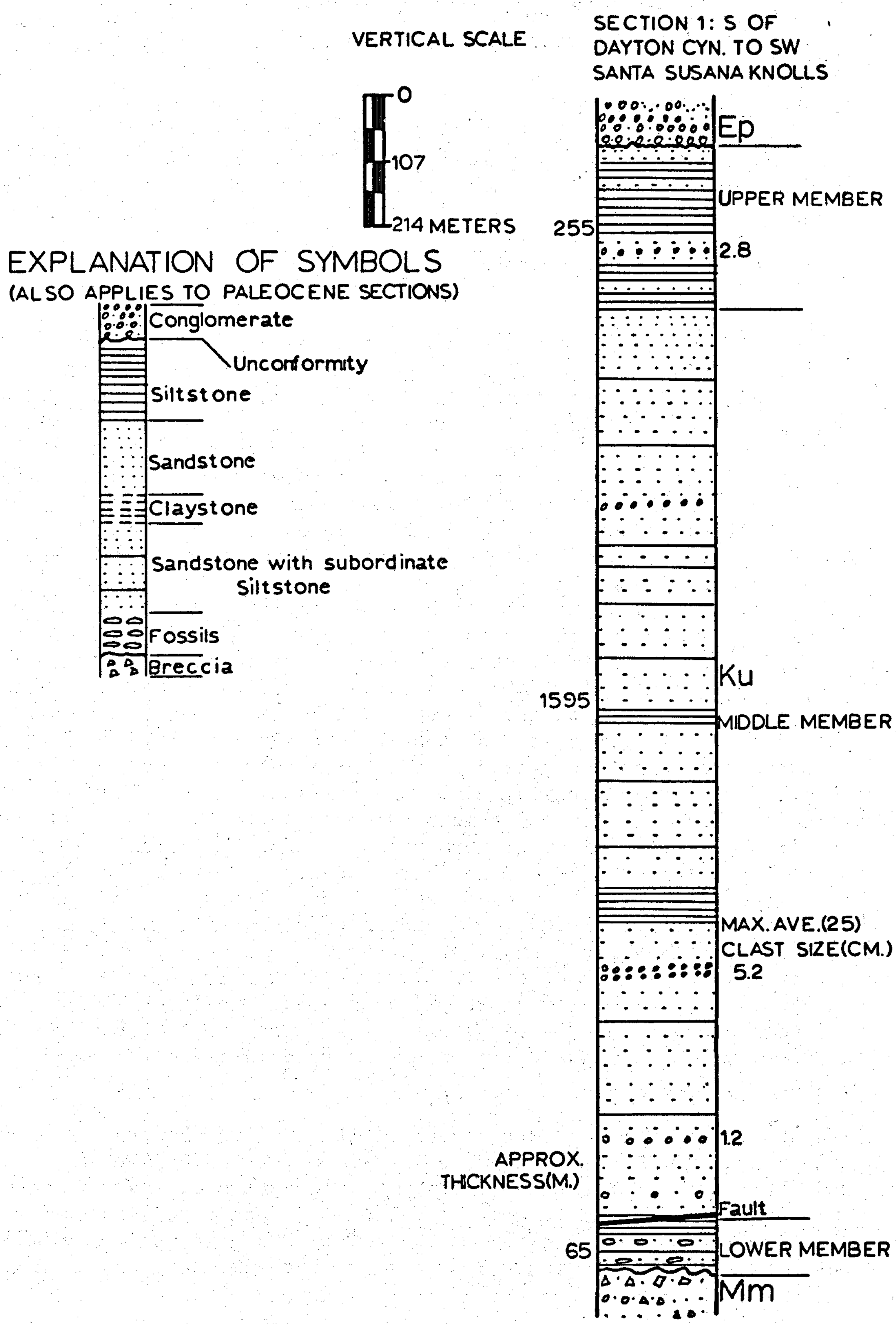


FIGURE 3.
Upper Cretaceous stratigraphic section.

less resistant bedding units and outcrop patterns.

Paleocene Strata

Overlying the Upper Cretaceous strata is the Paleocene section (Fig. 2) consisting of the Simi Conglomerate, Las Virgenes Sandstone and "Martinez" Marine Member as described by Nelson (1925). Age of these strata, based on "Martinez" Marine Member foraminifera is Ynezian (Mallory, 1959).

Descriptive sections of the Paleocene strata are shown in Figure 4.

The Simi Conglomerate contains the following descriptive features: 1) The contact with the underlying "Chico" Formation is disconformable with local cut and fill structures common along the contact. 2) Lithologic characteristics of the unit change rapidly to the west as shown in Figure 4. East of Runkle Canyon the unit predominately consists of thin-to thick-bedded, moderate to poorly sorted, pebble-to boulder-conglomerate with subordinate interbeds of medium-to very coarse-grained, poorly sorted, buff sandstone. West of Runkle Canyon, the thick-bedded conglomerate begins to grade into two separate lithologic units. The lowest unit is a thin-bedded, red to pink sequence of conglomerate, sandstone, siltstone and pisolitic sandy claystone that thickens to the west, attaining a maximum thickness of 10 meters. The upper unit is a medium-to very coarse-grained, poorly sorted, micaceous, light-gray to white sandstone. Lenticular interbeds of dark-gray carbonaceous shale are commonly interspersed in the sandstone. The above sandstone unit is considered the Las Virgenes Sandstone west of Runkle Canyon. East of Runkle Canyon the Sandstone grades into conglomerate that can no longer be separated from the underlying Simi Conglomerate. 3) Conglomerate clast size and conglomerate bed thickness decrease to the west. 4) The lower portions of the Simi Conglomerate are non-fossiliferous. 5) The top of the Simi Conglomerate and Las Virgenes Sandstone contain _in-situ_ brackish water megafossils as described by Fantozzi (1955) and Zinsmeister (personal communication, 1973). 6) Conglomerate clasts are generally well rounded, poorly sorted, and imbricated. 7) Sandstone interbeds, within the Simi Conglomerate, are lenticular, parallel-laminated and contain rare large-scale, trough-shaped cross-bedding. 8) Portions of the Simi Conglomerate and the Las Virgenes Sandstone west of Runkle Canyon, display fining-upward sequences and rare large-scale trough-shaped cross-bedding.

The "Martinez" Marine Member overlies the Simi Conglomerate east of Runkle Canyon and the Las Virgenes Sandstone west of Runkle Canyon. This unit consists of interbedded medium-to fine-grained, moderate to well sorted, fossiliferous, light-brown sandstone and fossiliferous brown-to bluish-gray, siltstone. Characteristics of this unit include: 1) Sandstone is more prevalant near the base of the Member. 2) Increases in siltstone and fine-grained, calcareous sandstone occur upsection. 3) Carbonaceous fragments are common within the sandstone near the base of the section. 4) _In-situ_ thick-shelled marine fossils are common in the lower portions of the ember. 5) _In-situ_ thin-shelled marine fossils are common in the upper portions of the Member. 6) Calcareous

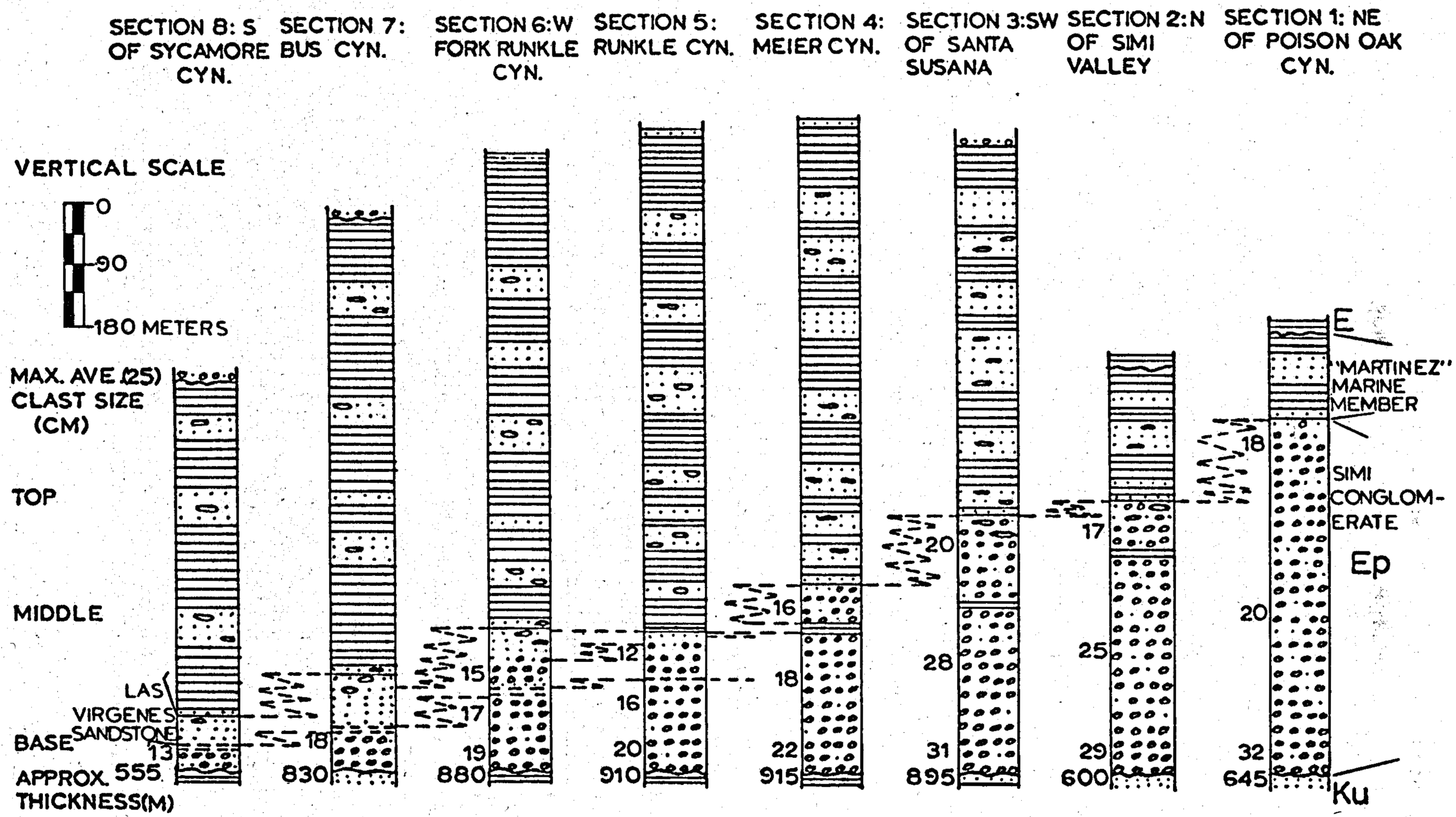


FIGURE 4.

Paleocene stratigraphic sections.

concretions occur near the top of the Member. 7) Foramineria data suggest a littoral to bathyal water depth for this unit (Mallory, 1959).

PALEOCURRENT DIRECTIONS

Paleocurrent data were obtained from the middle and upper members of the "Chico" Formation and from the Simi Conglomerate. The data present a statistical representative of paleocurrent direction throughout the areas studied as shown in Figure 2. Abundant data were obtainable from micro-cross-laminations in the Upper Cretaceous strata and from pebble imbrication in the Paleocene strata. Pebble imbrication, groove casts and small-scale cross-bedding were rare in the Upper Cretaceous strata. Paleocurrent summaries are shown in Figure 5.

DEPOSITIONAL ENVIRONMENTS

Descriptive lithologies, paleocurrent directions, and sedimentary structures, when compared to published diagnostic characteristics, allow postulation of the following depositional environments for the Upper Cretaceous and Paleocene strata.

Upper Cretaceous Strata

Deposition of the "Chico" Formation can be subdivided into two phases: one, includes the deposition of the sediments of the lower member, and two, the deposition of the sediments of the middle and upper members. The lower member consists of fossiliferous sandstone and siltstone beds. Many of the fossils are whole, thick-shelled mollusks with articulated valves. The interbedded siltstone units have well preserved bedding planes that could indicate a quiet-water deposition, in which the sediments were probably carried seaward by ocean currents and deposited from suspension. The coarser sand and fossil interbeds are more indicative of a rough water environment. Bedding is poorly preserved and thick, water-worn shell fragments are numerous. The coarse sand was probably carried offshore by strong ocean currents during stormy periods and deposited on the ocean bottom.

The majority of the middle and upper members are composed of coarse-grained clastic sediments containing sedimentary features indicative of deposition by turbidity currents. Further evidence for sediment deposition by turbidity currents is found over the entire two members in the form of Bouma sequences. The Pelagic interval (siltstone) within the Bouma sequences was probably deposited from suspension by ocean currents between successive turbidity flows.

Thick-bedded siltstone units with subordinant thin-bedded, rippled, sandstone appear to have been deposited from suspension and incorporated with offshore ocean bottom currents.

The paleocurrent indicators within the Bouma sequences indicate a general consistent deviation of current flow between the pebble imbrication and groove casts, and the micro-cross-laminations. Pebble imbrications indicate a mean direction of sediment transport to the northwest.

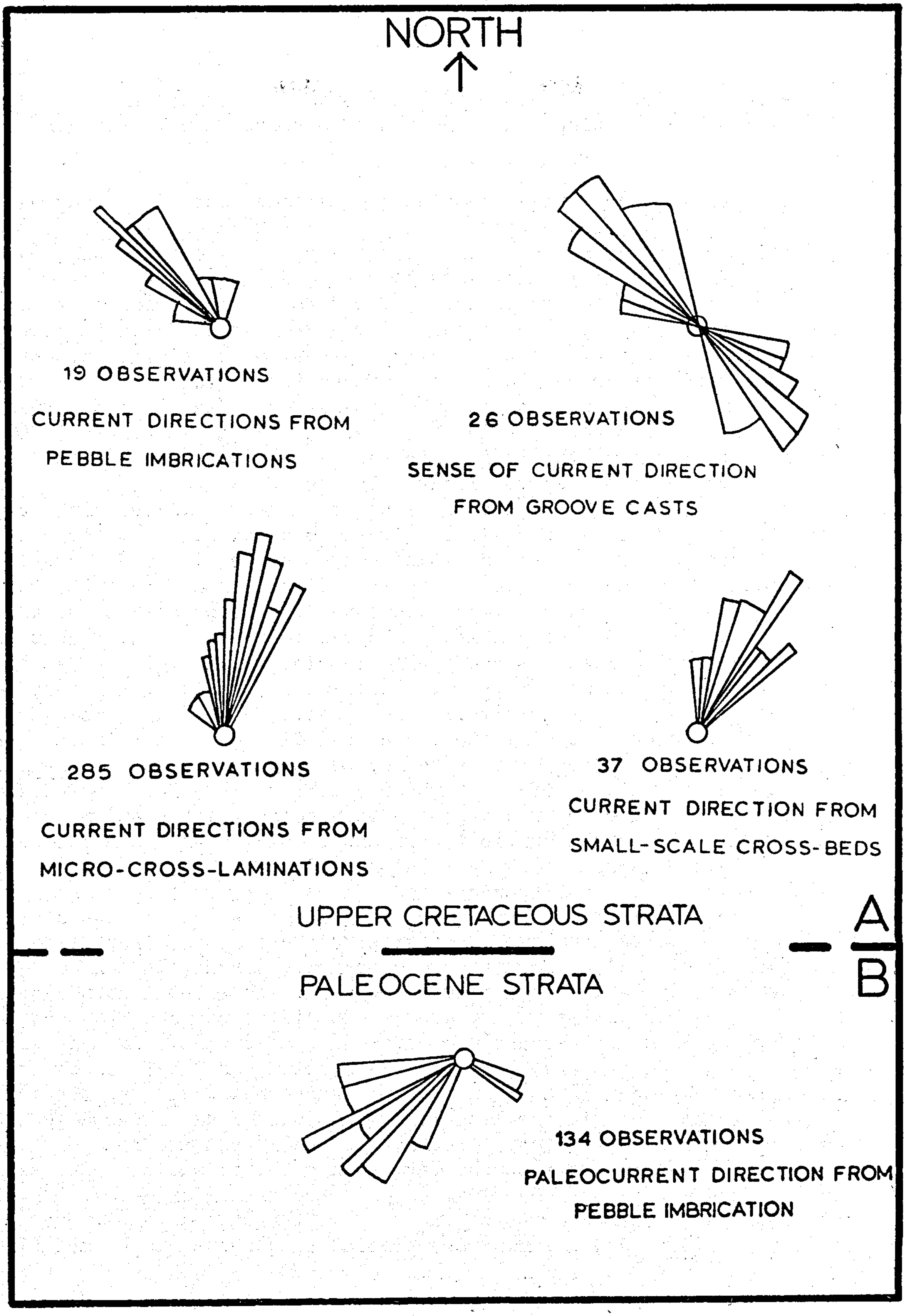


FIGURE 5.
Paleocurrent directions.
A. Upper Cretaceous strata.
B. Paleocene strata.

Groove casts give a northwest-southeast sense of current flow. Micro-cross-laminations indicate a direction of current flow to the north-northeast.

The above discrepancies between the paleocurrent directions may be explained by the following ideas. 1) Walker (1967) characterizes the deposition of the Bouma intervals in terms of flow regimes (Fig. 6). The lower flow regime is analogous to the c, d, and e intervals of Bouma. Walker defines flow regime in terms of bed form which suggests a gradually changing flow regime of a turbidity current that tends to decrease during its deposition. As the flow decreases the turbidity current can no longer hold the grains in suspension and these grains are then deposited. Turbidity currents usually consist of a "tail" that carries smaller grains in suspension in the lower flow regime. Walker (1967) states that "Although the 'tail' generally slows down through the tractional ranges of flow regime, relatively static sea water is drawn in behind the tail and turbulence patterns could result in changing current directions. If a large-scale inward movement of sea water behind the tail produces relatively constant eddy systems, (micro) cross-laminations could be formed oblique to the main direction of the turbidity current. In this case, the (micro) cross-laminations directions would be divergent from the sole marks." The paleocurrent variation between the micro-cross-laminations and pebble imbrication and groove casts across the formation may in part be explained by an irregular eddy system. Generally, the pebble imbrication-groove casts and micro-cross-lamination paleocurrent directions are less divergent in thinner turbidite sequences. This reduced divergence may be caused by a smaller influx of water behind the "tail" of the turbidity current. 2) Parkash and Middleton (1970) attribute the variation between sole markings and micro-cross-laminations to either a turbidity current flowing down a sinuous channel or a turbidity current flowing from one side of a canyon to the other in a sinuous pattern. The finer-grained sediments would tend to be left behind by the more rapidly flowing coarse-grained sediments. As a result, the finer sediments may have a different direction of current flow. The paleocurrent directions from the sole markings across the "Chico" Formation are relatively uniform. Therefore a current flowing down a sinuous channel is rather unlikely. However, a turbidity current may have deviated slightly in direction because of bottom irregularities. If this were the case, a slight discrepancy between sole markings and micro-cross-laminations might appear. 3) Small lenses of sandstone, occurring between siltstone beds, contain small-scale cross-bedding that shows a general northeast current direction. These sandstone lenses are not part of the Bouma sequences and are somewhat rare across the formation. The small-scale cross-bedding may have formed by the reworking or deposition of sediments by traction currents. Shepard (1963) states that there appears to be no definite depth limit to appreciable currents on the sea floor.

The small-scale cross-bedding units may be a clue to the deviation

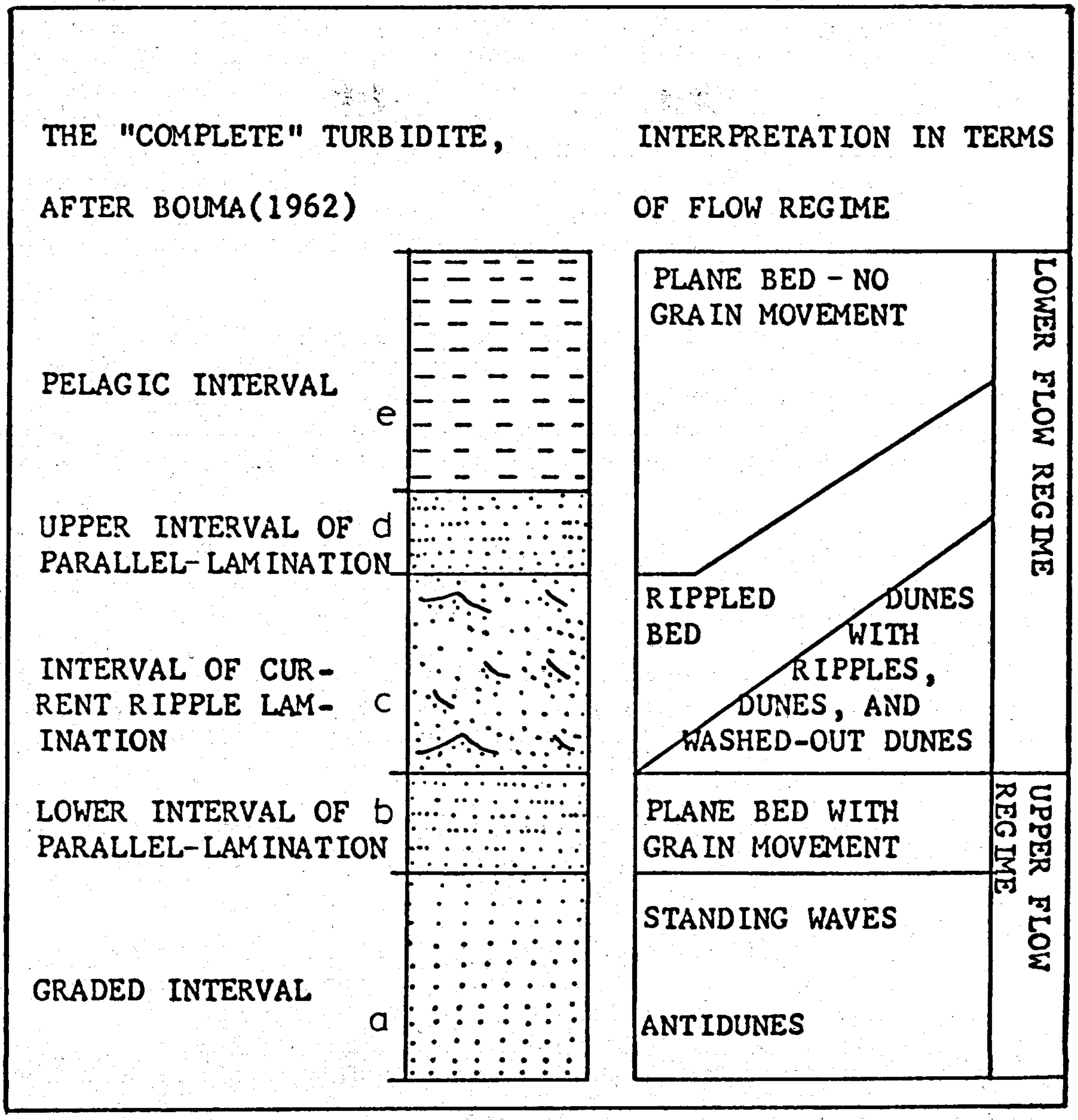


FIGURE 6.
Comparison of turbidite sequences and flow regimes (Walker, 1967).

between pebble imbrication, groove casts, and micro-cross-lamination paleocurrent directions. As the micro-cross-laminations were about to be deposited from a turbidity current travelling in a north-northwest direction, a persistent traction current may have exerted a northeast to easterly component of force. This component of current force would tend to cause an actual depositional direction of the micro-cross-laminations in a north to northeast direction. The northeast direction of the traction current is reasonable because of the general northeast component of paleocurrent direction shown by the small-scale cross-bedding.

Walker (1967) compiled a list of features for proximal versus distal turbidites (Fig. 7). Proximal turbidites are deposited in a near-shore environment on continental shelves, in submarine canyons, on submarine fans, and at the base of submarine fans. Distal turbidites are deposited in a far-shore environment on the ocean or basin floor, or on abyssal plains.

Characteristics of the turbidites of the "Chico" Formation based on representative detailed measurements (Sage, 1971) plus general observations across the formation follow:

A. Beds thick: Approximately 50 percent of the beds measured are greater than 15 centimeters thick. Generally, the beds across the formation are greater than 15 centimeters and they are often over 3 meters thick.

B. Beds coarse-grained: Approximately 48 percent of the beds measured consist of medium-to very coarse sand. Generally, grain sizes across the formation are very coarse.

C. Individual sandstones often amalgamate: In 17 percent of the measurements the sandstones amalgamated. Generally, within the formation the coarse-grained sandstones tended to amalgamate.

D. Beds irregular in thicknesses: Bedding is highly irregular in thickness across the entire formation.

E. Scours, washouts and channels common: conglomerate filled channels, scours, and washouts are common at the base of the turbidite sequences.

F. Mudstone partings between sandstone poorly developed. Sand/mud ratio high: Mudstone partings are poorly developed in the thick-bedded, coarse-grained units. Sand/mud ratio varies from about 1:1 to about 10:1. Generally, the sand is more abundant than the mud. Two exceptions to this are found in a thick siltstone-sandstone unit near the summit of the Simi Hills, and in the siltstone interbeds of the upper member.

G. Beds ungraded or crudely graded: A majority of the beds are well-graded.

PROXIMAL	DISTAL
A. Beds Thick	A. Beds Thin
B. Beds Coarse Grained	B. Beds Fine Grained
C. Individual Sandstones Often Amalgamate	C. Individual Sandstones Rarely Amalgamate
D. Beds Irregular in Thickness	D. Beds Regular in Thickness
E. Scours, Washouts and Channels Common	E. Few Small Scours, No Channels
F. Mudstone Partings Between Sandstones Poorly Developed or Absent. Sand/Mud Ratio High	F. Mudstone Layers Between Sandstones Well Developed. Sand/Mud Ratio Low
G. Beds Ungraded or Poorly Graded	G. Beds Well Graded
H. Base Of Sand Always Sharp, Top Often Sharp Many AE Sequences	H. Base of Sand Always Sharp Top Grades Into Finer Sediment, AE Sequences Rare
I. Laminations and Ripples Occur Infrequently	I. Laminations and Ripples Very Common
J. Scour Marks Occur More Frequently than Tool Marks	J. Tool Marks Occur More Frequently than Scour Marks

FIGURE 7
Comparison of proximal versus distal features of turbidity current deposits (Walker, 1967).

H. Base of sandstone always sharp, top often sharp, many a-e sequences: Eighty-five percent of the measured intervals have sharp sand bases; 86 percent of the intervals' tops are sharp; and 25 percent are complete a-e Bouma sequences. The same general percentages should hold true across the formation.

I. Laminations and ripples occur infrequently: Ripples and laminations occur infrequently; in approximately one-third of the measured sequences.

J. Scour marks more frequent than tool marks: Tool marks and scour marks were rare in the Formation.

From the above criteria, one can postulate that the turbidity sequences of the "Chico" Formation are proximal turbidites. The degree of proximity is difficult to determine, however, because the beds do not contain material coarser than pebble size, beds are well graded, a-e sequences are not too common; and the sand to mud percentage is about equal.

The grain size is determined in part by the relief, lithology, and erosional factors in the source area, plus the distance of the source area from the shore. Thus, the grain size within the rocks should depend in part upon the size of the materials supplied.

Beds are well graded which precludes a very proximal environment because segregation of the grains must occur over "some distance" of turbidity current flow to produce grading.

Many a-e sequences are missing. This may be due to non-deposition because of the rapidity of emplacement, or many of the intervals may have been scoured or eroded away by the impinging coarse-grained sediments of the next successive flow.

The equal sand to mud percentages occur only in limited areas and are related to a decrease in the amount of sand-sized material deposited by each successive turbidity current.

In summary, it is postulated from available data, that the clastic material of the middle and upper members was deposited on the lower portions of a large submarine fan complex primarily by north-northwesterly flowing turbidity currents, by northeasterly traction currents, and from suspension.

Paleocene Strata

The Simi Conglomerate, Las Virgenes Sandstone and "Martinez" Marine Member present at least four separate depositional environments. The lower portion of the Simi Conglomerate was probably deposited by a southwesterly-flowing braided river complex (Fig. 8). The lower conglomerate portion grades westerly into the red conglomerate-claystone which was probably deposited in a southwesterly-flowing meandering river and lagoonal environment (Fig. 9A and 9B). The claystone deposits consist of discontinuous pods of carbonaceous shale, and sandy pisolitic claystone.

CHARACTERISTICS OF ALLUVIAL FAN AND BRAIDED RIVER DEPOSITS

GEOMETRY: prismatic; fan or blanket shape; downslope trending complex of channel lentils of various sediment types; deposits perpendicular to depositional strike; upslope portion of deposit fan shaped.

LITHOLOGY: poorly sorted conglomerate and coarse-grained sandstone; subordinate siltstone,carbonaceous shales, peat and coal; sandstone usually micaceous; lateral, vertical,and downslope decrease in grain size; sorting may improve downslope; fining- upward sequences of conglomerate-sandstone-isolated shale; unit commonly grades into meandering river downslope.

SEDIMENTARY STRUCTURES: lenticular channel deposits of conglomerate,sandstone and downslope,occasional siltstone and carbonaceous shale;pebble imbrication; conglomerate commonly inverse graded and matrix supported; vertical sequences of conglomerate,massive to graded sandstone,large-scale cross-bedded and parallel-laminated sandstone.

PALEOCURRENT PATTERNS: locally trend downslope; regionally fan-shaped; source upcurrent.

FOSSILS: rare vertebrates; common plant fragments.

References: Doeglas (1962), Beerbower (1964), Allen (1965), Duff (1967), Klein (1967), Selley (1970), Fisher (1971).

FIGURE 8

Characteristics of alluvial fan and braided river deposits.

CHARACTERISTICS OF MEANDERING RIVER DEPOSITS

GEOMETRY: sheet; coalesced conglomerate and sandstone channels enclosed in shale.

LITHOLOGY: coarse-to fine-grained sandstone and shale with subordinate conglomerate, peat and coal, and claystone; micaceous sandstone common; downslope decrease in grain size.

SEDIMENTARY STRUCTURES: fining-upward sequences of conglomerate, large-scale cross-bedding and parallel-laminations within sandstone, rippled sandstone, and laminated siltstone; conglomerate and sandstone usually graded.

PALEOCURRENT PATTERNS: wide scatter; regionally parallel to paleoslope.

FOSSILS: plant debris; rare vertebrates; fresh to brackish-water megafossils.

References: Beerbower (1964), Allen (1965), Klein (1967), Potter (1967), Shelton (1967), Selley (1970).

A

B

CHARACTERISTICS OF LAGOONAL DEPOSITS

GEOMETRY: sheets or shoestrings parallel to paleo-strike; often discontinuous.

LITHOLOGY: patchy distribution of claystone, siltstone, fine-grained sandstone, peat and coal; clastic size may change locally where alluvial channels present.

SEDIMENTARY STRUCTURES: conglomerate channels occasionally present; laminated fine grained sandstones and siltstones; pods and seams of peat and coal.

PALEOCURRENT PATTERNS: rare except within alluvial deposits.

FOSSILS: fresh and brackish-water megafossils; plant fragments.

References: Moore (1966), Selley (1970).

FIGURE 9

A. Characteristics of meandering river deposits.
B. Characteristics of lagoonal deposits.

The pisolitic claystone is found within a distinctive marker bed about 1 meter thick. Overlying the red conglomerate-claystone, west of Runkle Canyon, is the Las Virgenes Sandstone which contains features of both a lagoonal-alluvial depositional environment. The "Martinez" Marine Member was deposited in a transgressive marine environment (Fig. 10).

PALEOGEOGRAPHY

Regional paleogeographic reconstruction of Upper Cretaceous strata are not feasible based only on study of strata in the eastern Simi Hills. However, paleocurrent data do indicate that source terrain for these strata existed directly to the south-southeast (this report) and east (Colburn, 1973).

Source terrain for the above Upper Cretaceous strata are not exposed in a direct south-southeast direction. Pre-Upper Cretaceous igneous basement terrain in the northern Santa Ana Mountains as described by Colburn (1973) may be similar to "Chico" Formation conglomerate clasts of the Simi Hills (Sage, 1971). However, northern Santa Ana Mountains igneous rocks are presently situated east of the Simi Hills Upper Cretaceous deposits and on the south side of the Malibu Coast-Santa Monica fault system. Juxtaposition of these strata with possible source terrain would require 50 to 80 kilometers of palinspastic restoration on the left-lateral Malibu Coast fault system as suggested by Colburn (1973).

Study of Paleocene strata in the Simi Hills, western Santa Monica Mountains, Elsinore and Santa Ana Mountains area (Sage, 1973), have allowed paleogeographic reconstruction for these strata which in turn can help account for the lack of source terrain directly south-southeast of the Upper Cretaceous strata of the eastern Simi Hills.

Paleocene geography is interpreted as consisting of a contiguous series of rivers flowing southwesterly into a lagoonal complex which was subsequently transgressed by marine waters. Figure 11A shows the configuration of the Paleocene geography for the Simi Hills, western Santa Monica Mountains, Elsinore, and Santa Ana Mountains localities.

The following episodes of movement are postulated as a means of positioning the reconstructed Paleocene localities of Figure 11A into their respective orientations today (Figure 11C).

The first episode of movement involves the Malibu Coast-Santa Monica fault system along which Yerkes and Campbell (1971) suggested 90 kilometers of left-slip movement in middle Miocene time. This hypothesis was based in part on the offset of a north-south trending pisolitic claystone unit in the Santa Monica Mountains and Santa Ana Mountains. Figure 11A shows a reconstructed lower Paleocene geography and Figure 11B shows the position of Paleocene strata at the end of middle Miocene time. A more realistic offset of 60 kilometers for the claystone unit is postulated for the following reasons: 1) the claystone represents a lagoonal deposit which probably closely parallels a northwest-southeast trending lower Paleocene shoreline; 2) the location of the claystone in the Simi Hills reduces the postulated 90 kilometers of left-slip; and 3) palinspastic

CHARACTERISTICS OF TRANSGRESSIVE MARINE DEPOSITS

GEOMETRY: thin sandstone sheets or shoestrings commonly parallel to paleostrike; thick lateral sequences of sandstone and shale.

LITHOLOGY: 1) coarse–to fine–grained,poor to well sorted sandstone overlying alluvial or lagoonal deposit; common pebble conglomerate and micaceous concentrations, and isolated peat or clay lentils and pods 2) preceeding lithology overlain by moderate to well sorted, coarse-to fine-grained sandstone,shale and limestone; grain size decreases up section.

SEDIMENTARY STRUCTURES: gradational or abrupt lateral and vertical contacts; sand unit directly above alluvial or lagoonal deposit commonly coarsens upward and contains large-scale cross-bedding and parallel-laminated sandstone; overlying sandstone-shale sequence may contain parallel-laminations and ripple marks.

PALEOCURRENT PATTERNS: large-scale cross-bedding dips on or offshore and is bipolar if within tidal channel.

FOSSILS: shallow to deepwater marine megafossils overlie fresh to brackishwater megafossils and plant fragments.

References: Klein (1967), Potter (1967), Shelton (1967), Selley (1970).

FIGURE 10

Characteristics of transgressive marine deposits.

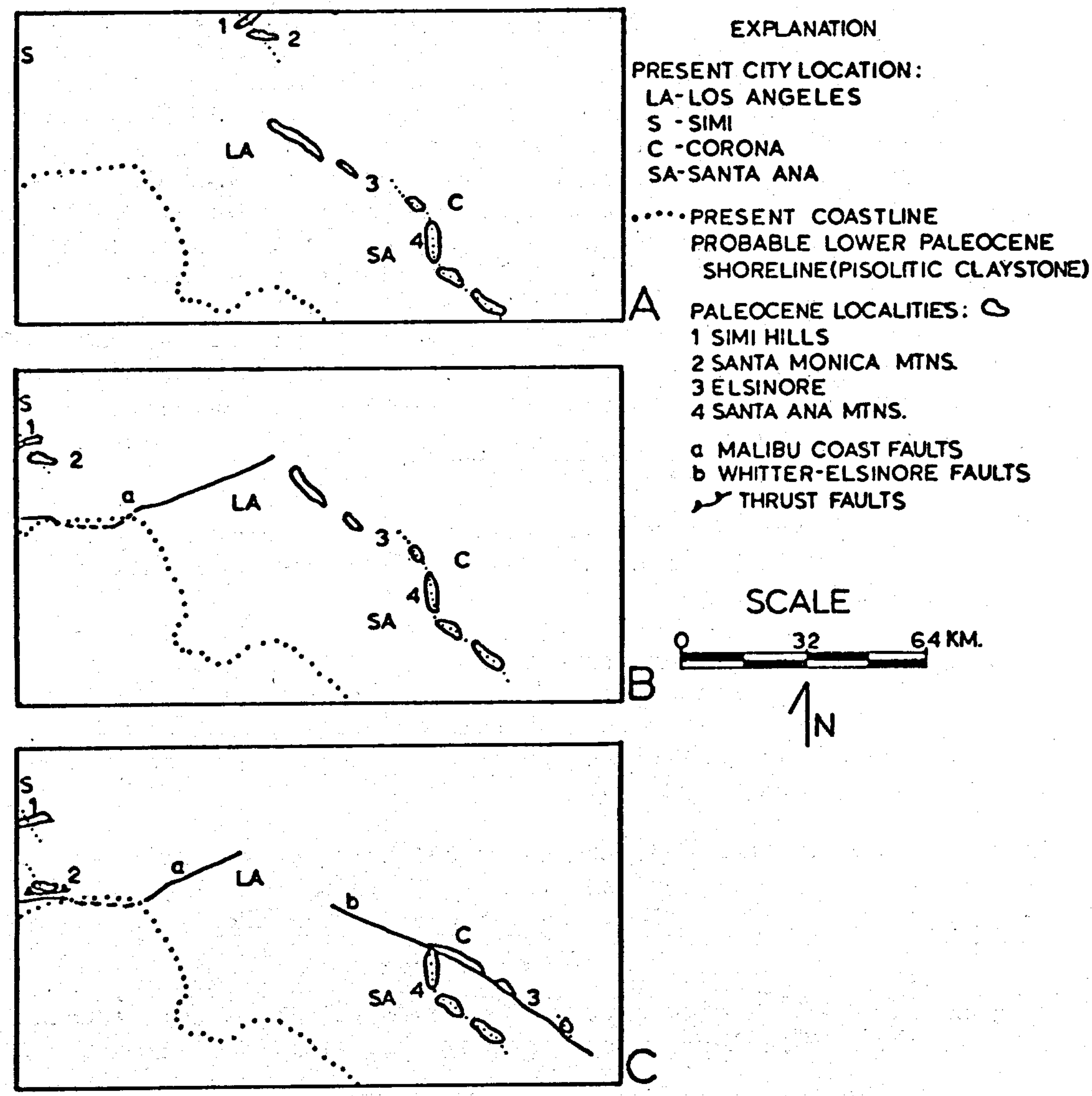


FIGURE 11.

A. Palinspastic restoration of Paleocene geography.
B. Position of Paleocene strata in late middle Miocene time.
C. Position of Paleocene strata today.

restoration of Paleocene strata by the Whittier-Elsinore fault system was not considered in the original 90 kilometer estimate. The 60 kilometer offset is probably only accurate to ±5 kilometers since a distinctive facies "wedge-out line" could not be located; hence, areas of similar sedimentary sequences were chosen as areas of offset.

A second episode of movement is shown in Figure 11C where approximately 40 kilometers of right-slip is suggested along the Whittier-Elsinore fault system due to offset of the claystone unit. Lamar (1961) also postulated about 40 kilometers of right-slip based on offsets of Paleocene marine facies during late Miocene to early Pliocene time. Additional movement of the Simi Hills and Santa Monica Mountains localities to the north and west also occurred along the San Gabriel fault system. Crowell (1962) cites documentation of approximately 50 kilometers of right-slip along this system primarily during Pliocene time.

A third episode of movement is shown in Figure 11C where late Pliocene to early Pleistocene, north to south thrusting, took place in the Simi Hills-Santa Monica Mountains area (Yerkes and Campbell, 1971).

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UPPER PALEOCENE-MIDDLE EOCENE PLANKTONIC BIOSTRATIGRAPHY FROM THE GREAT VALLEY OF CALIFORNIA AND ADJACENT AREAS, AND CORRELATION TO THE WEST COAST MICROFAUNAL STAGES

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INTRODUCTION

Planktonic microfossils are now employed on a worldwide basis as a means of detailed biostratigraphic analysis. At present, planktonic foraminifera and calcareous nannoplankton studies in various parts of the world have established these two groups as the most significant for inter-regional correlations. This has resulted in so-called standard zonations, often used with a number notation: for planktonic foraminifera, see Berggren (1972); and for calcareous nannoplankton, see Martini (1971). These two zonations have gained recognition as scales for worldwide biostratigraphy and are often used in the sense of chronozones. For the Upper Paleocene-Middle Eocene interval under consideration, the standard planktonic foraminiferal zonation follows that of Bolli (1957a,b; 1966) for Trinidad. For the same interval, the calcareous nannoplankton zonation agrees with the compilation of Mohler and Hay and Hay (*in* Hay *et al.*, 1967; also Hay and Mohler, 1967). For purposes of comparison, these latter papers will be referred to as the standards as they are the more direct sources of the data.

For biostratigraphic and chronostratigraphic subdivision of Paleogene strata from California, the microfaunal scheme of Mallory (1959) is most commonly used. Oppel-zones of benthonic foraminifera are utilized to define a sequence of zones and stages widely employed on the West Coast.

Mallory (1959) also provides information on previous attempts at subdivision, including some data of the informal molluscan zonation, or the so-called megafaunal scheme. The papers on calcareous nannoplankton of Bramlette and Sullivan (1961) and Sullivan (1964, 1965) provide another means of analyzing the same strata (*e.g.*, Mohler and Hay and Hay *in* Hay *et al.*, 1967; Hay and Mohler, 1967). The work of Sullivan (1964, 1965) is directly comparable to that of Mallory in that he makes use of the same sections and samples utilized earlier by Mallory (1959).

The planktonic foraminifera have promise as another means for analyzing Paleogene strata in California. Reports of such studies for parts of this interval have appeared (*i.al.*, Milow *in* Milow and Ennis, 1961; Bandy and Kolpack, 1963; Lipps, 1967; Steineck and Gibson, 1971; Steineck *et al.*, 1972, Gibson, in press). A fully documented zonation for the lower Tertiary of California is now being prepared for publication (*cf.* Schmidt, 1970); an outline of that zonation is presented here.

In the present paper, a planktonic foraminiferal zonation for the Ynezian-Narizian interval (Mallory, 1959) will be discussed. This planktonic foraminiferal zonation will be compared to the standard planktonic references. This will be followed by a correlation to the West Coast marine stages, including the data attainable from the calcareous nannoplankton.

PLANKTONIC FORAMINIFERAL ZONATION

Six planktonic foraminiferal zones can be consistently diagnosed for Upper Paleocene through Middle Eocene strata from California. Included is one interval in which a portion of the standard reference sequence is thought to be missing. The terminology for the zonation conforms to that suggested by the INTERNATIONAL SUBCOMMISSION OF STRATIGRAPHIC CLASSIFICATION (1972). Except for the first and last zones, all zones are interval-zones, defined by the appearance (entry) and disappearance (exit) of index taxa. Other taxonomic occurrences relevant to the zonation are also mentioned (see also Figure 1).

Whenever possible, the index species of the Trinidad standard zonation have been utilized (Bolli, 1966). However, regional differences, probably temperature-related, exclude some of the index species reported from Trinidad so that other index species have been chosen for the Lower-Middle Eocene interval in California. In general, correspondence of zones between the California and Trinidad reference sections decreases from the lowest to the highest zones recognized (Figure 2). For the Lower-Middle Eocene interval,

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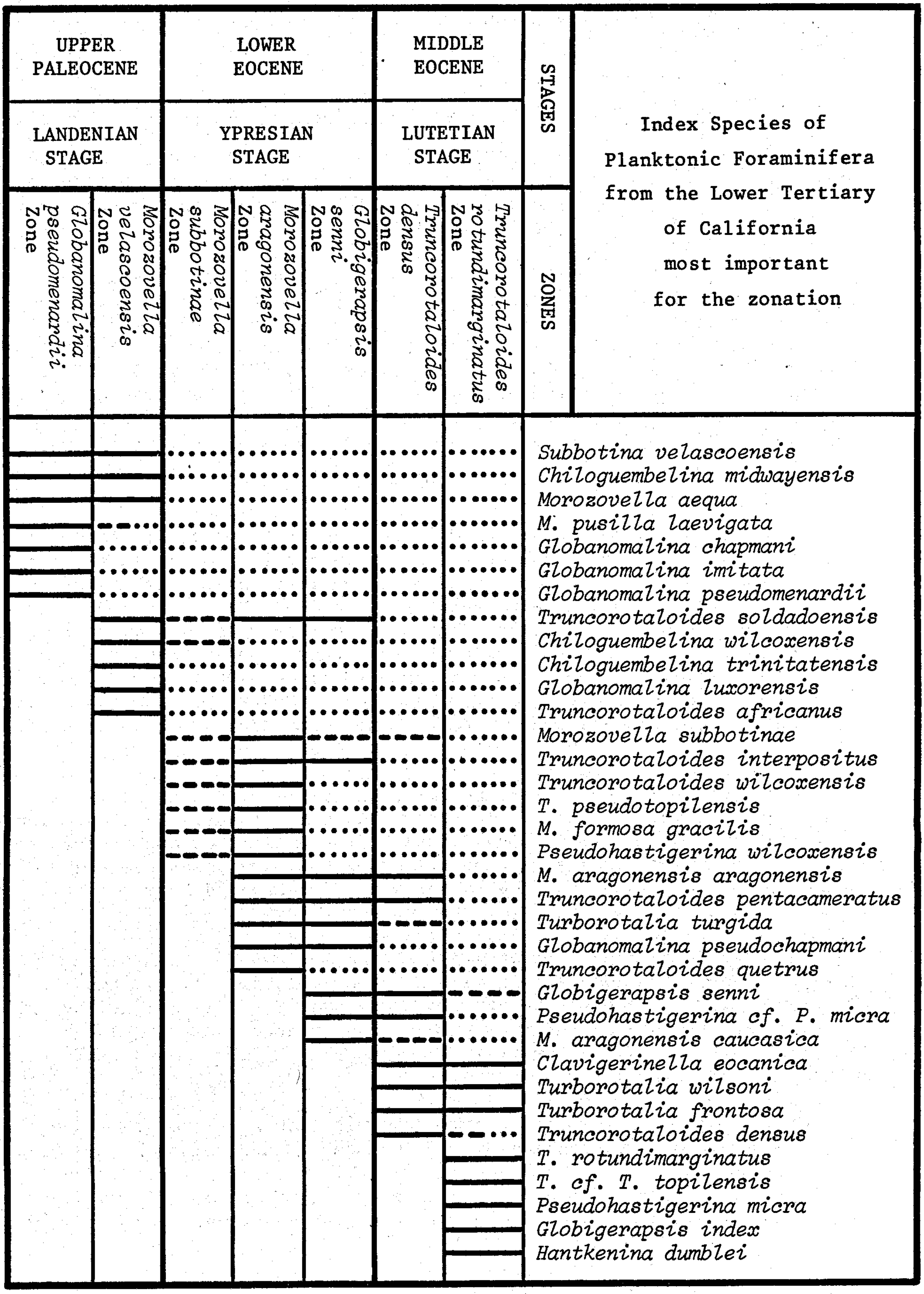
Figure 1

Compiled range chart of key index species of planktonic foraminifera from the lower Tertiary of California. The generic assignments are based on the author's ideas concerning lineage studies (*cf.*Mc Gowran, 1968; Berggren, 1968). The position of the aperture and the development of a keel are considered less important than wall microstructure and presumed phylogeny (*cf.* Lipps, 1966; McGowran, 1968).


UPPER PALEOCENE
LOWER EOCENE
MIDDLE EOCENE
STAGES
LANDENIAN STAGE
YPRESIAN STAGE
LUTETIAN STAGE
Index Species of Planktonic Foraminifera from the Lower Tertiary of California most important for the zonation
Globanomalina pseudomenardii Zone
Morozovella velascoensis Zone
Morozovella subbotinae Zone
Morozovella aragonensis Zone
Globigerapsis senni Zone
Truncorotaloides densus Zone
Truncorotaloides rotundimarginatus Zone
ZONES
Subbotina velascoensis
Chiloguembelina midwayensis
Morozovella aequa
M. pusilla laevigata
Globanomalina chapmani
Globanomalina imitata
Globanomalina pseudomenardii
Truncorotaloides soldadoensis
Chiloguembelina wilcoxensis
Chiloguembelina trinitatensis
Globanomalina luxorensis
Truncorotaloides africanus
Morozovella subbotinae
Truncorotaloides interpositus
Truncorotaloides wilcoxensis
T. pseudotopilensis
M. formosa gracilis
Pseudohastigerina wilcoxensis
M. aragonensis aragonensis
Truncorotaloides pentacameratus
Turborotalia turgida
Globanomalina pseudochapmani
Truncorotaloides quetrus
Globigerapsis senni
Pseudohastigerina cf. P. micra
M. aragonensis caucasica
Clavigerinella eocanica
Turborotalia wilsoni
Turborotalia frontosa
Truncorotaloides densus
T. rotundimarginatus
T. cf. T. topilensis
Pseudohastigerina micra
Globigerapsis index
Hantkenina dumblei

a correlation between California and the North Caucasus (Subbotina, 1953; Krasheninnikov, 1969) is apparent when faunules of the two areas are compared.

Globanomalina pseudomenardii Range-zone (Upper Paleocene): This zone is recognized worldwide by the total-range of the zonal marker. Besides *Globanomalina pseudomenardii* (BOLLI), *G. chapmani* (PARR) and *Morozovella pusilla laevigata* (BOLLI) are restricted to this zone. *Morozovella velascoensis* (CUSHMAN) and *Subbotina velascoensis* (CUSHMAN) appear for the first time at the base of this zone (Bolli, 1957a).

This zone is represented at the base of several lower Tertiary sequences in California: northern Simi Valley ("Martinez" and lower Santa Susana Formations, Ynezian and Bulitian); Lodo Gulch (lower Lodo Formation, Ynezian); Media Agua Creek (lower Lodo Formation, Ynezian, except uppermost three samples of Mallory, 1959); and Martinez area (Vine Hill Sandstone, Ynezian). At the western end of the Santa Ynez Range, the basal Anita Formation (= type area of the Ynezian Stage) is reported to contain a rich planktonic assemblage, including *Globanomalina pseudomenardii* (Allison, 1964, p. 9; Gibson, in press).

Morozovella velascoensis Interval-zone (Upper Paleocene): As defined by Bolli (1957a, 1966), this zone includes the interval from the last occurrence of *Globanomalina pseudomenardii* (BOLLI) to the last occurrence of the zonal marker. *Chiloguembelina trinitatensis* (CUSHMAN & RENZ) and *Truncorotaloides africanus* (EL-NAGGAR) seem to be restricted to this zone. *Globanomalina luxorensis* (NAKKADY), a species showing the transition of *Globanomalina* to *Pseudohastigerina*, appears in this zone (Schmidt, 1968). *Chiloguembelina midwayensis* (CUSHMAN), *Morozovella velascoensis* (CUSHMAN), and *Subbotina velascoensis* (CUSHMAN) become extinct at the top of the zone (Bolli, 1957a; Beckman, 1957).

This zone is recognized in the northern Simi Valley section (upper Santa Susana Formation, Penutian) and at Lodo Gulch (lower Lodo Formation, Ynezian). For the most part, the strata in these two sections represented by this zone can be assigned to the *Discoaster multiradiatus* calcareous nannoplankton Zone (Mohler and Hay *in* Hay *et al.*; Hay and Mohler, 1967).

Unrepresented interval equivalent to the Morozovella subbotinae Interval-zone (Lower Eocene): According to Bolli (1957a, 1966), the *"Globorotalia rex"* Zone (= *Morozovella subbotinae* Zone) is defined by the presence of the zonal marker from the last occurrence of *Morozovella velascoensis* (CUSHMAN) to the first occurrence of *M. aragonesis* (NUTTALL) and *M. formosa formosa* (BOLLI).

In the Lodo Gulch section a paraconformity 150 feet from the base of the Lodo Formation is indicated by the absence of the *Morozovella subbotinae* Zone. No lithologic change is apparent at this discontinuity, but the residue contains a concentration of glauconite and a relatively low percentage of planktonic foraminifers. In their study of calcareous nanno-

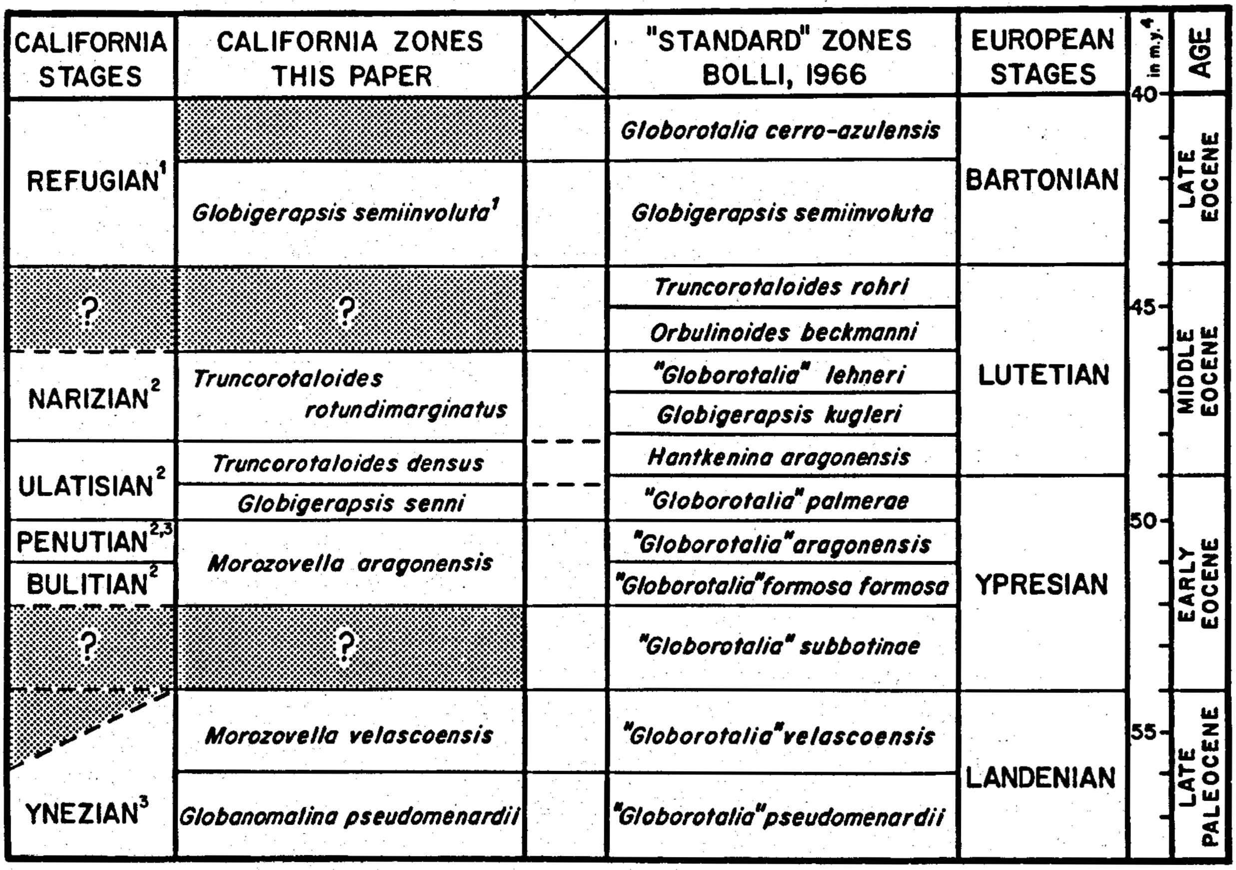


Figure 2

Correlation chart of the California lower Tertiary with the European stages by means of planktonic foraminifera. The Refugian Stage assignment is from Lipps, 1967 (1); *Globigerapsis semiinvoluta* (KEIJZER) is now known to be a junior synonym of *G. mexicana* (CUSHMAN). The stage assignments are based upon planktonic distributions in the Media Agua Creek section (2) and in the type area of Mallory's stages (3). The time-scale follows that of Berggren, 1969 (4).

plankton from the type Lodo Formation, Bramlette and Sullivan (1961, p. 135) point out that the species turnover between units "2" and "3" (= *Discoaster multiradiatus* and *Marthasterites tribrachiatus* Zones)is so abrupt that a discontinuity in time or facies is apparent. Two additional zones, the *Marthasterites contortus* and *Discoaster binodosus* Zones, elsewhere have been introduced at the level of this suspected hiatus (Mohler and Hay *in* Hay *et al.*, 1967).

The *Morozovella subbotinae* Zone was not found in any California section that I have studied. Utilizing Sullivan's (1964, 1965) lists of calcareous nannoplankton from other California lower Tertiary sections, it is not possible to recognize the *Marthasterites contortus* Zone, and only occasionally short sequences of the *Discoaster binodosus* Zone (Mohler and Hay *in* Hay *et al.*, 1967; Hay and Mohler, 1967). The *Morozovella subbotinae* planktonic foraminiferal Zone correlates within the limits of these two calcareous nannofossil zones (Hay and Mohler, 1969).

Strategic sampling from continuous sequences elsewhere may reveal planktonic foraminifers of the *Morozovella subbotinae* Zone. This zone is reported by Gibson (in press) from the Anita Formation in the western Santa Ynez range.

Morozovella aragonensis Interval-zone (Lower Eocene): This zone is defined as extending from the first occurrence of the zonal marker to the first occurrence of *Globigerapsis senni* (BECKMANN). It includes the *"Globorotalia" formosa formosa* and *"G". aragonensis* Zones of Bolli (1966). The two zones are separated in the Trinidad sequence by the first occurrence of two rather indistinct species, *"Globigerina" taroubaensis* BRONNIMANN and *"G". turgida* FINLAY, and the co-occurrence of the extremely rare *Morozovella formosa formosa* (BOLLI). *Truncorotaloides quetrus* (BOLLI) is an index species restricted to this interval-zone.

Pseudohastigerina wilcoxensis (CUSHMAN & PONTON) and *Morozovella formosa gracilis* (BOLLI) make their last appearance in the *Morozovella aragonensis* Zone. In the Lodo Formation at the base of this zone, the gradual transition of *M. aragonensis aragonensis* (NUTTALL) from *M. lensiformis* (SUBBOTINA) is evident. This interval includes rare *M. marginodentata* (SUBBOTINA) and *M. subbotinae* (MOROZOVA) so that the lowest samples at the Lodo Gulch and Media Agua Creek localities may represent the uppermost portion of the *"Globorotalia" formosa formosa* Zone (*sensu* Bolli, 1957a, 1966).

In the type Lodo Formation, the *Morozovella aragonensis* Zone includes strata that Mallory (1959) assigned to his Bulitian Stage. In the Santa Barbara Embayment area along Las Cruces Road, the lower "Poppin shale" member of the Anita Formation contains a diverse plankton-rich assemblage of this zone (see Sullivan, 1965, loc. A-8855, correlated to the Penutian).

In the Media Agua Creek section, the listed occurrence of key planktonic species (Mallory, 1959, 1970), and comparative samples, indicates the uppermost Ynezian, Bulitian, and Penutian (type) stages can be assigned to the *Morozovella aragonensis* Zone. *Pseudohastigerina wilcoxensis* (= *Nonion wilcoxensis* of Mallory, 1959) is a good marker species for the *Morozovella aragonensis* Zone in California.

Globigerapsis senni Interval-range Zone (Lower Eocene): This zone is delimited by the first occurrence of the zonal marker prior to the first occurrence of *Truncorotaloides densus* (CUSHMAN). In this zone *Morozovella aragonensis caucasica* (GLAESSNER) is more prevalent than *Morozovella aragonensis s.s.* Other species that occur in the underlying *Morozovella aragonensis* Zone but are more abundant in the *Globigerapsis senni* Zone include *Globanomalina pseudochapmani* (SUBBOTINA) and *Truncorotaloides pentacameratus* (SUBBOTINA).

The *Globigerapsis senni* Zone is comparable to the "*Globorotalia*" *palmerae* Zone (Bolli, 1957b; 1966). "*Globorotalia*" *palmerae* CUSHMAN & BERMUDEZ has a limited geographic distribution worldwide, apparently restricted to tropical regions (Schmidt and Raju, 1973). The evolutionary appearance of *Globigerapsis senni* (from "*Globigerina*" *turgida* FINLAY) is thought to be approximately the same as that for "*Globorotalia*" *palmerae*. The interval from the first occurrence of *Globigerapsis senni* (BECKMANN) to the first occurrence of *Truncorotaloides densus* (CUSHMAN) is thought to be a means of delimiting the "*Globorotalia*" *palmerae* Zone in high-latitudinal areas (*op cit.*, p. 177). This also agrees with Bolli's (1957b, fig. 26) range chart for the zone in question. "*Globigerina*" *senni* is now considered by me to be the first representative of the genus *Globigerapsis* (*cf.* Mallory, 1970).

In the Lodo Gulch section the *Globigerapsis senni* Zone comprises the upper 900 feet of the type Lodo Formation (Penutian and Ulatisian). Along Las Cruces Road the upper "Poppin shale" of the Anita Shale (Ulatisian) contains a plankton-rich assemblage of the *Globigerapsis senni* Zone (Sullivan, 1965, loc. D-1017). In the Media Agua Creek section, the reported initial occurrence of *Globigerapsis senni* (=*Sphaeroidina gredalensis* COOK in Mallory, 1959) corresponds to the Lower Ulatisian boundary.

Truncorotaloides densus Interval-zone (Middle Eocene): This zone is distinguished by the joint occurrence of the zonal marker and *Morozovella aragonensis s.l.*, prior to the extinction of the latter. In addition to *Truncorotaloides densus* (CUSHMAN), *Turborotalia wilsoni* (COLE), *Clavigerinella eocanica* (NUTTALL), and *Turborotalia frontosa* (SUBBOTINA) make their appearance in this zone. The zonal markers are the same as for the "*Acarinina*" "*crassaformis*" Zone of Soviet micropaleontologists (Subbotina, 1953; Krasheninnikov, 1969). *Acarinina* "*crassaformis*" *sensu* Subbotina and "*Globorotalia*" *bullbrooki* BOLLI are judged to be junior synonyms of *Truncorotaloides densus* (see Cifelli, 1972).

In the standard zonation of Trinidad (Bolli, 1957b, 1966), the four species mentioned above appear initially in the *Hantkenina aragonensis* Range-zone. *Hantkenina aragonensis* NUTTALL appears to be restricted to a more tropical environment, and is rarely encountered in mid-latitude deposits.

Topotype material from the Woodside Faunule described by Graham and Classen (1955) has yielded a plankton-rich faunule of this zone, which is considered to belong to the Ulatisian Stage (Mallory, 1959, p. 219).

From the Media Agua Creek section, a shale interbed of the lower Point of Rocks Sandstone Member of the "Tejon" formation contains a *Truncorotaloides densus* Zone assemblage (similar to UCMP loc. A-7037, Mallory, 1959, Upper Ulatisian). Similarly, topotype material from the Canoas Siltstone from the Oil City section can be assigned to this zone. The last two localities can be correlated to the *Discoaster sublodoensis* Zone (Hay in Hay *et al.*, 1967; Hay and Mohler, 1967).

Truncorotaloides rotundimarginatus Assemblage-zone (Middle Eocene): This zone is defined by the joint occurrence of *Truncorotaloides rotundimarginatus* (SUBBOTINA), *T. cf. T. topilensis* (CUSHMAN), *Globigerapsis index* (FINLAY), and *Hantkenina dumblei* WEINZIERL & APPLIN subsequent to the last occurrence of *Morozovella aragonensis s.l.* Species from the underlying *Truncorotaloides densus* Zone also present in this zone include *Clavigerinella eocanica* (NUTTALL), *Turborotalia wilsoni* (COLE), *T. frontosa* (SUBBOTINA), and *Pseudohastigerina micra* (COLE) of increased size and abundance.

This assemblage of species is comparable to the *"Acarinina" rotundimarginata* Zone of the north Caucasus (Subbotina, 1953; Krasheninnikov, 1969). *Hantkenina dumblei* WEINZIERL & APPLIN, which has been reported rarely in California Narizian strata, is identical to *H. liebusi* SCHOKHINA as recognized by Soviet micropaleontologists (see Subbotina, 1953, p. 132). In the north Caucasus, *Hantkenina liebusi* is restricted to the *"Acarinina" rotundimarginata* Zone (Krasheninnikov, personal communication). In the Trinidad sequence *Globigerapsis index* (FINLAY) and *Hantkenina dumblei* are reported to make their appearance in the *Globigerapsis kugleri* Zone (Bolli, 1957b).

Several plankton-rich Narizian localities can be assigned to the *Truncorotaloides rotundimarginatus* Zone. In the Santa Barbara Embayment area, the lower Cozy Dell Formation along Las Cruces Road (type for the assemblage-zone) has the most diverse planktonic fauna (same as UCMP loc. A-8862, Sullivan, 1965) including typical *T. rotundimarginatus*, *Turborotalia frontosa* and *Hantkenina dumblei*. Topotype material from the Santa Rosa Road Faunule described by Hornaday (1965) can also be assigned to this zone. Along the western border of the San Joaquin Valley organic shale members of the Kreyenhagen Formation contain planktonic assemblages of the *Truncorotaloides rotundimarginatus* Zone: lower members of the type Kreyenhagen Shale, Garza Creek (Cushman and Siegfus, 1942, members "J", "H", and "G"); type Kellogg Shale and Sidney Flat Shale, Mount Diablo area (Clark and Campbell, 1942).

Globigerapsis semiinvoluta Range-zone (Upper Eocene): From the western Santa Ynez Mountains of the Santa Barbara area, Lipps (1967, p. 996) has recorded several planktonic species from two localities near the top of the Gaviota Formation in Arroyo el Bulito. This planktonic assemblage, rare in numbers and species, contains *Globigerapsis semiinvoluta* (KEIJZER) and other long-ranging Eocene species. In Trinidad, *G. semiinvoluta* is restricted to the Upper Eocene zone bearing its name (Bolli, 1957b, 1966).

CORRELATION WITH WEST COAST MARINE STAGES

Mallory (1959, fig. 7) has illustrated the distribution of his microfaunal stages in a stratigraphic chart for the California lower Tertiary. Similarly, Sullivan (1965, fig. 2) has related his provisional nannoplankton faunizones to Mallory's stage terminology, utilizing many of the same sections and samples available to Mallory. In Figure 3, stage assignments for three important stratigraphic sections have been plotted in relation to the standard zonations for planktonic foraminifera and calcareous nannoplankton.

In comparison, the microfaunal stage boundaries show some inconsistencies when correlated to the planktonic zonations. Only the Ynezian and Narizian stages, the lower and uppermost of Mallory's lower Tertiary stages, demonstrate good correspondence from section to section. The *Globanomalina pseudomenardii* Zone (Upper Paleocene) has its inception within the Ynezian Stage; the base of the Narizian Stage corresponds to the base of the *Truncorotaloides rotundimarginatus* Zone (Middle Eocene) consistently in all sections studied. For intermediate strata correlated to the Bulitian, Penutian, and Ulatisian stages, different zonal assignments occur from section to section. As a result, the available planktonic evidence from the type localities of Mallory's stages is of particular significance in relating the two biostratigraphic schemes.

The papers of Sullivan (1964, 1965) on calcareous nannoplankton provide another source for evaluating the type areas of Mallory's stage succession. His distribution charts of calcareous nannofossils have been utilized in the discussion below concerning the correlation of the California lower Tertiary stages to the standard planktonic zonations (see also Mohler and Hay and Hay *in* Hay *et al* ., 1967; Hay and Mohler, 1967, 1969; Martini, 1971; Berggren, 1972).

Ynezian and Bulitian Stages (type: Arroyo el Bulito, Santa Barbara County; the type zones for these two stages, Media Agua Creek): In the type area of the Anita Formation, Sullivan (1964, p. 168, 173, table 2) has described a nannoplankton-bearing interval designated the South Gully Zonule and the Watershed Faunule. This interval contains foraminifers assignable to theupper zone of Mallory's type Ynezian Stage. The South Gully Zonule can be referred to the *Heliolithus riedeli* Zone, Upper Paleocene, and the Watershed Faunule to the *Discoaster multiradiatus* Zone, Upper Paleocene (Hay and Mohler, 1967, p. 1520-1521). The *Globanomalina pseudomenardii* Zone is known to occur in strata from the lower Anita Formation (Allison, 1964).

Fossil nannoplankton are not reported in the type Bulitian Stage in the interval above the Watershed Faunule and below the limestone lenses in the middle part of the Anita Formation (Sullivan, 1964, p. 168). A sparse nannoplankton assemblage, the Sierra Blanca Faunule, occurs in the sandy limestone lenses which have been correlated to the Penutian Stage (Mallory, 1959, p. 36). This assemblage can be assigned to the *Marthasterites tribrachiatus* Zone (Lower Eocene). Although bracketed between the *Discoaster multiradiatus* Zone and the *Marthasterites tribrachiatus* Zone, the strata of the type Bulitian Stage cannot be assigned definitely to either the

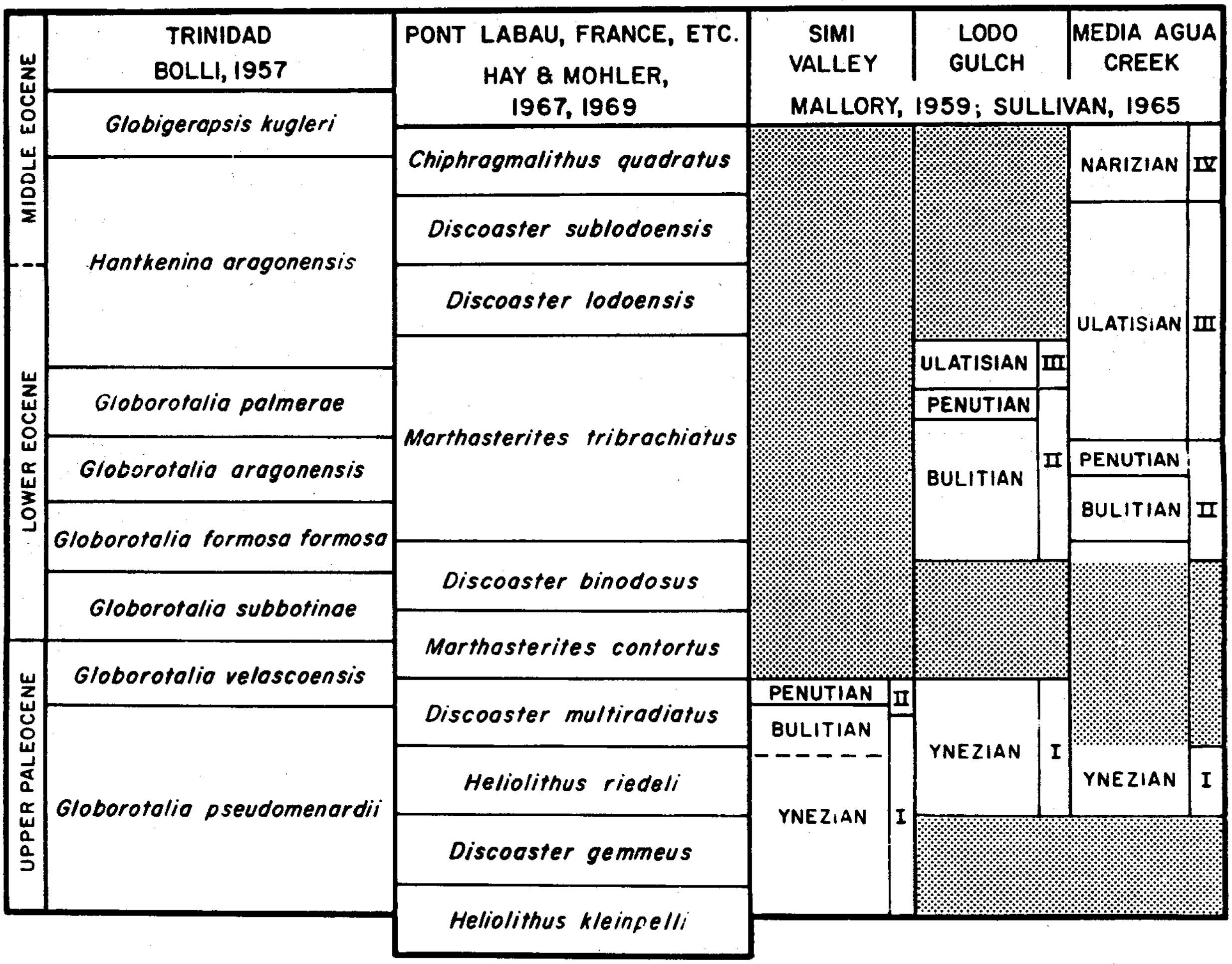


Figure 3

Correlation chart of three important California lower Tertiary sections in relation to planktonic zonations based upon planktonic foraminifera and calcareous nannoplankton. Planktonic foraminifera: this report and correlation to the Trinidad section (Bolli, 1957a,b, 1966; see Fig. 2). Calcareous nannoplankton: Bramlette and Sullivan (1961), Sullivan (1964, 1965), Mohler and Hay and Hay (*in* Hay *et al.*, 1967), Hay and Mohler (1967, 1969).

Upper Paleocene or the Lower Eocene by means of the planktonic evidence presented by Sullivan (1964, 1965). On the basis of detailed sampling in Arroyo el Bulito, Gibson (in press) has shown that the type Ynezian-Bulitian interval can be assigned to the Upper Paleocene both by planktonic foraminifera and calcareous nannoplankton, with the possible exception that the basal Anita strata may be older. It is also important to consider the distribution of plankton at Media Agua Creek, actually the better documented type locality for the 4 oppel-zones recognized in the Ynezian and Bulitian Stages (Mallory, 1959, 1970; see following discussion).

Penutian Stage (type: Media Agua Creek, Fresno County): Mallory's (1959, 1970) samples from the type Penutian Stage are included in the upper part of Sullivan's (1965, p. 9) *Braarudosphaera* Zonule. This calcareous nannoplankton zonule can be assigned to the *Marthasterites tribrachiatus* Zone (Hay and Mohler, 1967, p. 1523). Also Mallory's samples from the type zones of the underlying Bulitian Stage, the *Bulimina bradburyi* Zone and the *Valvulineria wilcoxensis* Zone, belong to the *Braarudosphaera* Zonule, or the lower part of the *Marthasterites tribrachiatus* Zone (Lower Eocene).

As discussed earlier, the type Penutian Stage interval can be assigned to the upper part of the *Morozovella aragonensis* Zone. Also the type zones of the Bulitian Stage belong to the *Morozovella aragonensis* Zone (Lower Eocene). Except for the top three samples (as listed by Mallory, 1959, 1970), the type zones for the underlying Ynezian Stage belong to the *Globanomalina pseudomenardii* Zone (Upper Paleocene).

Ulatisian Stage (type: Ulatis Creek, Solano County): Sullivan (1965, p. 18) has discussed the two stratigraphic units from the "Vacaville" shale that comprise Mallory's type Ulatisian Stage. The lower unit, the "blue-gray mudstone" member (240 feet thick) contains a calcareous nannofossil assemblage designated the Lower "Vacaville" Zonule. The "chocolate-brown silty mudstone" member (80 feet thick) is separated from the lower member by a glauconitic sandstone bed and is barren of microfossils other than arenaceous foraminifers.

In the Lower "Vacaville" Zonule the nannofossil distribution is sparse but characterized by the joint occurrence of *Discoaster lodoensis* and rare *Marthasterites tribrachiatus*. The concurrent-range of these taxa suggests correlation to the upper part of "Biostratigraphic Unit 3" (Bramlette and Sullivan, 1961, p. 135), or the *Marthasterites tribrachiatus* Zone. This biostratigraphic interval from the upper part of the type Lodo Formation contains planktonic foraminifers of the *Globigerapsis senni* Zone (Lower Eocene).

The biostratigraphic assignment of the upper unit of the type Ulatisian Stage, the "chocolate-brown silty mudstone" member, remains equivocal, as it lacks calcareous nannofossils (Sullivan, 1965, p. 19). For the "Vacaville" shale interval, Mallory (1959, p. 40) provides no specific documentation of the two zones in the type Ulatisian Stage. The occurrence of the upper zone of the Ulatisian Stage has yet to be demonstrated in the type section (Sullivan, 1965).

Again, for the Media Agua Creek section, Mallory (1959, 1970) has indicated the distribution of foraminifers in closely spaced stratigraphic sampling. The two zones of the Ulatisian Stage have been distinguished in the upper Lodo Formation and the basal "Tejon" formation, respectively. Sullivan (1965, table 6) has studied the distribution of calcareous nannoplankton from these same samples. For the Ulatisian Stage interval Sullivan's Upper Lodo Zonule and Lower "Tejon" Faunule have been assigned to the upper part of the *Marthasterites tribrachiatus* Zone, to the *Discoaster lodoensis* Zone, and to the *Discoaster sublodoensis* Zone(Hay *in* Hay *et al.*, 1967, p. 438, fig. 7; Hay and Mohler, 1967, p. 1523-1524). These zones indicate a Lower-Middle Eocene transitional sequence.

In terms of the planktonic foraminiferal zonation, Ulatisian strata of the Media Agua Creek section belong to the *Globigerapsis senni* Zone (Lower Eocene) and the *Truncorotaloides densus* Zone (Middle Eocene).

Narizian Stage (type: Devils Den area, Kern County): Calcareous nannofossils have not been studied from the type Narizian section (Sullivan, personal communication). However, in the adjacent section at Media Agua Creek, Sullivan (1965, table 6) has included Mallory's samples, which delineate the transition between the upper zone of the Ulatisian Stage and the lower zone of the Narizian Stage, in his Lower "Tejon" Faunule and Middle "Tejon" Faunule. Hay (*in* Hay *et al.*, 1967, p. 438) has utilized these two faunules for the type reference localities of the *Discoaster sublodoensis* Zone and the *Chiphragmalithus quadratus* Zone, respectively.

In all the six sections studied by Sullivan (1965), the base of Mallory's Narizian Stage corresponds well to the base of his provisional "Faunizone IV" (= *Discoaster sublodoensis* Zone-*Chiphragmalithus quadratus* Zone boundary *sensu* Hay in Hay *et al.*, 1967). This prominent datum is distinguished not only by a distinct turnover in calcareous nannoplankton (Sullivan, 1965, p. 28) but also in species of benthonic foraminifera (Hornaday, 1965, p. 33).

Planktonic foraminifera in several scattered localities suggest that the Lower Narizian- *Chiphragmalithus quadratus* Zone datum conforms to the boundary between the *Truncorotaloides densus* Zone (Middle Eocene) and the *T. rotundimarginatus* Zone (Middle Eocene). The lower Cozy Dell Formation along Las Cruces Road contains the most diverse planktonic foraminiferal assemblage of this zone so far. Other Narizian plankton-rich faunules from the Santa Barbara Embayment area and from the San Joaquin-Sacramento Valley area belong to the *Truncorotaloides rotundimarginatus* Zone.

Narizian Stage (Middle Eocene or Upper Eocene?): In California, the Narizian Stage is traditionally assigned to the Upper Eocene (Mallory, 1959, p. 80; Hornaday, 1965, p. 30). In all Narizian localities studied to date, not one planktonic species has been recovered that is restricted to the Upper Eocene.

It seems that Milow (*in* Milow and Ennis, 1961, p. 32) first put forth the suggestion that most of the West Coast Narizian should be recognized as Middle Eocene (Lutetian). He stated that planktonic foraminifers in the upper units of the Poway Formation, a Narizian equivalent exposed near San Diego, indicate a synchronization well below the top of the Middle Eocene of the Gulf Coast, Mexico, and Caribbean sections. His findings in the San Diego area have been corroborated by Steineck *et al.* (1972).

Bandy and Kolpack (1963, p. 120, text-fig. 4) correlated the Cozy Dell Shale of the Tecolote Tunnel (central Santa Ynez Mountains near Santa Barbara) with the Lutetian Stage (Middle Eocene). They considered the few planktonic species present as diagnostic for the lower part of the Middle Eocene standard planktonic foraminiferal zonation. Steineck and Gibson (1971) have also concluded a Middle Eocene assignment for some Upper Ulatisian and Narizian localities. Upper Eocene is known to be represented in California by strata from the Refugian Stage, as can be determined by planktonic microfossils. Planktonic foraminifera from the type area of the Refugian Stage (Lipps, 1967) and calcareous nannoplankton from the Church Creek Formation, a Refugian equivalent near Monterey (Brabb, Bukry, and Pierce, 1971), indicate independently a Late Eocene Age assignment.

With calcareous nannofossils, it is possible to demonstrate a first-order correlation for Lutetian sediments in the Paris basin and the Upper Ulatisian-Narizian sequence from Media Agua Creek. Calcareous nannoplankton in the type area for the Middle Eocene, described by Bouché (1962), can be assigned to the *Discoaster sublodoensis* Zone (Hay *in* Hay *et al.*, 1967). This standard nannofossil zone has as its typical reference the work of Sullivan (1965) from Media Agua Creek (Upper Ulatisian, sample A-7047). In Belgium the Sands of Wemmel (type Wemmelian Stage, which is generally correlated to the uppermost part, or substage, of the Lutetian sequence) contains a flora assignable to the overlying *Chiphragmalithus quadratus* Zone (or more correctly the *Chiphragmalithus alatus* Zone, Achuthan and Stradner, 1969; Martini, 1971). Similarly, the reference assemblage for this calcareous nannofossil zone (Hay *in* Hay *et al.*, 1967) comes from the Media Agua Creek section (Sullivan, 1965, sample A-7023, Narizian). This forms an unequivocal means for assigning Upper Ulatisian and Narizian strata from California to a Lutetian Stage assignment, and by second-order correlation to the corresponding planktonic foraminiferal zone equivalents (Figures 2,3).

Planktonic foraminifera are not well represented in the shallow-water deposits of the Paris basin and the adjoining North Sea basin. The index species necessary to make an assignment at the zonal level are not present (Bronnimann *et al.*, 1968). However, the species reported show good correspondence to those in the combined *Truncorotaloides densus-T. rotundimarginatus* Zone interval from California.

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Paleogene Lyropectens and Vertipectens from the Transverse and southern Coast Ranges of California

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Paleogene ancestors of the giant pectinids that characterize Miocene megafaunal stages are geographically more restricted than their Neogene descendants. Figure 1 shows the Paleogene/Neogene boundary delineated by species of Vertipecten and Lyropecten, omitting the 8-10 Neogene taxa younger than middle "Vaqueros" stage. The boundary separates the lower and middle parts of the "Vaqueros" megafaunal stage and agrees with the Zemorrian/Saucesian boundary dated as 22.5 m.y. (Turner, 1970). The upper and middle parts of the "Vaqueros" stage are arbitrarily considered Miocene and the lower "Vaqueros" Oligocene, although Vertipecten and Lyropecten species also support a major boundary at the base of the lower "Vaqueros" stage, the Paleogene/Neogene division preferred by Addicott (1974) and Berggren and Van Couvering (1974).

Vertipecten and Lyropecten are of greatest use in correlating shallow neritic deposits in the Santa Ynez Mountains, southern Coast Ranges, northeastern La Panza Range and Channel Islands. They are potentially helpful in interpreting sections in the Caliente Range and the area south of the Cuyama Valley, although several key species are missing there and diagnostic foraminifera are not associated with the pectinids. More evidence is needed to verify what mapping suggests: that in the Cuyama area critical Oligo-Miocene species of Lyropecten and Vertipecten range higher than elsewhere in California (Vedder and Repenning, 1975).

Paleogene giant pectinids that are useful in correlation are illustrated in Plates 1 and 2. The Vertipectens are V. alexclarki Addicott, which is restricted to the Wygal Sandstone Member of the Temblor Formation in the eastern central Temblor Range, V. yneziana (Arnold) and V. perrini (Arnold). V. yneziana occurs in the Santa Ynez Mountains from the middle Gaviota Formation to the Alegria Formation. Higher in the Alegria section there are morphologic forms between the Refugian species V. yneziana and the lower "Vaqueros" index fossil V. perrini, which is abundant in the Vaqueros Formation north of Morro Bay in the vicinity of Morro and Toro Creeks (Prior, 1974). Although V. perrini was reported from the upper members of the Vaqueros Formation at its type locality in the Junipero Serra Peak quadrangle (Thorup, 1943), these specimens are the Neogene species V. nevadanus (Conrad) of the middle "Vaqueros" stage. Comparative morphologic studies of material from the Santa Ynez and southern Coast Ranges and the Poso Creek area northeast of Bakersfield document a phylogenetic progression from V. yneziana to V. perrini to V. nevadanus in about 12-15 m.y.

Paleogene Lyropectens are L. submiguelensis (Loel & Corey) and L. magnolia (Conrad), both of the lower "Vaqueros" stage. L. submiguelensis occurs in the northeastern La Panza Range (M2831) and on Santa Rosa Island (A-311) with Turritella inezana. It is older than the Neogene species L. miguelensis from the upper "Vaqueros" stage and not, as originally described, a subspecies of it.

Lyropecten magnolia has two forms whose chronostratigraphic ranges are not completely known. The "many ribbed form" has 8-9 ribs (Pl. 2, figs. 4, 5) and is commonly associated with Vertipecten perrini in the Santa Ynez, eastern Temblor, and La Panza Ranges. Smaller, 5-6 ribbed specimens of the "Ojai form" (Pl. 2, fig. 3) occur in the Ojai Valley (A-326), Kern River area, San Emigdio Range and Pescadero Beach, San Mateo County. Incomplete stratigraphic data suggest that the "many ribbed form" is lower and middle lower "Vaqueros" stage, except in the Cuyama area where it occurs in rocks mapped as middle "Vaqueros." The few ribbed "Ojai form" is uppermost lower "Vaqueros." The significance of these two forms and the Cuyama area occurrences are under further investigation.

Special problems concerning fossil localities and stratigraphic positions were discussed with Warren O. Addicott, who also offered suggestions on the manuscript, and with J. G. Vedder and T. W. Dibblee, Jr. I thank them all for their help.

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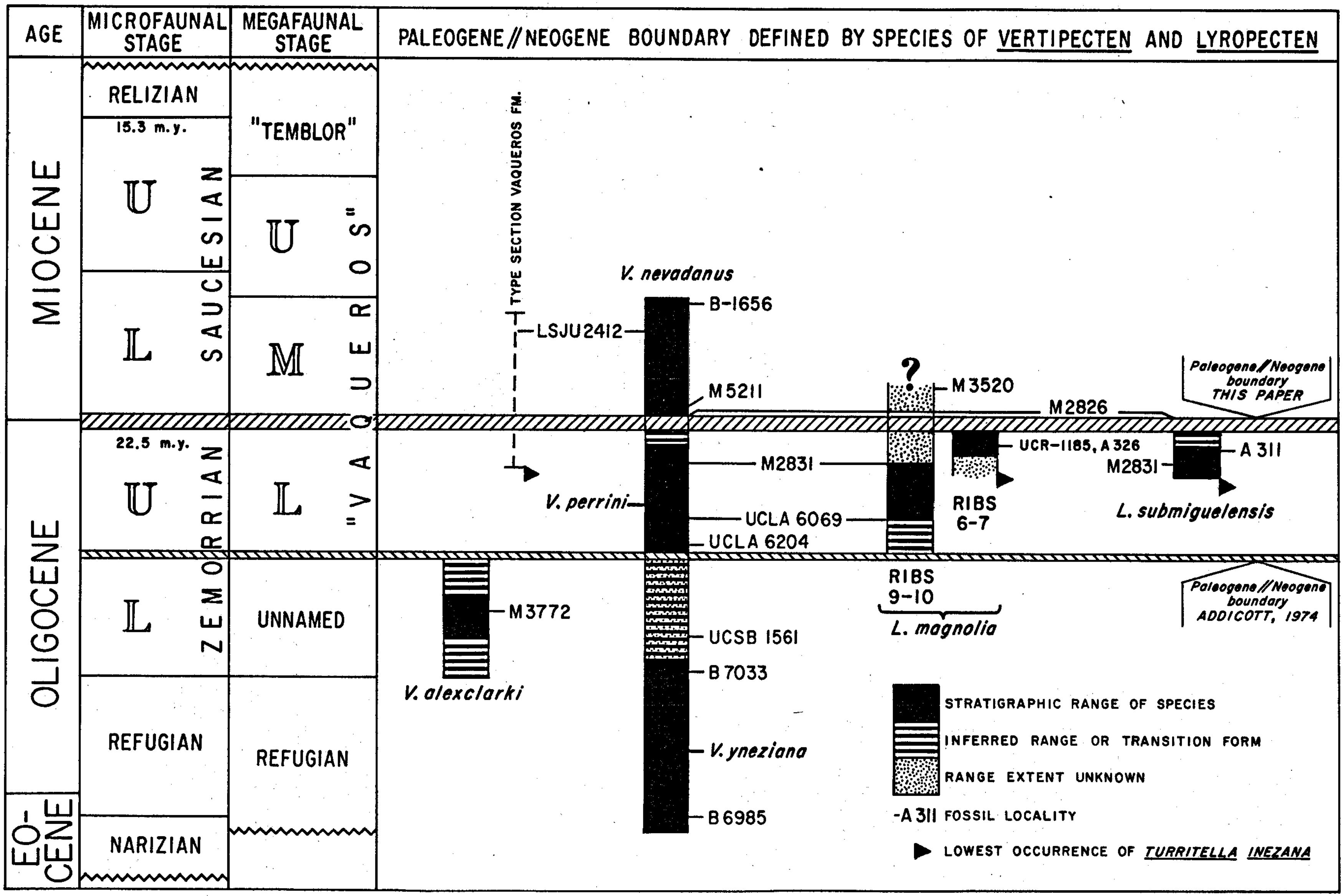
AGE
MICROFAUNAL STAGE
MEGAFAUNAL STAGE
PALEOGENE//NEOGENE BOUNDARY DEFINED BY SPECIES OF VERTIPECTEN AND LYROPECTEN
MIOCENE
OLIGOCENE
EO-CENE
RELIZIAN
15.3 m.y.
U
L
SAUCESIAN
22.5 m.y.
U
L
ZEMORRIAN
REFUGIAN
NARIZIAN
"TEMBLOR"
U
M
"VAQUEROS"
L
UNNAMED
REFUGIAN
TYPE SECTION VAQUEROS FM.
LSJU2412
V. nevadanus
B-1656
M5211
M2831
V. perrini
UCLA 6069
UCLA 6204
UCSB 1561
B 7033
V. yneziana
B 6985
M3772
V. alexclarki
?
M 3520
M2826
UCR-1185, A 326
RIBS 6-7
RIBS 9-10
L. magnolia
A 311
M2831
L. submiguelensis
Paleogene//Neogene boundary THIS PAPER
Paleogene//Neogene boundary ADDICOTT, 1974
STRATIGRAPHIC RANGE OF SPECIES
INFERRED RANGE OR TRANSITION FORM
RANGE EXTENT UNKNOWN
-A 311 FOSSIL LOCALITY
LOWEST OCCURRENCE OF TURRITELLA INEZANA

FIGURE 1

FOSSIL LOCALITIES

Abbreviations:

- A- University of California Museum of Paleontology, Berkeley (UCMP)
- B- University of California Museum of Paleontology, Berkeley
- M- U.S. Geological Survey, Menlo Park Cenozoic locality (USGS)
- LSJU Stanford University
- UCLA University of California, Los Angeles
- UCR University of California, Riverside
- UCSB University of California, Santa Barbara
- USNM United States National Museum, Washington, D. C.

Megafaunal Stage	Locality, all in California
middle "Vaqueros"	B-1656 Kern Co., Knob Hill 7 1/2' qd., sec. 32, T. 27 S., R. 29 E., Freeman-Jewett Silt
	M-2826 San Luis Obispo Co., La Panza 15' qd., Hay Cn., sec. 21, T. 30 S., R. 17 E., Painted Rock Ss.
	M-5211 Kern Co., Rio Bravo Ranch 7 1/2' qd., SW flank of Pyramid Hill, Jewett Sand
	LSJU 2412 Monterey Co., Junipero Serra 15' qd., sec. 3, T. 20 S., R. 6 E., type section Vaqueros Fm.
middle or lower	M-3520 San Luis Obispo Co., Cuyama 7 1/2' qd., sec. 11, T. 10 N., R. 25 W., Vaqueros Fm.
lower "Vaqueros"	A-311 Santa Rosa Island
	A-326 Ventura Co., Matilija 7 1/2' qd., SW of Ojai, NW of mouth of Lion Cn., Vaqueros Fm.
	M-2831 San Luis Obispo Co., La Panza 15' qd., Hay Cn., sec. 21, T. 30 S., R. 17 E., Painted Rock Ss.
	UCLA 6069 San Luis Obispo Co., Cypress Mt. 7 1/2' qd., sec. 4, T. 28 S., R. 10 E., Vaqueros Fm.
	UCLA 6204 Morro Bay No. 7 1/2' qd., between Morro & Toro Cks., sec. 4, T. 29 S., R. 11 E., Vaqueros Fm.
	UCR 1185 Kern Co., Pine Mt. 7 1/2' qd., sec. 4, T. 28 S., R. 29 E., probably Vedder Sand
Unnamed	M-3772 Kern Co., Las Yeguas Ranch 7 1/2 qd., sec. 23, T. 28 S., R. 19 E., Wygal Ss. Mbr., Temblor Fm.
Refugian	UCSB 1561 Santa Barbara Co., Sacate 7 1/2' qd., Santa Anita Cn., Alegria Fm.
	B-7033 Santa Barbara Co., Sacate 7 1/2' qd., ridge between W. branches of Cuarta Ck., Alegria Fm.
	B-6985 Santa Barbara Co., Los Olivos 15' qd., above Gaviota Cn in Nojoqui Ck., Gaviota Fm.

PLATE I EXPLANATION

Figs.

1, 3 Vertipecten nevadanus (Conrad). Left, right valves, respectively. Hypotype USNM 647085 from M-5211, Pyramid Hill, Kern County, lower Miocene, middle "Vaqueros" stage Jewett Sand. Type species of Vertipecten. Good example of Vertipecten right valve hinge and byssal area. Height 12.3 cm, length 12.2 cm.

2 Vertipecten nevadanus (Conrad). Interior hinge of a specimen from M-1561, Pyramid Hill, Jewett Sand. Note smooth cardinal area, absence of teeth, in contrast to Lyropecten hinge (Pl. II, fig. 6).

4, 5 Vertipecten perrini (Arnold). Posterior view, left valve, respectively, of holotype LSJU 13 from upper Oligocene, lower "Vaqueros" stage. Locality interpreted to be UCLA 6204, north of Morro Bay, San Luis Obispo County, Vaqueros Formation. Side view shows typical Vertipecten profile: flat right valve, convex left valve. Compare equally convex valves of a typical Lyropecten (Pl. II, fig. 7). Height 15 cm, length 16 cm.

6 Vertipecten yneziana (Arnold). Left valve of hypotype LSJU 9262 from Eo-Oligocene, Refugian or upper Narizian stage. UCMP locality B-6985, Lompoc quadrangle. Gaviota Fm. Height 9.5 cm, length 9.8 cm.

7 Vertipecten alexclarki Addicott. Left valve of holotype USNM 646529 from the lower Oligocene unnamed stage, USGS locality M-3772, east side central Temblor Range. Wygal Sandstone Member of the Temblor Formation. Note fine microsculpture, narrow umbonal angle restored from another specimen. Height 8.2 cm, length 6.3 cm.

Note phylogenetic progression from V. yneziana to V. perrini to V. nevadanus, figs. 6 to 5 to 1, in about 12-15 m.y.

Photographs by Kenji Sakamoto, U.S. Geological Survey, Menlo Park, California.

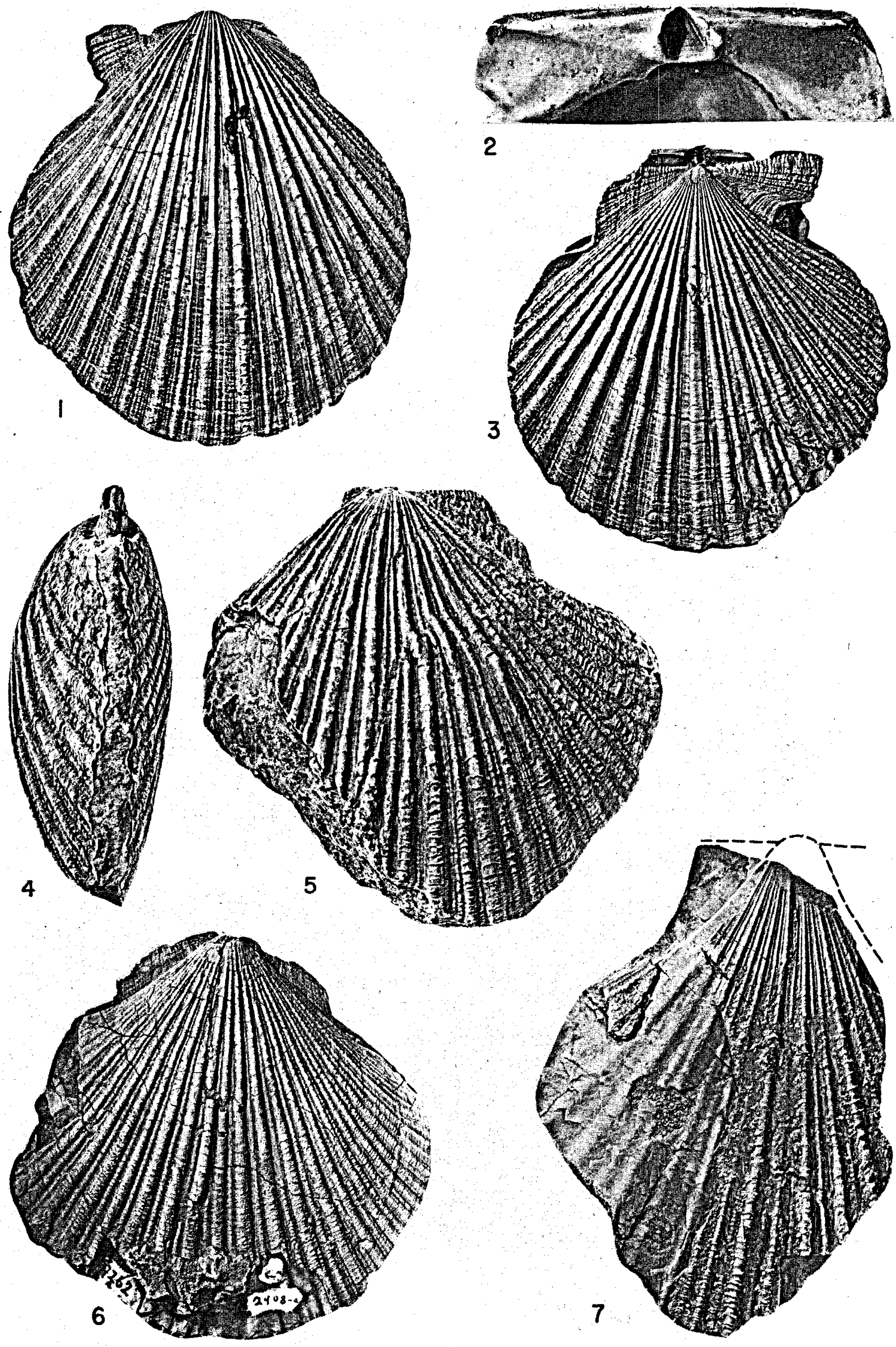

PLATE I

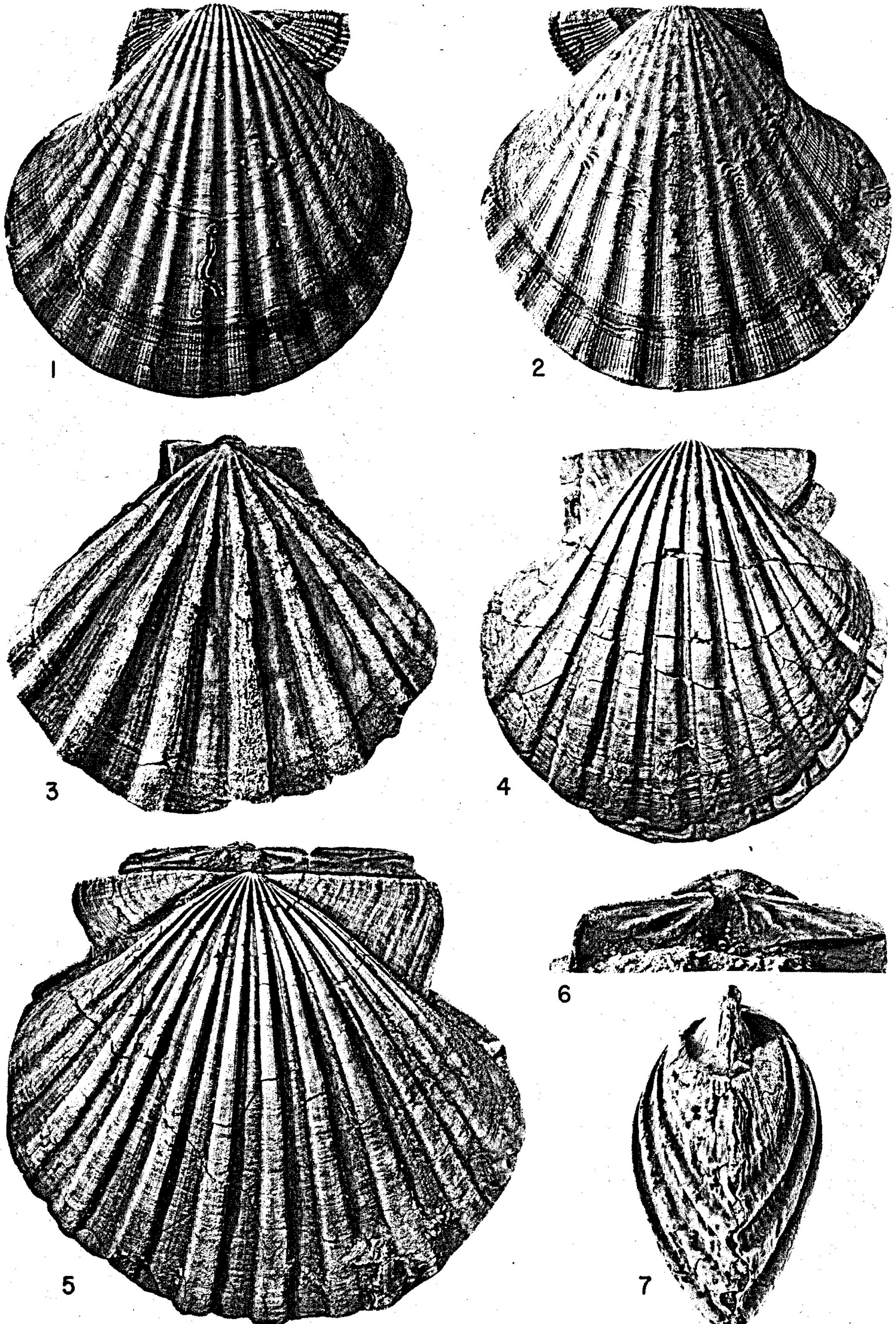

PLATE II

PLATE II EXPLANATION

Figs.

1, 2 Lyropecten submiguelensis (Loel & Corey). Right, left valves, respectively, of holotype UCMP 31737 from upper Oligocene lower "Vaqueros" stage. UCMP locality A-311, Santa Rosa Island. Vaqueros Formation. Height 6.7 cm, length 7 cm.

3 Lyropecten magnolia (Conrad). Few ribbed "Ojai form, left valve of hypotype UCMP 31734. Upper Oligocene, uppermost lower "Vaqueros" stage. UCMP locality A-326, Ojai Valley. Vaqueros Formation. Height 9.7 cm, length 10.9 cm.

4, 5 Lyropecten magnolia (Conrad). Many ribbed form, right and left valves, respectively. Upper Oligocene, lower "Vaqueros" stage. Possibly middle "Vaqueros" in the Cuyama area. USGS locality M-3520, Caliente Range. Vaqueros Formation. Height 14.5 cm, length 17 cm. Hypotype USNM 647534.

6 Lyropecten estrellanus (Conrad). Interior hinge of holotype USNM 13317, type species of the genus Lyropecten. Upper Miocene, Santa Margarita Formation, San Juan River area, San Luis Obispo County. Hinge length 5 cm. Note prominent cardinal teeth.

7 Lyropecten magnolia (Conrad). Side view of a specimen showing typical Lyropecten profile, right and left valves equally convex.

AGE, CORRELATION, AND POSSIBLE TETHYAN AFFINITIES OF MOLLUSKS FROM THE LODO FORMATION OF FRESNO COUNTY, CALIFORNIA

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INTRODUCTION

Marine mollusks from the basal Lodo Formation were examined by Anderson and Pack (1915:66-67), White (1939), Stewart (see Schoellhamer and Kinney, 1953), and Terry (1964). This paper lengthens to 65 the list of known megainvertebrate species and singles out significant age and stage indicators. Besides the main locality, LSJU 2073 = UCMP A-9717, 10 others are discussed, all of which at one time or another have been considered basal Lodo. However, the presence of the gastropod *Cophocara stantoni* Stewart at 4 of these localities in the Chounet Ranch quadrangle suggests that those beds are Cretaceous, and referrable to either the lower part of the Laguna Seca Formation or the Cima Sandstone Member of the Moreno Formation.

Mapping Upper Cretaceous and basal Tertiary beds in the Chounet Ranch quadrangle is difficult because of the scarcity of megafossils, the lithologic similarity of rock types, and the obliteration of outcrops by soil cover and bulldozers prospecting for gypsum. Attempts to recollect fossils from Chaney Ranch, Marca and Gres Canyons were unsuccessful despite the presence of good material in the collections of the University of California Museum of Paleontology and Stanford University.

Stratigraphic problems which the Lodo fossils may help solve include the relations between the Lodo, Laguna Seca, and Moreno Formations and delineation of the Cretaceous/Paleocene boundary in this part of California. Mollusks from the type area of the Laguna Seca Formation in the Ortigalita Peak quadrangle indicate that it spans the Cretaceous-Paleocene boundary. In Rattlesnake Canyon fossils 50 feet above the base of the Laguna Seca are Cretaceous; in Laguna Seca Creek, in the middle part of the formation, Paleocene fossils are present.

Finally, many Lodo mollusks are remarkably similar to those in the Kincaid Formation of the Gulf Coast lower Midway Group and to Thanetian Stage assemblages of the Paris Basin. On first sight, the Lodo species appear Tethyan, related to taxa of the Paleogene Mediterranean and Indo-European province. Closer study shows that the similar forms (genera and in some cases, species) are not Tethyan but cosmopolitan taxa of Paleocene age, referable to a more northerly, warm temperate paleozoogeographic province.

LOCALITY DATA AND FOSSIL OCCURRENCES

Figures 1 and 2 show localities in sections from the Tumey Hills and Chounet Ranch quadrangles. Four localities originally reported as Lodo or Laguna Seca Formation (Payne, 1951) yielded Cophocara stantoni Stewart (Pl. II, figs. 17, 18), which is a Maastrichtian fossil (Saul, oral commun., 1975) found also in the basal Laguna Seca in Ortigalita Peak quadrangle (UCMP A-6607). One locality in Gres Canyon (UCMP D-6356) yielded many of the same species found in the basal Lodo, but its lithology suggests the Laguna Seca Formation.

The most important assemblage of Lodo mollusks occurs in the Tumey Hills quadrangle at LSJU 2073 = UCMP A-9717, in the bluff east of Panoche Road, about 1/4 mile south of the junction between Panoche and Silver Creeks (Stop 1 on SEPM field trip, fall, 1974). Most of the fossils are fragmented, chalky, and poorly preserved, although collections by White in 1939 yielded some outstanding specimens. This locality represents the basal 30 feet of section in an area where the Lodo is 1,197 feet thick (Schoellhamer and Kinney, 1953). Figure 1 shows the outcrop and the basal lithologic sequence that can be traced southeast along strike at least as far as the type locality of the Lodo (LSJU M-74), in the 1-X section of Martin (1943), just south of Lodo Gulch (White, 1938). The section at LSJU 2073 is Cretaceous Moreno shale (purplish-chocolate mudstone chips), unconformably overlain by a fossiliferous glauconitic sandstone, well-sorted unfossiliferous grey sand, and an upper marly fossiliferous sand that weathers to a yellow concretionary ledge. This lithologic sequence is repeated in the basal type Lodo but the concentration of mollusks is lacking from the sandy layers. Here the rich shallow neritic assemblage of LSJU 2073 is represented by only scattered, leached solitary corals (mainly Trochocyathus zitteli), small oysters, and small venerid clams.

Northwest of LSJU 2073, across Panoche Creek on the southeastern flank of the Panoche Hills, are 2 localities bearing basal Lodo mollusks, LSJU 454 and CAS 31318. Two hundred feet stratigraphically below the latter is CAS 31318a, described on specimen labels as "The lowest sandstone reef above the Moreno." Fossils from CAS 31318a differ from the basal Lodo assemblage at the other 2 localities; tentative identifications suggest that the assemblage is Cretaceous or Paleocene older than the assemblage at LSJU 2073. The material is well preserved and merits further collection and study.

AGE AND CORRELATION OF THE BASAL PART OF THE LODO FORMATION

Mollusks present at the base of the Lodo Formation are Paleocene, lower Martinez megafaunal stage species. They are not Paleocene to Eocene in age as commonly reported (Mallory, 1959), but many forms are ancestral to Eocene species and morphologically similar to them (for example, "Polinices" susanaensis in the Lodo, and "P." hornii in the Meganos). Diagnostic Martinez stage indicators are starred in Table 1. The Martinez zones recognized by Dickerson (1914)--Meretrix dalli, Trochocyathus zitteli, and Solen stantoni--are not separable in the basal Lodo, where most of the species from all of the zones occur

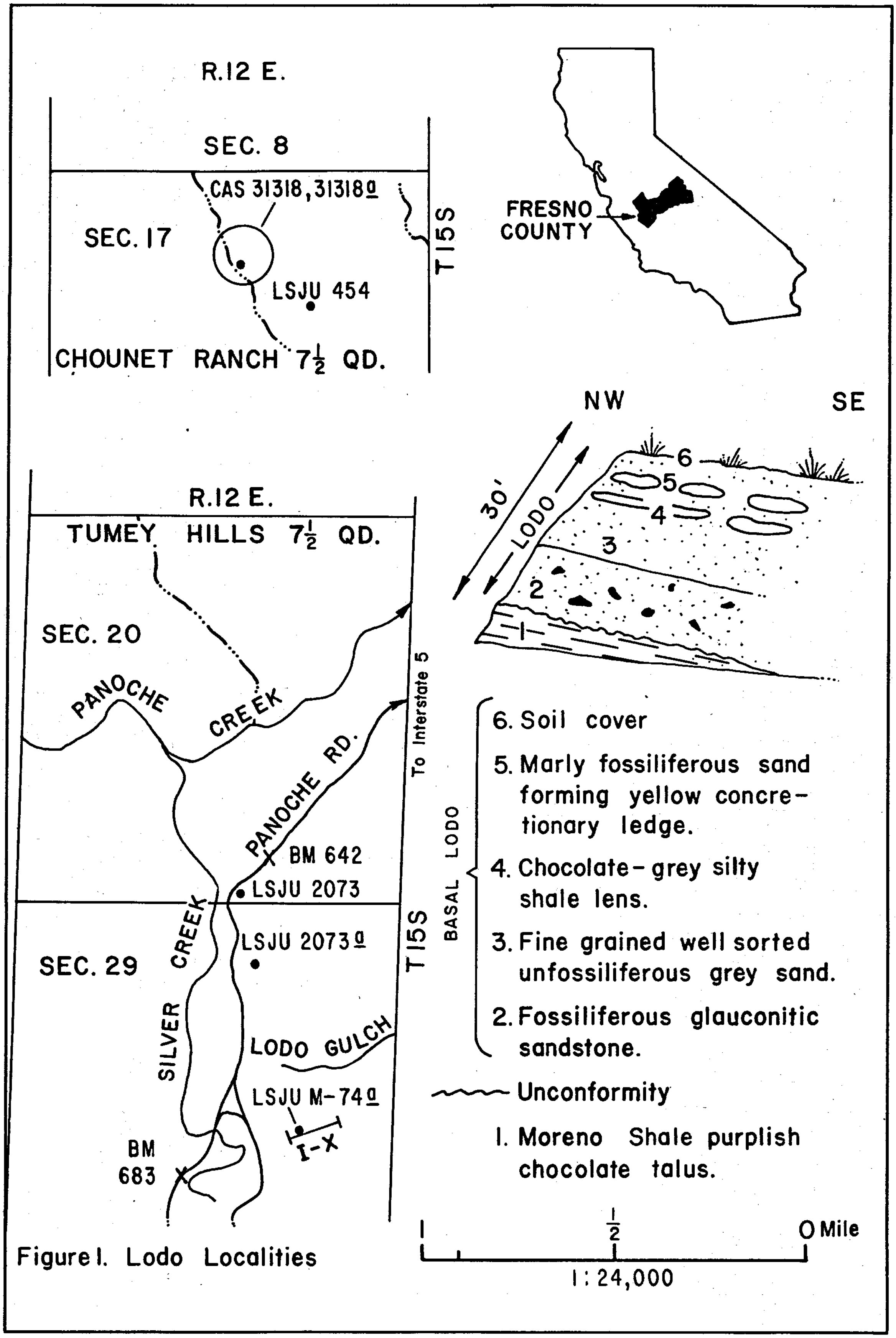

Figure I. Lodo Localities

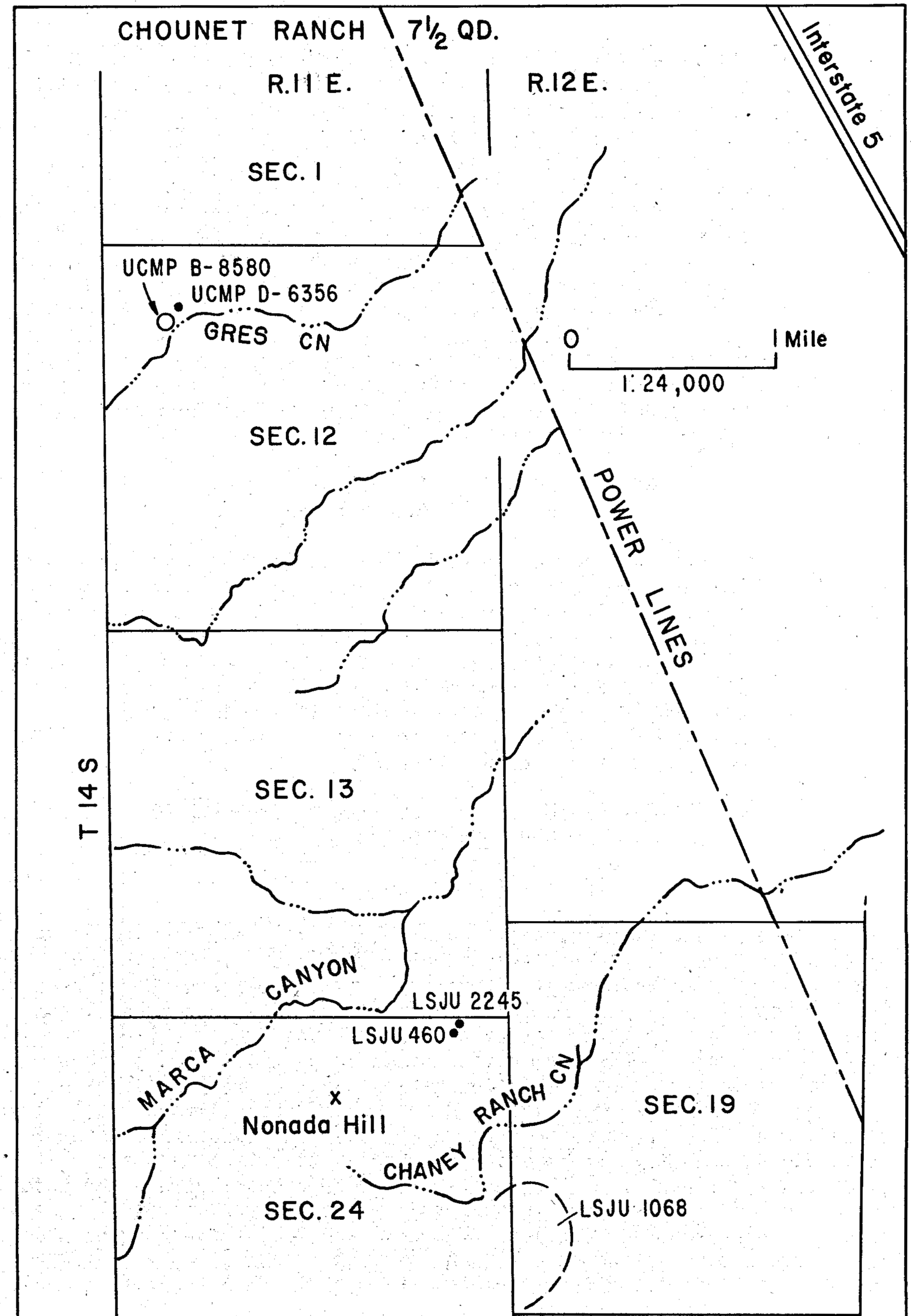

Figure 2. Northern Chounet Ranch Localities

together. Calcareous foraminifera occurring with the mollusks at LSJU 2073 are Ynezian (Mallory, 1959:91) The molluscan assemblage at LSJU 2073 is equivalent in age to that of the middle Laguna Seca Formation at its type locality in Laguna Seca Creek (UCMP A-6604), although lithologically the Laguna Seca represents a shallower shelf deposit (Briggs, 1953:38). The basal Laguna Seca Formation in Rattlesnake Canyon (UCMP A-6607) is Cretaceous, probably Maastrichtian, based on the presence of Cophocara stantoni and a fasciolariid gastropod also found in 4 localities in the Chounet Ranch quadrangle. The only basal Lodo-middle Laguna Seca molluscan assemblage known from the Chounet Ranch quadrangle north of Escarpado Canyon is from Gres Canyon (UCMP D-6356), less than 200 feet geographically from UCMP B-8580, which yields Cretaceous, basal Laguna Seca molluscan species. It remains for field mapping and foraminiferal studies to determine whether these Cretaceous beds should be assigned to the Laguna Seca Formation or the Cima Sand Member of the Moreno Formation.

MODE OF DEPOSITION OF THE BASAL LODO AS IMPLIED BY THE MOLLUSCAN FAUNULE

The molluscan assemblage at LSJU 2073 consists of warm temperate to subtropical shallow neritic to sublittoral species which live on a sandy substrate. Except for the basal fossiliferous sands the Lodo Formation in this area consists of 1,160 feet of deep-water mudstones that thin to the northwest (Schoellhamer and Kinney, 1953). The sandy horizon bearing the shallow-water mollusks can be traced over at least 3/4 mile, although the megafaunal assemblage itself is restricted to less than 1/4 mile. This localized occurrence suggests deposition by currents, perhaps in a submarine canyon.

MEGAINVERTEBRATES IDENTIFIED FROM THE BASAL LODO AND SUBJACENT UNITS

(Plates I, II, Tables 1, 2)

Plates I and II illustrate some typical Lodo species as well as distinctive but only tentatively identified forms. Identifications were made primarily from the literature, in some cases with reference to type specimens. New species are not formally described here, and tentative names are given for taxa currently undergoing systematic revisions (turrids, Hickman; naticids, Marincovich). Some of the commonest, most diagnostic Martinez taxa (e.g., "Meretrix" stantoni) have been generically misidentified in most of the California Tertiary literature. As they require systematic revision beyond the scope of this paper, such taxa are listed in quotes. Asterisks mark the most important Martinez stage indicators. One difference between the Lodo and other Martinez stage assemblages is the absence of infaunal genera such as Solen and the nuculids. Tables 1 and 2 list the 54 gastropods, 20 pelecypods, 2 scaphopods, 1 nautiloid cephalopod, 3 corals, and 3 brachiopods identified from the basal Lodo and from 6 localities formerly identified with the Lodo but now recognized as older.

TABLE 1.--SPECIES FROM THE BASAL PART OF THE LODO FORMATION, LOCALITIES LSJU 2073 = UCMP A-9717, LSJU 454, LSJU M-74a.

* denotes Martinez stage indicator
\+ denotes species illustrated in this paper
" " indicates that generic taxonomic assignment is incorrect or questionable

Many minute gastropod species were present at LSJU 2073 but not identified for this paper.

Gastropods

Macrarene sp.
*+Turritella infragranulata Gabb, 1864
*+Turritella pachecoensis Stanton, 1896
Turritella reversa Waring, 1917
+Turritella stocki Merriam, 1941
+Metacerithium packardi Nelson, 1925
+Epitonium n. sp.
(? Epitonium aff. E. cookii Gardner, 1933)
Calyptraea diegoana (Conrad, 1855)
[= C. calabasasensis Nelson, 1925]
Calyptraea sp. cf. C. mammilaris Broderip, 1835
+Polinices susanaensis Nelson, 1925
Polinices sp. cf. P. nuciformis (Gabb, 1864)
Polinices sp. aff. P. rectus Tegland, 1933
+"Polinices" sp. cf. "P." pinyonensis Dickerson, 1914
"Ampullella sp. cf. A. schencki Vokes, 1939"
Crommium andersoni (Dickerson, 1914)
Lacunaria sp. aff. L. striata (Gabb, 1866)
+Cypraea n. sp.
+Gisortia sp. cf. G. clarki Ingram, 1940
*Priscoficus caudata (Gabb, 1866)
"Fusitriton" sp. aff. Murex (Argobuccinum) mansfieldi Gardner, 1933
"Ranellina" sp. aff. R. pilsbryi Stewart, 1927
+Colubraria (Colubraria) n. sp.
+Typhis n. sp.
Latirus sp. cf. L. roseburgensis Hendon in Turner, 1938
Latirus sp.
"Latirus" buwaldana (Dickerson, 1915) [Whitneyella auctt.]
"Fusinus" simiensis Nelson, 1925
Fusinus calabasensis Nelson, 1925
+Columbarium sp.
"Exilia" sp. cf. E. talliaferroi Vokes, 1939
*Brachysphingus liratus (Gabb, 1864)
*Brachysphingus sinuatus Gabb, 1866
*"Neptunea" mucronata Gabb, 1866
Olivella mathewsonii Gabb, 1864
Olivella sp.
+Pseudoliva sp. [not P. inornata Dickerson or P. howardi (Dickerson)]
+Pseudoperissolax blakei subsp. praeblakei Vokes, 1939
*Retipirula crassitesta (Gabb, 1866)
*+Heteroterma striata Stanton, 1896

Heteroterma trochoidea Gabb, 1866
+"Surculites" mathewsonii (Gabb, 1864)
*"Surcula" merriami Dickerson, 1914
+"Turricula" sp.
+"Turricula" waringi Nelson, 1925
turrid, "Turritella martinezensis Gabb" of Waring, 1917
+Pleurofusia sp. aff. P. fresnoensis (Arnold, 1910)
Pleurofusia sp.
*Tornatellaea pinguis (Gabb, 1864)
Gilbertia sp.
Cylichnina sp. cf. C. tantilla (Anderson & Hanna)
Physa sp.

Scaphopods

Dentalium cooperi Gabb

Pelecypods

Acila (Truncacila) decisa (Conrad, 1855)
*+Cucullaea mathewsonii Gabb, 1864
*Glycymeris veatchii major (Stanton, 1896)
+Brachidontes lawsoni (Nelson, 1925)
+Crassatella compacta Gabb, 1866
+Crassatella sp.
"Cyrena" sp. cf. C. studleyi (Dickerson, 1914)
*+Eomiltha turneri (Stanton, 1896)
+Saxolucina sp.
*+"Meretrix" stantoni Dickerson, 1914
+Venericardia keenae Verastegui, 1953 = V. argentea Verastegui, 1953
+Venericardia mulleri Verastegui, 1953
"Arctica" weaveri (Dickerson, 1914)
[= Spisula (?) weaveri n. sp. Packard of Dickerson, 1914]

Brachiopods

Eogryphus sp. cf. E. tolmani Hertlein and Grant, 1944
brachiopod sp. represented by 2 brachial valves, long muscle scars

Corals

*Flabellum remondianum Gabb, 1864
Deltocyathus whitei Durham, 1943
oculinid coral, Archoheia sp. ?

LSJU M-74a, basal 20 ft of Lodo Formation at its type locality, the I-X section of Martin, 1943

Acila sp.
disarticulated oysters
leached, disarticulated small clams
*Trochocyathus zitteli (Vaughan, 1900)
small, solitary coral

LSJU 454

Eomiltha turneri (Stanton, 1896)
oysters
Terebratulina tejonensis waringi Hertlein and Grant, 1944

TABLE 2.--SPECIES FROM LOCALITIES IN THE CHOUNET RANCH QUADRANGLE, FROM THE LODO FORMATION AND SUBJACENT UNITS.

+ denotes species illustrated in this paper

LSJU 460

+Cophocara stantoni Stewart, 1927
Brachysphingus sp.
Pseudoliva sp.
Fasciolariid gastropod sp. a
? "Dosinia milthoidea" Waring, 1917

LSJU 1068

Cophocara stantoni Stewart, 1927
Tornatellaea sp., cf. T. pinguis Gabb, 1864
Fasciolariid gastropod
Pseudoperissolax blakei (Conrad, 1855)
small, solitary corals

LSJU 2245

+Cophocara stantoni Stewart, 1927
Brachysphingus sp. ?
Fasciolariid gastropod mold

UCMP D-6356

Brachysphingus sinuatus Gabb, 1866
Tornatellaea pinguis Gabb, 1864
Nucula sp.
Nuculana sp.
Yoldia sp.
Cucullaea mathewsonii Gabb, 1864
Solen sp.
coral, Astrocoenta sp.

UCMP B-8580, Gres Canyon, Chounet Ranch quadrangle

Cophocara stantoni Stewart, 1927
naticid juv. ?
Fasciolariid gastropod sp. a

CAS 31318

Olivella mathewsonii Gabb, 1864
Eomiltha turneri (Stanton, 1896)
many unidentified minute gastropods
nautiloid, Eutrephoceras stephensoni (Dickerson, 1914)
internal mold of a heart urchin
Trochocyathus zitteli (Vaughan, 1900) mold
seed

CAS 31318a

Brachysphingus sp.
"Neptunea" sp. aff. "N. mucronata" Gabb, 1866
Tornatellaea sp. cf. T. pinguis Gabb, 1864
Opisima ? cf. O. pacifica Anderson, 1958
+Acila (Truncacila) sp., not A. (T.) decisa (Conrad, 1855)
"Semelid" clam, cf. "Semele" packardi (Dickerson, 1914)
Teredo ridden wood fragment
Dentalium sp.
brachiopod, Eogryphus sp. ?
"Rhynconella (?) sp." Dickerson, 1914

CORRELATION OF THE LODO FORMATION WITH THE GULF COAST MIDWAY GROUP

Dickerson (1914:117-120) discussed genera common to the Martinez and Midway Formations and concluded that the Martinez stage was partly equivalent to and partly older than the Midway. Dickerson compared Martinez specimens with figures of Midway taxa, correlating genera rather than species. For the present study, congeneric, possibly conspecific, forms were compared using Lodo specimens and Gardner's monograph (1933). Taxonomic affinity seems greater between Lodo and Kincaid Formation mollusks of the lower Midway stage than between Lodo and upper Midway Wills Point Formation taxa. In the absence of readily available Midway collections, no attempts were made to tabulate percentages of species in common with the Lodo or to test Dickerson's claim that the Martinez stage is in part older than the lower Midway. The close affinity of many species is remarkable, however, considering the absence of known Paleocene dispersal routes between the Gulf of Mexico and California north of the area between Guatemala and Panama.

POSSIBLE AFFINITIES BETWEEN LODO, NORTHERN EUROPEAN, AND TETHYAN FAUNAS

At first perusal of literature on Paleogene mollusks, a number of Lodo species look very similar to Paris Basin and Mediterranean (Tethyan) forms, a correspondence with interesting implications for the extent of the east-west trending Tethyan sea in the Paleocene.

The presence of Tethyan genera in the Eocene of the eastern and southern United States (especially in marly units) was discussed by Palmer (1957). Some of the same genera have also been reported from California (Palmer, 1957, 1967). The most diagnostic Tethyan taxa, such as the neritid gastropod Velates, occur in the upper Eocene of Florida, the lower Eocene Llajas and the middle Eocene Domengine Formations of California. The absence in California of diagnostic Tethyan genera older than early Eocene suggests that the Lodo mollusks with European affinities are cosmopolitan warm-water taxa rather than Mediterranean and Indo-European Tethyan forms.

Before discussing the relation between Lodo and European mollusks, it is important to consider the extent of the Paleocene Tethyan Sea in the Mediterranean region. During the Paleocene epoch, a period of transgression in western Europe (Gignoux, 1955:474-476), the Tethys was connected by a narrow strait to Nigeria (Adegoke, 1972) but did not extend as far north as the Paris Basin, which was inundated from the northwest by a warm temperate, possibly subtropical sea. Some of the Paleocene cosmopolitan mollusks that inhabited that sea remained there through the middle Eocene, when the Tethys was connected to the Paris Basin. As a result, the Lutetian stage fauna of the Paris Basin is a mixture of cosmopolitan warm temperate and Tethyan subtropical species. In California faunas from the middle Eocene Domengine Formation and lower Eocene Llajas Formation are also of mixed origins, having North American, cosmopolitan, and Tethyan elements. Typical Tethyan mollusks include the following: Velates, Batillaria, Eovasum, Calyptraphorus, Vulsella, Terebellum, Carolia, Clavilithes, Campanile, and Gisortia (Palmer, 1967). Of these, only Gisortia occurs in the Lodo, in a form very different from the Tethyan Gisortia s.s.

The Lodo fauna, therefore, is not Tethyan, although it includes elements of a warm, widespread Paleocene sea. It lacks the true Tethyan Paleogene markers although it contains large numbers of forms also found in the Paris Basin. Some of these genera, Cucullaea, Glycymeris, Brachidontes, Eomiltha, for example, are known from at least the Cretaceous of western North America, indicating a cosmopolitan distribution for some of the Lodo taxa before the Paleocene. It is remarkable how very close, almost conspecific in some cases, the Lodo and Paris Basin Paleocene forms are. As recognized by Weaver (1905), the Martinez fauna corresponds to that of the Thanet Sands and the Bracheux Beds, a correlation shared by the mollusks from the basal part of the Lodo Formation. Table 3 lists some of the Lodo species that are closely related to taxa from the Bracheux Sands, sables de Rilly, and "sable inférieur" which crop out northwest and northeast, respectively, of Paris near the towns of Beauvais, Châlons-sur-Vesle, Noailles, Oise, Jonchery (Farchad, 1936). There are more pelecypods than gastropods in common between the Lodo and Bracheux assemblages. There are more gastropod but fewer pelecypod species and individuals in the basal Lodo Formation, but more pelecypods in the Bracheux sands.

TABLE 3.--SOME CONGENERIC. IN SOME CASES CONSPECIFIC, MOLLUSKS OCCURRING IN THE LODO FORMATION IN FRESNO COUNTY AND THE BRACHEUX BEDS IN THE NORTHERN PARIS BASIN. LIST COMPILED FROM SPECIMENS IN THE CLOEZ COLLECTION, UNIVERSITY OF CALIFORNIA MUSEUM OF PALEONTOLOGY, AND THE STAADT COLLECTION, STANFORD UNIVERSITY, AS WELL AS FARCHAD (1936) AND COSSMANN (1895-1925). LOCALITY DATA REGISTERED AT THE UNIVERSITY OF CALIFORNIA MUSEUM OF PALEONTOLOGY, BERKELEY.

Lodo--LSJU 2073 = UCMP A-9717	Bracheux Sands	Loc.
"Arctica" weaveri (Dickerson, 1914) ["Spisula (?) weaveri Packard of Dickerson]	Meretrix (Pitaria) obliqua (Deshayes)	UCMP B-7178
Cucullaea mathewsonii Gabb, 1864	Cucullaea incerta Deshayes	UCMP B-5406
"Cyrena" sp. cf. "C." studleyi (Dickerson, 1914) [corbiculid clam]	Cyrena cuneiformis	UCMP D-2213
Eomiltha turneri (Stanton, 1896)	"Lucina" contorta Defrance	(Farchad, 1936)
Crassatella compacta Gabb, 1866	Crassatella bellovacina (Deshayes)	UCMP D-2216
Glycymeris veatchii major (Stanton, 1896)	Glycymeris terebratularis (Lamarck)	UCMP B-7195
Venericardia mulleri Verastegui, 1953	Venericardia petuncularis Lamarck	
Tornatellaea pinguis (Gabb, 1864)	Tornatellaea parisiensis Deshayes	
Gilbertia sp.	Gilbertia sp.	

Figure 3 indicates stage correlations based on the basal Lodo mollusks and the Bracheux assemblage. It is hoped that specimens from rocks stratigraphically lower than the Lodo can be identified and used to locate more precisely the Danian/Martinez stage boundary in the eastern Panoche Hills (see Hornaday, 1974).

SUMMARY

Although the fossiliferous layers at LSJU 2073 are not geographically extensive, they fix the base of the Lodo Formation as Paleocene in age, lower Martinez stage, the equivalent of the Thanetian stage Bracheux beds of the northern Paris Basin. The Lodo mollusks are shallow neritic to sublittoral, mainly sandy substrate forms, and their geographically

FIGURE 3.--POSITION OF MOLLUSK-BEARING BASAL LODO SANDSTONES WITHIN MEGAFAUNAL STAGES OF CALIFORNIA AND EUROPE.

	California megafaunal stage	Localities in SE Panoche Hills area	Paris Basin Formation	European megafaunal stage
	Domengine			Lutetian
lower Eocene	Capay			Ypresian
	Meganos			
Paleocene	Martinez	LSJU 2073 (mollusk-bearing basal Lodo sands) and UCMP D-6356	Bracheux Sands	Thanetian
				Montian
	Danian	??CAS 31318a		Danian
Cretaceous	Maastrichtian	LSJU 460, LSJU 1068, LSJU 2245, UCMP B-8580, UCMP A-6607, *Cophocara stantoni*-bearing sandstones and conglomerates		Maastrichtian

restricted occurrence at the base of a sequence of deep-water mudstones suggests localized deposition by currents. They serve as an important reference point for unravelling the biostratigraphic relations between the Cretaceous and Paleocene, Danian and Martinez boundaries in the eastern Panoche Hills area, where formations mapped as Moreno, Laguna Seca, and Lodo have yet to be delineated.

ACKNOWLEDGMENTS

It is a pleasure to acknowledge the help of the following: J. Wyatt Durham, for discussions of faunas, localities, and literature; J. H. Peck and Jean Durham, for loans of material from the collections of the University of California Museum of Paleontology and California Academy of Sciences, respectively; Louie Marincovich and Carole J. Hickman for taxonomic help; T. W. Dibblee, Jr., for discussions of stratigraphic units; A. Myra Keen, my advisor for a master's thesis on the Lodo faunule, for continued interest, encouragement, and help with identifications.

PLATE I

All specimens from the Lodo Formation, LSJU 2073 = UCMP A-9717

Figure 1. Metacerithium packardi Nelson, 1925, juv. UCMP hypotype 14196. Ht. 1.2 cm.

2. Columbarium sp., abapertural view of specimen characterized by flat triangular spines on the keel. LSJU hypotype 10224. Ht. 2.4 cm.

3, 6. Turritella pachecoensis Stanton, 1896. 3, LSJU hypotype 10244, ht. 5.2 cm. (growth line inked in). 6, UCMP hypotype 14197, ht. 6.8 cm.

4. Turritella infragranulata Gabb, 1864. Abapertural view of LSJU hypotype 10225. Ht. 7.9 cm.

5. Turritella stocki Merriam, 1941. LSJU hypotype 10226. Ht. 4.2 cm.

7. Turricula sp. Side view showing turrid notch in an incomplete specimen. LSJU hypotype 10227. Ht. 4.5 cm.

8. Turricula sp. May be a younger individual of the same species as Fig. 7. Abapertural view of UCMP hypotype 14198. Ht. 3 cm.

9. Pleurofusia sp. aff. P. fresnoensis (Arnold, 1910). Abapertural of UCMP hypotype 14199. Ht. 2.7 cm.

10. "Turricula" waringi Nelson, 1925. Abapertural view of UCMP hypotype 14200. Ht. 1.9 cm.

11, 12. Epitonium n. sp., aff. E. cookii Gardner, 1933, from the Kincaid Formation. Abapertural, apertural views, respectively, of LSJU hypotype 10228. Arrow points to characteristic basal cord. Ht. 1.7 cm.

13. Crassatella sp. UCMP hypotype 14201. Ht. 1.1 cm, length 2 cm.

14, 15. Pseudoliva sp. not P. inornata Dickerson or P. howardi (Dickerson). Fig. 14 is adult hypotype LSJU 10229, ht. 3.2 cm. Fig. 15 is a younger individual, UCMP hypotype 14202, ht. 2.1 cm.

16, 17. Typhis n. sp. Two views of UCMP hypotype 14203. Ht. 1.5 cm. Specimen is incomplete and poorly preserved but has 7 varices on the body whorl aligned with varices on preceding whorls.

18, 21. Eomiltha turneri (Stanton, 1896), interior and exterior views, respectively of LSJU hypotype 10230. Ht. 4.8 cm, length 6 cm.

19. Colubraria (Colubraria) n. sp. LSJU hypotype 10231. Ht. 2.1 cm. Specimen has fine, cancellate microsculpture, curved varices spaced 3/4 of a whorl apart.

20, 23. Cucullaea mathewsonii Gabb, 1864. Interior and exterior views, respectively, of hypotype LSJU 10232. Ht. 4.5 cm, length 5 cm.

22. Saxolucina sp. or a variant of Eomiltha turneri, figs. 18, 21. Hypotype LSJU 10233. Ht. 7 cm, length 6.8 cm.

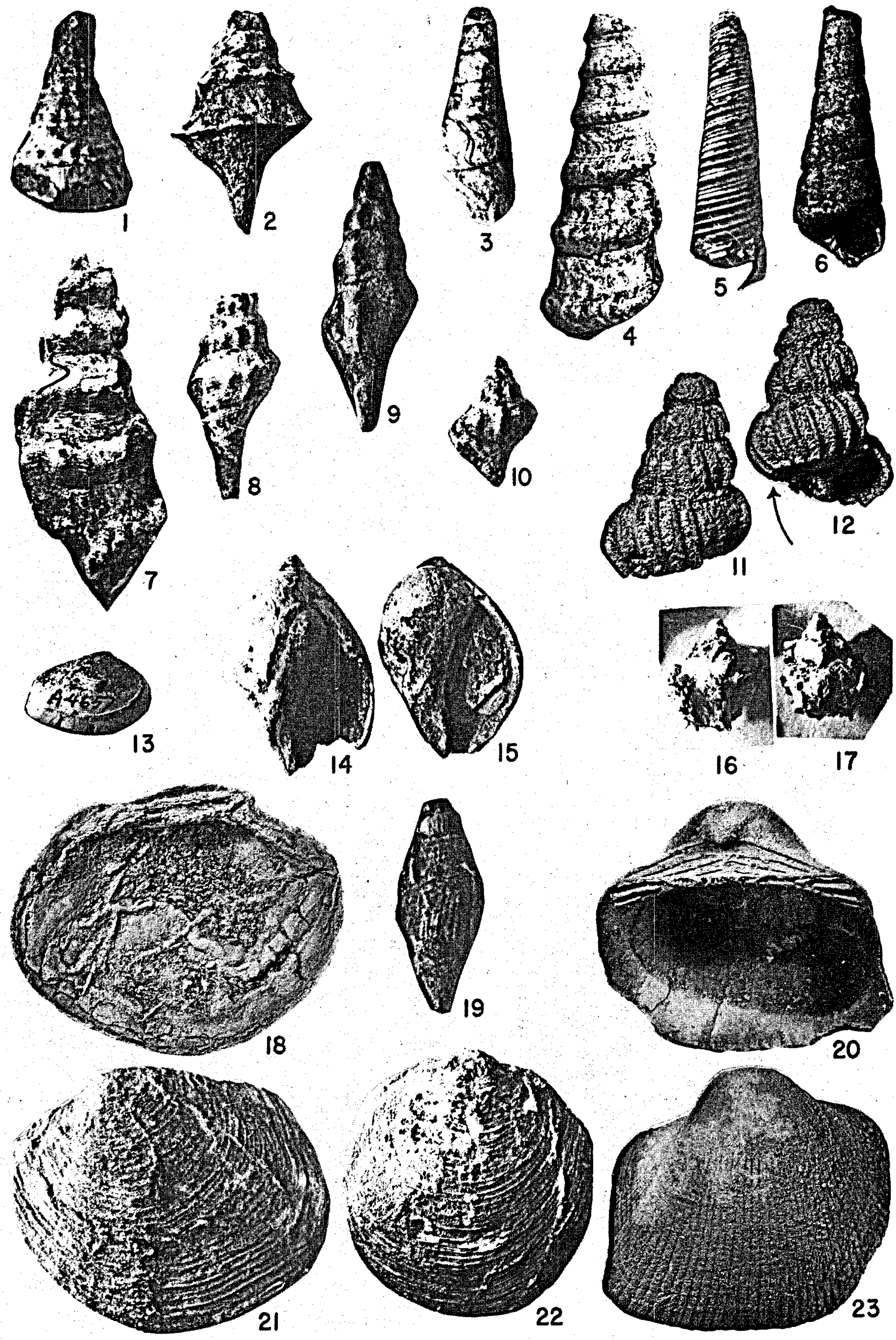

PLATE I

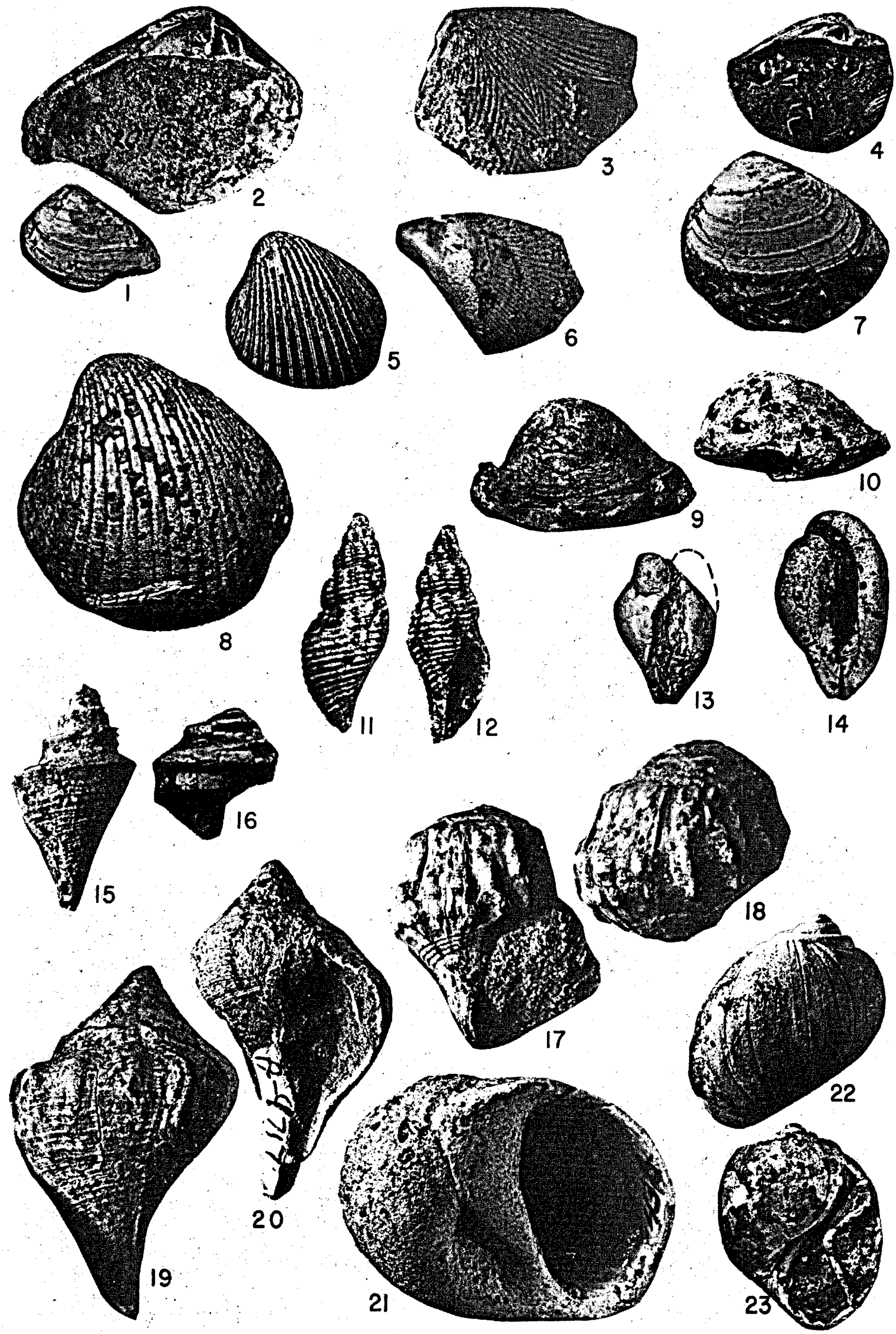

PLATE II

PLATE II

All specimens except figs. 3, 17, and 18 from the Lodo Formation, LSJU 2073 = UCMP A-9717

Figure 1, 2. Crassatella compacta Gabb, 1866. Hypotype LSJU 10234. Ht. 2.2 cm, length 3 cm.

3. Acila (Truncacila) sp., not A. (T.) decisa (Conrad). CAS hypotype 55758 from CAS 31318a. Ht. 1.1 cm, length 1.5 cm.

4, 7. "Meretrix" stantoni Dickerson, 19 . Fig. 4 shows venerid type of interior hinge in hypotype UCMP 14204. Ht. .8 cm, length 1.2 cm. Fig. 7 is interior view of left valve, hypotype UCMP 14205. Ht. 1.3 cm, length 1.7 cm.

5. Venericardia (Glyptoactis) keenae Verastegui, 1953. Holotype, a right valve, LSJU 7992, from LSJU 2073. Ht. 3.3 cm, length 3.7 cm.

6. Brachidontes lawsoni (Nelson, 1925). Hypotype UCMP 14206. Longest dimension 1.4 cm.

8. Venericardia mulleri Verastegui, 1953. Hypotype UCMP 14207. Ht. 6.4 cm, length 5.7 cm.

9, 13. Gisortia sp. cf. G. clarki Ingram, 1940. Fig. 9, side view, anterior end to right, fig. 13 of apertural view (lip restored) of hypotype LSJU 10235. Ht. 2.2 cm, length 3.9 cm.

10, 14. Cypraea sp., adult individuals. Fig. 10, side view of hypotype LSJU 10236. Ht. 1.7 cm, length 3.3 cm. Fig. 14, apertural view of hypotype UCMP 14208. Ht. 2.3 cm, length 5 cm.

11, 12. "Latirus" cf. L. buwaldana (Dickerson, 1915) [Whitneyella auctt]. Abapertural, apertural views, respectively, of hypotype LSJU 10239. Ht. 2.2 cm.

15. "Surculites" mathewsonii (Gabb, 1864). Abapertural view, hypotype LSJU 10237. Ht. 2.5 cm.

16. Pseudoperissolax blakei subsp. praeblakei Vokes, 1939. Abapertural view, hypotype LSJU 10238. Ht. 1.4 cm.

17, 18. Cophocara stantoni Stewart, 1927. Fig. 17, apertural view of hypotype LSJU 10240 from LSJU 2245, ht. 2.5 cm. Fig. 18, abapertural view of hypotype LSJU 10241 from LSJU 460, ht. 2 cm. Cretaceous, lower Laguna Seca Formation or a member of the Moreno Shale?

19, 20. Heteroterma striata Stanton, 1896. Fig. 19, abapertural view of hypotype LSJU 10245, from LSJU 2073, ht. 4 cm; fig. 20, abapertural view of hypotype UCMP14209, ht. 3.5 cm.

21. Polinices susanaensis Nelson, 1925. Apertural view, hypotype LSJU 10242. Length 3.3 cm.

22, 23. "Polinices" sp. cf. "P." pinyonensis Dickerson, 1914. Fig. 22, abapertural view, hypotype UCMP 14210, ht. 2.8 cm; fig. 23, apertural view (right angled fragment in aperture is not part of the shell) of hypotype LSJU 10243. Ht. 3.2 cm.

LOCALITY DATA

LSJU Leland Stanford University   CAS California Academy of Sciences

UCMP University of California Museum of Paleontology (See Figs. 1, 2 for maps)

<u>Fresno County, California, Tumey Hills 7 1/2' quadrangle</u>

LSJU 2073 = UCMP A-9717 = UCMP A-4657 = UCMP A-1284 = UCMP A-4295 = UWa A-2500 of Mallory, 1959

E. side of Panoche Pass road about 1/4 mile south of the junction of Panoche and Silver Creeks. About 2,000 ft W., 100 ft N. of SE cor. sec. 20, T. 15 S., R. 12 E. Lodo Formation, basal glauconitic sandstone sands and shale lenses (see Fig. 1).

LSJU 2073a, 1,000 ft SE along strike from LSJU 2073, in bluff above road.

Lodo Formation, same horizon as LSJU 2073.

LSJU M-74 Type locality of the Lodo Formation (White, 1938), NE 1/4 SE 1/4 sec. 29, T. 15 S., R. 12 E. I-X section of Martin (1943), the lower 200 feet of the type section in a wash south of the first canyon south of Lodo Gulch. Megafossils labelled M-74a, I-X section, were collected by Smith, 1974, from the lower 20 ft of the I-X section. Specimens came from the micaceous sandy layers just above the Moreno shale talus and from the yellowish sandy concretionary layer just above the soft, well-sorted grey sand (see Fig. 1 for the same lithologic sequence at LSJU 2073).

<u>Fresno County, California, Chounet Ranch 7 1/2' quadrangle</u>

LSJU 454 Just north of Panoche Creek, 1,800 ft S., 1,650 ft W. of NE cor. sec. 17, T. 15 S., R. 12 E. Basal Lodo Formation. Coll. Max Payne; 454a coll. P. Verastegui, 1948.

CAS 31318 1/4 to 1 mile north of Panoche Creek, near center of sec. 17, T. 15 S., R. 12 E., on east side of south-trending gully, 100 ft above wash. Collections from 2 concretionary sandy masses, the more westerly one lying on the brown Moreno Shale. Coll. C. C. Church, J. J. Bryan, 1940. [Species identified for this paper suggest the Lodo Formation.]

CAS 31318a Sec. 17, T. 15 S., R. 12 E., beds 200 ft stratigraphically lower than those of CAS 31318. In sandstone reef adjacent to brown Moreno Shale, in lowermost sand above the Cretaceous. Coll. Church, Hanna, Bryan, Kotik, 1940. [Mollusks identified as older than the Lodo assemblage, either Cretaceous or earlier Paleocene.]

LSJU 460 300 ft S., 650 ft W. of NE cor. sec. 24, T. 14 S., R. 11 E. 300 ft stratigraphically below Domengine Paleocene. Basal Laguna Seca Formation. [Mollusks imply Cretaceous or Paleocene older than the Lodo assemblage at LSJU 2073 or LSJU 454.]

LSJU 1068 Sec. 19, T. 14 S., R. 13 E. Coll. R. T. White. [Mollusks imply Cretaceous or Paleocene older than the Lodo assemblage at LSJU 2073.]

LSJU 2245 100 ft S., 700 ft W. of NE cor. sec. 24, T. 14 S., R. 11 E. "Basal Laguna Seca Sand," Paleocene. 300 ft below base of the Domengine. Coll. R. A. C. Brown, Muller, Payne, Schenck, 1940. [Mollusks imply Cretaceous or Paleocene older than the Lodo assemblage at LSJU 2073.]

UCMP B-8580 Gres Canyon, SE 1/4 NW 1/4 sec. 12, T. 14 S., R. 11 E. North slope of Gres Canyon near left hand base of "G" in "Gres" (Chounet Ranch 1:24,000, 1956 ed.). Basal conglomerate at Cretaceous/Paleocene contact. Dull yellowish-grey-white sandy pebble conglomerate. Coll. Paleo. class, 1964. "Lodo or Laguna Seca Fm." [Fossils imply Cretaceous or Paleocene older than the Lodo assemblage at LSJU 2073.]

UCMP D-6356 SE 1/4 NW 1/4 sec. 12, T. 14 S., R. 11 E. North bank of Gres Canyon at approximately the 920-foot contour at the point of "G" in "Gres" (Chounet Ranch 1:24,000, 1956 ed.). About the middle of SE 1/4 of sec. 12. Exposure 30-40 ft thick, rocks buff to brown sandstones, conglomeratic in places. Fossils from the conglomerate. Laguna Seca Formation. Coll. Paleo. class, 1972. [Mollusks imply Paleocene, equivalent of basal Lodo assemblage at LSJU 2073 and of middle Laguna Seca Formation assemblage at UCMP A-6604.]

Merced County, California, Ortigalita Peak 15' quadrangle

UCMP A-6604 Laguna Seca Creek, about 1,100 ft S. 60° W. of junction of north fork of Laguna Seca along small spur 400-500 ft north of stream bed near center of W 1/2 sec. 18, T. 12 S., R. 11 E. Martinez Sandstone [Laguna Seca Formation], about middle of formation. Coll. Briggs, 1948-49. [Fossils are Paleocene, some of the same species as in the basal Lodo Formation at LSJU 2073.]

UCMP A-6607 North bank of Rattlesnake Canyon, about 50 feet stratigraphically above base of Martinez Formation [Laguna Seca Formation], about half way up stream bank in middle of E 1/2 NW 1/4 sec. 34, T. 11 S., R. 10 E. Good coralline faunule. [Mollusks imply Cretaceous or Paleocene older than the Lodo assemblage at LSJU 2073; assemblage same as that at UCMP B-8580.]

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THE ROLE OF COAL

By Dr. C. M. Swinney

SETTING THE STAGE

Clearly the largest hydrocarbon resource on earth is coal. (See Fig. 1). It represents both for the world and for the United States about three-quarters of the total hydrocarbon supply, with the remaining one-quarter comprised of petroleum, natural gas, oil shale and tar sand. Fortunately, the United States, including Alaska, has about 45% of the total coal resource. Coal, therefore, must become increasingly important as a source of hydrocarbons both for energy supply as well as industrial uses. There is no reason to believe that the Pacific Coastal States will vary greatly from the rest of the nation in their dependence upon utilization of coal for energy.

The rate at which coal will be integrated into the energy supply spectrum on the Pacific Coast will be dependent upon several factors:

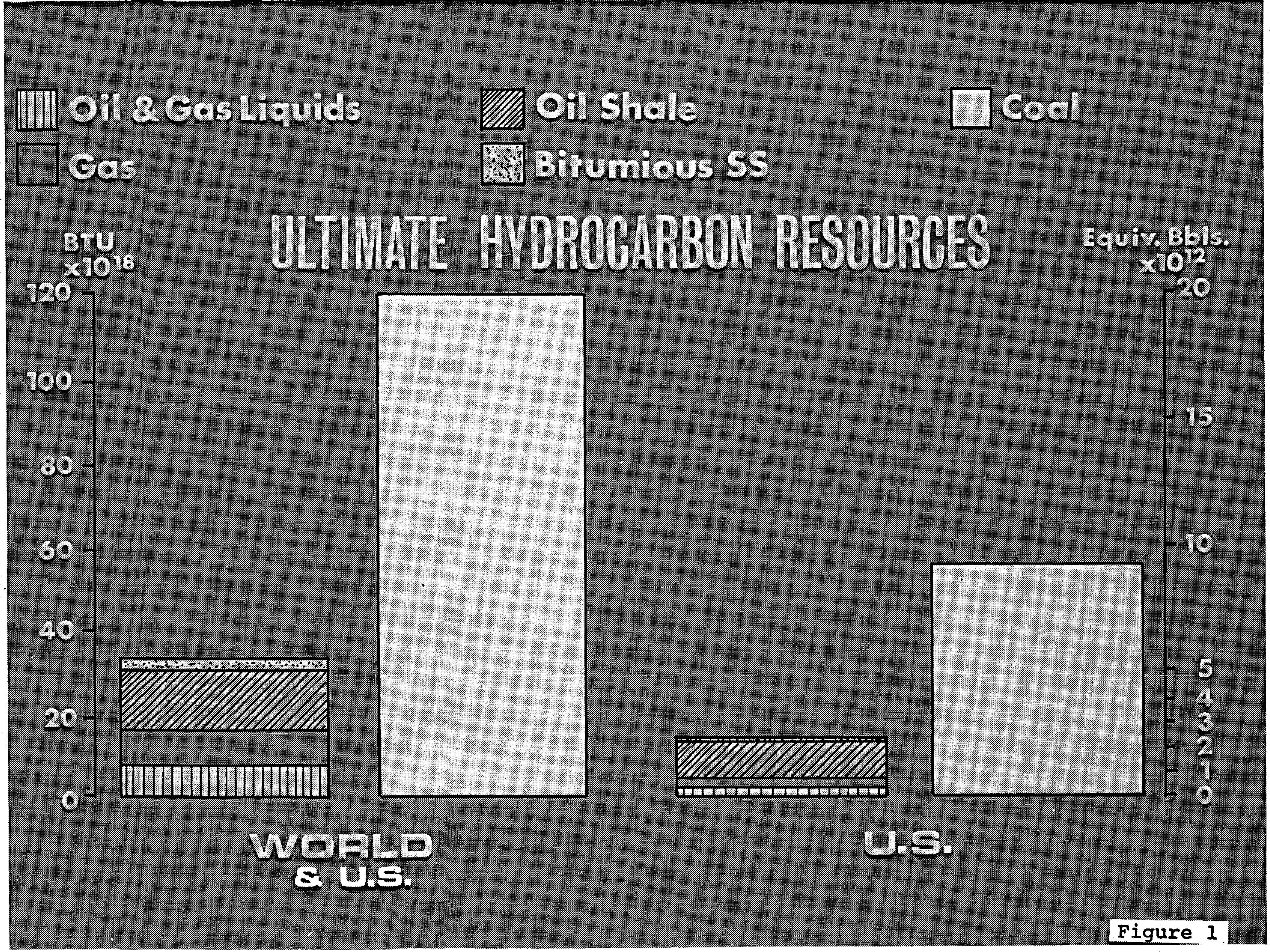
1. The supply and cost of petroleum and natural gas;
2. The overall status of the economy;
3. Federal, State and Local governmental policies and regulations;
4. Economically feasible alternative energy sources;
5. Environmental considerations, generally encompassed by No. 3.

These items are not listed in order of importance, since any one of the factors, or combination of these factors, would certainly influence the use of coal as an energy source.

In this discussion of coal utilization, two time frames will be considered. The first, a relatively short span of time, extending out some 15 years to the year 1990; and the second, a longer term view, extending beyond the year 2000.

FACTORS INFLUENCING COAL USE ON THE PACIFIC COAST

Consider now the factors listed in the first section of this paper and their impact on the utilization of coal as a source of energy in the Pacific Coastal States. Of those mentioned, probably the two having the greatest impact in the next 10-15 years, are (1) policies and regulations promulgated by the governmental agencies and (2) the extent of new discoveries of petroleum reserves.



Oil & Gas Liquids
Oil Shale
Coal
Gas
Bitumious SS
ULTIMATE HYDROCARBON RESOURCES
BTU x10[18]
Equiv. Bbls. x10[12]
120
100
80
60
40
20
0
20
15
10
5
4
3
2
1
0
WORLD & U.S.
U.S.

Figure 1

Before discussing the future, consider briefly the past. The United States experienced phenomenal industrial growth and developed into a highly industrialized and affluent society for one reason only. The land contained abundant and easily recovered natural resources. The energy resources, particularly petroleum, have played a major role in creating the industrialized society of today.

Over the past 75 years, discovery of major oil and gas fields in the United States progressed at a rapid rate, particularly between 1900 and 1955. The Country had abundant, low cost energy, and developed the means of using it. Government policy and regulations encouraged maintaining low cost energy supplies to the consumer. The result has been an annual growth rate in energy use of some 3.6% since 1955, with projections indicating that such a rate will likely continue through 1985. From the late 1950's to date, even with highly sophisticated exploration techniques and improved onshore and offshore drilling equipment, the finding rate for major oil and gas reserves has rapidly dropped. Finding and producing the remaining domestic reserves of petroleum will require a much greater effort and will cost far more than in the past.

Production of domestic oil and gas reserves peaked in the early 1970's, suggesting, therefore, that half of the total reserve has been produced. Even if additional major domestic discoveries are made, this will only postpone the decline by a few years.

Looking ahead to the next 10-15 years, increasing amounts of petroleum must come from outside the Country or a shift must be made to alternative energy resources. Some 10-12 years ago several Pacific Coast utilities began a shift away from the burning of oil and gas for electric power generation. The alternatives were coal and nuclear fuel, with the priority resting with nuclear reactors. Currently, three nuclear generating stations, producing about 1500 Mw, are operating in California. During this year, 1975, an additional plant in Oregon will come on line with an output of about 1100 Mw. Coal-burning electrical generating stations located in New Mexico, Arizona, Nevada and Washington input some 3600 megawatts of electric power into the West Coast energy supply. The total output of both the nuclear and coal-fired plants is only about 3-1/2% of the West Coast total energy demand.

The energy shortage of late 1973 and early 1974 accomplished several things: It highlighted the nation's complete dependence on a low-cost energy supply. It emphasized, although perhaps not fully realized as yet, that such energy sources are depletable. It also made the nation more conservation-minded and it created consternation and confusion in governmental agencies, particularly the Federal Government.

Without belaboring all the reasons why an energy supply shortage developed so quickly, and they are numerous, ranging all the way from environmental restrictions to the oil embargo of the Organization of Petroleum Exporting Countries, it is sufficient to say that we no longer have, or will have, low-cost energy in the time frame which we are currently discussing.

The world's supply of petroleum will likely increase, but costs of finding and producing it will be high. Much of the supply will be offshore or in remote areas that have not yet been explored. New discoveries may eventually bring about a greater geographic dispersion of the world's oil reserves, but lead time for exploration and development is such that little change in the basic supply pattern could occur prior to the mid-1980's. Until, and if, such a realignment of oil reserves takes place, the OPEC will try to maintain production which will be conducive to sustaining prices close to or above their current levels. In many of these countries, such as Saudi Arabia, the intent is to use the oil as a basis for developing an industrialized nation. Short of a disaster, such as a major war, these nations are going to make the most of their oil assets to accomplish their purposes. They realize they have a depleting resource and they certainly will maximize its use.

Economic & Environmental Impact

The U.S. economy, with serious inflation problems, cannot expect to make up deficits of energy supply by importing increasing amounts of costly foreign oil. Therefore, there will be a major emphasis placed upon shifting our hydrocarbon energy base from petroleum to coal. The Administration has already taken the position that petroleum is too valuable to burn for the production of electric power. Thus to the extent possible, existing power plants will convert to coal and new planned electric generation will be either nuclear or coal-burning.

Southern California Edison, my employer, is currently constructing two 1150 megawatt nuclear units at San Onofre. In addition, the Company plans to be a 40% owner of the projected 3,000 megawatt coal-fired generating facility in Southern Utah. Both the nuclear plants and the coal-fired units will begin coming on line about 1980. Other Pacific Coast utilities have similar plans.

Environmental considerations, particularly air quality, have added greatly to the cost of energy to the consumer. A given sized plant produces the same amount of product, whether it be gasoline, kilowatts, or whatever, even though its cost of construction and operation may double as a result of steps taken to protect the environment. Cost of product, therefore, increases. A part of our current inflation results from the impact of clean-up procedures and operations which do not add to productivity.

It is most unfortunate that at a time of great need for domestic petroleum reserves, exploration is at almost an all time low. Greatly needed is a Federal energy policy that will provide economic incentives, along with an aggressive leasing program on the Public Domain. Instead, pricing control and tax penalties are suppressing the search for oil.

State and local policies and regulations, particularly in California, are going to add still further to the pressing need to develop coal resources. Apparently, the current thinking within the State Energy Resources Conservation and Development Commission favors prohibition of any further offshore exploration or drilling for petroleum on State-controlled lands. Attempts to block such developments beyond the three-mile limit on Federal leases by denying access to the coast is also being considered. Any potential offshore oil that could ease the oil import problem over the next 10-15 years is not likely to become available and will place still further strain upon an already shaky economy.

Manifestly, a pressing need exists to provide energy from coal as quickly as possible, not only for electric power genration, but for the production of gaseous and liquid hydrocarbons to supplement natural petroleum products.

Deterrents to Coal Development

Coal, like oil and gas, has its own share of economic, environmental, and governmental problems, all of which bear strongly on its rate of development and integration into the energy mix for the Pacific Coast. In the face of rapidly rising costs, the United States Congress passed a Surface Mining bill, which has been estimated by some to increase electric utility fuel costs by about 55%. The National Coal Association estimates that at least 100 million tons of coal now produced annually by surface methods may no longer be available. This loss could be replaced by oil, which is a poor alternative, or from underground coal mines that do not exist at this point in time. If underground coal mining capacity cannot be brought on stream on quickly enough, oil would be required at a replacement cost of an additional $3.3 billion, most of which would be absorbed by electric utility customers. In addition, increased cost of reclamation for surface mined coal (the bill required a 25¢/ton tax on all deep mined coal and a 35¢ per ton tax on surface mined coal) could make the total cost of the bill come to about $4 billion a year. These are the numbers which suggest this piece of legislation would increase fuel costs for the nation's electric utilities by 55%. President Ford has used a pocket veto to stop this legislation, but it is almost certain that it will come up again in the new Congress.

It is ironic that while one part of government, the Administration, presses for increased development of our coal resources to reduce the nation's dependency on foreign sources, another part of government, the Congress, provides laws and regulations that retard or block such activity. There is no problem in land restoration. The Europeans have been doing this for generations and the land is returned to its prior use after mining ceases. The problem rests with added taxes, superimposed layers of local, state and federal jurisdiction, hearings, and regulatory red tape. The results are long delays and abnormally high costs.

COAL AS AN ENERGY SOURCE FOR THE PACIFIC COAST

How will coal, as an energy source, increasingly supply the Pacific Coast energy mix? As mentioned earlier, it is already making some impact as a source for electric power generation. In the coming 10-15 years, electric generation and, to a lesser extent, manufactured gas, will be the methods by which energy from coal is utilized. Existing and planned electric generating facilities are mine-mouth and located at the coal deposits. Such installations are generally at considerable distances from load centers and require long transmission lines. Plants which will convert coal to more environmentally acceptable fuel are in the offing and among the first will be installations that will convert coal to high Btu gas to replace diminishing natural gas supplies. Initially, such plants are also likely to be mine-mouth installations.

One important factor to consider, however, is that no matter how much pressure there may be to bring coal-derived fuels into our energy mix, the rate at which this takes place will be slow. Technology for the production of gaseous fuel from coal is already in hand. Even with known technology, however, the lead time, from the development of a mine and construction of a plant, until product is produced, may be as much as ten years. Two to four years of this time may be involved with environmental considerations. Proposed legislation will discourage exploration and may prevent some reserves from being developed.

Production of clean liquid fuels from coal is just entering the demonstration stage. Only an all-out crash program would speed this timetable up. This is not normally a desirable way to proceed, but if our industrial complex falters for want of energy, it may be necessary.

COAL CONVERSION SYSTEMS

Burning coal directly in a boiler is the most efficient way, at present, to produce electricity. For gas service use, i.e., distribution by a gas utility, gasification to SNG (Substitute Natural Gas) appears to be the preferred method. In both cases, the impact on the coal resource is about the same. In other words, a ton of coal produces just about the same amount of end use energy whether its burned to produce electric power or converted to SNG.

Direct combustion of coal to produce electric power is more environmentally abrasive than conversion to other forms of fuel. Therefore, coal conversion systems that yield liquid and gaseous fuels having less environmental impact will be developed in the coming 10-15 years. Even at a loss in overall efficiency, such fuels will likely be burned to generate electric power. As mentioned later, non-fossil fuel energy sources must be developed for the production of electricity, thus conserving our hydrocarbon resources for industrial use.

Synthesizing liquid and gaseous fuels from coal is nothing new. Long before petroleum made its debut on the energy scene, coal was providing illuminating gas, coal oil, tar, resins and carbon. With the launching of the petroleum era in the late 1850's, oil and natural gas took over the role that had been occupied for years by coal. This was particularly true in the United States. In Europe coal still continued to supply minor amounts of gas for industrial purposes and, of course, during World War II coal provided fuels for the German war effort.

Depending upon the severity of treatment, coal conversion processes can be optimized to produce high Btu gas, suitable as a replacement for natural gas, or various grades of liquids and even a clean de-ashed solid.

Gasification Processes

Gasification of coal is a commercial technology, therefore, a discussion of coal conversion processes will begin with a review of gasification concepts.

A simplified diagram illustrating gasification of coal is shown in Figure 2. Crushed or pulverized coal is reacted with steam and oxygen, or air, under pressure in a closed vessel. The resulting product, called producer gas, is further treated in a second stage to yield product gas whose heating value will vary depending upon the severity of the treatment. To obtain a high Btu gas which can substitute for natural gas, producer gas is hydrogenated to yield a product rich in methane.

Two commercial gasification processes, Lurgi and Koppers-Totzek, are available today. Both are German concepts and stem from development during World War II. The Lurgi process, probably the best known, cannot handle caking coal. Therefore, many of the coals occurring in the Eastern United States cannot be gasified by this process. The Koppers-Totzek gasifier is capable of handling any type of coal and will, therefore, likely have more universal application. Both systems are capable of producing either low or high Btu gas, depending upon the degree of methanation applied to the producer gas. A number of other gasification processes are being investigated in this Country in the hopes of improving upon the economics of the two German processes. Figure 3 lists various processes and indicates their present status. As shown, all are capable of producing medium to high Btu gas and a number of them produce a low Btu gas.

Several commercial size gasification plants producing SNG are expected to be built in the near future. Two, the El Paso Natural Gas Company and the Texas Eastern-Pacific Lighting Company projects, are ready to start construction as soon as all permits can be obtained. Four others are in the planning stages as shown in Figure 4. In the case of all but the Northern Natural Gas Company project, a Lurgi gasification system is being used with methanation to upgrade the producer gas to high Btu pipeline gas. At the time the data were compiled, Northern Natural Gas Company had not yet decided on the process it will use. In addition to the planned commercial facilities, at least six processes are being actively investigated in the pilot plant stage. Figure 5 shows the status of these various gasification concepts and there are probably others that have recently come under development that are not listed.

In situ Coal Gasification

The above discussion deals with surface plants utilizing mined coal. In situ gasification of coal is also being investigated. This involves the ignation of coal in place in the presence of air, oxygen, steam-air, or steam-oxygen mixtures. The process has been amply demonstrated

COAL GASIFICATION

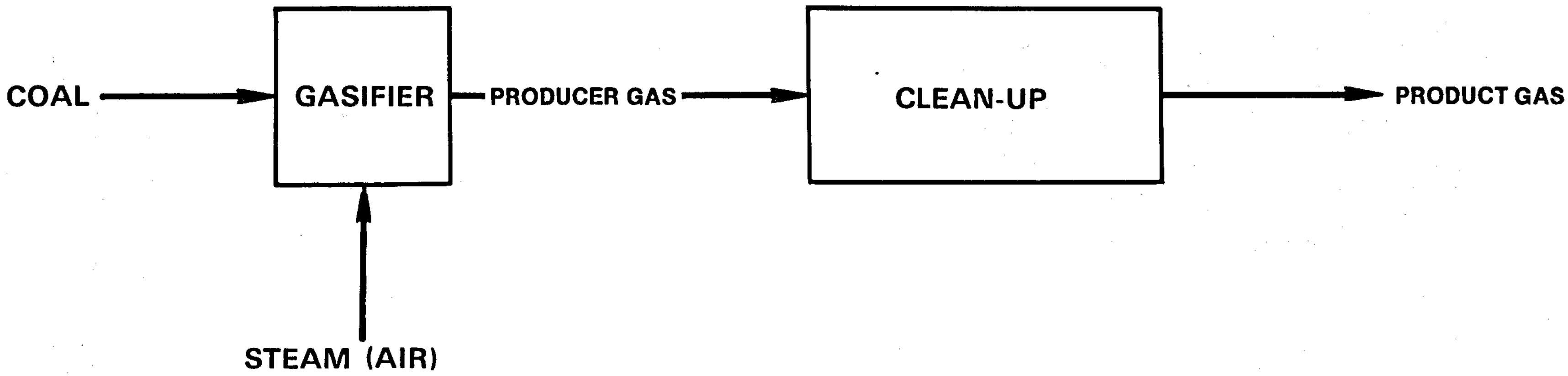


Figure 2

STATUS OF TECHNOLOGY OF COAL GASIFICATION

Process	Heating Value			Reactor			Op. Pressure		
	Low 100-250	BTU/SCF Medium 250-550	High 950-1000	Fluid Bed	Entrained Bed	Moving Bed	0-15	(Psi) 100-500	1000-1500
Commercial									
Lurgi	X	X	X			X		X	
Koppers-Totzek	X	X	X		X		X		
Pilot Plant									
Bi-Gas	X	X	X		X				X
CO_2 Acceptor		X	X	X	X			X	
Hygas	X	X	X	X					X
Pre - Pilot									
Atgas	X	X	X	Molten Iron			X		
Molten Salt		X	X	Molten Salt					X
Synthane	X	X	X	X					X

Figure 3

SNG from Coal

Planned Commercial U. S. Plants

Process	Company	Location	Capacity Feed (Tpd)	Capacity SNG MMscf/d	Status
Lurgi	El Paso Natural Gas Co.	New Mexico	26,600	250	Ready to begin construction. Cost about $450-500 million. Start-up - 1977
Lurgi	Texas Eastern Trans. Co. Pacific Lighting Co.	New Mexico	29,000	250	Ready to start construction. Cost about $450-$500 million. Start-up - 1977
Lurgi	Texas Gas Transmission Co.	Illinois			Coal reserves acquired. Planning & design
Lurgi	Eastern Gas & Fuel Associates	New Mexico			Coal reserves acquired. Planning
Lurgi	Panhandle Eastern Pipeline	--			Planning stage.
--	Northern Natural Gas Cities Service	Powder River Basin, Montana	110,000	250 X 4	Coal reserve acquired. Planning a $1.5 billion plant.

Figure 4

COAL GASIFICATION PROCESSES UNDER DEVELOPMENT

Process	Company	Location	Status
CO_2 Acceptor	Consolidation Coal Co.	Rapid City, S.D.	Pilot plant in operation (40 tpd)
Bigas	Bituminous Coal Research	Horner City, Pa.	Pilot plant under construction (120 tpd)
Hygas	Inst. of Gas Technology	Chicago, Ill.	Pilot plant operable. Investigating three variations of process.
Atgas	Applied Technology	--	Has a $1.1 million EPA/AGA contract
Molten Salt	M. W. Kellogg Co.		OCR dropped project. Kellogg continuing with process
Synthane	U.S. Bureau of Mines	Bruceton, Pa.	Pilot Plant operable (70 tpd)

Figure 5

on small scale, and the Russians operated a 15,000 kW generating plant for a number of years on low Btu gas produced in situ.

The U.S. Bureau of Mines is currently working with an in-situ project at Hanna, Wyoming. The test is in a 30-foot thick seam under some 400 feet of cover. As in all previous in situ operations, the produced gas is of poor quality, averaging about 85 Btu/scf. Some difficult problems need to be solved before in situ methods can be considered to be technically or economically feasible. Such items as control of the reaction to produce high Btu gas, establishing and maintaining permeability, leakage control, and groundwater intrusion represent the principal areas of investigation. If and when techniques are found to make in-situ gasification attractive, a great deal of coal, particularly deeply buried seams, could become producible.

Liquefaction Processes

Production of liquid fuels from coal is not as far advanced as is gasification. Coal liquefaction, like gasification, involves reacting coal, with or without a catalyst, in a closed vessel. Figure 6 lists the various techniques for coal liquefaction. Presently, one commercial process is in operation in South Africa.

There are some advantages in producing liquid rather than gaseous products as shown in Figure 7. A liquid, being more concentrated than gas is easier, and less costly, to transport and store. It is also easier on the coal resource, having a thermal efficiency for conversion of about 80% versus 65% for gasification. Last, but not least, the investment in plant is less for liquefaction and water requirements are lower. It is for these reasons that a number of utility companies, as well as oil companies, are interested in processes which produce liquids from coal. Petroleum refineries can utilize a synthesized crude oil from coal as feed stock even though the material is higher in aromatics than petroleum crude.

Figure 8 lists the four processes being developed for the production of liquids from coal and indicates the conditions pertaining for the conversion of coal to liquids. The only large size commercial plant producing liquids from coal today is government-owned and operated and is located in South Africa. This plant, at Sasol, utilizes the Lurgi technique to gasify coal, followed by a Fischer-Tropsch reaction to yield gasoline. This process is not currently considered to be economical in the United States. Of the other processes listed, all are in early stages of investigation. Figure 9 indicates the status of liquefaction technology in the U.S.

COAL LIQUEFACTION

TECHNIQUES:

- GASIFICATION - SYNTHESIS (FISCHER - TROPSCH)
- MILD NON-CATALYTIC HYDROGENATION (SOLVENT EXTRACTION)
- MORE SEVERE CATALYTIC HYDROGENATION
- PYROLYSIS OR DESTRUCTIVE DISTILLATION

Figure 6

ADVANTAGE OF LIQUID PRODUCT

- MORE CONCENTRATED FORM OF ENERGY (CHEAPER TO TRANSPORT)
- MORE EASILY STORABLE
- LESS HYDROGEN REQUIREMENT: COAL ⟶ LIQUID ⟶ GAS
- HIGHER THERMAL EFFICIENCY (80% vs. 65% FOR SNG)
- ECONOMIC ADVANTAGE
- LESS ENVIRONMENTAL IMPACT (WATER REQUIREMENTS & WATER POLLUTION PROBLEMS)

Figure 7

COAL LIQUEFACTION PROCESSES

PROCESS TYPE	CONDITIONS	EXAMPLE PROCESS
FISCHER - TROPSCH SYNTHESIS	COAL GASIFIED TO SYNTHESIS GAS: CO, H_2	SASOL SOUTH AFRICA (NOT ECONOMIC FOR U. S.)
SOLVENT EXTRACTION PLUS MILD HYDROGENATION PLUS HYROCRACKING	800° F, 1000 psi 750° F, 500 psi	SRC CSF
CATALYTHIC HYDROGENATION	850° F, 2700 psi	H-COAL
PYROLYSIS	1600° F, LOW PRESSURE	COED

Figure 8

STATUS OF COAL LIQUEFACTION TECHNOLOGY

PROCESS	DEVELOPER	CAPACITY	DATE COULD START COMMERCIAL DESIGN	LIQUID YIELD BBLS/TON	MAIN PRODUCTS	PRODUCT SULFUR & ASH CONTENT	
						% SULFUR	% ASH
I. GASIFICATION-SYNTHESIS							
FISCHER-TROPSCH	LURGI		COMMERCIAL		GASOLINE		
II. MILD NON-CATALYTIC HYDROGENATION							
SRC	GULF	50 TPD	1976	2.8-3.0	EXTRACT (HEAVY FUEL OIL)	0.3	0.1
III. CATALYTIC HYDROGENATION							
CSF	CONSOL	20 TPD	1976	3.0	DISTILLATE	0.3	0.1
H-COAL	HRI	3 TPD	1977	3.0	DISTILLATE/FUEL OIL	0.3	0.1
FIXED BED	FMC	30 TPD	1976	-	-	-	-
FIXED BED HYDRO	USBM	0.06 TPD	1978	2.9	DISTILLATE	0.19	1.0
CCL	GULF	0.06 TPD	1978	3.1	DISTILLATE/FUEL OIL	0.04	0.02
IV. PYROLYSIS							
COED	FMC	36 TPD	NOW	1.0	DISTILLATE, SNG, CHAR	0.08	
FLASH CRACKING	GARRETT R&D	15 TPD	1977	1.8	DISTILLATE, GAS, CHAR	50 % REMOVAL	
TOSCOAL	TOSCO	25 TPD	1976	1.0	CHAR, OIL, GAS		

Figure 9

COAL CONVERSION RESEARCH AND DEVELOPMENT

Much of the work to be performed on the various processes, both for gasification and liquefaction, has been a cooperative program between the Office of Coal Research and various companies or industrial groups. Consolidation Coal Company, now a subsidiary of Continental Oil Company, has done a great deal of work on coal conversion. A newly formed subsidiary of Continental Oil Company, Conoco Coal Development Company, has combined all the work of Consolidation Coal as well as Conoco, and will be responsible for coal conversion activities. CCDC is currently operating a gasification pilot plant at Rapid City, South Dakota. During the late '60's, Consolidation Coal Company operated a pilot plant to produce synthetic fuels from coal, located at Cresap, West Virginia. The plant was closed down in 1970, but is being reactivated by Fluor Corporation for continued studies of the process. Pittsburgh and Midway Coal Company, a subsidiary of Gulf Oil Company, is operating a 50-ton per day pilot plant near Tacoma, Washington, to further develop a solvent-refined method of producing liquid fuels from coal.

Federal Support of Research and Development

The level of research on coal conversion methods in the United States over the past 10-12 years has been modest. OCR has spent approximately $160 million during this period of time in support of the various processes discussed.

With Washington concerned in shifting to a coal economy to implement Project Independence, a great deal more money will be channeled into coal conversion research and development. Indeed, in 1974 the Office of Coal Research extended invitations for proposals for coal conversion programs to the industry. Response to their invitation was poor. Many companies apparently felt that they were being asked to put up funds and act as a contractor for the Federal Government, rather than being able to develop the processes which they preferred. Interestingly enough, an unsolicited proposal submitted to the Office of Coal Research by Old Ben Coal Company, a subsidiary of Sohio, was rejected. This submittal had been made to the OCR prior to its invitation for proposals. Recently one proposal was accepted, that of Coalcon Company, a jointly-owned subsidiary of Union Carbide Corporation and General Tire and Rubber Company. The contract is for $237.2 million, with the initial government studies being funded to the extent of $21 million. The proposed plant will be a 2600 ton per day coal unit producing 3,900 barrels per day of liquids and 22 million cubic feet of gas. The on-stream date is estimated to be late 1979.

Industry-Sponsored Demonstration Plant

Southern California Edison Company seriously considered responding to the OCR invitation, but for the reasons mentioned above, decided to attempt to privately finance an investigation of a coal conversion process in conjunction with other companies. To date Edison, Conoco Coal Development Company, Mobil Research and Development Company, and Electric Power Research Institute have signed an agreement to carry out the preliminary engineering studies for a plant based on Consolidation Coal Company's synthetic fuel process. It is expected that other companies will join in this venture. The proposed demonstration plant would be capable of handling about 600 tons of coal per day, yielding some 1800 barrels of clean liquid fuel per day. It is anticipated that a commercial plant, processing 35,000 tons of coal per day, and producing a little over 100,000 barrels of clean liquid fuel per day, could be brought on stream by 1982. Such fuel could replace petroleum in electric power generating plants located in or near the metropolitan areas along the West Coast.

Economic Incentives

Much of the basic research and development work has already been accomplished during the past 10-12 years that the OCR has been carrying out its program. It would now seem that the quickest way to bring conversion processes to commercial fruition would be for the Federal Government to provide economic incentives, including price protection, during the payout period for such facilities. Industry would thus have a much sounder justification for committing the huge sums of money necessary to build conversion plants. Investment, in 1974 dollars, in coal conversion plants could be as much as $10 billion by 1985, with product priced at about $12 per barrel and $2.50 per mcf for oil and gas, respectively.

The OPEC nations will certainly carefully monitor progress in synthesis fuels and can easily post a price for oil that will be below that required to economically build and operate a facility producing liquid fuels from coal. The long lead times required to bring coal conversion plants on line, necessitate the commitment of funds prior to an economic climate that will support such investment. To provide for a smooth transition to coal based fuels and avoid severe shortages, economic incentives must be provided, particularly since we are so heavily dependent upon imported petroleum.

COAL RESOURCES

With a shifting of our supply of energy from petroleum to coal, it is gratifying to note, as mentioned in the beginning of this paper, that our largest domestic hydrocarbon resource is coal. In the Western States and Alaska, the United States Geological Survey estimates the coal resource to be approximately 1.5 trillion short tons with overburden depths of less than 3,000 ft. It is reasonable to assume that about half of this coal is recoverable. The Pacific Coastal States themselves, however, contain very little coal. For all practical purposes, California contains no coal of commercial interest, Oregon has approximately 400 million tons, and it is estimated that Washington has about 36 billion tons of coal in place. Wyoming, Montana, Alaska, Colorado, New Mexico, Utah, and Arizona, are the principal coal-bearing States that could be expected to provide energy derived from coal to the Pacific Coast. Figures 10 & 11 show the distribution of coal in this region.

Some generalizations about the Western coals can be made. They are of Cretaceous and Tertiary Age and are thus younger than the Paleozoic coals of the Eastern United States. They are low sulfur and frequently occur in multi-seam deposits, with some seams attaining thicknesses of as much as 100 ft. They are sub-bituminous high volatile coals and non-coking. Individual seams are lenticular in character, although a given seam may extend over a considerable area.

WATER SUPPLIES

A commodity as important as the coal resource itself is water required for both processing and cooling in coal conversion facilities. For example, a 120,000 bpd syn-crude plant uses about 13,000 gallons of water per minute or 4 bbls. per barrel of oil produced. A large SNG plant, producing about a billion cubic feet per day, uses some 30,000 gallons of water per minute or a little over 1 million barrels of water per day. Thus, serious consideration must be given to water supply, particularly in the semi-arid western states.

Development of synthetic fuels production to supplement petroleum supplies requires an effective program between various states and the Federal Government to resolve water rights and allocations, thus permitting the construction of necessary pipelines and aqueducts. The water problem is not a simple one and immediate action is needed if coal conversion projects are to move forward.

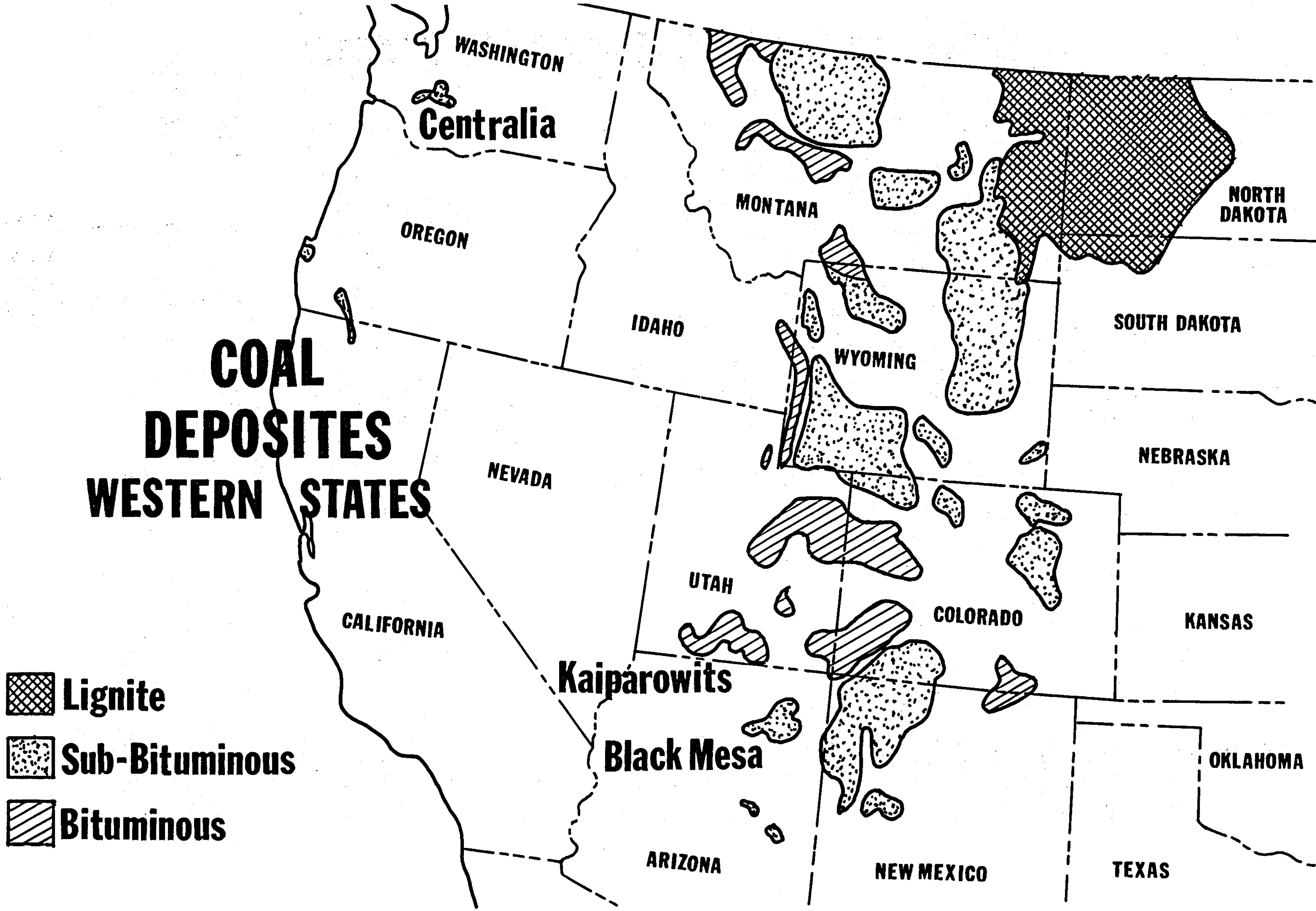
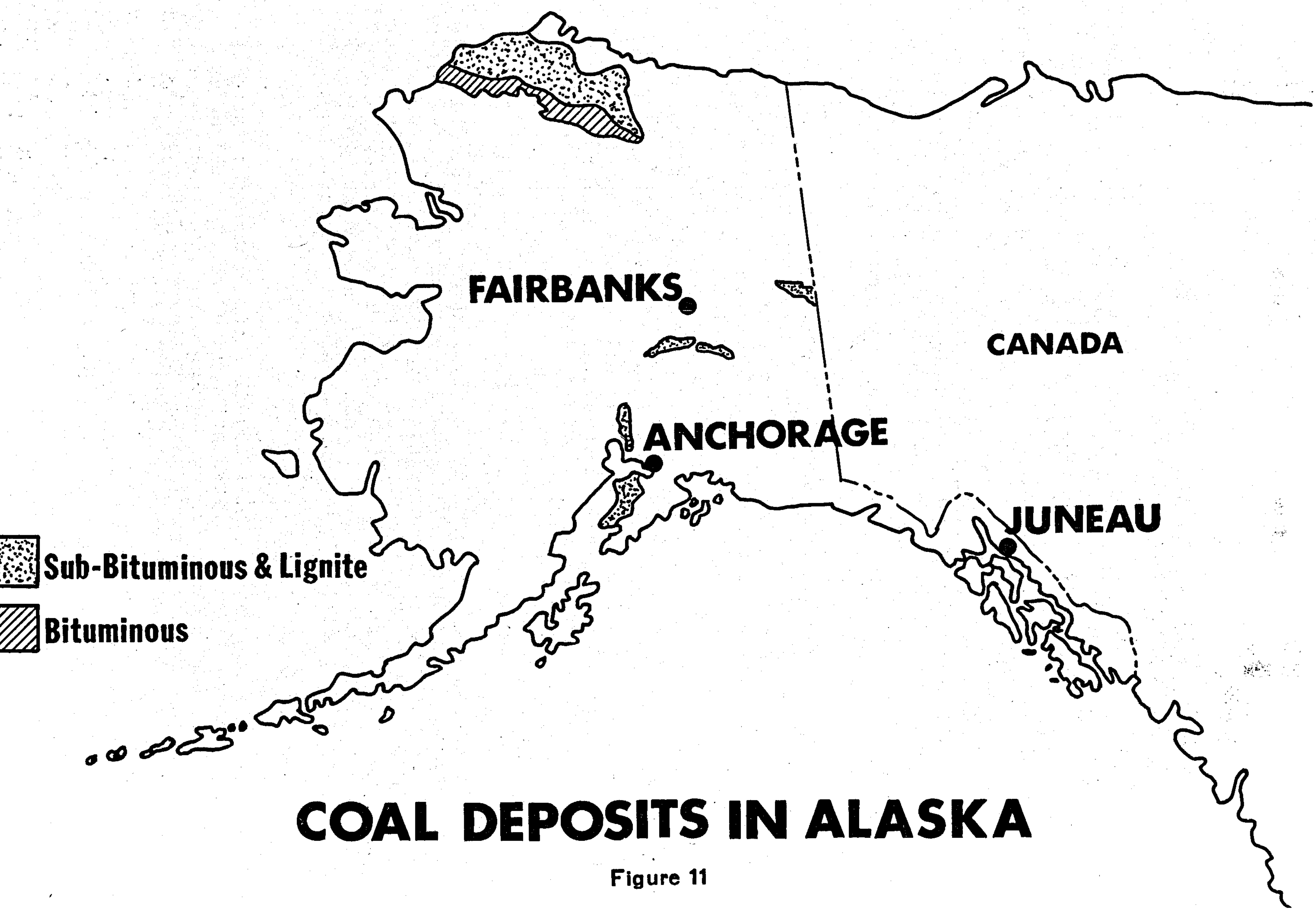

COAL
DEPOSITES
WESTERN STATES
Lignite
Sub-Bituminous
Bituminous
WASHINGTON
Centralia
OREGON
IDAHO
MONTANA
NORTH
DAKOTA
SOUTH DAKOTA
WYOMING
NEBRASKA
NEVADA
UTAH
COLORADO
KANSAS
CALIFORNIA
Kaiparowits
Black Mesa
ARIZONA
NEW MEXICO
OKLAHOMA
TEXAS

Figure 10



COAL DEPOSITS IN ALASKA

Figure 11

ENERGY FROM COAL FOR THE PACIFIC COAST - CURRENT AND FUTURE DEVELOPMENTS

As mentioned earlier, some electric power from coal generating facilities is already entering the Pacific Coast energy mix. Currently, Southern California Edison Company is receiving its 48% share of two jointly owned 795 megawatt coal-burning units at the Four Corners Station located near Farmington, New Mexico. The Los Angeles Department of Water & Power is a 21% participant in the Navajo Plant located near Page in Northern Arizona. This facility consists of three 750 megawatt units which burn coal supplied by a mine at Black Mesa in Northern Arizona. Edison will purchase some surplus energy from the Navajo Plant until such time as the participants can utilize the entire output.

Both Edison and the Department of Water & Power receive energy from the Mohave Generating Station, located in the southern tip of Nevada. This facility is jointly owned by several utilities, with Edison serving as the operator. Edison's share of the output is 52% and the Department of Water & Power receives about 20%. Coal for the power plant is supplied from the Black Mesa coal mine and transported to the power plant via a slurry pipeline. The station's net output is approximately 1580 megawatts. A coal-fired 1400 megawatt electric generating station, located near Centralia in Washington, operated by Pacific Power & Light Company, provides electric energy to utilities in the northwest power area.

These locations are shown on Figure 12. The utilities along the Pacific Coast and neighboring states to the east are connected by fairly firm interties. Interties through Utah and Idaho, however, are relatively low voltage and not capable of carrying very large electrical loads. (See Figure 12). Nevertheless, electrical energy produced by coal-fired generating facilities in the states lying in the Rocky Mountain and Plateau areas are capable of supplying electrical energy to the Pacific Coast in time of need.

Planned Coal Facilities

A major coal-fired electric generating facility is in the advanced states of engineering and will be located on the Kaiparowits Plateau in Southern Utah. Arizona Public Service Company, San Diego Gas & Electric Company, Salt River Project, and Southern California Edison Company are the participants in the project, with Southern California Edison acting as operator. The station will consist of four 750 megawatt generating units located at mine-mouth, utilizing

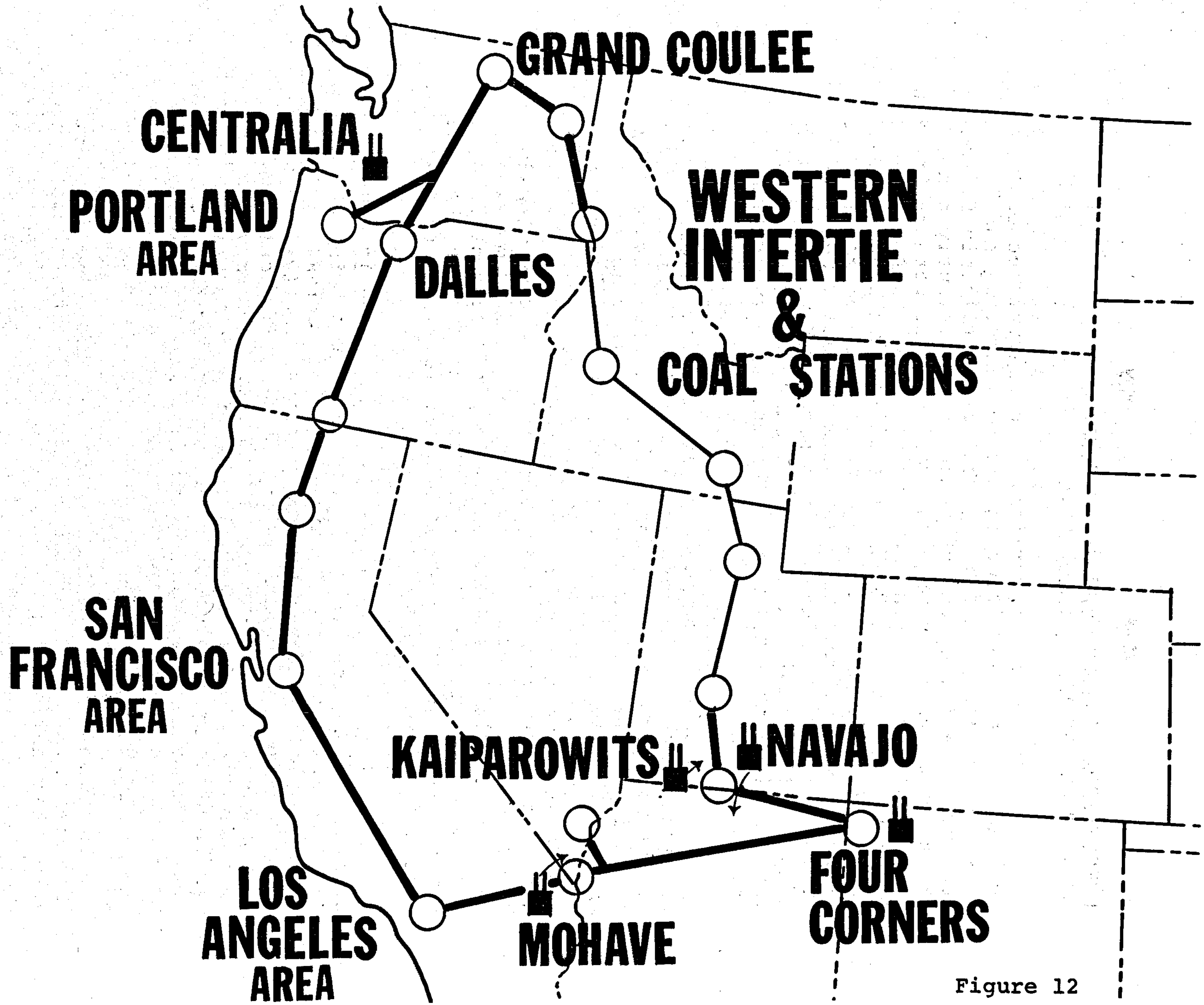

GRAND COULEE
CENTRALIA
PORTLAND
AREA
DALLES
WESTERN
INTERTIE
&
COAL STATIONS
SAN
FRANCISCO
AREA
KAIPAROWITS
NAVAJO
LOS
ANGELES
AREA
MOHAVE
FOUR
CORNERS

Figure 12

coal produced from the Kaiparowits Coal Field. San Diego Gas & Electric Company and Southern California Edison Company will together receive over half of the output of the 3,000 megawatt station. The first unit is expected to be on stream by mid-1981. This facility has been delayed by about three years and undergone increase in costs of about 60% as a result of environmental considerations.

Although most of the coal-based energy which will be used in the Pacific Coastal States in the next 15 years will be in the form of electricity, some may begin to enter the mix in the form of gas and liquid from coal conversion plants and a minor amount may be burned directly as fuel for the manufacture of Portland cement.

The first major increments of coal-based energy, other than electric power, entering the Pacific Coast fuel mix will be gas. (See Figure 3). El Paso Natural Gas Company is preparing to build a large Lurgi gasification plant to be located some 25 miles south of Farmington, New Mexico. The plant will be mine-mouth and will utilize subbituminous coal found in that area. Texas Eastern Transmission Company and Pacific Lighting Company are jointly planning to build a similar plant in the same vicinity. The two plants are in the order of 250 million cubic feet capacity per day, utilizing about 27,000 tons of coal for the process. About half of the gas produced is expected to come to the Pacific Coast. Plans call for bringing the facilities on stream by 1977. This probably will not be soon enough to avoid serious gas shortages in California.

THE LONG TERM

We are living during one of the most crucial periods of modern civilization. The decisions and courses of action taken over the next decade could make the difference between continued development as a vital industrialized civilization or decline to a cultural level that existed prior to the inception of a socio-industrial complex. The problems facing us are intricate and multitudinous, involving both the sociological as well as the technological aspects of our society. Furthermore, they are largely international in character and actions taken by the United States to solve domestic situations will have a substantial impact worldwide.

Continued Growth of Energy Demand

This is not the place to discuss the factors that give rise to an industrialized society or to ponder the underlying reasons behind the enormous contrasts that exist between the technically developed nations of North America, Western Europe, and Japan, and the primarily agrarian areas of the world. It is sufficient to note that the industrialized societies, particularly the United States, have achieved a remarkable standard of living, mainly through the use of energy. The annual per capita consumption of energy in the United States is equivalent to about 55 barrels of oil or some 16 tons of coal. The other industrialized countries of the world are approaching this level of energy consumption and the emerging nations of the world are striving to become industrialized. The result, of course, is a continued expanding need for raw materials, particularly the energy raw materials, to sustain the existing technologically developed countries and provide the industrial complex for the emerging nations.

To maintain a level approximating today's productivity, we will continue to use additional increments of energy simply because it will take more energy to provide the materials which we use. The low cost easily recovered natural resources are being exhausted and lower grade, higher cost, materials will take their place. Additionally, if we maintain or improve environmental protection programs, these too will require additional increments of energy. Therefore, it can be assumed that the growth rate of energy use will continue at some level, possibly 2% or 3% annually, and very likely at a higher rate in the countries throughout the world that are striving to industrialize.

Declining Petroleum Resources

Petroleum production in the United States peaked several years ago and we are now following a decline curve. Production of world petroleum resources will likely peak within the next 20 years. Clearly, therefore, we must shift our energy base from petroleum to other energy sources, that is, coal, oil from shale and other bituminous deposits, nuclear energy, thermonuclear fusion, solar energy, and heat from the earth itself. Implicit in using any of these sources of energy is the crying need to improve conversion efficiency.

It has been suggested that a no growth policy be adopted to maintain our present standard of living and extend the life of our energy resources. Even if we should achieve such a status in this country and, assuming that we develop more efficient ways of converting energy for our use, the need for energy resources will still continue to grow for the reasons mentioned above. If we instead determine that we will hold our energy requirements at no growth, then also for the reasons just stated, our standard of living deteriorates. That this will happen runs contrary to human nature, since the tendency is to strive to improve living conditions, rather than allow them to retrograde.

For all practical purposes, the only energy sources currently available are the fossil fuels. If the entire world could suddenly be placed at the same industrial level as that of the United States, the remaining utlimate oil reserve would be used up in some 30 years and the coal reserve would be finished in a little over a century. Therefore, there is little hope that the underdeveloped nations of the world will ever achieve standards of living now enjoyed by industrialized nations if the fossil fuels are the only available energy source. It further follows that there will be no chance that the activities of highly industrialized nations can be maintained at present levels for very long. Indeed, we are seeing cutbacks taking place already in our industrial complex which affect our standards of living.

Conservation of Hydrocarbon Resources

Based on the above, our basic energy requirements must be furnished by electricity, which can be produced from sources other than hydrocarbons. It is imperative that we conserve our hydrocarbon resources, particularly the huge coal reserves, as well as our dwindling petroleum supplies, for uses other than energy generation. The most vital task facing us in the coming years is to develop electrical energy from renewable sources such as solar energy or thermonuclear reactions whose fuel supply is virtually infinite. Beyond the year 2000, therefore, the bulk of our energy will come from electricity generated from non-hydrocarbon sources and our remaining reserves of coal and petroleum will be used only for much higher level industrial purposes. During the interim period, however, we will be heavily dependent upon coal reserves to carry our energy load until the alternative sources for electric power generation are developed.

SUMMARY

Coal will begin replacing petroleum as a raw material energy source on the Pacific Coast in ever increasing amounts during the next 15-20 years. It will initially be in the form of electrical power, but increasing amounts will enter the energy mix in the form of SNG and as synthesis crude or distillates. Beyond the year 2000, all hydrocarbons, coal and petroleum alike, will be much too valuable to consume to produce energy. If the socio-industrial complexes of the world are to survive and if emerging countries are ever to attain levels of industrialization similar to the Western World, then our basic energy load must be carried by renewable, or extremely long-lived sources. Thermonuclear and solar generation of electric power offer this possibility. Coal is capable of meeting the energy requirements for a period of time beyond the year 2000 while alternative sources are being developed.

One further point. Industrialized societies are very vulnerable to disruption. With increasing competition for resources that is the result of the process of industrialization of the under-developed areas of the world, the need to avoid a major war is obvious. The industrialized nations survived the last war only because a large reserve of resources, particularly petroleum, remained to be developed. We are probably approaching a point of no return - indeed, we may already have passed it - whereby a major disruption of the industrialized societies of the world would be irreversible and we would again return to an agrarian culture able to support only a small fraction of today's population.

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BIOSTRATIGRAPHY OF THE UMPQUA GROUP, SOUTHWESTERN OREGON

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ABSTRACT

The studies of F.E. Turner (1938) on the stratigraphy and Mollusca of the Eocene of western Oregon form a background for the study of the Foraminifera of a portion of the Lower Tertiary marine volcanic and sedimentary rocks of southwestern Oregon. These rocks include the Siletz River Formation, the Umpqua Group, and the Tyee and Elkton Formations, in ascending stratigraphic order. Two hundred and twenty five species of smaller Foraminifera found in eighty-eight samples and four species of "orbitoidal" Foraminifera found in five samples are described from measured sections along the North Umpqua River, the Middle Fork of the Coquille River, the South Fork of the Coquille River, and twelve other localities throughout southwestern Oregon.

The presence of ecologically diagnostic forms of smaller Foraminifera, "orbitoidal" Foraminifera and larger marine invertebrates in the Siletz River Formation, the Umpqua Group, and the Elkton Formation indicates that deposition of these units took place in warm shallow waters of sublittoral to neritic depths with connections to the open ocean occasionally prevailing.

The presence of chronologically diagnostic congregations of smaller Foraminifera in the Siletz River Formation, the Umpqua Group and the Elkton Formation indicates that these units are referable to, respectively, the Penutian Stage, Lower Penutian-Upper Ulatisian Stages and the Upper Ulatisian Stage as defined by V.S. Mallory (1959) in California. The Tyee Formation is questionably referred to Mallory's (1959) Ulatisian Stage.

Penutian equivalents of the Siletz River Formation and the lower portion of the Umpqua Group include the Metchosin volcanics, Crescent Formation and the lower portion of the "Scow Bay" Formation of the Quimper Peninsula area in the Pacific Northwest; the upper Santa Susana Formation, lower Anita Formation, Sierra Blanca limestone, lower Arroyo Hondo member of the Lodo Formation, lower Las Juntas shale and the lower Muir sandstone in California. Ulatisian equivalents of the upper portion of the Umpqua Group include the upper part of the "Scow Bay" Formation of the Quimper Peninsula area in the Pacific Northwest; the lower Llajas Formation, upper Anita Formation, Gredal, Arroyo Hondo and Yokut members of the Lodo Formation, upper Muir sandstone, and the lower Vacaville shale in California. Ulatisian equivalents of the Tyee and Elkton Formations include the basal portion of the Yamhill Formation of northwest Oregon; the Metchosin volcanics and McIntosh

Formation of southwest Washington; the "Maynard" sandstone of the Quimper Peninsula area; and the upper Llajas Formation, Canoas silt, Domengine sandstone and upper Vacaville shale of California.

INTRODUCTION

The area in which the fossiliferous rocks studied for this paper are exposed lies in southwestern Oregon. It extends from Lat. 42 30' N. to Lat. 45 N., and from the 123rd Meridian to the Pacific coast (see Location Map), and includes portions of the Western Cascades, Coast Range, and Klamath Mountains physiographic provinces.

The Paleogene fossiliferous rocks of southwestern Oregon are part of a thick sequence of Cenozoic marine and continental sedimentary and volcanic rocks, ranging in age from lower Eocene to Pleistocene, which are widely distributed in both western Oregon and western Washington. These rocks were deposited in a structural embayment of the Cordillera which was bounded by the pre-Tertiary rocks of the Northern Cascades of Washington, the Wallowa Mountains of eastern Oregon, and the Klamath Mountains of southwestern Oregon.

To gain information about the heretofore little known foraminiferal fauna of the Lower Tertiary of Western Oregon and to establish the degree of correlation which might exist between the evidence offered by the Mollusca, the "orbitoidal" Foraminifera, and the smaller Foraminifera, the writer has studied the Umpqua Group and the formations that immediately underlie and overlie it. These studies are part of the continuing biostratigraphic studies of the west Coast Tertiary foraminiferal faunas which have been carried out over the past three decades by paleontologists associated with the Department and Museum of Paleontology, Berkeley.

In general, an attempt was made to measure and collect from the foraminiferal portions of the North Umpqua and Middle Fork Coquille sections studied by Turner (1938) for his classic work on the Mollusca and Stratigraphy of the western Oregon Eocene. In addition, samples taken from significant stratigraphic intervals in the lower and middle Eocene throughout much of western Oregon were studied, and the pertinent literature on the stratigraphy and paleontology of the lower Tertiary of this area was reviewed.

Field work entailed in this project was carried out through portions of the summers of 1961, 1962, and 1963. Additional field studies were made in the fall of 1961, in the spring of 1964, and in the summer of 1974. Detailed mapping in the vicinity of those sections which were measured and collected from by the writer was carried out, aided by mapping in stratigraphically critical areas. The measurement of the section exposed along the South Fork of the Coquille River was done by Mr. Steve Born in 1962, as a portion of his studies for the Master's Degree at the University of Oregon. Mr. Born also did the detailed mapping in the vicinity of this section and collected the foraminiferal samples presented in the present paper.

All specimens included in this study are on deposit at the University of California's Museum of Paleontology at Berkeley.

Thanks are due the following persons for their suggestions, assistance, and encouragement: R.M. Kleimpell, V.S. Mallory, W.B.N. Berry, R.L. Hay, J.E. Allen, E.M. Baldwin, H.E. Wheeler, J.W. Durham, W.W. Rau, Boris Laiming, L. Kuenzi, H. Gower, D. Peck, S. Born, L. Burns, R. Gonsalves, J. Marr, J. Anderson, R. Kienle, K. Bird, L. Gaston, and A. Callender. Expenses were defrayed through the generosity of the Department of Paleontology and the Museum of Paleontology, University of California, Berkeley.

STRATIGRAPHY

General. Ideally, in order to establish a standard chronologic biostratigraphic sequence for the Umpqua Formation, one should be able to show that the sequence is under demonstrable superpositional control, that it represents continuous and uninterrupted deposition, that it is paleontologically controlled at both bottom and top, and that it is continuously fossiliferous. The following discussion is intended to demonstrate how well the Umpqua sequence fulfills these ideal requirements.

Historical Review. Eocene deposits in Oregon were early recognized by W. White and by Professor Thomas Condon, the pioneer Oregon geologist, in 1885 and again in 1889.

Diller (1893) summarized the state of knowledge of the Eocene in Oregon, mentioning more discoveries of Eocene fossils by Condon in the Roseburg area. In 1896, Diller stated his conclusions about the stratigraphic sequence of beds referred to the Eocene in western Oregon, saying that "...in general the oldest Eocene strata are those composed of volcanic material, and they are closely associated with the lavas to which they belong. Next above them comes a great mass of shales, containing here and there much material of igneous origin, and in the upper part of the series massive beds of sandstone predominate." (p. 456) In the same paper, Diller also applied the first specific terminology to rocks of the Oregon Tertiary, referring to the "Arago beds," which lie between the pre-Tertiary and the "Miocene sandstones" near Cape Arago. The names of the Umpqua and Tyee Formations, the most widespread of any of the Tertiary units of western Oregon, were established by Diller in the Roseburg Folio (U.S.G.S., 1898). Further subdivision of the Arago beds by Diller (1899) produced the formational terms "Coaledo" for the upper coaly beds of the Arago, and "Pulaski" for the more sandy lower portion of this group. These two terms were again employed by him in the Coos Bay Folio (U.S.G.S., 1901), but in the Port Orford Folio (U.S.G.S., 1903), he ignored this previous subdivision and referred all the Eocene strata to the "Arago Formation." Actually, strata of the so-called Pulaski Formation of the Coos Bay region, and of the so-called Arago Formation of Diller's usage in the Port Orford area, are now known to represent the Umpqua and the Tyee Formations instead. These formations had been named by Diller himself in the Roseburg Folio. A further terminological complication exists in that the name "Pulaski" was preoccupied at the time it was proposed by Diller.

Further studies on the stratigraphy and paleontology of the marine Paleogene sequence of western Oregon were accomplished by Diller (1907). Arnold and Hannibal (1913, 1914), Dickerson (1914), Washburne (1914), Smith and Packard (1919), Clark (1921), Hertlein and Crickmay (1925), Schenck (1927, 1928), Cushman and Schenck (1928), Turner (1929), Merriam and Turner (1937), Weaver (1937), Berthiaume (1938), Vokes (1939), Bentson

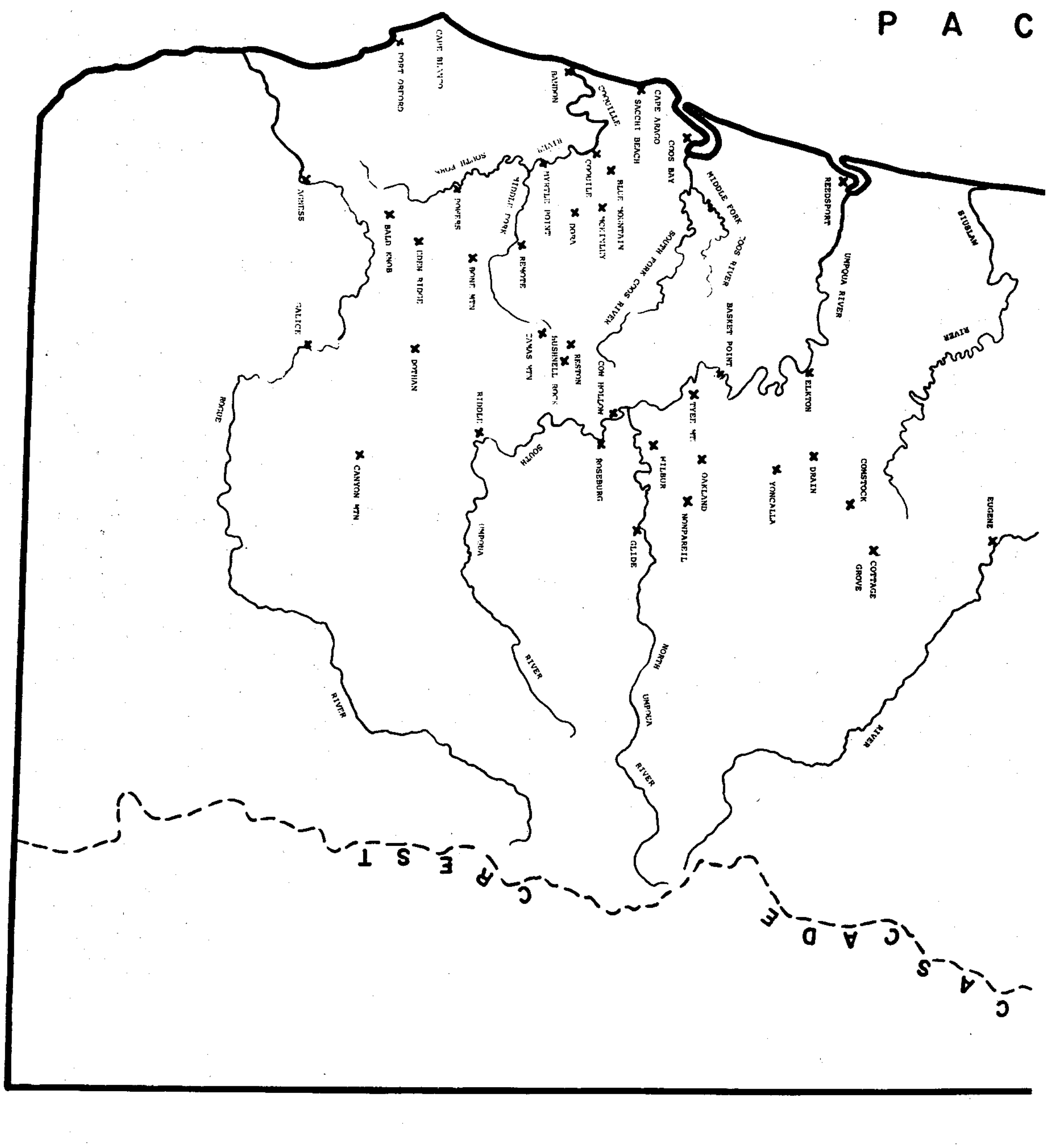
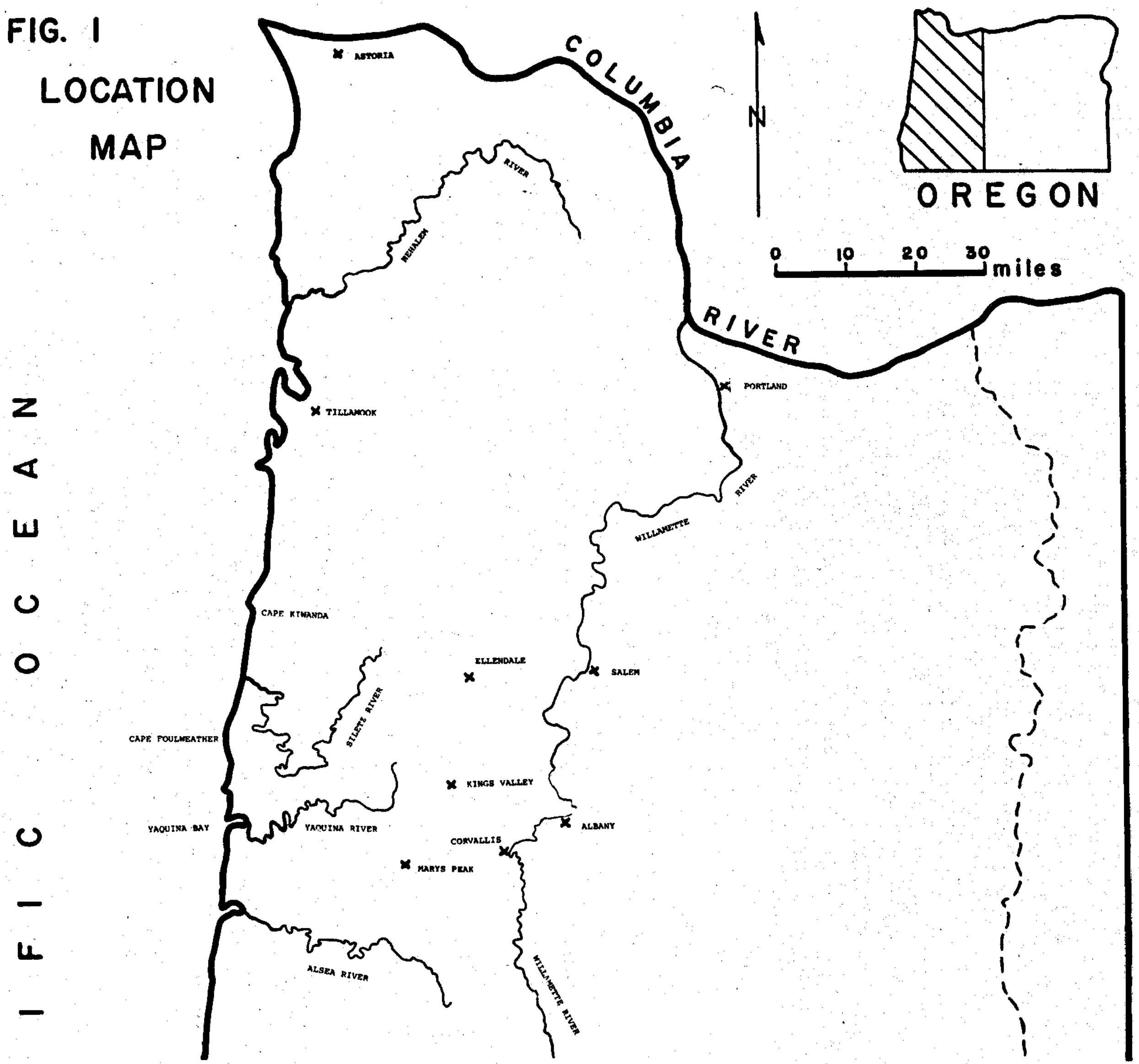

P A C
SIUSLAW
RIVER
EUGENE
RIVER
COMSTOCK
COTTAGE GROVE
UMPQUA RIVER
REEDSPORT
ELKTON
DRAIN
YONCALLA
CASCADE
MIDDLE FORK
COOS RIVER
BASKET POINT
TYEE MT.
OAKLAND
NONPAREIL
COOS BAY
CAPE ARAGO
SACCHI BEACH
SOUTH FORK COOS RIVER
WILBUR
NORTH
UMPQUA
RIVER
GLIDE
BLUE MOUNTAIN
MCKINLEY
COQUILLE
COW HOLLOW
ROSEBURG
DORA
RESTON
BUSHNELL ROCK
BANDON
MYRTLE POINT
CAMAS MTN
SOUTH
RIVER
REMOTE
MIDDLE FORK
RIDDLE
UMPQUA
BONE MTN
SOUTH FORK
POWERS
CAPE BLANCO
EDEN RIDGE
DOTHAN
PORT ORFORD
BALD KNOB
CANYON MTN
RIVER
AGNESS
GALICE
ROGUE
CREST

FIG. I
LOCATION
MAP



(1941), Weaver (1942), Allen and Baldwin (1944), Weaver, et. al. (1944), Warren and Norbisrath (1946), and Snavely and Baldwin (1948).

A major stratigraphic synthesis was accomplished by Turner (1938), in a paper which covered the general geology, areal distribution, stratigraphic sequence, and fossil Mollusca of the Eocene strata of western Oregon. An attempt was made by him to divide the Umpqua into an upper and a lower unit, defining each on the basis of the fauna contained therein. This same criterion was used to separate the Tyee and Umpqua Formations. Turner correlated the Umpqua with the Capay, considering that it might also be partly equivalent to the Domengine of California. He also correlated the Tyee Formation with the Domengine, and the Coaledo with the Tejon of California and the Cowlitz Formation of Washington. For his discussion of the stratigraphy of the Coos Bay region, Turner retained Diller's terminology of "Arago," "Pulaski," and "Coaledo."

Beck (1943), studying the Foraminifera of the type locality of the Cowlitz Formation of Washington, stated that at least the top 360 feet of the Coaledo Formation were equivalent in age to the Cowlitz.

In 1944, Bandy, describing a foraminiferal faunule from Cape Blanco, Oregon, referred the outcrops of black mudstone exposed there to the Arago Formation, and assigned it to the middle Eocene.

Further studies of the Eocene Foraminifera of Oregon were carried out by Cushman, Stewart, and Stewart (1947). They described three foraminiferal faunules; one from an unnamed formation exposed at Helmick Hill, near Salem; and two from the Coaledo Formation at Yokam Point and at Sunset Bay, in the Coos Bay area. The authors correlated all three faunules with the faunules of the Cowlitz Formation of Washington.

Still another foraminiferal faunule from the Eocene of Oregon was described by Cushman, Stewart, and Stewart in 1949. This was from the Moody shale member of the Toledo Formation in the Yaquina Bay region. It was correlated by them with the faunules of the beds at Helmick Hill and the Bastendorf shale at Coos Bay.

Mallory (1953), comparing the Eocene of California, Oregon, and Washington, stated that the middle member of the Lodo Formation at Media Agua Creek, on the west side of the San Joaquin Valley in California, the Nabury member of the Lodo at Devils' Den nearby, the Sierra Blanca limestone of the Santa Barbara Coast, and the Capay Formation on the west side of the Sacramento Valley of California, were equivalent in age to the lower Umpqua of Oregon and the Crescent Formation of Washington. The assignment of the lower Eocene age, "Capay" or C-Zone (in the terminology of Laiming, 1939), to these strata was based upon the common occurrence of Pseudophragmina psila, Actinocyclina aster, and several age-restricted species of smaller Foraminifera (p. 2781).

In a series of reports for the Oregon Department of Geology and Mineral Indistries, Stewart (1956-1957) described foraminiferal faunules from most of the Tertiary Formations of western Oregon. The Umpqua Formation in its type area near Glide was correlated with the C-B3 Zones of Laiming's (1939) California Tertiary sequence, and a range through the B2-B1 Zones was indicated for the Tyee Formation at Basket Point, on the Umpqua River, the locality from which Turner described the Mollusca of the "type Tyee." Unpublished work in later years includes the stratigraphically detailed work of Bird (1967), on the Elkton Formation; and of Gaston (1974) on the type Yamhill Formation.

The Subjacent Formations. The term pre-Tertiary as used herein refers to that large body of folded and sheared metamorphosed sedimentary and volcanic rocks, and sedimentary rocks, ranging in age from Silurian to mid-Cretaceous, which crop out immediately to the south and southeast of the area occupied by the Tertiary Formations of western Oregon, largely in the Klamath Mountains (see Wells, 1961), and are in contact with the overlying Umpqua Formation. They include the "Dothan" (Diller and Kay, 1924), "Rogue" (Wells and Walker, 1953), "Galice" (Diller, 1907), "Riddle" (Imlay, et al., 1959), and "Days Creek" Formations (Imlay, et al., 1959).

Gneiss formed by the regional metamorphism of the Galice, Rogue, and Dothan Formations is shown in places on the geologic map of western Oregon (Wells, 1961), to be in contact with the Umpqua Group.

The masses of serpentine and other ultramafic rocks which, in certain areas, are in contact with the Umpqua, were originally intruded into the Jurassic and Cretaceous rocks as peridotite and dunite bodies and later altered to their present composition (Baldwin, 1959). Later intrusions or later folding apparently also took place in Tertiary time, as indicated by attitudes in the Umpqua sediments near some of these bodies.

The contact of the Umpqua with the pre-Tertiary units mentioned above has been variously described by different authors as a fault, an unconformity, or a contact of undetermined nature.

The Umpqua Group. In 1898, the United States Geological Survey published the Geologic Folio Atlas of the Roseburg Quadrangle, by J.S. Diller. This classic paper contains the original descriptions of the two most widespread Tertiary units of western Oregon, the Umpqua and the Tyee.

Concerning the petrographic nature of the Umpqua, Diller noted that it consisted of an extensive series of sandstones and shales, interbedded with less abundant conglomerates, and minor beds of tuff, coal, and limestone, overlying a thick sequence of basalts.

Diller (1898) went on to describe the thickness, type section, and distribution of the Umpqua, saying that "it is by far the thickest formation in the Roseburg Quadrangle, but on account of the lack of good exposures of certain members of the series the whole could not be accurately measured. The best outcrops are along the Little River, where a continuous section of a portion of the series is well exposed. This portion has a thickness of about 7500 feet. It is interrupted on the northwest by the large mass of diabase, beyond which ... about 4500 feet of still lower beds are seen, making a total thickness of approximately 12,000 feet for the entire exposed formation. It increases in thickness to the northwest and has wide distribution throughout the Coast Range ... The Umpqua Formation in places contains many fossils, some of which are especially characteristic. Along Little River, for a distance of 3-½ miles, they are abundant."

Diller next discussed the huge thickness of flows, pillow lavas, tuffs and agglomerates which underlie the Umpqua sedimentary rocks. He referred to these volcanics as "diabase," but clearly did not completely understand their mode of origin. Actually, it is easy to see why Diller was confused, for in addition to extrusive basaltic rocks, the Umpqua (as defined by Diller) has several gabbroic sills and dikes, emplaced at a later time than the extrusion of the lavas. Diller proposed modes of origin for each of these rock types, but did not realize that they were parts of separate episodes of igneous activity.

The contact with the subjacent strata was described by Diller (1898) as an angular unconformity, although he did not mention a locality where this could be seen.

Turner (1938), followed Diller's stratigraphic terms, commenting on the origin of certain rock types, but did not elaborate on the original usage.

Baldwin (1974) subdivided the Umpqua, defining and naming what he interpreted to be three mappable units within the formation, thus permitting its elevation to group status. These subdivisions of the Umpqua Group are, in ascending stratigraphic order, the Roseburg, Lookingglass, and Flournoy Formations. The Lookingglass consists of three members, named Bushnell Rock, Tenmile, and Olalla Creek; and the Flournoy of two, named White Tail Ridge and Camas Valley. The reader is referred to Baldwin's paper (1974) for the original descriptions of these units.

The writer is inclined to regard the apparent unconformity between the Roseburg and Lookingglass, interpreted by Baldwin mainly from differences of attitude in separated outcrops, as more probably due to differences in competence of the Roseburg and the basal conglomerates of the Lookingglass (Bushnell Rock member), the former tending to fold while the latter fractured. No unconformity was observed by the writer between the Lookingglass and Flournoy, as described by Baldwin along Highway 42 between Camas Mountain and Remote, although the mapped basal contact of the Flournoy does appear to be discordant in places with patterns seen in the subjacent units.

The volcanics of Baldwin's Roseburg are referred to in the following discussion as a separate formation, the Siletz River Formation. The Siletz River Volcanic Series was described by Snavely and Baldwin (1948), with a type section exposed along the Siletz River in the western central Coast Range (see Location map). The authors considered the volcanics to be equivalent in part to the Tillamook volcanics of Warren and Norbisrath (1946), the Metchosin (Crescent of some authors) volcanics of Washington and British Columbia, and the volcanics associated with the Umpqua Formation (part of Diller's "diabase"). The writer interprets the Umpqua volcanics as representing the same lithogenetic unit as the Siletz River volcanics, because of similar lithology and stratigraphic position, as well as similar structural trends, and proximity of outcrops.

The Siletz River Formation is in fault contact with the pre-Tertiary to the south of Roseburg (Wells, 1961), and its basal contact has not been recorded as exposed anywhere in western Oregon. The formation is widely distributed, cropping out extensively in the northern, central, and southern Coast Range; in the southern Willamette Valley; and in the Roseburg area. In places, in the northern and central Coast Range and in the southern Willamette Valley, the volcanics conformably underlie and interfinger with waterlaid tuffs, basaltic sandstones, and basaltic conglomerates which contain a "Capay" molluscan fauna, and Foraminifera which, according to Rau (in Baldwin, _et al_., 1955), indicate an age of "B2-C Zone" in Laiming's (1939) classification of the lower Tertiary. The Tyee sandstone, the Elkton siltstone, or their correlatives, or younger sediments lie with apparent unconformity on the basalts or their associated sediments. The King's Valley siltstone of the eastern central Coast Range, and the Roseburg apparently are conformable on the Siletz River Formation, or interfinger with it at their bases.

The thickness of this formation is unknown, since its base has never been observed, but it is estimated by certain authors as including possibly as much as 10,000 feet of flow rock. In the type section, Snavely and Baldwin measured a minimum possible thickness of 3,000 - 5,000 feet.

In the vicinity of Glide, along the North Umpqua River, just a short distance from the type section on Little River, rocks which belong to the Roseburg Formation are preserved in a shallow syncline in the underlying volcanics. They consist of a basal conglomerate, overlain by dark mudstones and rhythmically bedded siltstone and sandstone. The contact with the overlying Lookingglass Formation is a fault zone about 1/8 mile in width. The beds upstream from the fault, belonging to the Lookingglass, consist of massive basal conglomerates, thick sandstones with interbedded lignitic shales, and a massive mudstone unit at the top of the sequence. The top of this mudstone is separated by a covered interval from the base of the overlying Tyee sandstone. Erosion before deposition of the Tyee has probably removed the Flournoy Formation in this section.

To the north of Roseburg, in the Drain and Anlauf Quadrangles, Hoover (1963) has described in some detail the sediments overlying the volcanics. A total thickness of 5,000 feet of rocks, referable to the Roseburg Formation was measured between the Siletz River and Tyee Formations. No rocks similar to the Lookingglass or Flournoy Formations are known to occur in this area.

The Roseburg has been mapped in the central Coast Range as the King's Valley siltstone by Vokes, et al., (1954), who considered it to be a member of the Siletz River Formation.

Baldwin (1973) has mapped the extent of the Siletz River, Roseburg, Lookingglass, and Flournoy Formations in Coos County. The biostratigraphically important sections along the Middle and South Forks of the Coquille River are included in his paper. Both the Tyee sandstone and the Coaledo Formation are in contact with the Umpqua Group in this area. The total thickness of the Umpqua in this area is unknown, but must amount to several thousands of feet.

The Superjacent Formations. Lying stratigraphically above the Umpqua Group in much of western Oregon is the Tyee sandstone, also of Eocene age. It was named by Diller (1898) from its exposures along the bold escarpment on the eastern face of Tyee Mountain, in the northwestern corner of the Roseburg Quadrangle. According to Turner (1938), the Tyee as exposed west of the Roseburg Quadrangle is about 5,000 feet thick, composed principally of massive micaceous sandstone, occasionally cross-bedded, with lesser amounts of shale. Baldwin (1974), corraborated these observations.

In the southern Coast Range, near the Klamath Mountains, the Tyee is a prominent ridge-former in the vicinity of Bone Mountain, Eden Ridge, and Bald Knob (see Location map). Here coal is interbedded in places with the massive sandstone, and a thin conglomerate appears at the base of the unit. At Eden Ridge, where the Tyee overlies the Umpqua Formation, fossil wood has been observed in interbeds within the sandstone. Where the Middle Fork of the Coquille crosses the Coast Range, the Tyee occurs again as a ridge-former, exposed at higher elevations on both sides of the stream, but not in its bed.

To the west, in the Coos Bay Quadrangle, Allen and Baldwin (1944) discussed the petrographic nature of the Tyee at some length. As in other areas, small coal beds occur, and mud cracks were found in some places. Near McKinley and Dora (see Location map) the Tyee overlies a thick sequence of Umpqua sediments, but on Blue Mountain it rests on the Siletz River Formation.

Northward, in the central Coast Range, 5,000 - 6,000 feet of Tyee sandstone rests on the Siletz River Formation and on the "lower member" of the Umpqua Formation, referred in this area to the King's Valley siltstone (Vokes, et al., 1954). The beds in the Tyee are often sharply defined at their bases, grading upward through medium to fine-grained sandstone and followed by siltstone. Here rhythmic bedding is more pronounced, the grading being repeated over and over again in vertical sequence.

In the northern Coast Range, the Tyee sandstone has also been referred to as the Burpee Formation, and is thought by some authors to be more nearly of terrestrial deposition than the typical Tyee. Approximately 5,000 feet of rhythmically bedded massive micaceous sandstones with siltstone interbeds overlie the Siletz River Formation in the Dallas, Valsetz, and Spirit Mountain Quadrangles, in the lower Siuslaw River area, and along the coastal region inland from Cape Kiwanda to Cape Foulweather (see location map).

In the vicinity of Corvallis, the Tyee overlaps the King's Valley siltstone and the Siletz River Formation, respectively, from the west to the east. About 4,000 feet or more of massive micaceous blue-gray arkosic sandstone containing wrinkled biotite and muscovite flakes and overlying a basal basalt pebble conglomerate were recorded by Vokes, et al., (1954).

At the southern end of the Willamette Valley 5,000 feet of Tyee sandstone are exposed, overlain by the Lorane shale. The base of sandstone is not exposed in this region, but to the south, in the Anlauf and Drain Quadrangles (Hoover, 1963), it rests on the Siletz River Formation and the Umpqua Formation.

The nature of the contact between the Tyee sandstone and the underlying units, particularly the Umpqua, has been discussed by various authors, including Diller (1896), Turner (1938), and Baldwin (1973, 1974). It will be noted that nowhere has it been demonstrated that the Tyee rests upon the truncated bedding of the Umpqua Group, although both Diller (1896) and Baldwin (1973, 1974) have stated that such a possibility exists, based upon their observance of discordant attitudes in adjacent outcrops of the two units, and Baldwin (1974) has observed cut and fill structures at the base of the Tyee. It is more probable therefore, that the Tyee is at best disconformable on the Umpqua, and overlaps it and rests upon the Siletz River Formation in many places in the Coast Range.

Baldwin (1961) designated 2,000 - 3,000 feet of dark gray argillaceous siltstone and thinly bedded sandstones, occurring near the town of Elkton, on the Umpqua River (see Location map), as the type section of a unit which he named the "Elkton siltstone member of the Tyee Formation." Later (in 1974), he referred to this unit formally as the "Elkton Formation".

In its type area, the Elkton Formation rests conformably on sandstone characteristic of the Tyee Formation. At Basket Point, to the south, it lies immediately above, and apparently again conformable upon, the type section of the Tyee. West of Basket Point the Coaledo rests upon the Elkton (Baldwin, 1961). The molluscan fauna which Turner (1938) collected from the "Tyee type (Basket Point)" was probably obtained from the Elkton Formation, according to his locality data.

Northward, along the southern end of the Willamette Valley, siltstone indistinguishable from the Elkton has been mapped as the "Lorane shale" (Vokes, et al., 1951). This "shale" consists of dark gray argillaceous siltstones, 600 feet thick, containing a foraminiferal faunule which has been assigned to Laiming's "B1-B1a" Zones. The Elkton in this area apparently is conformable upon the Tyee sandstone, although Vokes et al., were not completely certain of this relationship.

In the Coast Range adjacent to the west central Willamette Valley, a siltstone characteristic of the Elkton conformably overlies the Tyee, according to Vokes, et al., (1954).

A probable thickness of over 1,000 feet was indicated by Baldwin (1947) in the Dallas and Valsetz Quadrangles for the Elkton Formation, which appears to be the upper portion of his "Umpqua-Tyee." It is apparently conformable upon the basal sandstone of this latter unit, which probably represents the Tyee sandstone in this area.

To the southwest of its type area, the Elkton may be represented by the beds at Sacchi Beach, three miles south of Cape Arago, and by the Eocene shales at Cape Blanco (see Location map). The former beds, mapped as Umpqua by Allen and Baldwin (1944), occur in the axis of a faulted anticline in the Coaledo Formation. The upper contact with the Coaledo is not exposed, and tne lower portions of the beds are in fault contact with the Coaledo.

The dark shales at Cape Blanco, from which a foraminiferal faunule has been described by Bandy (1944), may represent the southernmost occurrence of the Elkton Formation. Unfortunately, the beds are much slumped, showing no depositional structures. No base nor top to the section, nor indeed even its thickness, is known.

In the Sheridan and McMinnville Quadrangles, southwest of Portland, rocks which may be partially equivalent in age to the Elkton Formation have been mapped by Baldwin et al., (1955) as the Yamhill Formation. The type section consists of 5,000 feet of dark gray shales and siltstones outcropping along Mill Creek and the Yamhill River. The base, in this area, is unconformable on the Siletz River Formation, according to the authors.

STRUCTURAL GEOLOGY

The major structural pattern exhibited by the lower Tertiary rocks of southwestern Oregon is that of a series of broad gentle folds and faults trending northeast-southwest. This pattern is itself only a portion of a still greater eastward indentation of the lower Tertiary and pre-Tertiary rocks of the Cordillera, the axis of which is approximately coincident with the Columbia River.

For a detailed illustration of the major folds and faults of western Oregon, the reader is referred to the U.S.G.S. Geologic Map of Oregon west of the 121st Meridian (Wells, 1961), and to papers by Hoover (1963) and Baldwin (1964, 1973, 1974).

A structural pattern which figures greatly in the interpretation of the stratigraphy of the Umpqua Group occurs along the northwestern border of the main area of outcrop of the Siletz River Formation near Roseburg. The northeastward extension of this outcrop pattern, which is basically a minor anticlinorium, has been mapped by Hoover (1963) as the "Coon Creek Anticline." He showed a high-angle reverse or thrust fault along the northwest limb of this structure on the geologic cross-sections accompanying his map, but did not elaborate on this in his text. The dips along the northwest flank are steep, up to 90°. To the southwest, this flank of the anticlinorium is much broken up by faulting, as can be seen in outcrop and roadcut exposures from the vicinity of the Bonanza Mine, near Nonpareil, to U.S. Highway I-5. This zone of deformation has been named the Bonanza Fault by Baldwin (1964), who recognized it as a high-angle reverse fault which thrusts the Siletz River Formation from the southeast over the Roseburg Formation to the northwest. Although Baldwin has traced this structure on his map only as far as the Umpqua River near Melrose, structural complications to the south as far as Dutchman Butte indicate that the Umpqua Group is probably involved in several high angle reverse faults.

On the North Umpqua River, downstream from Glide, a north-northeast trending fault zone several hundred yards wide affects both the Roseburg and Lookingglass Formations, thus obscuring their contact relations in this critical section.

Along the Little River, between Glide and Peel, the Lookingglass is overthrust from the southeast by serpentine, and serpentine is again involved along fault contacts with the Roseburg and Siletz River Formations in Coos County along the Middle and South Forks of the Coquille River.

Elsewhere, many folds and faults occur in the Paleogene units of western Oregon, far too many to be adequately discussed in this paper. In general, the basalts of the Siletz River Formation and the sandstones of the Tyee Formation have played the role of structurally competent bodies, being involved usually in broad folds with relatively low dips. The stress to which they have been subjected has been taken up mainly by faulting. On the other hand, the finer and thin-bedded sediments of the Umpqua Group, being less competent, display a greater amount of folding, and the Roseburg Formation exhibits this to a greater degree than the Lookingglass and Flournoy Formations. The greater number of competent beds, in the form of massive conglomerates and sandstones, which occur in the latter units, probably accounts for this difference. Broad folds and dips up to 45°, but usually less, are exhibited by these Formations, whereas the Roseburg is often contorted into tight isoclinal folds. This difference may have been enhanced by proximity to major faults such as those described above.

PALEONTOLOGY

The Mollusca. Throughout the Paleogene of western Oregon, fossil Mollusca are common to abundant in sediments either interbedded with, or otherwise closely associated with those containing fossil Foraminifera. Most of the studies of fossil Mollusca from this interval in western Oregon have been concerned with single isolated samples, and only one, that of Turner (1938), has dealt with a biostratigraphic study of this important group of organisms.

In this paper, Turner listed assemblages of fossil mollusca from many localities in units which he referred to as "lower Umpqua", "upper Umpqua", and "Tyee." These divisions were based by Turner on the presence of certain fossils, as he stated on page 32 of his text:

"...the Tyee and Umpqua divisions are recognized on the basis of 'guide fossils' rather than any marked difference of the faunas as a whole. Within the Umpqua the distinction between the upper and lower portion is made with greater difficulty and is sometimes impossible."

The fauna listed by Turner for the Umpqua west of Roseburg comes from beds lithologically indistinguishable from the Roseburg Formation. The fauna from the section exposed along the North Umpqua near Glide occurs in the Lookingglass Formation and corresponds to the lower part of his "Tyee" in that section. Turner listed fossil mollusca from his "lower Umpqua" near Glide (presumably the localities shown on his map near Beckley Ferry) in his general checklist for Eocene Formations of California, Oregon, and Washington, but he did not include these in his discussion of the Glide fauna. These localities are included by the writer in the Roseburg Formation. Along the Middle Fork of the Coquille, Turner listed fossils from the "lower" and "upper" Umpqua and from the "Tyee." Turner's "Tyee" is not the Tyee Formation, but corresponds approximately to the Flournoy Formation. Turner's "upper Umpqua" and a portion of his "lower Umpqua" correspond to the Lookingglass Formation. Only a part of Turner's "lower Umpqua", and at that the part for which he listed no fossils, falls within the unit recognized by the writer as the Roseburg Formation.

Turner's (1938) "Tyee type" molluscs come from the Elkton Formation as exposed at Basket Point. This molluscan fauna is very little different from that of the faunule collected by Turner from an exposure at the overpass on the old Pacific Highway 1/2 mile south of Comstock. (see Turner, 1938, p. 19, 21, 38.) According to Hoover (1963, p. 24) the beds at Comstock appear to be equivalent to the Elkton Formation. Turner's "North Umpqua" and "Middle Fork Coquille R." molluscs (listed on his checklist for the Tyee Formation) were collected from the upper part of the Umpqua Group (see above).

The Foraminifera. The foraminifers discussed in this paper came from the Siletz River Formation, the Umpqua Group, and the Elkton Formation. More specifically, they are from the upper sedimentary rocks of the Siletz River Formation exposed in the quarry at Ellendale; from the rhythmically bedded siltstones and fine sandstones, and mudstones of the Umpqua Group exposed along the banks of the South and Middle Forks of the Coquille River and the North Umpqua River, and in stream and road cuts at points between these sections; and from siltstones referred to the Elkton Formation, exposed at Basket Point and Sacchi Beach. For detailed geographic and stratigraphic location of these fossiliferous sections, the reader is referred to the geologic maps and the columnar sections in this paper.

The interbedding of mollusc-bearing sandstones and foraminiferal sandstones, siltstones, and mudstones is at a maximum in the Umpqua Group. In addition, association in the same beds of molluscs and "smaller" foraminifers, and of both "smaller" and "orbitoidal" foraminifers, as well as of "orbitoidal" foraminifers and molluscs, and occasionally of all three, are found in the Umpqua Group. The Elkton Formation at Basket Point contains both molluscs and "smaller", foraminifers, and at the type section (near Elkton), corals, molluscs, and both "orbitoidal" and "smaller" Foraminifera have been found (Baldwin, 1961).

The details of the distribution of the Foraminifera of the Siletz River, Umpqua, and Elkton Formations are graphically represented on the checklist accompanying this paper.

In general, the greatest degree of specific diversity in the Siletz River and Umpqua Formations is displayed by the Lagenidae, which is also one of the most numerous families represented. The agglutinating foraminifers, represented by several families, are more numerous, but less diverse specifically, than the lagenids. Rotalids are just somewhat less numerous and specifically diverse than these first two groups, and the anomalinids display even less numerical abundance and diversity. The Buliminidae are represented by fewer individuals but more species than the anomalinids. The Nonionidae and Miliolidae are about equally less numerous and diverse than are the Buliminidae. Abundant specimens but few species of two families of "larger" foraminifers, the Camerinidae and the Discocyclinidae, occur in various beds within the Siletz River Formation and the Umpqua Group.

In the Elkton Formation, representatives of several families of agglutinating Foraminifera are present, and they are the most abundant and most diverse, specifically, of any of the groups present. The lagenids, although much less numerous than the agglutinating foraminifers, are nearly as diverse, and are followed closely in the same pattern by the rotalids. The Buliminidae show nearly as much diversity in species as the rotalids, but are much less numerous. Anomalinids, although nearly as numerous as the agglutinating foraminifers, are even less diverse specifically than the buliminids, and show the least specific diversity of any family represented. Rare specimens of the Discocyclinidae occur in the type area.

PALEO-ECOLOGY

General. The bathymetric divisions used herein are intended to indicate depth of deposition only in a relative way, and for this reason, absolute depths in feet or meters are not given. These bathymetric divisions are: littoral, the region between high and low tides (corresponding to Natland's Zone II); neritic, the depths between lowest tide and the edge of the continental shelf (corresponding to Natland's Zone III); and bathyal, the region between the edge of the continental shelf and the base of the continental slope (corresponding to Natland's Zone IV).

The term "warm" used hereinafter refers to marine waters with an annual minimum surface temperature of about 20° - 16°C., and is to be contrasted with the terms "cool" (annual minimum surface temperature of about 16° - 10°C.) and "cold" (annual minimum surface temperature of about 10°C. and colder).

The mode of life of all foraminifers discussed below is to be considered as benthonic (bottom-dwelling), unless specified as pelagic (open-ocean planktonic).

Siletz River Formation. The presence of Operculina, a form found today only in the warm shallow waters of the Indo-Pacific (Cushman, 1955), seems to indicate that the waters in which the upper sedimentary beds of the Siletz River Formation were deposited were of the sort characteristically found today in the tropics. Further evidence for warm conditions of the shallower waters is given by the presence of "orbitoidal" Foraminifera, the closest analogs to which are found among the Recent "larger" Foraminifera of shallow tropical waters (Cushman, 1955; Bandy, 1960). Marine megafossils associated with these fossil foraminifers include reef-dwelling corals, bryozoa, and Ostrea, which tend to reinforce the interpretation of shallow, warm waters of upper neritic depth as the principal depositional environment for the sedimentary portions of this Formation. These conditions seem to have prevailed throughout most of the time that Siletz River sediments were being deposited, for the association listed above is found in nearly all fossil collections from this Formation.

Umpqua Group. The abundance and diversity of lagenids throughout the foraminiferal portions of this unit seem to indicate deposition in marine waters of medium (neritic and upper bathyl) depths (Cushman, 1955). Specimens of Operculina and Pseudophragmina, abundant in some samples (see checklist) would seem to indicate (for parts of the Umpqua as for the Siletz River Formation) that at particular times and places deposition took place in much more shallow water, and that these shallower waters were still warm (Cushman, 1955; Bandy, 1960). Common specimens of Vaginulinopsis, a large and ornamented lagenid, would seem to reinforce the idea of warm temperatures at shallow depths (Mallory, 1959, p. 32). Occasional occurrences of common to abundant pelagic foraminifers, such as Globorotalia and Globigerina (see checklist), indicate that surface connections to the open sea were present (Cushman, 1955). Megafossils found in the coarser interbeds of the rhythmically bedded portions of this unit, in the more massive sandstones, and in the foraminiferal mudstones, include large Turritellas (Turritella meganosensis protumescens) and giant Venericards, both of which are indicators of warm shallow waters of upper neritic depth, such as are found in the modern tropics (J.P. Smith, 1919).

Locally, deposition may even have taken place above the strand line, at least in two areas, as evidenced by the occurrence of lignite seams near the base of the Lookingglass Formation in the Middle Fork Coquille section, and below the base of the uppermost mudstone in the North Umpqua section.

Tyee Formation. The large amount of plant debris and coaly and woody material found in this Formation suggest deposition took place at near-shore depths or possibly even above sea level. As the writer will mention elsewhere in this paper (see section on Age and Correlation), well-substantiated occurrences of marine megafossils in the Tyee sandstone are non-existent. All of the published "Tyee" molluscs appear to come from the siltstones of the overlying Elkton Formation.

Elkton Formation. Foraminifera are not particularly conspicuous in those occurrences of the Elkton Formation incorporated in this study. Common specimens of Buliminella, a form which in modern seas ranges from the bathyal to the littoral zones (Natland, 1933), yields little clue as to the depth of deposition of this Formation. The presence of the large and ornate lagenid Vaginulinopsis may indicate warm temperatures at shallow depths, characteristic of the modern tropics, for the portions of this Formation in which it is common (see checklist; also see Mallory, 1959, p. 32). According to J.W. Durham (in Baldwin, 1961), corals and echinoids found in the type section of the Formation indicate that deposition there took place in water about 300 feet deep (upper neritic zone) under warm surface conditions. The occurrence of "orbitoidal" foraminifers, noted by Baldwin (1961) in the type section, would seem to reinforce the idea of warm shallow waters as the environment of deposition (Cushman, 1955; Bandy, 1960) of the Elkton Formation, at least at the type locality.

Yamhill Formation. According to Gaston (1974), "The lowermost part of the type Yamhill Formation was deposited at middle to lower bathyal depths in poorly aerated water of a silled basin. A gradual shallowing occurred, reaching lower neritic conditions during the deposition of the more clastic sediments of the middle sandstone member, which were probably derived from the volcanic area to the south. Connection with open ocean currents during this time was good. In the southern part of the basin, a return to bathyal conditions followed the deposition of the middle sandstone member. In the central parts of the basin to the north, contemporaneous deposition occurred at a slightly deeper upper to middle bathyal depth. A trend toward shallower conditions and good connection with open ocean currents occurred during the deposition of the upper type Yamhill Formation."

AGE AND CORRELATION

Mollusca. The original age assignments which have been given to the Formations of the western Oregon Paleogene were based on the Mollusca, the study of which has resulted, in Oregon as it did in the California Lower Tertiary, in the blocking out of the major Epochs and their subdivisions.

Reference is made in the following discussion to the "Domengine" and "Capay Stages" of the California Lower Tertiary molluscan chronology. In the application of these terms, confusion has been brought about by the lack of adequate superpositional control and the lack of knowledge concerning the stratigraphic ranges of individual species. These inherent inadequacies prevent close correlation between the megafossil "Stages" and the chronology based upon smaller Foraminifera in the West Coast Paleogene.

Most of the species found in the Siletz River Formation occur also in the superjacent Umpqua Group, which has, at least in its lower portion, been correlated with the Capay Formation of California (see below). The Crescent Formation of Washington also contains many of the forms listed from the Siletz River Formation and is probably stratigraphically (as well as chronologically) equivalent to the tuffaceous sediments of the latter Formation.

The first attempt to make correlations of the Umpqua with deposits in other regions at a more refined level than that of Period-Epoch was made by Dickerson (1914). He correlated the beds exposed at Glide (near the confluence of Little River and the North Umpqua River) with the fauna of his "Siphonalia sutterensis Zone" as exposed at Marysville Buttes and near Oroville, California.

In 1921, B. L. Clark noted that Dickerson's correlation of the

Umpqua with the Marysville and Oroville Eocene was correct, and he further correlated the latter two with the Meganos Formation of the Mt. Diablo region. But Clark also showed that Dickerson's stratigraphic interpretations were incorrect, and that his "Siphonalia sutterensis Zone" was the oldest, and not the youngest, Eocene, and was the shallow water facies of Dickerson's oldest "Zone."

Turner (1938) suggested a correlation of his "lower Umpqua" (actually the Lookingglass Formation) along the Middle Fork of the Coquille with the beds west of Roseburg (which are referable to the Roseburg and Lookingglass Formations).

Turner correlated the Glide fauna with both the "Capay" and "Domengine" molluscan "Stages" of California, listing approximately equal numbers of species in common with both the "Domengine" and "Capay Stages." He also correlated the Glide fauna with the fauna of his "upper Umpqua" along the Middle Fork of the Coquille.

From his "lower Umpqua" west of Roseburg Turner listed species which he considered to be of particular significance, commenting:

"These species are believed to indicate that the beds in which they are found correspond more closely in age to the Capay stage and lower Llajas of California than to the Tejon, Domengine, or Meganos."

Turner correlated a molluscan fauna from an exposure at an overpass along the Pacific Highway south of Comstock (see Turner, 1938, p. 19, 21, 38;) with that of the "Domengine Stage" of California, on the bases that: 1) the Venericardia found in the Tyee was identical with ones found in the upper Llajas Formation and the Rose Canyon shales of Southern California, which are considered to be equivalent in age to the Domengine Formation (see Vokes, 1939); and that 2) Turritella uvasana hendoni var. A. of the Tyee more closely resembled the Turritella applini group of the Rose Canyon shales that any other group of West Coast Turritella.

Turner also correlated the Basket Point molluscs (from the Elkton Formation) with the faunas of the Rose Canyon shales, the upper Llajas Formation, and the Domengine Formation of California on the same bases that he correlated the Tyee near Comstock with these Formations.

Later studies by Trumbull and Durham (in Baldwin, 1961) of the megafossils from the type section of the Elkton Formation have corroborated Turner's conclusion as to the age of this Formation.

Foraminifera. A sample (D-955) from the sediments immediately overlying the basalts of the Siletz River Formation in a quarry at Ellendale, west of Salem (see checklist) has yielded a foraminiferal assemblage which includes:

Species	California Teilzone
Anomalina garzaensis	L. Penutian - U. Narizian
Robulus alato-limbatus	L. Penutian - U. Narizian
Operculina cushmani	U. Bulitian - U. Ulatisian

These data do not permit a greater refinement of age that a range from the lower Penutian (Plectofrondicularia kerni Zone) to the upper

Ulatisian (Amphimorphina californica Zone) Stages.

Rau (in Baldwin, et al., 1955) recorded a foraminiferal assemblage from the upper sedimentary strata of the Siletz River Formation in the Mary's Peak and Alsea Quadrangles, and assigned to it an age of "B-2" to "C" in Laiming's classification. This is a somewhat more restricted age than is provided by the writer's data as summarized above, since the interval "B-2" to "C" in Laiming's zones is approximately equivalent to Mallory's Penutian Stage plus only the lower Zone (Vaginulinopsis mexicana Zone) of his Ulatisian Stage. An age determination approximately equivalent to that provided by the writer's foraminiferal data is indicated by the presence of a "Capay" molluscan fauna in this Formation, particularly in its type area (Snavely and Baldwin, 1948. See also this paper, Paleontology, the Mollusca).

The age of this Formation may very well be restricted to the interval assigned it by Rau (op. cit.), however, since it is overlain by the sedimentary beds of the Roseburg Formation which, as discussed below, appear to be Penutian and no younger wherever the Formations are in demonstrable superposition.

The foraminiferal fauna of the Roseburg exposed along the North Umpqua River near Glide (see checklist, this paper) includes the following chronologically diagnostic congregation:

Species	California Teilzone
Asterigerina crassaformis umbilicatula	L. Penutian - L. Narizian
Cassidulina globosa	L. Penutian - __________
Globigerina bulloides	L. Penutian - __________
Martinottiella eocenica	L. Penutian - U. Narizian
Robulus alato-limbatus	L. Penutian - U. Narizian
Uvigerina lodoensis miriamae	L. Penutian - U. Ulatisian
Nonion micrum	L. Penutian - L. Narizian
Cibicides fortunatus	U. Ynezian - U. Penutian
Nonion wilcoxensis	U. Ynezian - U. Penutian

An age of Penutian is indicated or this section by the overlap of the teilzones shown here.

Samples collected from the western limb of the Roseburt Anticline (see checklist) contain:

Species	California Teilzone
Cassidulina globosa	L. Penutian - __________
Globigerina bulloides	L. Penutian - __________

Martinottiella eocenica	L. Penutian - U. Narizian
Plectina garzaensis	L. Penutian - U. Narizian
Uvigerina lodoensis miriamae	L. Penutian - U. Ulatisian
Cibicides fortunatus	U. Ynezian - U. Penutian
Anomalina tennesseensis	U. Ynezian - U. Penutian

The overlap in teilzones of these species, and especially of the Cibicides, seems again to indicate an age of Penutian for this sequence.

Along the Middle Fork of the Coquille River, the Roseburg contains (see checklist) this chronologically diagnostic congregation:

Species	California Teilzone
Anomalina garzaensis	L. Penutian - U. Narizian
Martinottiella eocenica	L. Penutian - U. Narizian
Cibicides fortunatus	U. Ynezian - U. Penutian

This section again seems to be Penutian in age, based on the overlap of the teilzones listed here.

A sample (D-954) collected from the rhythmically bedded sandstones and siltstones (probably Roseburg Formation) exposed along Yellow Creek, between Powers and Myrtle Point (see checklist), contains the following chronologically diagnostic congregation:

Species	California Teilzone
Martinottiella eocenica	L. Penutian - U. Narizian
Uvigerina lodoensis miriamae	L. Penutian - U. Ulatisian
Quinqueloculina yequaensis	U. Penutian - U. Ulatisian

The overlap of the teilzones presented here would seem to indicate an age of late Penutian to late Ulatisian for this section.

Samples (D-956-929) collected from the Lookingglass along Four-mile Creek, near the coast south of the mouth of the Coquille River (see checklist) contain this congregation:

Species	California Teilzone
Cibicides fortunatus	U. Ynezian - U. Penutian
Pseudophragmina psila	L. Bulitian - U. Penutian
Robulus alato-limbatus	L. Penutian - U. Narizian

Thus an age of Penutian is indicated for these samples.

The following congregation was found in beds of the Lookingglass exposed at the drainage divide between Estes and Salmon Creeks, southwest of Powers (D-944, see checklist):

Species	California Teilzone
Bulimina debilis	L. Bulitian - U. Ulatisian
Pseudophragmina psila	L. Bulitian - U. Penutian

An age of Bulitian to Penutian is possible for this sample.

A sample collected from the Lookingglass at the drainage divide between the South Fork of the Coquille River and the Roque River (D-954, see checklist) contained only one chronologically diagnostic species, Cibicides fortunatus, which ranges from the upper Ynezian (Bulimina excavata Zone) to the upper Penutian (Alabamina wilcoxensis Zone) in California.

The Lookingglass Formation exposed along the North Umpqua River near Glide (see checklist) yielded the following congregation:

Species	California Teilzone
Globigerina bulloides	L. Penutian - ------------
Robulus alato-limbatus	L. Penutian - U. Narizian
Pseudophragmina psila	L. Bulitian - U. Penutian
Cibicides fortunatus	U. Ynezian - U. Penutian

An age of Penutian apparently is indicated for this section, but a possibly more restricted age of late Penutian (Alabamina wilcoxensis Zone) is suggested by the occurrence of Quinqueloculina yeguaensis, which seems to be restricted to that interval in California.

(Note that the Glide molluscan fauna, which Turner (1938) correlated with both the "Capay" and "Domengine" molluscan faunas of California came from this section of the Lookingglass Formation).

A mudstone exposed in a spillway excavated on the Magness Farm on Buckhorn Creek, south of Glide (D-901-902, see checklist) and referable to the Lookingglass Formation, has yielded a foraminiferal fauna which includes:

Species	
Pseudoglandulina ovata	L. Penutian - U. Narizian
Robulus alato-limbatus	L. Penutian - U. Narizian
Robulus cf. R. pseudomammiligerus	U. Ynezian - U. Ulatisian
Nodosaria latejugata	L. Ynezian - U. Ulatisian
Vaginulinopsis mexicana vacavillensis	U. Ynezian - U. Ulatisian

An age assignment of early Penutian (*Plectofrondicularia kerni* Zone) to late Ulatisian (*Amphimorphina californica* Zone) is permitted for this sequence.

Several species which the writer has regarded as diagnostic of the age of the foregoing sections are considered to have the same range in the Oregon Lower Tertiary as they do in the Lower Tertiary of the California Coast Ranges, for they occur in the Siletz River Formation and Umpqua Group in company with the same species with which they are associated in California. These include:

Anomalina qarzaensis	*Plectina garzaensis*
Robulus alato-limbatus	*Anomalina tennesseensis*
Operculina cushmani	*Quinqueloculina yeguaensis*
Asteriqerina crassaformis umbilicatula	*Pseudophragmina psila*
Cassidulina globosa	*Epistomina partschiana*
Globigerina bulloides	*Bulimina debilis*
Martinottiella eocenica	*Pseudoglandulina ovata*
Uvigerina lodoensis miriamae	*Robulus* cf. *R. pseudomammiligerus*
Nonion micrum	*Nodosaria latejugata*
Cibicides fortunatus	*Vaginulinopsis mexicana vacavillensis*
Nonion vilcoxensis	*Bulimina guayabalensis*

The beds at Sacchi Beach, apparently part of the Elkton Formation, contain a foraminiferal faunule which includes:

Species	California Teilzone
Amphimorphina californica	U. Ulatisian
Gyroidina orbicularis planata	U. Ulatisian - U. Narizian

This would seem to indicate an age of late Ulatisian (*Amphimorphina californica* Zone) for these beds.

In the type section of the Elkton Formation, Stewart (1957) found the following faunule:

Anomalina cf. *A. coalingensis*	*Marginulina mexicana* var. *A. Laiming*

Cibicides cf. C. D. Cushman and McMasters

M. mexicana var. B. Laiming

Dentalina cf. D. approximata

Nodosaria latejugata

D. communis

Quinqueloculina cf. Q. yequaensis

D. consobrina

Eponides ellisorae

Robulus inornatus

Gyroidina soldanii octocamerata

R. cf. R. midwayensis

R. pseudovortex

Textularia labiata

The Elkton formation at Basket Point included the folowing species also identified by Stewart (1957):

Bathysiphon (?) sp.

E. cf. E. minimus

Cibicides cf. C. jeffersonensis

Gaudryina (?) sp.

C. cf. C. sp. D. Cushman and McMasters

Gyroidina soldanii octocamerata

Cyclammina cf. C. clarki

Marginulina mexicana var. A. Laiming

Dentalina communis

Nodosaria latejugata

Eponides cf. E. ellisorae

Nonionella cf. N. frankei

Robulus inornatus

Both of these faunules were referred by Stewart to Laiming's "B-Zone."

Samples studied by W. W. Rau (in Baldwin, 1961) from the type section of the Elkton Formation were assigned by him to the "B-I" and "BIA" zones of Laiming's classification. This determination corresponds approximately to that made by the writer for the beds at Sacchi Beach.

Another faunule was described by W. W. Rau from a sample collected at the Comstock overpass by Hoover (1963, p. 28), from beds which appear to be part of the Elkton Formation. The following species were identified:

Gaudryina cf. G. coalingensis

Gyroidina cf. G. simiensis

Quinqueloculina sp.

Eponides cf. E. mexicanus

Robulus holcombensis

Cibicides cf. C. haydoni

Vaginulinopsis vacavillensis	Cibicides hodgei
Nodosaria latejugata	Cibicidoides coalingensis

Rau equated this faunule with those which he had studied from the type section of the Elkton Formation and from the Lookingglass Formation of the North Umpqua River section, and with the fauna of Laiming's "B-1 Zone" of California.

Stewart (1957) recorded much the same faunule from the same locality, and assigned the same age to it.

The foraminiferal faunule listed by Stewart (1957) from the "Glide section Tyee?", "Basket Point type Tyee," and the "Elkton Tyee," did not come from the Tyee Formation. The first of these is from the uppermost mudstone of the Lookingglass Formation in the North Umpqua River section, and the latter two are from the Elkton Formation, which Stewart refers to as "High Tyee."

Concerning the Yamhill Formation in its type area, where it rests unconformably upon the Siletz River Formation, Gaston (1974) has stated: "The foraminiferal fauna of the type Yamhill Formation can best be correlated with Mallory's Narizian stage. Of the 2350 ft. of the type Yamhill, the lower 1600 ft. can be assigned to the lower Narizian Bulimina corrugata zone and the remaining 750 ft. to the Upper Narizian Amphimorphina jenkinsi zone.

Apparently contradictory evidence for the age of some of the foregoing sections is given by specimens of several species which do not occur in the California Lower Tertiary in company with the species with which they are associated in the Umpqua Group and Siletz River Formation.

The first of these is Bolivina incrassata, which is found in a section exposed on Hill 622, one mile north of Myrtle Point, and in the Roseburg Formation in the North Umpqua section (see checklist), in association with a faunule which the writer regards as Penutian in age (see above). Mallory (1959) assigned a teilzone of lower Ynezian to upper Bulitian to this species in California, but R.M. Kleinpell (oral communication, 1964) has informed the writer that it occurs in the Canoas silt, which Mallory has assigned to the upper Zone of his Ulatisian Stage on the basis of other evidence.

Vaginulinopsis echinata, for which Mallory (1959) has listed a teilzone of lower Ynezian to lower Bulitian, occurs in the Roseburg Formation in the North Umpqua section (see checklist) in association with a faunule which the writer has assigned to the Penutian Stage (see above). At least seven of the species represented in this section do not range below the Penutian Stage in California, and the writer therefore concludes that the teilzone of V. echinata in Oregon must be different from its teilzone in California, possibly due to a longer range in the former area.

The occurrence of Bulimina curtissima in the Roseburg Formation of the North Umpqua section, and in the Roseburg of the Middle Fork Coquille section (see checklist), in association in both cases with a faunule interpreted by the writer on all other lines of evidence as Penutian in age (see above), also appears to be anomalous, for Mallory has stated that the species ranges in the California Lower Tertiary from the lower Ulatisian to the lower Narizian. In the Oregon sections listed here, it occurs in association with Cibicides fortunatus and Nonion wilcoxensis, both species which do not range above the Penutian Stage in California, according to Mallory (1959).

Another similar occurrence is that of Nonion applini, which seems to be restricted to deposits of Ulatisian age in California. This species occurs in faunules from the Roseburg of the North Umpqua section and from exposures of the Umpqua Group on the western limb of the Roseburg Anticline (see checklist), both of which have been assigned a Penutian age by the writer (see above). It is also found in the beds exposed on the Magness Farm (see checklist), which the writer regards as Penutian in age. Nonion applini is associated in these sections with Cibicides fortunatus and Nonion wilcoxensis, which do not range above the Penutian in California.

Cyclammina pacifica, a species which ranges from the upper Ulatisian to the upper Narizian in California, is found in the Roseburg Formation in the North Umpqua section (see checklist), which the writer regards as Penutian in age (see above). Here it is associated with Cibicides fortunatus and Nonion wilcoxensis, both species which do not occur in California in strata higher than the upper Penutian.

Haplophragmoides obliquicameratus, a species restricted to strata of Narizian age in the Lower Tertiary of California, is found in the Roseburg Formation in the North Umpqua section (see checklist), to which the writer has assigned an age of Penutian (see above). It is associated in this section with Cibicides fortunatus and Nonion wilcoxensis, which do not range above the Penutian Stage in California, and with Uvigerina lodoensis miriamae, which does not range above the Ulatisian Stage in California. It seems more probable that the teilzone of H. obliquicameratus in the Oregon Lower Tertiary differs from that in California, rather than that an extension of ranges is warranted for these three other species.

Mallory has stated that Verneuilina triangulata appears to be restricted to the lower Penutian in the California Lower Tertiary. It occurs in the Roseburg Formation exposed along the North Umpqua River, and in the mudstone of the Lookingglass Formation exposed on the Magness Farm (see checklist), both of which contain a faunule assigned by the writer to the upper Penutian (see above). This difference in age is not outstandingly great, however, and may be more apparent than real, for the age of the former section is based upon the presence of Quinqueloculina yeguaensis (restricted to the upper Penutian in California and somewhat discontinuous in its occurrence there), and the age of the latter section is based upon the occurrence of a single form which does not range below the upper Penutian in the California Lower Tertiary (Bulimina guayabalensis).

Two species, Alabamina wilcoxensis californica and Nonion planatum, which apparently do not range stratigraphically lower than the lower Ulatisian Stage in California, are found in the Umpqua Group. The former occurs in the samples from the western limb of the Roseburg Anticline, and the latter is found in that section as well as in the Roseburg Formation of the Middle Fork of the Coquille (see checklist) The writer has assigned an upper age limit of late Penutian to these sections, based in both cases on the presence of Cibicides fortunatus, which does not range higher than this interval in the California Lower Tertiary, and which is associated in other sections of the Umpqua Group (see above) with several other species which possess a similar upper age limit in California. The extension of the ranges of all three of these species may be warranted by this evidence.

Pseudoglandulina cyclindracea, a species which ranges no higher stratigraphically than the lower Bulitian in California, is found in the Roseburg Formation along the Middle Fork of the Coquille River (see checklist) in association with Anomalina garzaensis and Martinottiella eocenica, which do not range below the lower Penutian in California. Thus it seems that the range of P. cylindracea in the Oregon Lower Tertiary differs from its range in the Lower Tertiary of the California Coast Ranges.

Exposures in road cuts along Hill 622, one mile north of Myrtle Point, contain a faunule (see checklist) which the writer tentatively assigns to the Penutian Stage on the basis of the joint occurrence of Globigerina bulloides and Verneuilina triangulata. Both of these species do not range below the Penutian Stage in California, and the latter may not be restricted to the lower Penutian in Oregon, as it apparently is in California (see above). The association of Nodosaria macneili with these species in this section may warrant the extension of its range in the West Coast Lower Tertiary, for it is not known in California from beds higher than the upper Bulitian. Similarly, the association of Globigerina bakeri, which is apparently restricted to the lower Ulatisian in California, with the species mentioned above, may warrant the extension of its range also, and its occurrence in the Lookingglass in the South Fork Coquille section, to which the writer has assigned an age of late Penutian to late Ulatisian (see above), may thus not warrant a further restriction of the age of that section. The apparently restricted range of this species in California may well have been caused by its pelagic habit, which would account for a somewhat discontinuous distribution in the near-shore facies of the California Lower Tertiary.

Buliminella grata convoluta, a subspecies which ranges from the lower Ulatisian to the lower Narizian in California, is found in the Roseburg in the Middle Fork Coquille section (see checklist), which the writer regards as Penutian, and no younger, in age.

Cibicides laurisae, which is restricted to the Narizian Stage in California, occurs in the Siletz River Formation at Ellendale and in the Umpqua Group in the sections exposed in the west limb of the Roseburg Anticline and on the Magness Farm (see checklist). All three of these sections are regarded by the writer as being no younger than Penutian.

In the South Fork Coquille section of the Lookingglass Formation (see checklist), Cibicides praecursorius, a species restricted to the Ynezian Stage in California, occurs in association with a congregation regarded as no older than Penutian by the writer.

Gyroidina guayabalensis, a restricted lower Ulatisian species in California, occurs in the Roseburg in the Middle Fork Coquille section (see checklist) in company with Penutian foraminifers. This difference may be only minor, however, since it revolves about the problem of the boundary between two adjacent stages.

Cibicides susanaensis, a species which ranges no higher than the lower Bulitian in California, is found in both the Roseburg Formation of the Middle Fork Coquille section and the Lookingglass Formation of the North Umpqua River section (see checklist) in company with Penutian Foraminifera.

Another minor discrepancy of ranges is shown by the occurrence of

Eponides minima, which ranges no lower than the lower Ulatisian Stage in California, with foraminifers considered to be no younger than Penutian by the writer (see Estes Creek locality on checklist).

The age interpretation for the Paleogene in Western Oregon may be summarized as follows: the Siletz River Formation appears to correspond in age to that portion of the California Paleogene referred to the Penutian Stage. This is based upon the occurrence of chronologically diagnostic foraminifers and molluscs in this Formation, plus its stratigraphic position beneath the Umpqua Group. The Umpqua appears to be Penutian in age in most of the sections studied, but may be as young as Ulatisian in at least one section (the Lookingglass of the Middle Fork Coquille section). This determination corresponds approximately to Turner's (1938) assignment of a "Capay" to "Domengine" age to the Umpqua molluscan fauna. The Tyee and Elkton Formations apparently are equivalent in age to those strata in California which are assigned to the upper portion of Laiming's "B-Zone" or Mallory's Ulatisian Stage. This is approximately equivalent to Turner's determination of a "Domengine" age for the molluscs from these Formations and seems to corroborate the "Domengine"-Ulatisian approximate equivalence in California.

As noted previously, twenty of the species considered by the writer as most significant chronologically occur in the Oregon Paleogene in company with foraminifers with which they are also associated in California, and thus apparently no extensions or changes of their ranges are warranted. Certain of the species present in the Siletz River Formation and the Umpqua Group appear, however, to possess teilzones which differ from those to which they are restricted in California, for they are found here in association with species which do not occur with them in the California Paleogene.

Interpretations made by the writer from the evidence herein presented are the bases for the local correlations of sections in the Oregon Coast Range. In general, the writer's studies have tended to corroborate the correlations made by Turner (1938), based on the fossil Mollusca. That is, those portions of the Oregon Tertiary sequence which turner considered to be equivalent to the Capay and Domengine Formations of California apparently are equivalent, respectively, to the Penutian and Ulatisian Stages of California. One difference should be noted, however. Whereas Turner correlated the Mollusca from the Glide section of the Umpqua Formation with the molluscs of both the Domengine and Capay Formations of California, the writer would correlate the Foraminifera with those of the Penutian Stage of California, an interval which, along with the lower part of the Ulatisian Stage, is approximately equivalent to the "Capay stage" of the West Coast molluscan terminology.

Elsewhere in the West Coast Ranges, Penutian equivalents of the Siletz River Formation and portions of the Umpqua Group include the Siletz River Formation of northwestern Oregon, the Metchosin volcanics, Crescent Formation, and lower portions of the "Scow Bay" Formation of the Quimper peninsula area (Thoms, 1959); and the upper Santa Susana Formation, lower Anita Formation, Sierra Blanca limestone, lower Arroyo Hondo member of the Lodo Formation, lower Las Juntas shale and the lower Muir sandstone of the California Paleogene.

Ulatisian equivalents of portions of the Umpqua Group include the upper part of the "Scow Bay" Formation of the Quimper peninsula area (Thoms, 1959); the lower Llajas Formation; upper Anita Formation; the

Gredal, Arroyo Hondo, and Yokut members of the Lodo Formation; upper Muir sandstone; and the lower Vacaville shale.

Ulatisian equivalents of the Tyee and Elkton Formations include the Metchosin volcanics and McIntosh Formation of southwestern Washington, the "Maynard" sandstone of the Quimper peninsula area (Thoms, 1959); and the upper Llajas Formation, Canoas Silt, Domengine sandstone, and upper Vacaville shale of California.

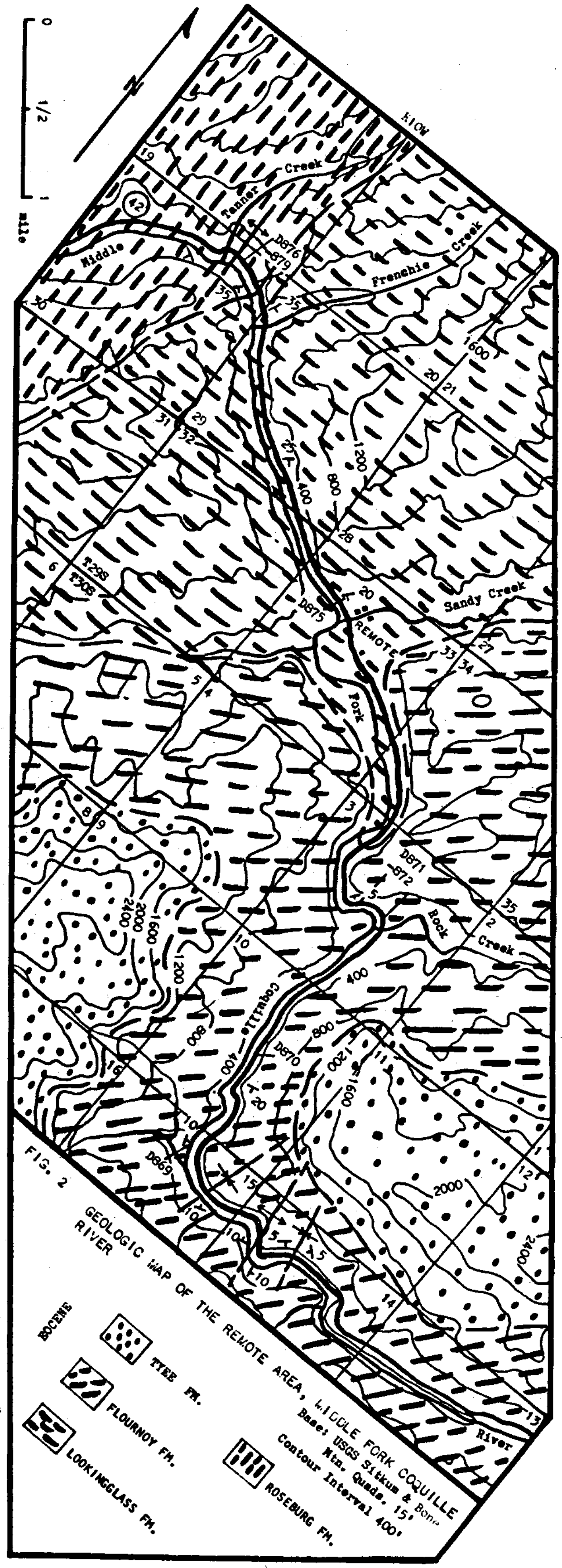


FIG. 2 GEOLOGIC MAP OF THE REMOTE AREA, MIDDLE FORK COQUILLE RIVER

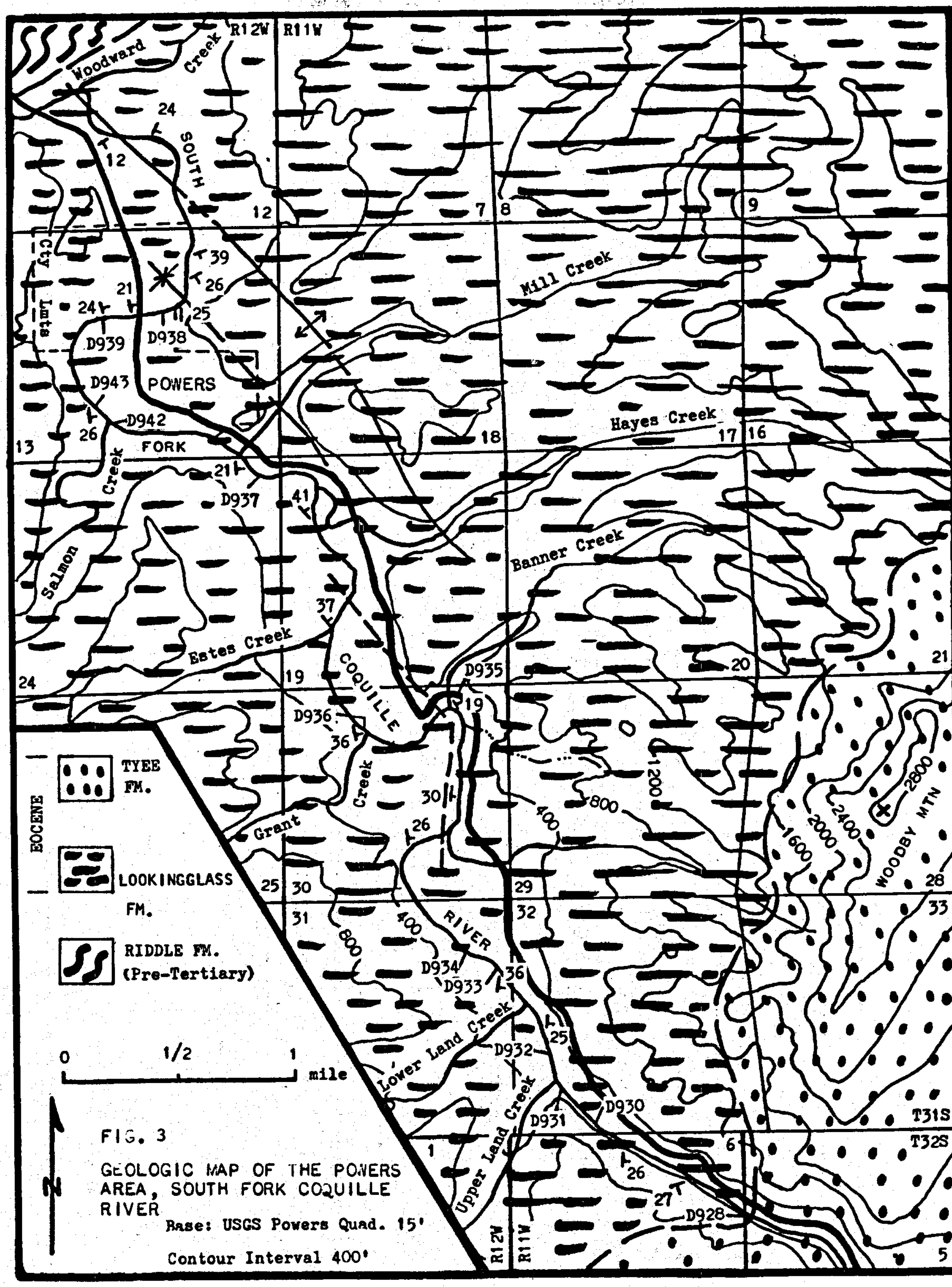


FIG. 3

GEOLOGIC MAP OF THE POWERS AREA, SOUTH FORK COQUILLE RIVER

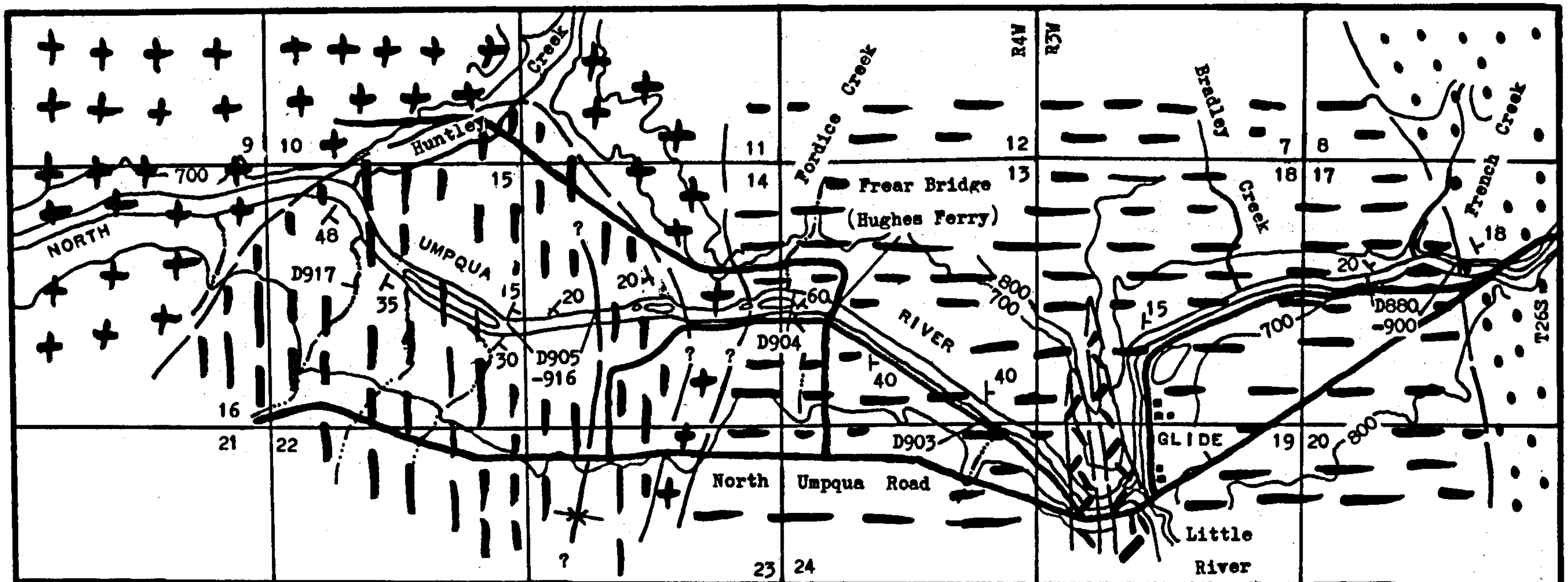


FIG. 4

GEOLOGIC MAP OF THE
GLIDE AREA
NORTH UMPQUA RIVER
OREGON

0 1/2 1 mile

CONTOUR INTERVAL 100'

BASE: USGS HYDROGRAPHIC CHART
UMPQUA RIVER

N

EOCENE

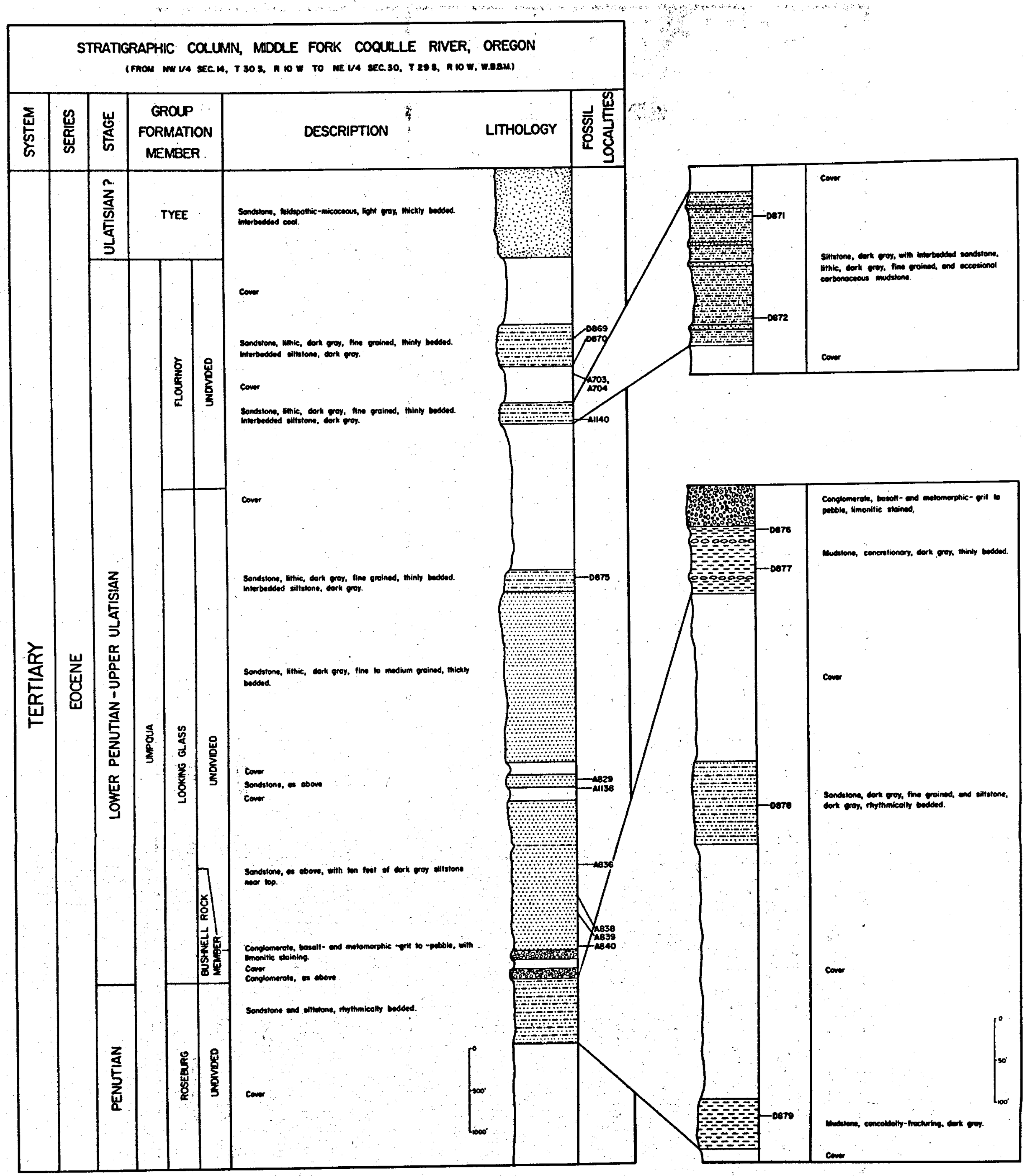
TYEE FM.

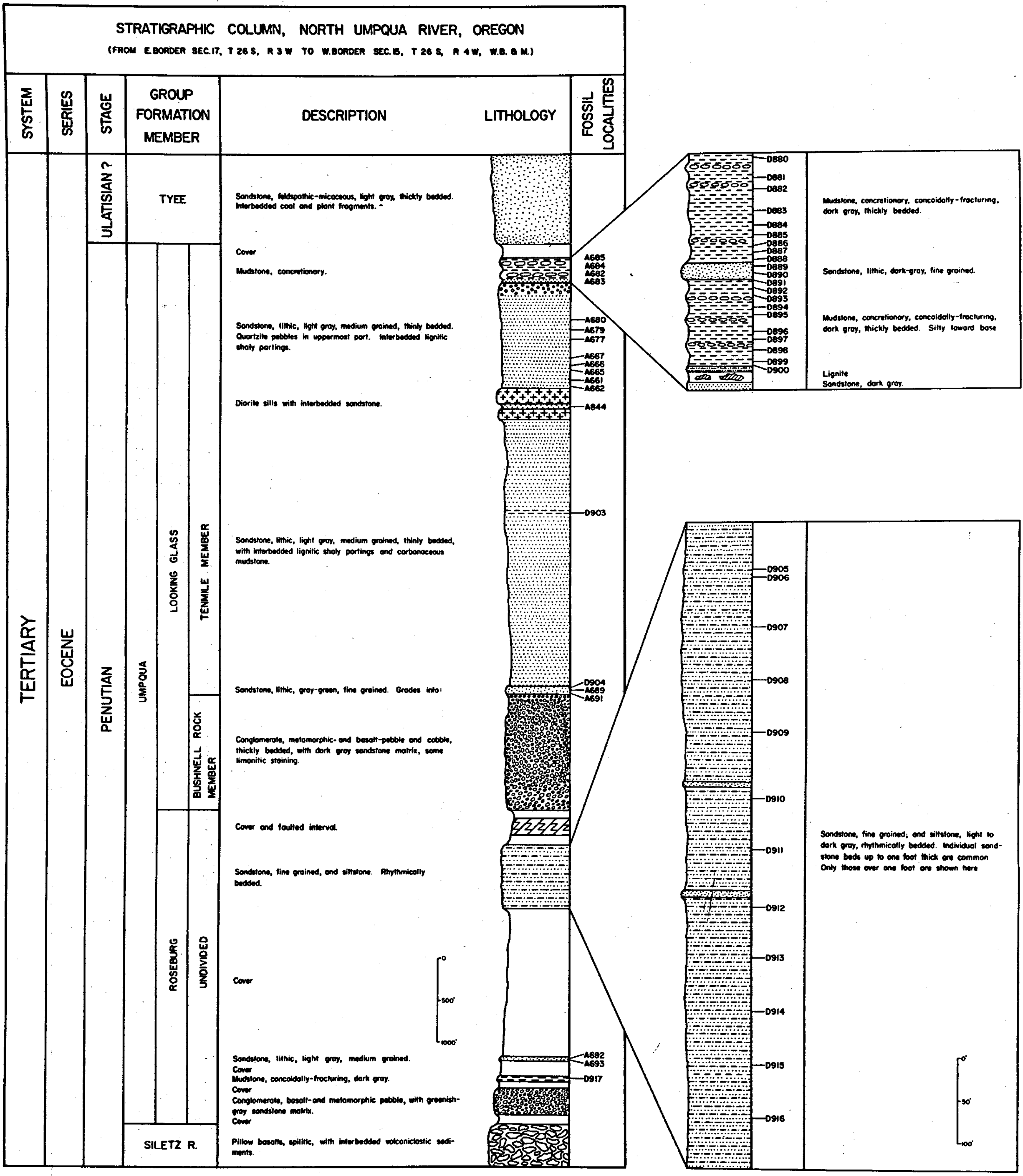
LOOKINGGLASS FM.

ROSEBURG FM.

SILETZ RIVER FM.

INTRUSIVES


STRATIGRAPHIC COLUMN, MIDDLE FORK COQUILLE RIVER, OREGON
(FROM NW 1/4 SEC. 14, T 30 S, R 10 W TO NE 1/4 SEC. 30, T 29 S, R 10 W, W.B.M.)
SYSTEM
SERIES
STAGE
GROUP FORMATION MEMBER
DESCRIPTION
LITHOLOGY
FOSSIL LOCALITIES
TERTIARY
EOCENE
ULATISIAN ?
LOWER PENUTIAN-UPPER ULATISIAN
PENUTIAN
TYEE
UMPQUA
FLOURNOY
UNDIVIDED
LOOKING GLASS
BUSHNELL ROCK MEMBER
ROSEBURG
Sandstone, feldspathic-micaceous, light gray, thickly bedded. Interbedded coal.
Cover
Sandstone, lithic, dark gray, fine grained, thinly bedded. Interbedded siltstone, dark gray.
Cover
Sandstone, lithic, dark gray, fine grained, thinly bedded. Interbedded siltstone, dark gray.
Cover
Sandstone, lithic, dark gray, fine grained, thinly bedded. Interbedded siltstone, dark gray.
Sandstone, lithic, dark gray, fine to medium grained, thickly bedded.
Cover
Sandstone, as above
Cover
Sandstone, as above, with ten feet of dark gray siltstone near top.
Conglomerate, basalt- and metamorphic -grit to -pebble, with limonitic staining.
Cover
Conglomerate, as above
Sandstone and siltstone, rhythmically bedded.
Cover
0
500'
1000'
D869
D870
A703, A704
A1140
D875
A829
A1138
A836
A838
A839
A840
Cover
D871
Siltstone, dark gray, with interbedded sandstone, lithic, dark gray, fine grained, and accasional carbonaceous mudstone.
D872
Cover
Conglomerate, basalt- and metamorphic- grit to pebble, limonitic stained.
D876
Mudstone, concretionary, dark gray, thinly bedded.
D877
Cover
Sandstone, dark gray, fine grained, and siltstone, dark gray, rhythmically bedded.
D878
Cover
0
50'
100'
D879
Mudstone, concoidally-fracturing, dark gray.
Cover

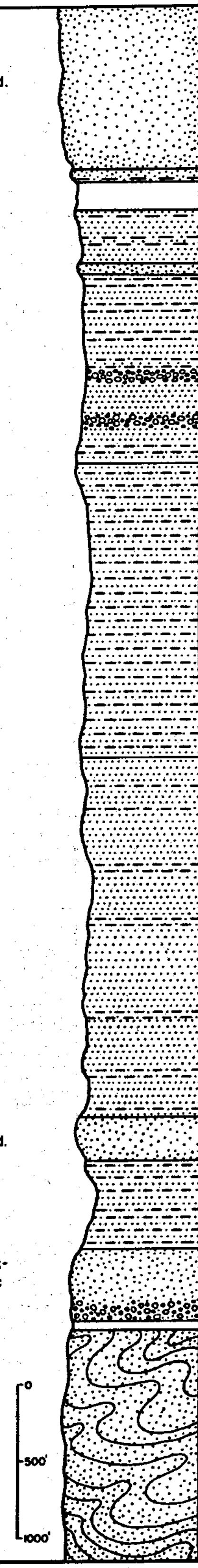

STRATIGRAPHIC COLUMN, NORTH UMPQUA RIVER, OREGON
(FROM E.BORDER SEC.17, T 26 S, R 3 W TO W.BORDER SEC.15, T 26 S, R 4 W, W.B. & M.)
SYSTEM
SERIES
STAGE
GROUP FORMATION MEMBER
DESCRIPTION
LITHOLOGY
FOSSIL LOCALITIES
TERTIARY
EOCENE
ULATISIAN ?
PENUTIAN
TYEE
UMPQUA
LOOKING GLASS
TENMILE MEMBER
BUSHNELL ROCK MEMBER
ROSEBURG
UNDIVIDED
SILETZ R.
Sandstone, feldspathic-micaceous, light gray, thickly bedded. Interbedded coal and plant fragments.
Cover
Mudstone, concretionary.
Sandstone, lithic, light gray, medium grained, thinly bedded. Quartzite pebbles in uppermost part. Interbedded lignitic shaly partings.
Diorite sills with interbedded sandstone.
Sandstone, lithic, light gray, medium grained, thinly bedded, with interbedded lignitic shaly partings and carbonaceous mudstone.
Sandstone, lithic, gray-green, fine grained. Grades into:
Conglomerate, metamorphic- and basalt-pebble and cobble, thickly bedded, with dark gray sandstone matrix, some limonitic staining.
Cover and faulted interval.
Sandstone, fine grained, and siltstone. Rhythmically bedded.
Cover
Sandstone, lithic, light gray, medium grained.
Cover
Mudstone, concoidally-fracturing, dark gray.
Cover
Conglomerate, basalt- and metamorphic pebble, with greenish-gray sandstone matrix.
Cover
Pillow basalts, spilitic, with interbedded volcaniclastic sediments.
0
500'
1000'
A685
A684
A682
A683
A680
A679
A677
A667
A666
A665
A661
A662
A844
D903
D904
A689
A691
A692
A693
D917
D880
D881
D882
D883
D884
D885
D886
D887
D888
D889
D890
D891
D892
D893
D894
D895
D896
D897
D898
D899
D900
Mudstone, concretionary, concoidally-fracturing, dark gray, thickly bedded.
Sandstone, lithic, dark-gray, fine grained.
Mudstone, concretionary, concoidally-fracturing, dark gray, thickly bedded. Silty toward base
Lignite
Sandstone, dark gray.
D905
D906
D907
D908
D909
D910
D911
D912
D913
D914
D915
D916
Sandstone, fine grained; and siltstone, light to dark gray, rhythmically bedded. Individual sandstone beds up to one foot thick are common. Only those over one foot are shown here
0'
50'
100'

STRATIGRAPHIC COLUMN, SOUTH FORK COQUILLE RIVER, OREGON

(FROM NW 1/4 SEC. 5, T 32 S, R 11 W TO E 1/2 SEC. 11, T 31 S, R 12 W, W.B.&M.)

SYSTEM	SERIES	STAGE	GROUP / FORMATION / MEMBER	DESCRIPTION	FOSSIL LOCALITIES
TERTIARY	EOCENE	ULATISIAN ?	TYEE	Sandstone, feldspathic-micaceous, light gray, thickly bedded. Interbedded coal.	
TERTIARY	EOCENE	UPPER PENUTIAN-UPPER ULATISIAN	UMPQUA / LOOKING GLASS / UNDIVIDED	Sandstone, dark gray, thickly bedded, silty at base.	D928
				Cover	
				Sandstone, lithic, dark gray, medium grained, thinly bedded, and interbedded siltstone, dark gray.	
				Sandstone, dark gray, medium grained, thickly bedded.	
				Sandstone, lithic, dark gray, medium grained, thinly bedded, with interbedded siltstone and stringers of metamorphic pebbles.	D930
				Sandstone, lithic, dark gray, fine grained, and dark gray siltstone. Rhythmically bedded.	D931, D932, D933, D934, D935
				Sandstone, lithic, dark gray, medium grained, thinly bedded, with occasional beds of dark-gray siltstone.	D936, D937, D938
				Sandstone, lithic, dark gray, medium grained, thickly bedded.	D939
				Sandstone, lithic, dark gray, medium grained, thinly bedded, with occasional beds of dark-gray siltstone.	D942, D943
			UMPQUA / LOOKING GLASS / BUSHNELL ROCK MEMBER	Sandstone, lithic, medium gray-green, medium grained, thickly bedded. Grades downward into conglomerate, metamorphic pebble and cobble.	
				Cover	
JURASSIC			RIDDLE	Siltstone, well indurated, dark gray, and interbedded sandstone, thinly bedded, carbonaceous.	

LITHOLOGY



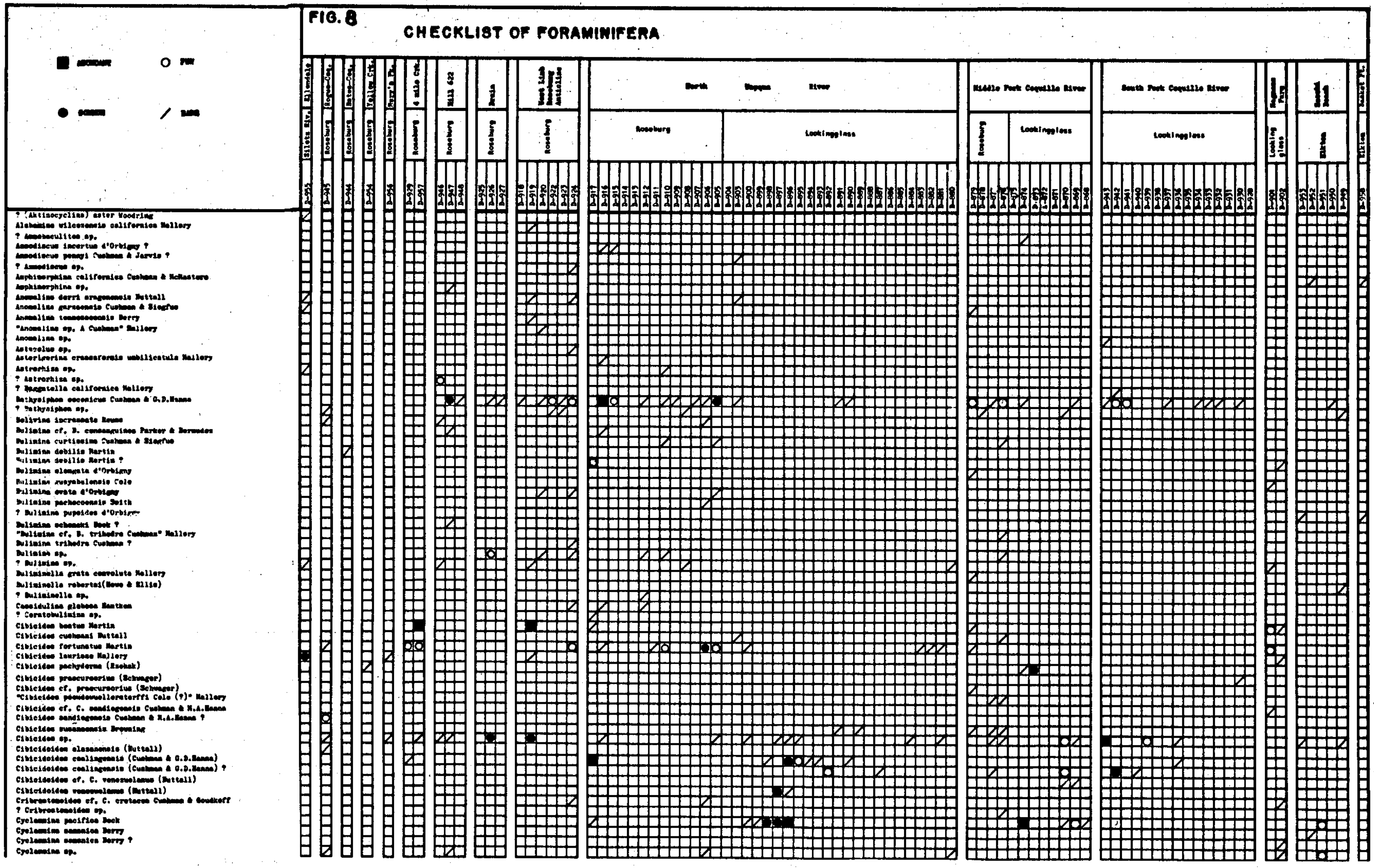
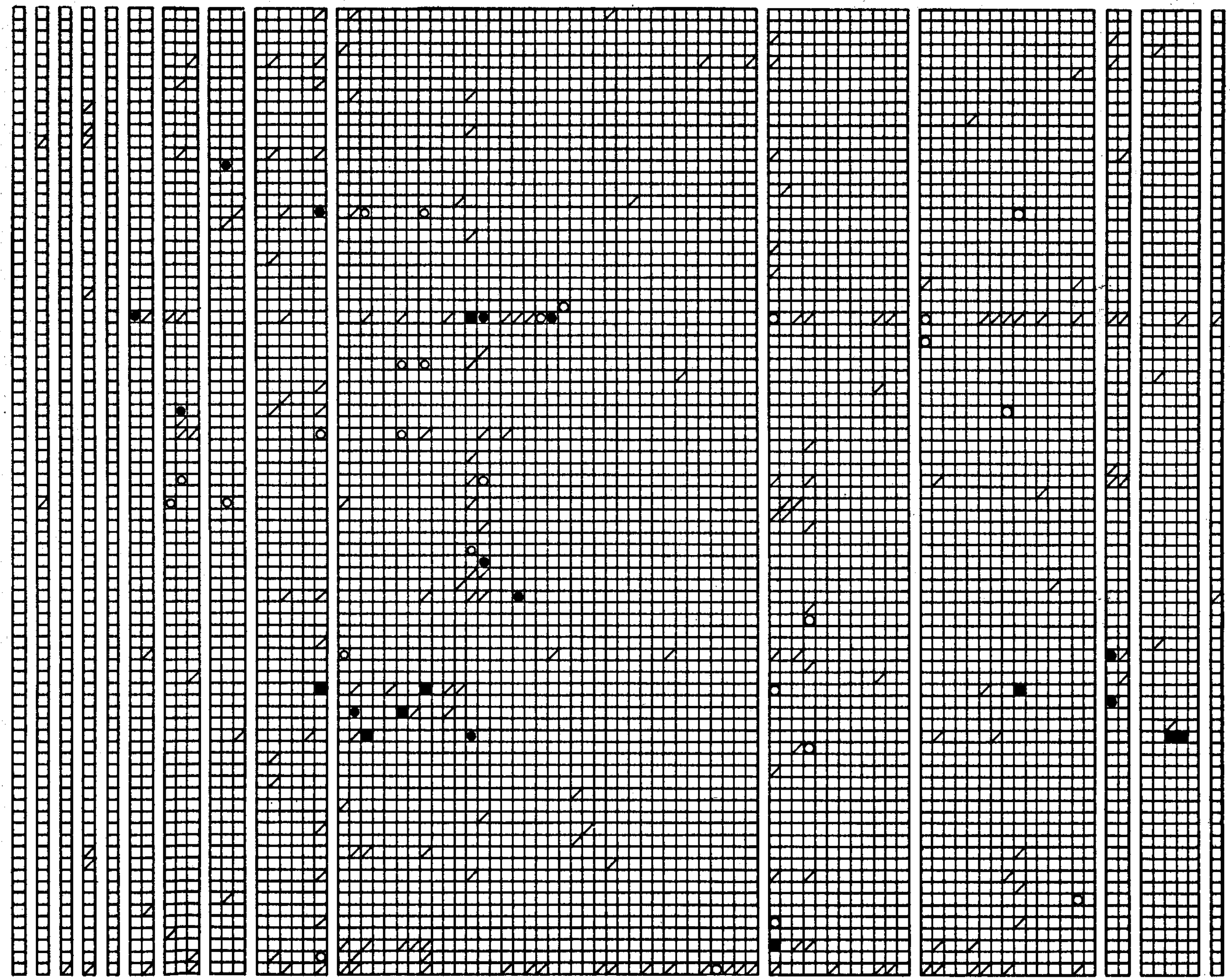


FIG. 8
CHECKLIST OF FORAMINIFERA
North Umpqua River
Middle Fork Coquille River
South Fork Coquille River
Roseburg
Lookingglass
Elkton
? (Aktinocyclina) aster Woodring
Alabamina wilcoxensis californica Mallory
? Ammobaculites sp.
Ammodiscus incertus d'Orbigny ?
Ammodiscus pennyi Cushman & Jarvis ?
? Ammodiscus sp.
Amphimorphina californica Cushman & McMasters
Amphimorphina sp.
Anomalina dorri aragonensis Nuttall
Anomalina garzaensis Cushman & Siegfus
Anomalina tennesseensis Berry
"Anomalina sp. A Cushman" Mallory
Anomalina sp.
Astacolus sp.
Asterigerina crassaformis umbilicatula Mallory
Astrorhiza sp.
? Astrorhiza sp.
? Bagatella californica Mallory
Bathysiphon eocenicus Cushman & G.D.Hanna
? Bathysiphon sp.
Bolivina incrassata Reuss
Bulimina cf. B. consanguinea Parker & Bermudez
Bulimina curtissima Cushman & Siegfus
Bulimina debilis Martin
Bulimina debilis Martin ?
Bulimina elongata d'Orbigny
Bulimina guayabalensis Cole
Bulimina ovata d'Orbigny
Bulimina pachecoensis Smith
? Bulimina pupoides d'Orbigny
Bulimina schencki Beck ?
"Bulimina cf. B. trihedra Cushman" Mallory
Bulimina trihedra Cushman ?
Bulimina sp.
? Bulimina sp.
Buliminella grata convoluta Mallory
Buliminella robertsi (Howe & Ellis)
? Buliminella sp.
Cassidulina globosa Hantken
? Ceratobulimina sp.
Cibicides beatus Martin
Cibicides cushmani Nuttall
Cibicides fortunatus Martin
Cibicides laurisae Mallory
Cibicides pachyderma (Rzehak)
Cibicides praecursorius (Schwager)
Cibicides cf. praecursorius (Schwager)
"Cibicides pseudowuellerstorffi Cole (?)" Mallory
Cibicides cf. C. sandiegensis Cushman & M.A.Hanna
Cibicides sandiegensis Cushman & M.A.Hanna ?
Cibicides susanaensis Browning
Cibicides sp.
Cibicidoides alazanensis (Nuttall)
Cibicidoides coalingensis (Cushman & G.D.Hanna)
Cibicidoides coalingensis (Cushman & G.D.Hanna) ?
Cibicidoides cf. C. venezuelanus (Nuttall)
Cibicidoides venezuelanus (Nuttall)
Cribrostomoides cf. C. cretacea Cushman & Goudkoff
? Cribrostomoides sp.
Cyclammina pacifica Beck
Cyclammina samanica Berry
Cyclammina samanica Berry ?
Cyclammina sp.

Dentalina approximata Reuss
Dentalina approximata Reuss ?
Dentalina colei Cushman & Dusenbury
? Dentalina colei Cushman & Dusenbury
Dentalina communis d'Orbigny
? Dentalina budensis Hantken
Dentalina consobrina d'Orbigny
Dentalina spinosa d'Orbigny
Dentalina spinosa arustica Smith
"Dentalina ? sp." Mallory
Dentalina sp.
Discorbis bainteni Mallory
? Discorbis sp.
Dorothia principiensis Cushman & Bermudez
Dorothia cf. D. principiensis Cushman & Bermudez
Dorothia principiensis Cushman & Bermudez ?
Dorothia sp.
? Dorothia sp.
Eggerella sp.
? Ellipsoglandulina sp.
Ellipsonodosaria nuttalli gracillima Cushman & Jarvis
Ellipsonodosaria plummerae Cushman
Ellipsonodosaria cf. E. plummerae Cushman
? Ellipsonodosaria sp.
Elphidium californicum Cook
Epistomina partschiana d'Orbigny
Eponides dorfi Toulmin
Eponides mexicana (Cushman)
Eponides cf. E. mexicana (Cushman)
Eponides minima Cushman
Eponides umbonata (Reuss)
Eponides cf. E. umbonata (Reuss)
Gaudryina cf. G. jacksonensis coalingensis Cushman & G.D.Hanna
Gaudryina cf. G. laevigata Franke
Gaudryina sp.
Globigerina bakeri Cole
Globigerina cf. G. bakeri Cole
Globigerina bulloides d'Orbigny
Globigerina decepta Martin
Globigerina cf. G. mexicana Cushman
Globigerina cf. G. ouachitaensis Howe & Wallace
Globigerina triloculinoides Plummer
? Globigerina triloculinoides Plummer
Globigerina sp.
? Globobulimina sp.
Globorotalia cf. G. californica Smith
Globorotalia cf. G. canariensis (d'Orbigny)
Globorotalia cerro-azulensis Cole
Globorotalia cerro-azulensis Cole ?
Globorotalia membranacea (Ehrenberg)
? Globorotalia sp.
Gyroidina condoni (Cushman & Schenck)
Gyroidina cf. G. condoni (Cushman & Schenck)
Gyroidina guayabalensis Cole
Gyroidina orbicularis obliquata Cushman & McMasters
Gyroidina orbicularis planata Cushman
Gyroidina soldanii octocamerata Cushman & McMasters
Gyroidina soldanii octocamerata Cushman & McMasters ?
Gyroidina sp.
Haplophragmoides eggeri Cushman
Haplophragmoides eggeri Cushman ?
Haplophragmoides obliquicameratus Marks
Haplophragmoides cf. H. obliquicameratus Marks
Haplophragmoides obliquicameratus Marks ?
Karreriella sp.
Lagena conscripta Cushman & Barksdale
? Lagena sp.
Lenticulina obovergens (Bornemann) ?
Lenticulina theta Cole
Lenticulina sp.
Loxostomum applinae (Plummer)
Marginulina subbullata Hantken
? Marginulina sp.
Marssonella oxycona Reuss
? Marssonella oxycona Reuss
Martinottiella eocenica Cushman & Bermudez
Nodogenerina cf. N. bradyi Cushman
? Nodogenerina sp.
Nodosaria affinis Reuss ?
Nodosaria arundinea Schwager
? Nodosaria arundinea Schwager
Nodosaria delicina Martin
Nodosaria ewaldi Reuss
Nodosaria latejugata Gümbel



Nodosaria macneili Cushman
? Nodosaria sp.
Nonion applini Howe & Wallace
Nonion micrum Cole
Nonion planatum Cushman & Thomas
Nonion cf. N. planatum Cushman & Thomas
Nonion wilcoxensis Cushman & Ponton
Nonionella florinense (Cole)
Operculina cushmani Cole
Parrella culter (Parker & Jones) ?
Parrella cf. P. culter midwayana (Cushman)
Parrella tenuicarinata (Cushman & Siegfus) ?
Parrella cf. P. tenuicarinata (Cushman & Siegfus)
Parrella sp.
? Parrella sp.
Planulina cf. P. venezuelana Nuttall
Plectina garzaensis (Cushman & Siegfus)
Pseudoglandulina conica (Neugeboren)
Pseudoglandulina cylindracea (Reuss)
Pseudoglandulina ovata (Cushman & Applin)
Pseudoglandulina sp.
? Pseudoglandulina sp.
Pseudophragmina psila (Woodring)
? Pseudophragmina psila (Woodring)
? Pseudophragmina sp.
Pullenia quinqueloba (Reuss)
Quinqueloculina cf. Q. imperialis Hanna & Hanna
Quinqueloculina imperialis Hanna & Hanna
? Quinqueloculina imperialis Hanna & Hanna
Quinqueloculina cf. Q. triangularis d'Orbigny
Quinqueloculina yeguaensis Weinzierl & Applin
Quinqueloculina yeguaensis Weinzierl & Applin ?
Quinqueloculina sp.
? Quinqueloculina sp.
Rhabdammina eocenica Cushman & G.D.Hanna
Rhabdammina eocenica Cushman & G.D.Hanna ?
? Rhabdammina eocenica Cushman & G.D.Hanna
Rhabdammina sp.
? Rhabdammina sp.
Robulus alato-limbatus Gümbel
Robulus alato-limbatus Gümbel ?
Robulus cf. R. alucinans Israelsky
Robulus cf. R. antipodum (Stache)
Robulus antipodum (Stache) ?
Robulus cf. R. mayi Cushman & Parker
Robulus cf. R. midwayensis (Plummer)
Robulus pseudocultratus Cole
Robulus pseudocultratus Cole ?
"Robulus cf. R. pseudo-mammiligerus (Plummer)" Mallory
Robulus pseudovertex Cole
Robulus terryi Coryell & Embich ?
Robulus turbinatus Plummer
Robulus turbinatus Plummer ?
Robulus welchi Church ?
Robulus sp. ? Israelsky
Robulus sp.
? Robulus sp.
Silicosigmoilina californica Cushman & Church
? Spiroloculina sp.
? Spiroplectammina eocenica (Cushman & Barksdale)
Spiroplectammina richardi Martin
Spiroplectammina tejonensis Mallory
Spiroplectammina sp.
Textularia sp.
Trifarina advena californica Mallory
? Tritaxilina colei Cushman & Siegfus
Trochammina cf. T. globigeriniformis (Parker & Jones)
? Trochamminoides sp.
Uvigerina elongata Cole
? Uvigerina garzaensis nudi-robusta Mallory
Uvigerina lodoensis siriensis Mallory
Vaginulinopsis echinata Thalmann
Vaginulinopsis cf. V. echinata Thalmann
Vaginulinopsis echinata Thalmann ?
Vaginulinopsis mexicana nudicostata (Cushman & G.D.Hanna)
Vaginulinopsis mexicana vacavillensis (Hanna)
Valvulineria childsi (Martin)
Valvulineria cf. V. involuta Cushman & Dusenbury
Verneuilina triangulata Cook
Verneuilina cf. V. triangulata Cook
Verneuilina triangulata Cook ?
? Verneuilina triangulata Cook
? Verneuilina sp.

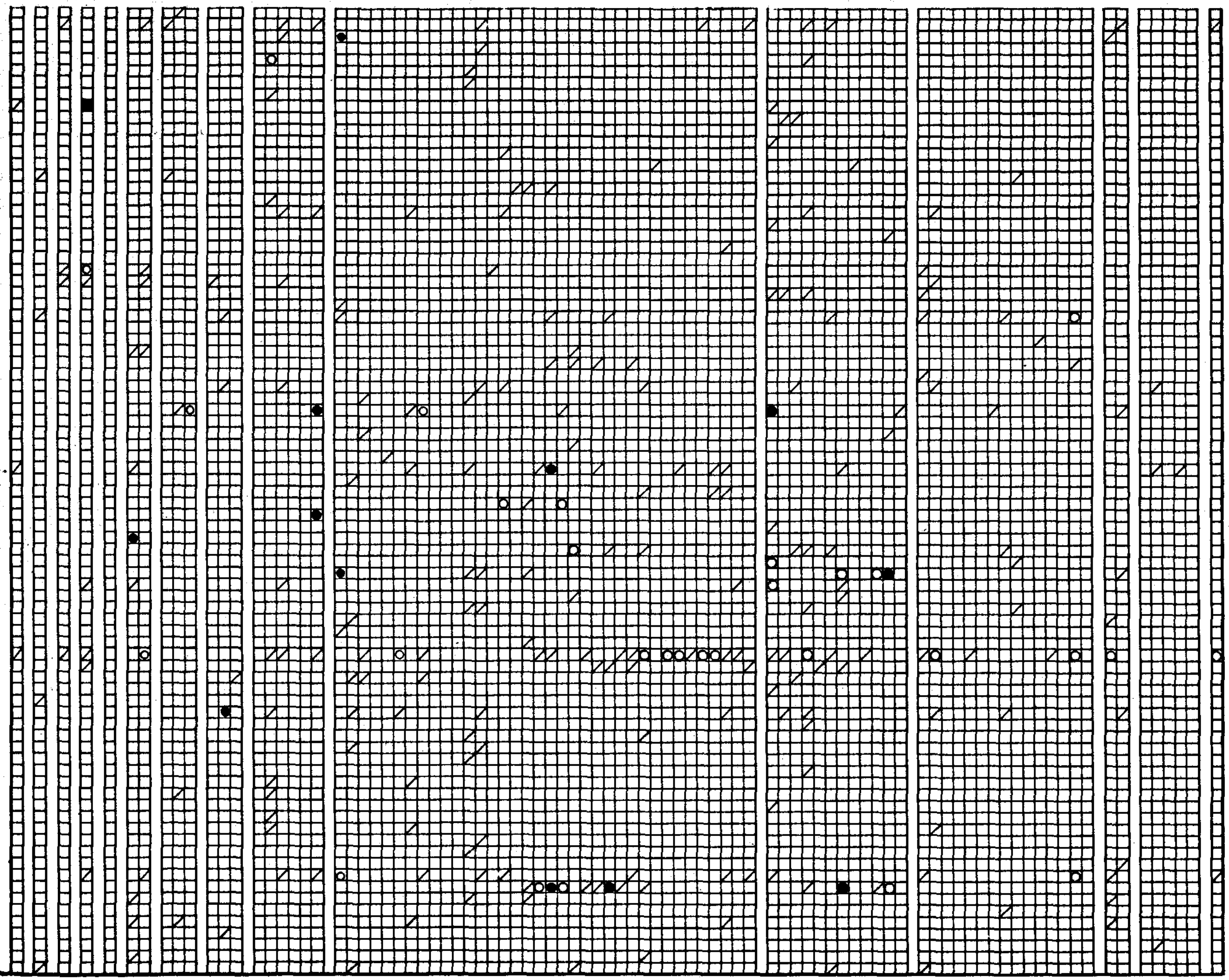


Plate I

Fig. 1a. Marsonella oxycona (Reuss) 75X D-916 Hypotype no. 40602
1b. Haplophragmoides obliquicameratus Marks 47X D-906 Hypotype no. 40603
2a,b. Spiroplectamina richardi Martin 75X D-876 Hypotype no. 40604
3a,b. Spiroplectamina tejonensis Mallory 40X D-876 Hypotype no. 40605
4a,b. Verneuilina triangulata Cook 94X D-929 Hypotype no. 40606
5a,b. Gaudryina cf. G. jacksonensis coalingensis Cushman 24X D-888 Hypotype no. 40607
6a,b. Martinottiella eocenica Cushman & Bermudez 50X D-874 Hypotype no. 40608
7. Silicosigmoilina californica Cushman & Church 27X D-876 Hypotype no. 40609
8a,b. Verneuilina triangulata Cook 63X D-952 Hypotype no. 40610
9a,b. Dorothia cf. D. principiensis Cushman & Bermudez 28X D-926 Hypotype no. 40611
10a,b,c. Quinqueloculina cf. Q. triangularis d'Orbigny 68X D-945 Hypotype no. 40612
11a,b,c. Quinqueloculina cf. Q. imperialis Hanna & Hanna 40X D-943 Hypotype no. 40613
12. Dentalina approximata Reuss 40X D-916 Hypotype no. 40614
13. Dentalina consobrina d'Orbigny 33X D-919 Hypotype no. 40618
14a,b,c. Quinqueloculina yeguaensis Weinzierl & Applin 58X D-890 Hypotype no. 40616
15. Dentalina spinosa ornatior d'Orbigny 63X D-916 Hypotype no. 40619
16. Lagena conscripta Cushman & Barksdale 68X D-919 Hypotype no. 40620
17. Pseudoglandulina cylindracea Reuss 42X D-879 Hypotype no. 40621
18a,b. Lenticulina theta Cole 63X D-895 Hypotype no. 40622
19. Marginulina subbullata Hantken 68X D-924 Hypotype no. 40624
20. Nodogenerina lepidula (Schwager) 34X D-947 Hypotype no. 40625
21. Nodosaria arundinea Schwager 34X D-879 Hypotype no. 40626
22. Nodosaria latejugata Gumbel 12X D-879 Hypotype no. 40627
23a,b. Robulus alato-limbatus Gumbel 68X D-906 Hypotype no. 40628
24a,b. Robulus antipodum (Stache) 25X D-924 Hypotype no. 40631
25a,b. Robulus articulatus texanus (Cushman & Applin) 27X D-921 Hypotype no. 40632
26a,b. Robulus cf. R. midwayensis (Plummer) 33X D-929 Hypotype no. 40633
27a,b. Robulus pseudovortex Cole 38X D-879 Hypotype no. 40634

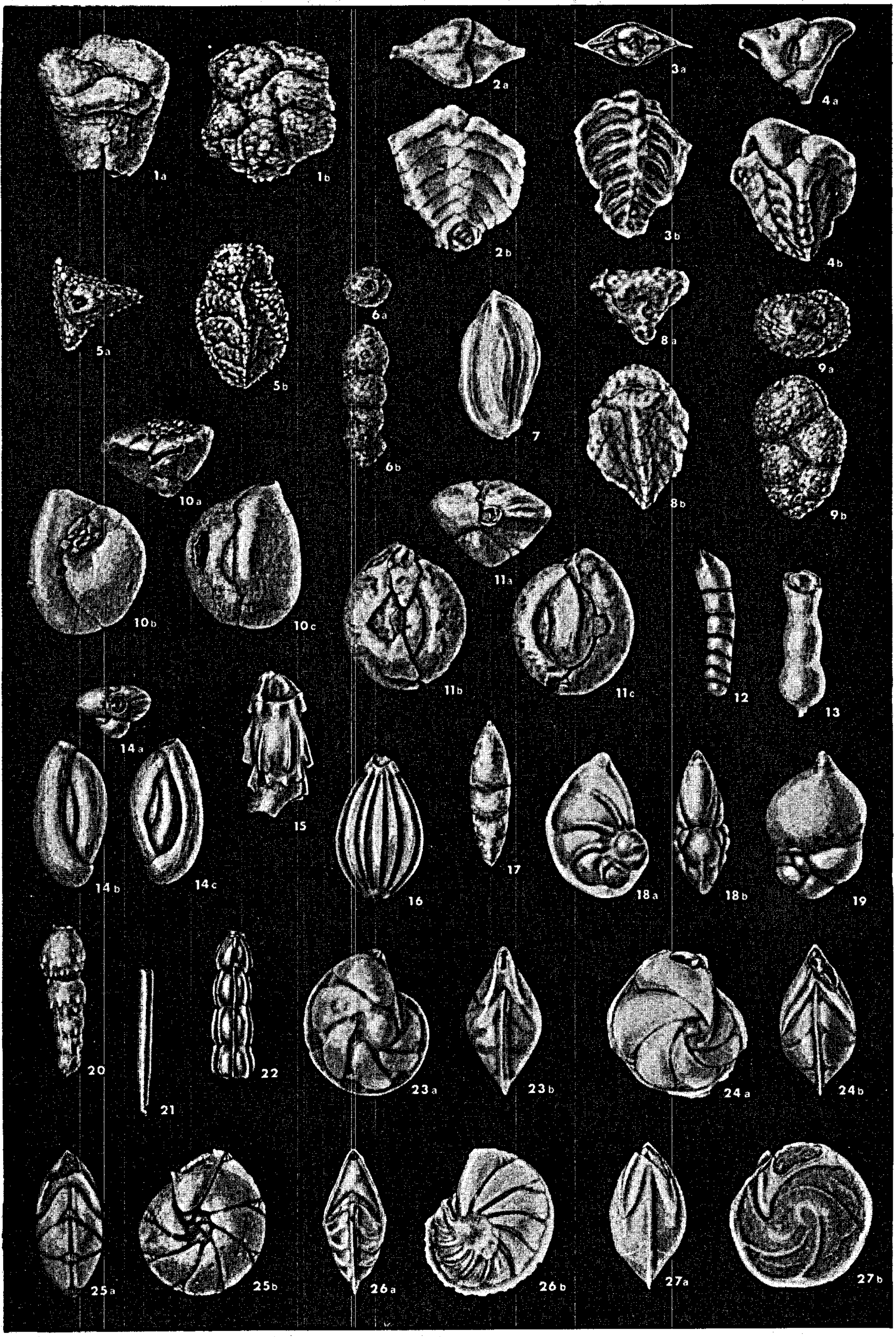

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Plate II

Fig. 1a,b. Robulus welchi Church 32X D-917 Hypotype no. 40636
2a,b. Vaginulinopsis echinata Thalmann 63X D-905 Hypotype no. 40637
3a,b. Vaginulinopsis cf. V. echinata Thalmann 50X D-906 Hypotype no. 40638
4a,b. Vaginulinopsis mexicana nudicostata Cushman & Hanna 38X D-920 Hypotype no. 40639
5a,b. Vaginulinopsis mexicana vacavillensis Cushman & Hanna 24X D-897 Hypotype no. 40640
6a,b. Nonion applini Howe & Wallace 54X D-901 Hypotype no. 40641
7a,b,c. Elphidium californicum Cook 34X D-930 Hypotype no. 40642
8a,b. Nonionella florinense (Cole) 47X D-919 Hypotype no. 40643
9a,b. Nonion planatum Cushman & Thomas 75X D-876 Hypotype no. 40644
10. Operculina cushmani Cole 27X D-954 Hypotype no. 40646
11. Amphimorphina californica Cushman & McMasters 26X D-592 Hypotype no. 40647
12. Plectofrondicularia vokesi Cushman, Stewart & Stewart 38X D-921 Hypotype no. 40648
13a,b. Bolivina incrassata Reuss 94X D-906 Hypotype no. 40649
14a,b. Bulimina cf. B. consanguinea Parker & Bermudez 63X D-947 Hypotype no. 40650
15a,b. Bulimina elongata d'Orbigny 89X D-879 Hypotype no. 40651
16a,b. Bulimina debilis Martin 44X D-944 Hypotype no. 40652
17a,b. Bulimina curtissima Cushman & Siegfus 94X D-910 Hypotype no. 40653
18a,b. Bulimina pupoides Nuttall 63X D-953 Hypotype no. 40654
19a,b. Bulimina guayabalensis Cole 68X D-901 Hypotype no. 40655
20a,b. Bulimina pachecoensis Smith 75X D-906 Hypotype no. 40656
21a,b. Buliminella grata-convoluta Mallory 125X D-879 Hypotype no. 40657
22a,b. Buliminella robertsi (Howe & Ellis) 94X D-949 Hypotype no. 40658
23a,b. Trifarina advena californica Cushman & Mallory 84X D-906 Hypotype no. 40659
24. Loxostomum applinae (Plummer) 32X D-905 Hypotype no. 40660
25. Bulimina ovata d'Orbigny 50X D-905 Hypotype no. 40661
26. Ellipsonodosaria plummerae Cushman 44X D-874 Hypotype no. 40662
27. Ellipsonodosaria nuttalli gracillima Cushman & Jarvis 44X D-906 Hypotype no. 40663
28. Uvigerina elongata Cole 94X D-879 Hypotype no. 40664
29a,b,c. Discorbis baintoni Mallory 107X D-906 Hypotype no. 40665

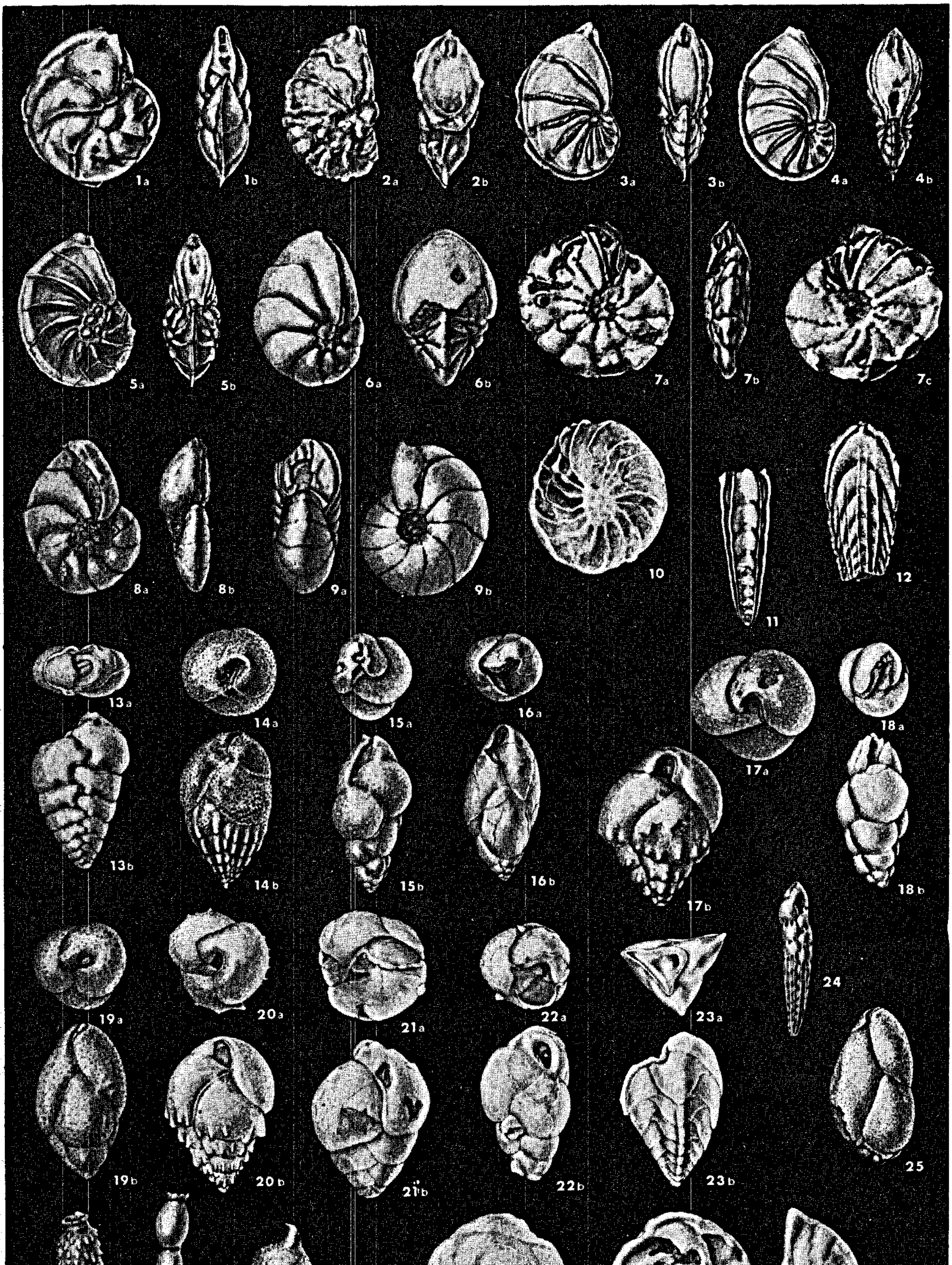
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Plate III

Fig. 1a,b,c. Eponides dorfi Toulmin 47X D-896 Hypotype no. 40666
2a,b,c. Eponides ellisorae Garret 54X D-921 Hypotype no. 40667
3a,b,c. Eponides mexicana Cushman 63X D-876 Hypotype no. 40668
4a,b,c. Eponides minima Cushman 68X D-943 Hypotype no. 40670
5a,b,c. Eponides umbonata (Reuss) 107X D-906 Hypotype no. 40671
6a,b,c. Gyroidina condoni (Cushman & Schenck) 47X D-900 Hypotype no. 40672
7a,b,c. Gyroidina orbicularis obliquata Cushman & McMasters 68X D-876 Hypotype no. 40673
8a,b,c. Gyroidina orbicularis planata Cushman 63X D-924 Hypotype no. 40674
9a,b,c. Gyroidina soldani octocamerata Cushman & Hanna 75X D-879 Hypotype no. 40675
10a,b,c. Valvulineria childsi Martin 125X D-929 Hypotype no. 40678
11a,b,c. Asterigerina crassiformis umbilicatula Mallory 84X D-916 Hypotype no. 40680
12a,b,c. Alabamina wilcoxensis californica Toulmin & Mallory 75X D-919 Hypotype no. 40681

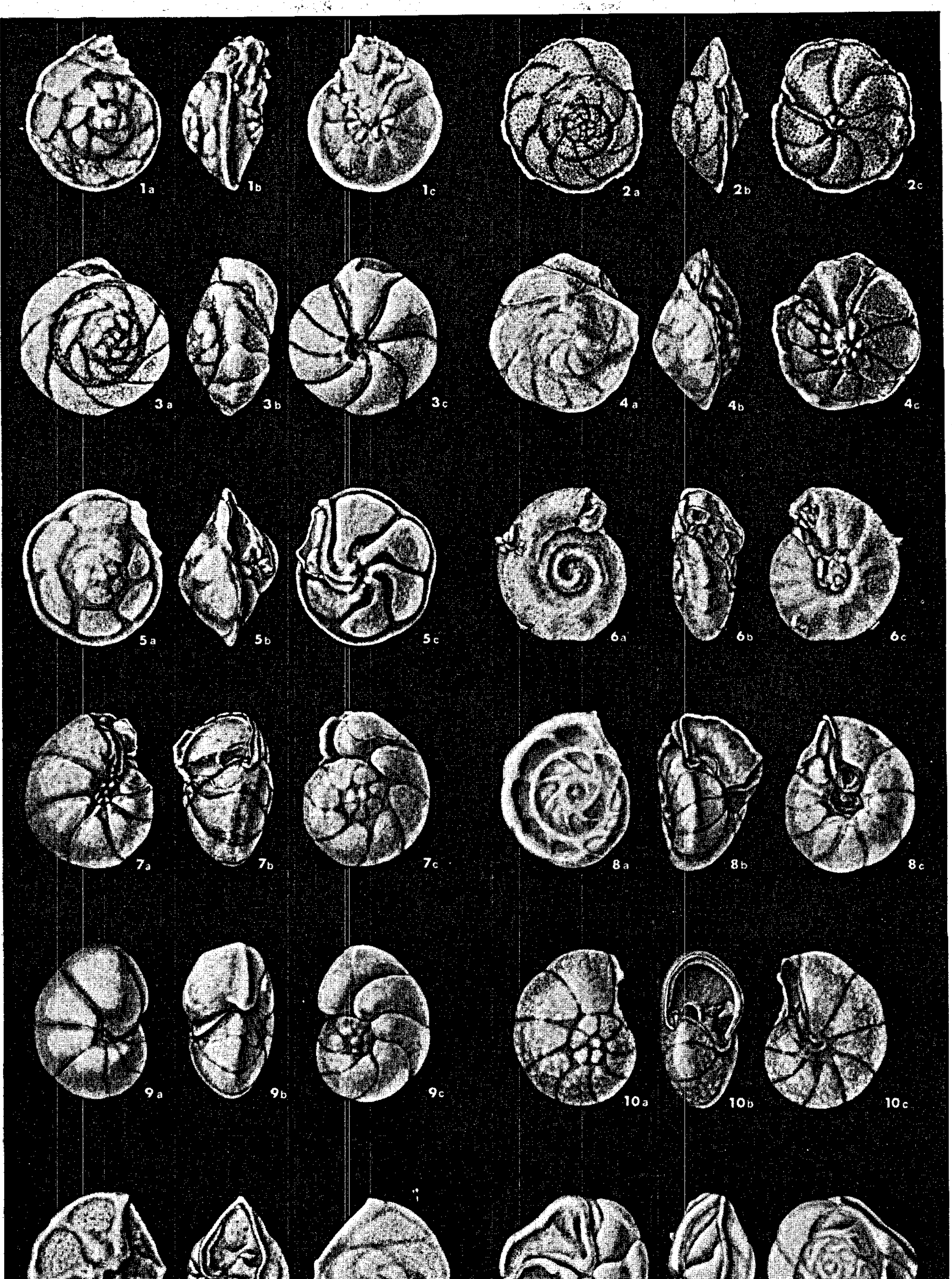
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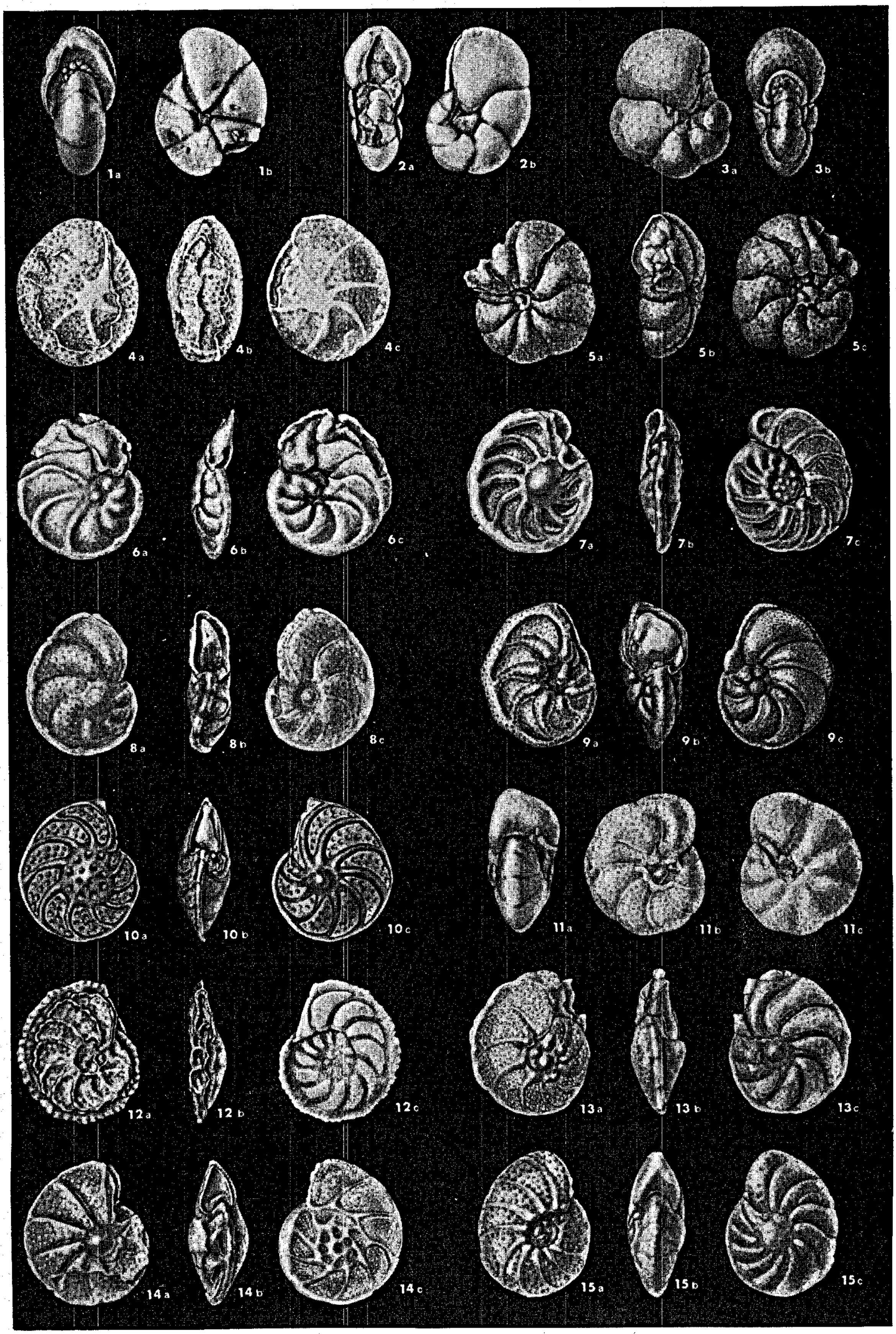
Plate IV

Fig. 1a,b. Pullenia quinqueloba Reuss 75X D-917 Hypotype no. 40682
2a,b. Nonion wilcoxensis Cushman & Ponton 125X D-906 Hypotype no. 40687
3a,b. Nonion micrum Cole 84X D-905 Hypotype no. 40688
4a,b,c. Anomalina tennesseensis W. Berry 107X D-919 Hypotype no. 40691
5a,b,c. "Anomalina sp. A. cushman" (of Mallory) 54X D-920 Hypotype no. 40692
6a,b,c. Cibicides beatus Martin 58X D-919 Hypotype no. 40693
7a,b,c. Cibicidoides coalingensis Cushman & Hanna 54X D-929 Hypotype no. 40694
8a,b,c. Cibicidoides alazanensis (Nuttall) 107X D-945 Hypotype no. 40695
9a,b,c. Cibicides cushmani Nuttall 68X D-903 Hypotype no. 40696
10a,b,c. Cibicides fortunatus Martin 84X D-906 Hypotype no. 40697
11a,b,c. Cibicides laurisae Mallory 54X D-902 Hypotype no. 40698
12a,b,c. Cibicides natlandi Beck 30X D-921 Hypotype no. 40699
13a,b,c. Cibicides pachyderma Rzehak 75X D-873 Hypotype no. 40700
14a,b,c. Cibicides sandiegensis Cushman & Hanna 68X D-921 Hypotype no. 40701
15a,b,c. Cibicides susanaensis Browning 84X D-976 Hypotype no. 40702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FORAMINIFERAL BIOSTRATIGRAPHY OF THE LATE EOCENE TO EARLY OLIGOCENE TYPE BASTENDORFF FORMATION, NEAR COOS BAY, OREGON

Ann Tipton

University of California, Santa Barbara

Introduction

Current research on West Coast Eo-Oligocene correlations and foraminiferal zoogeography has brought attention to a rich foraminiferal sequence occurring in the type section of the Bastendorff Formation near Coos Bay, on the southern Oregon coast. The southern-most occurrence of foraminiferal Narizian through Refugian sediments in the Pacific Northwest, the Bastendorff geographically links correlative sequences of California, where the West Coast foraminiferal stages were originally developed, with those of Oregon and Washington, where Rau's (1958, 1966) detailed biostratigraphic studies have given rise to a separate zonal (though not stage) classification based on Foraminifera.

Previous paleontological studies of the type Bastendorff have determined that the formation is late Eocene to early Oligocene. The present study aims to delimit the age of the Bastendorff more adequately in terms of the foraminiferal classification of stages and zones (Kleinpell, 1938; Schenck and Kleinpell, 1936; Mallory, 1959); to interpret the paleoecology of the formation; and to compare its foraminiferal content with that of near-correlative sequences in California, Oregon, and Washington.

Based on samples collected in 1950, the present study derives additional significance from the increasingly heavy vegetation covering the cliffs at Bastendorff Beach, type locality and still the most complete exposure of the formation. Armentrout (1967, pp. 14-15) reports that prior to 1925, along Bastendorff Beach "the shoreline extended from headland to headland with little or no beach development". The beach-cliff exposures of the Bastendorff Formation were then relatively fresh and accessible.

Construction of the south jetty at the entrance to Coos Bay in 1925 (see Figure 1) resulted in increased beach development, seaward retreat of high-water line away from the cliffs and establishment of vegetation. With the exception of the more resistant sandstones, the cliffs at Bastendorff Beach are now nearly entirely covered with dense brush. The samples reported on here were collected by John Browning and William Grier, for the Museum of Paleontology, University of California, Berkeley, more than 20 years ago from relativly fresh exposures of the Bastendorff mudstones. They constitute a detailed sampling of the formation that may never again be obtainable.

The present report is the result of a determination to record this excellent but apparently unduplicatable foraminiferal succession. It is hoped that the nannofossil content of the Browning-Grier samples will also be reported on by specialists to whom portions of the samples have been sent.

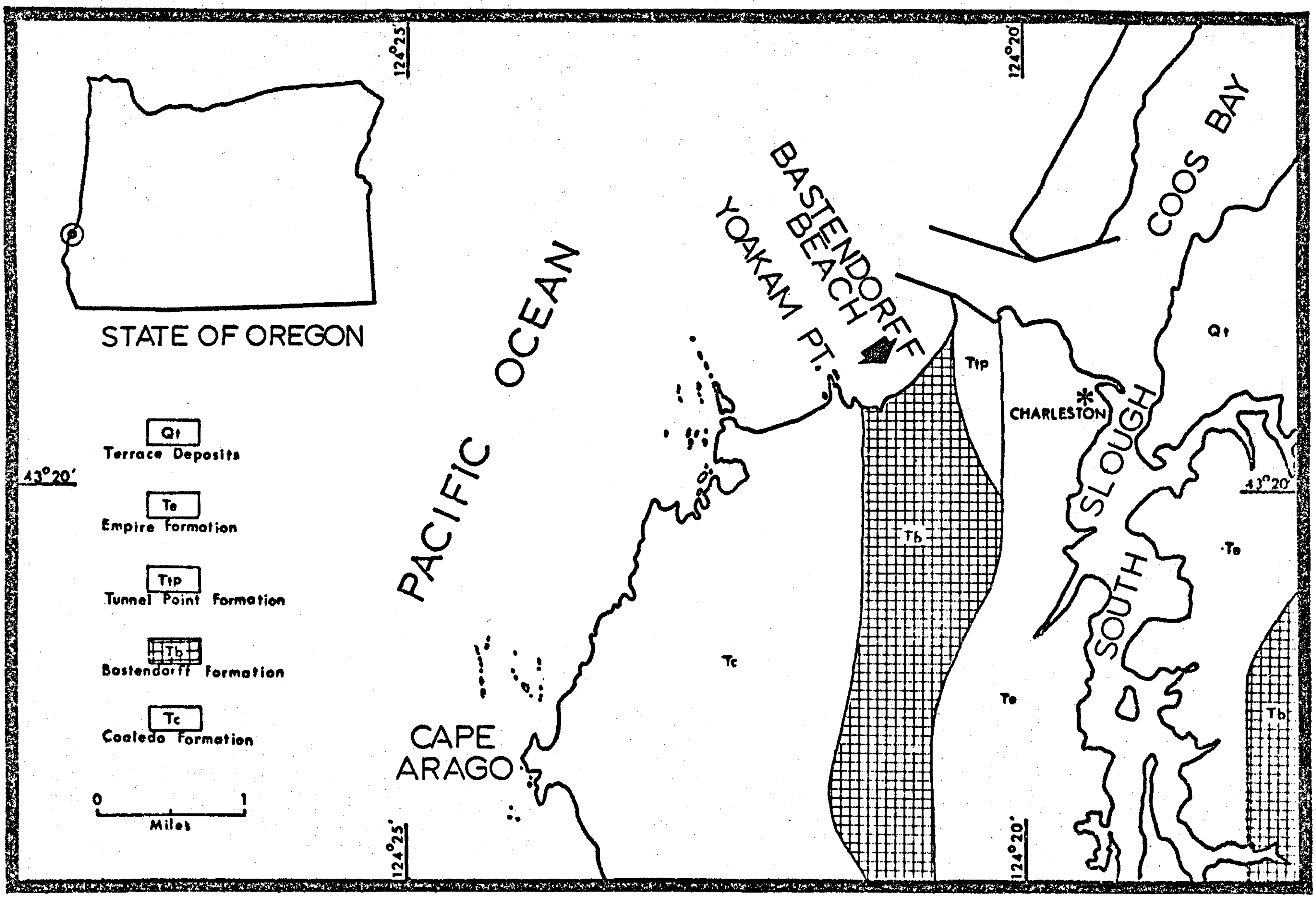


Figure 1. Location map, type Bastendorff Formation. Geologic contacts after Baldwin (1973).

Acknowledgements

The author is most grateful for the cooperation of Gordon Hornaday, Museum of Paleontology, University of California, Berkeley, in making available the Browning-Grier samples and locality descriptions, and for the assistance of David Doerner, Department of Geological Sciences, University of California, Santa Barbara, where portions of the samples have been deposited. Michael F. Donnelly assisted the author in the field and in drafting the plates. Dan McKeel examined the planktonic Foraminifera and offered suggestions as to their taxonomy. Thanks are extended to Occidental Petroleum Corporation, especially Stanford Eschner and Michael Donnelly, for help in preparing the manuscript. Mobil Oil Corporation and Union Oil Company of California provided financial assistance, and their continued support of the author's biostratigraphic studies is gratefully acknowledged.

Previous Studies

An excellent summary of the earliest stratigraphic studies of lower Tertiary strata near Coos Bay is that of Weaver (1945, pp. 31-36, 44-47). The Bastendorff Formation was originally described and named the "Bastendorf shale" by Schenck (1927). The exposures at Bastendorff Beach southwest of Coos Bay (see Figure 1) were designated as type locality. Cushman and Schenck (1928) described and illustrated foraminiferal faunules from the type "Bassendorf" and Keasey shales, concluding that the formations are correlative, "probably lowest Oligocene".

In designating the Refugian Stage of the West Coast Tertiary, Schenck and Kleinpell (1936, p. 220) included the "Bassendorf beach" section among the most critical in establishing the new Stage, which they assigned to the late Eocene or early Oligocene.

Allen and Baldwin (1944) mapped the Coos Bay area and described the stratigraphic units, establishing the correct spelling as "Bastendorff" Formation, in accordance with the spelling of the Bastendorff family name.

Weaver (1945) summarized a plane-table survey and detailed stratigraphic study of the Tertiary formations in the Coos Bay area. He assigned the "Bassendorf" formation to the uppermost Eocene and lowermost Oligocene, and the overlying Tunnel Point sandstones to the Oligocene. Plate 7 of Weaver (op. cit.) shows the section at Bastendorff Beach, and has been modified in part as Figure 6 of the present report.

Detling (1946) described and illustrated the succession of foraminiferal assemblages in 19 samples from the "Bastendorf" Formation at the type section, and in 29 samples from the underlying Coaledo Formation, though she did not show the stratigraphic allocation of her samples or the occurrences of the taxa according to sample.

In 1950, John Browning and William Grier carried out detailed sampling of the Bastendorff Formation at Bastendorff Beach, depositing some 85 samples in the microfossil collections of the Museum of Paleontology of University of California at Berkeley. Though studies of the Browning-Grier samples have been undertaken in the past (notably by John Marr, graduate research, University of California, Berkeley, 1967-1970), they have not previously been reported on in the literature.

Baldwin (1973, pp. 31-32) mapped Coos County and summarized the stratigraphic relations, evidence for age, and previous studies of the Bastendorff Formation.

Stratigraphic Relations

The easily eroded Bastendorff Formation is preserved in the southern Coos Bay area only at the axes of three structural downfolds of Tertiary strata trending roughly north to northeast. These are the South Slough syncline, including the exposures at Bastendorff Beach, the Sumner syncline some eight miles east of the type section, and the Riverton syncline ten miles southeast (see Baldwin, 1973, p. 31, and North and Middle sections, Geologic Map).

Predominantly silty mudstone, the Bastendorff grades abruptly, apparently conformably, downward into marine sandstones of the Coaledo Formation and upward into sandstones of the Tunnel Point Formation (op. cit.).

The upper sandstones of the Coaledo Formation (Diller, 1899) crop out prominently on Yoakam Point west of Bastendorff Beach. Narizian in age, the Coaledo "consists of a maximum of 6,000 feet of lower and upper sandstone separated by a mudstone member...The sequence typifies a transgressive-regressive cycle of deposition in which the middle fine-grained member represents the deeper water conditions resulting from maximum transgression" (Baldwin, 1973, p. 27). The Coaledo sandstones show cross-bedding, channeling, parallel lamination, and other evidences of deposition under the influence of traction currents. Coal is abundant locally. Baldwin (op. cit, p. 29) postulates a deltaic environment of deposition for the Coaledo, with the Upper Sandstone Member, underlying the Bastendorff, representing "an offlapping phase of sedimentation".

The Tunnel Point Formation (Dall, 1898; see also Weaver, 1945, pp. 50-52) crops out only at Bastendorff Beach, where Allen and Baldwin (1944) measured 800 feet of sandstone overlying the Bastendorff and overlain unconformably by Pliocene sandstones of the Empire Formation (see Armentrout, 1967). The Tunnel Point sandstones are thicker bedded low in the formation, with beds measuring 4 to 6 feet in thickness; higher in the formation, many beds are 4 to 8 inches thick. A tuffaceous and quartzo-feldspathic sandstone, coarse to medium grained, the Tunnel Point displays parallel lamination, small-scale cross-bedding, trough cross-bedding, channeling and contorted lamination. The molluscan fauna (see Weaver, 1945, pp. 50-51) appears to be current-concentrated particularly above scour surfaces, and many shells are broken. These features suggest a depositional environment of considerable current or wave energy.

At Bastendorff Beach, approximately 2200 feet of Bastendorff Formation are exposed along the sea cliffs, according to the measurement of Browning and Grier. (Weaver, 1945, measured a slightly greater thickness.) An additional 600 to 700 feet of unresistant lowermost Bastendorff is presumed to be concealed beneath the alluvium at the mouth of Miner Creek (see Figure 6).

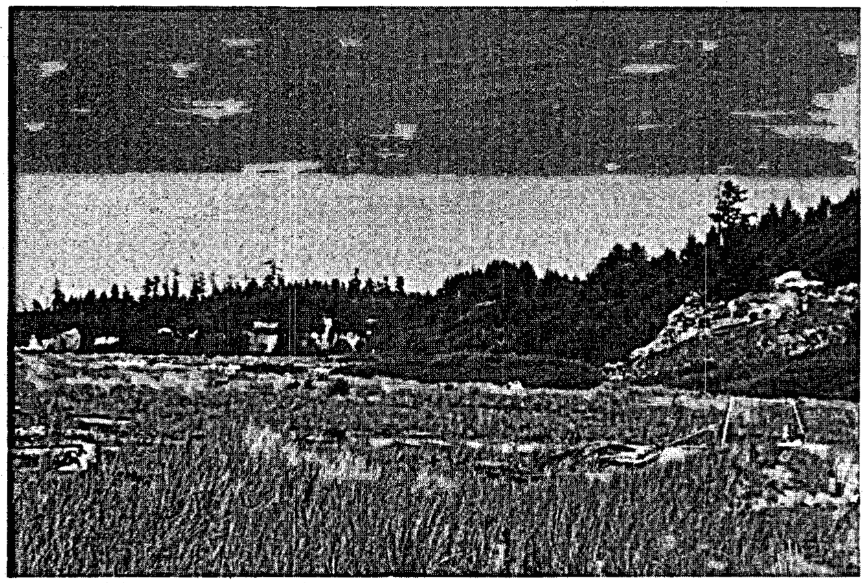


Figure 2. Bastendorff Beach, viewed toward east, August, 1974. Middle Bastendorff sandstone at right, Tunnel Point sandstone in left background. Upper Bastendorff mudstone covered by vegetation, center background.

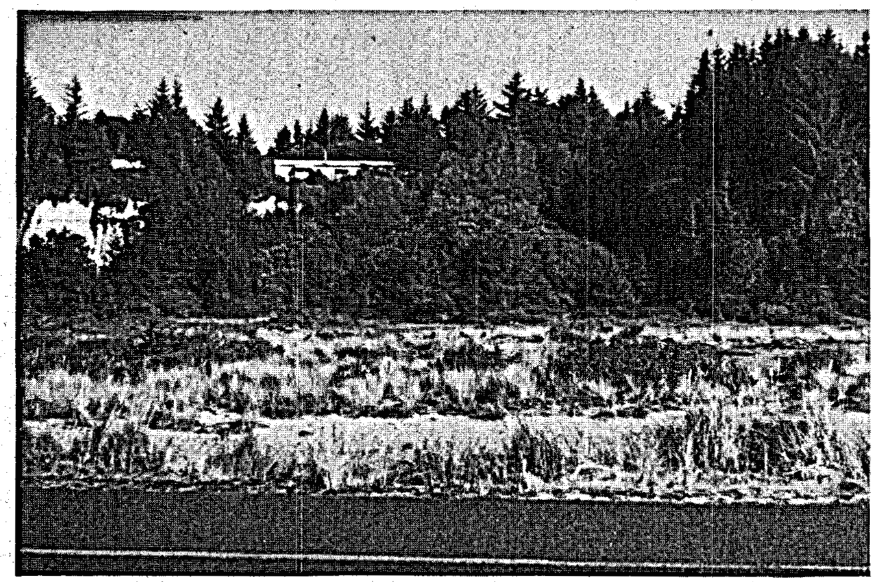


Figure 3. Bastendorff Beach, August, 1974, view from beach showing heavily vegetated area of Bastendorff-Tunnel Point formational contact. Tunnel Point sandstones in cliff at left, Bastendorff mudstone beneath trees at right.

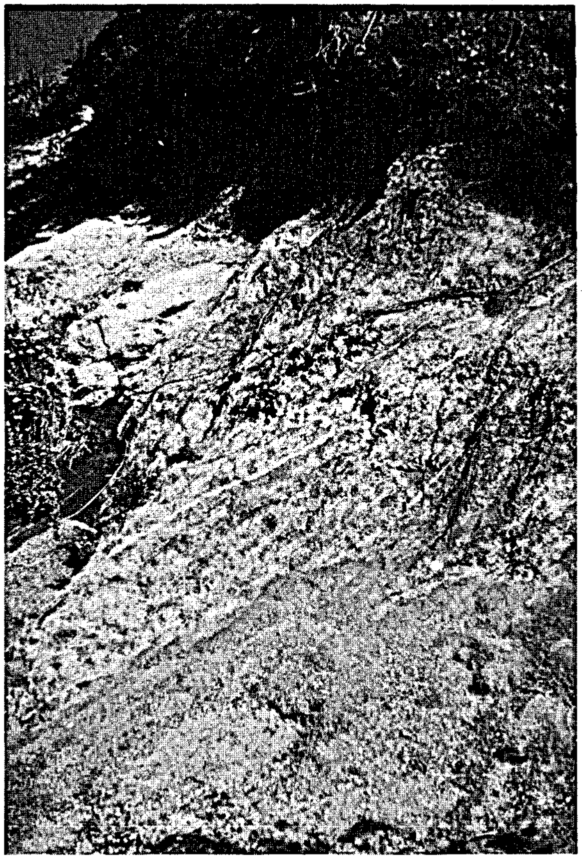


Figure 4. Mudstones of upper Bastendorff Formation, interbedded with two-inch thick sandstone beds, at center, Bastendorff Beach, August, 1974.

Figure 5. Resistant sandstones, interbedded with siltstones and mudstones, middle Bastendorff Formation, east of Miner Creek, Bastendorff Beach, 1974.

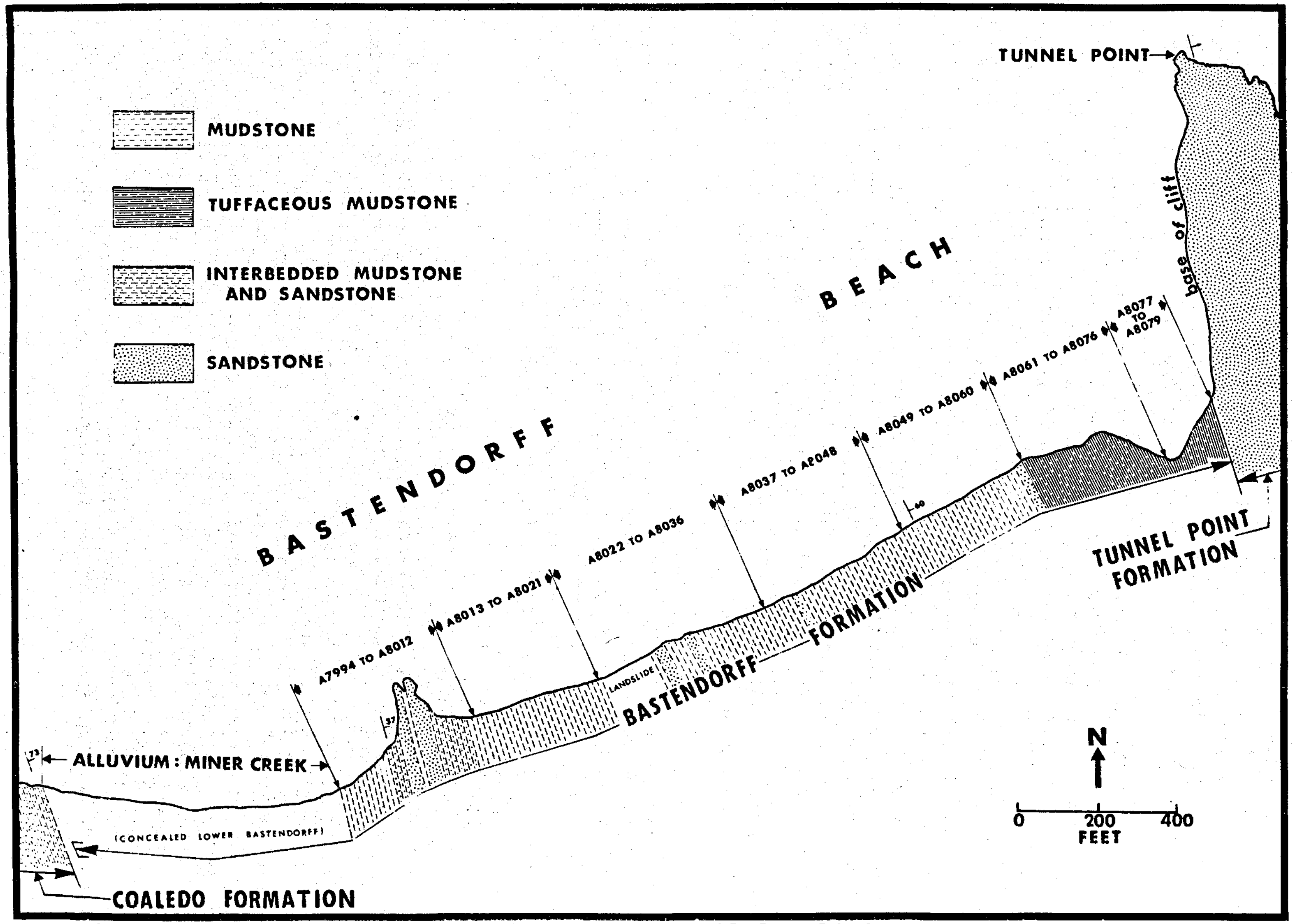


Figure 6. Allocation of Browning-Grier fossil localities, Bastendorff Beach. Lithologies and thicknesses modified from Weaver (1945, pl. 7).

Where attitudes are measurable, beds in the Bastendorff strike roughly N15W and dip 60 degrees or less to the east. The dominant lithology of the formation is silty mudstone ("shale" of Weaver, 1945), in part tuffaceous and interbedded locally with thin beds of siltstone or fine-grained tuffaceous sandstone. A prominent exception to this typically fine-grained texture occurs just east of the mouth of Miner Creek where well-indurated Bastendorff sandstone beds form a promontory, dividing the formation into lower (poorly exposed) and upper mudstone units (see Figure 6).

The thickness of the middle sandstone interval is difficult to ascertain precisely, due to the heavy cover of vegetation now found on all but the best indurated sandstone beds. Baldwin assigned the unit a thickness of 60+ feet. Browning and Grier (see locality descriptions, A-8001 to A-8011) and Weaver (1945, pl. 10) record slightly more than 200 feet of dominantly sandy lithology interbedded with finer-grained sediments. These larger measurements for the sandstone are here considered maximum values that include considerable proportions of finer-grained interbeds.

The Bastendorff sandstone as presently exposed (See Figure 5) consists of several sandstone subunits having individual beds 1 to 3 feet thick. The sandstone intervals are separated from one another by silty and shaley intervals 2 to 10 feet thick. The coarse-grained beds consist of light-gray (where fresh), tuffaceous and micaceous arkosic sandstone, medium grained and subangular, with a silty matrix. The most resistant beds contain iron-stained concretions aligned roughly parallel to bedding. Rare coaley layers and ripple markings occur in the siltstone interbeds.

Neither the base nor the top of the Bastendorff Formation is now exposed at the beach section. The lower contact with the Coaledo Formation is buried under the Recent alluvium of Miner Creek. The upper contact with the Tunnel Point is today obscured by thick vegetation, though Weaver (1945) found it be be well-exposed. The general agreement of strikes and dips on either side of the contacts suggests concordance, and the lack of paleontologically measurable hiatus suggests continuity of deposition for the three formations.

Paleontology

Browning and Grier collected two samples from the thinly bedded shale of the Coaledo Formation, 280 feet below its upper contact, and 85 samples from the Bastendorff Formation. The stratigraphic distribution of all their samples is described in the appendix of locality descriptions, and their approximate position along the beach-cliffs is shown in Figure 6. The author examined washed material from the samples and selected for checklisting those containing significant foraminiferal assemblages. Barren samples and samples containing sparse assemblages of agglutinated foraminifers were eliminated from further consideration. The stratigraphic allocation of the selected samples is shown in Figure 7, and their foraminiferal content is checklisted in Figure 8.

Diatoms and radiolarians are conspicuous throughout the section, frequently where calcareous foraminifers are lacking, and it is possible that siliceous or calcareous nannoplankton may also be abundant in some samples. The mud pecten Delectopecten peckhami (Gabb) occurs in Bastendorff mudstone exposed in a roadcut near the beach at roughly the stratigraphic interval

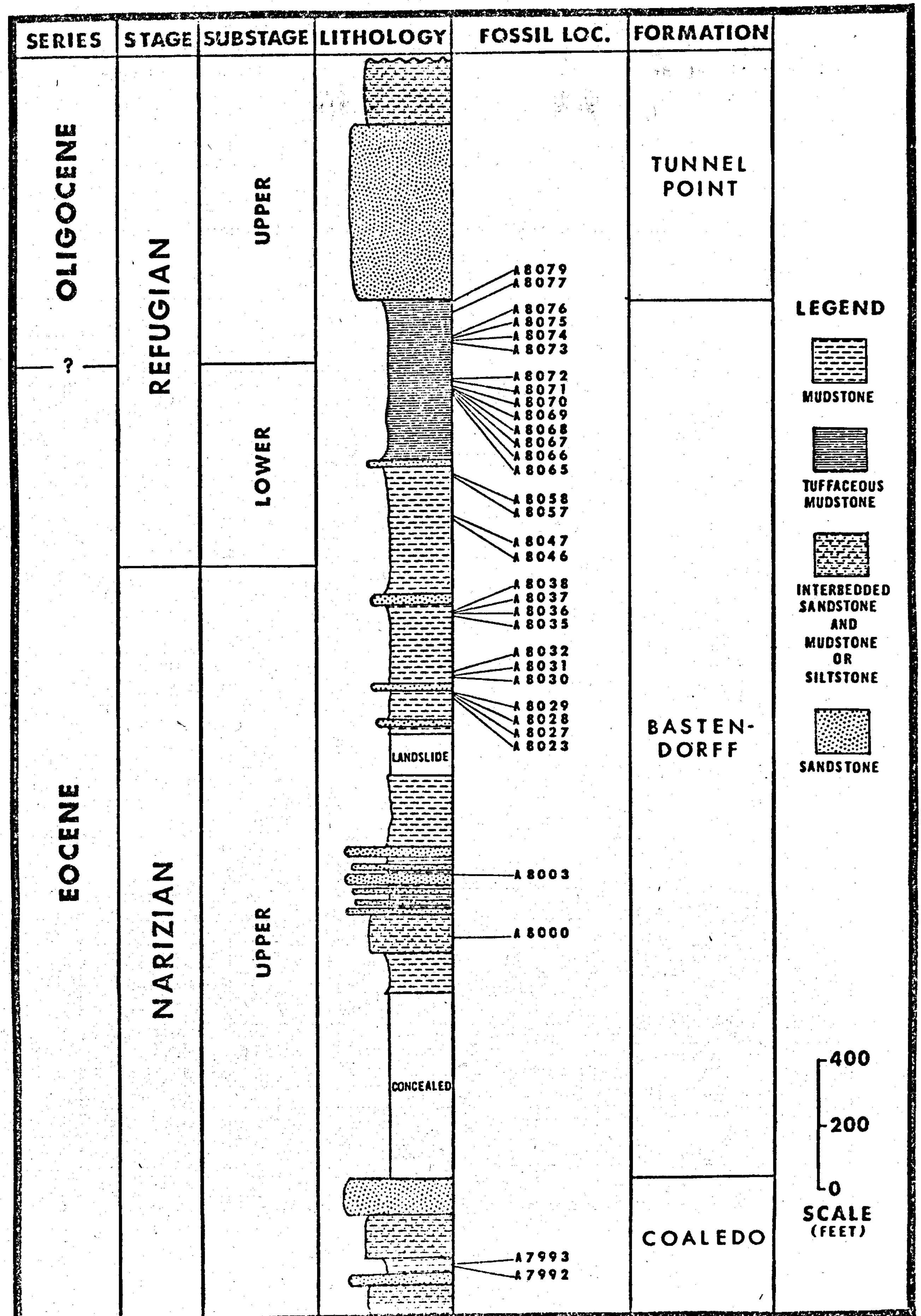
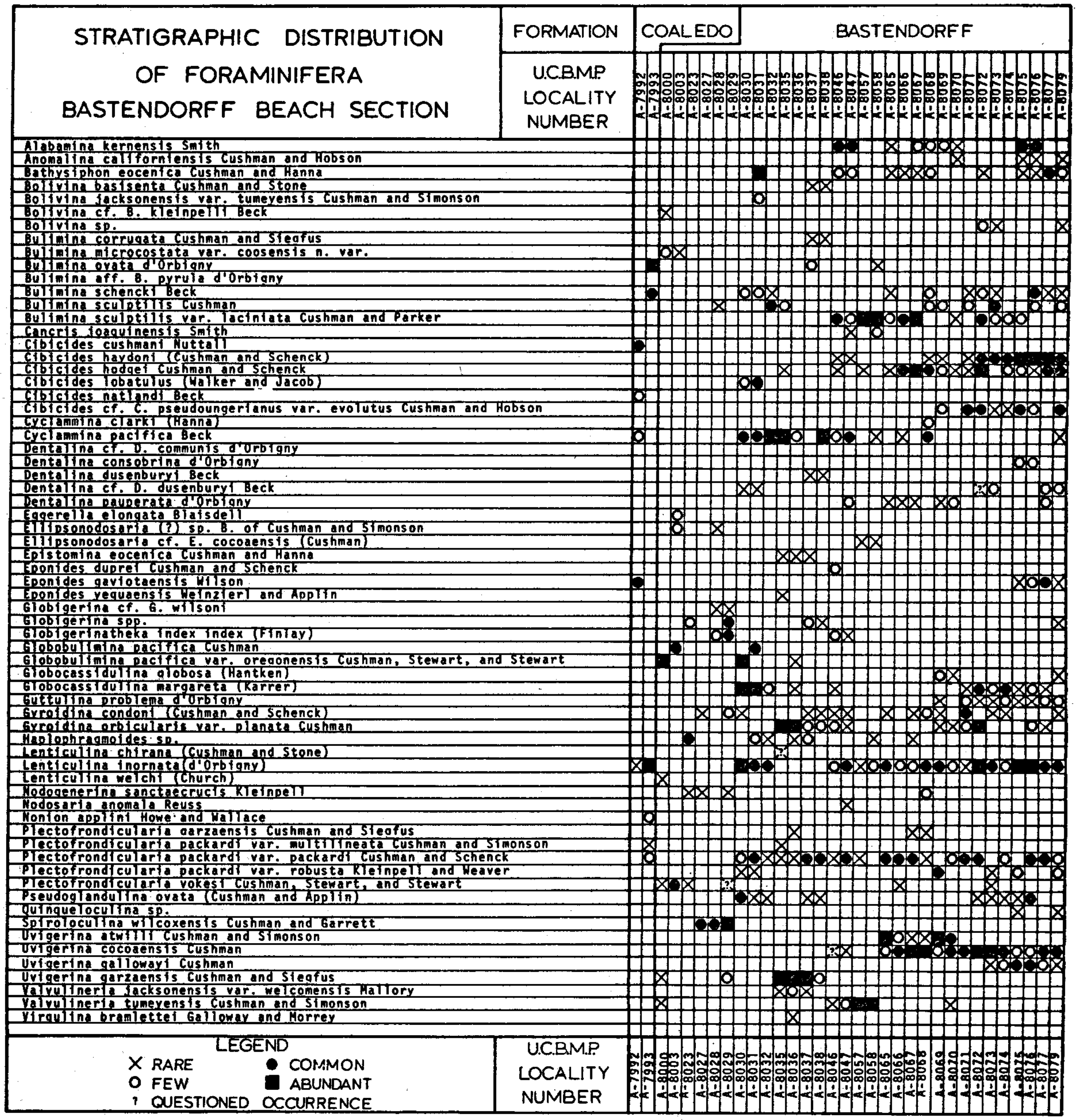


Figure 7. Stratigraphic allocation of checklisted samples.

Figure 8. Distribution of Foraminifera, type Bastendorff Formation.



of localities A-8048 to A-8052. From the upper 500 feet of the Bastendorff, Weaver (1945, p. 49) recorded poorly preserved Dentalium cf. porterensis Weaver, Cylichnina turneri Effinger, Nuculana cf. merriami (Dickerson), Spisula cf. packardi Dickerson, and Acila sp. Leaf impressions occur in the silty interbeds of the middle Bastendorff sandstone, but have not been studied.

Several samples from fine-grained interbeds in the Tunnel Point Formation were examined for microfossils, revealing only a few diatoms and no Foraminifera.

The foraminiferal assemblages of the Bastendorff Formation are dominantly benthonic (64 taxa). Several species of planktonic Foraminifera, all globigerinids, are most common in the lower part of the upper mudstone unit.

A single new taxon of Foraminifera was found, a variety of Bulimina microcostata Cushman and Parker, from the middle Bastendorff sandstone unit. The new variety will be formally designated and illustrated in a future publication.

Age

The samples from the upper Coaledo Formation (A-7992 and A-7993) as well as samples A-8000 through A-8038 of the uppermost lower Bastendorff mudstone, middle sandstone, and upper mudstone units are all referable to the Narizian Stage. Occurrences of Bulimina corrugata, Bolivina basisenta, Bulimina microcostata var., Cibicides cushmani, Cibicides natlandi, and Lenticulina welchi indicate that those strata are no younger than Narizian, based on the known teilzones of those species both in the Pacific Northwest and in California. Occurrences of Bulimina schencki, Bolivina basisenta, Plectofrondicularia packardi var. packardi, and Eponides gaviotaensis suggest an age no older than upper Narizian for the interval A-7992 through A-8038.

Thus, the highest demonstrably Narizian assemblage occurs some 750 feet above the top of the middle Bastendorff sandstone. The upper Narizian age of strata both above and below indicates that the unexposed lower portion of the Bastendorff that is concealed by alluvium at the mouth of Miner Creek is also upper Narizian.

The lowermost diagnostically Refugian assemblage is that of Loc. A-8046, some 300 feet above the highest conclusively Narizian assemblage. Cibicides haydoni and Uvigerina cocoaensis occur lowest there, along with the typically though not restrictedly Refugian species Alabamina kernensis, Bulimina sculptilis var. laciniata and Cibicides hodgei. Cibicides haydoni is diagnostically Refugian in California sequences, though Rau (1958) reports earlier occurrences in Washington. Uvigerina cocoaensis is restricted to the Refugian Stage throughout the West Coast.

The occurrences of the latter two species, in addition to Plectofrondicularia packardi var. packardi, Cibicides hodgei, and Bulimina sculptilis, as high as a few inches below the Bastendorff-Tunnel Point contact are conclusive evidence for the Refugian age of all the upper Bastendorff mudstone above Loc. A-8046.

Within that Refugian portion of the upper Bastendorff, the interval of samples A-8046 through A-8058 is probably referable to the lower part of the Stage, roughly correlative with the Sigmomorphina schencki Zone of Rau (1958), on the basis of the occurrences of Valvulineria tumeyensis, a species confined to lower Refugian and older strata in West Coast sequences.

The uppermost 150 feet of the formation (samples A-8073 to A-8079) bear Uvigerina gallowayi, a species strongly suggestive of upper Refugian age, correlative with the tentative Uvigerina vicksburgensis zone of Kleinpell and Weaver (1963) and the Eponides kleinpelli-Cassidulina galvinensis Zone of Rau (1958, 1966). Corroborative evidence for the upper Refugian age of the uppermost Bastendorff is Detling's (1946) recording of "Uvigerina sp." near the top of the formation, a form apparently conspecific with Uvigerina vicksburgensis Cushman.

The upper Refugian age of the highest Bastendorff beds implies that the Tunnel Point sandstone is no older than upper Refugian, thus not as old as shown by Armentrout (1973, Fig. 14). Armentrout assigns the Tunnel Point Formation to his (1973) Echinophoria dalli and Echinophoria fax molluscan zones for Oregon and Washington, middle and upper "Chehalian" Stage (now renamed the Galvinian Stage, Armentrout, this volume) and correlative with the middle and upper Refugian Stage. It would appear instead that, on the basis of the foraminiferal evidence, the Tunnel Point is no older than upper Refugian.

Paleoecology

The following paleobathymetric interpretations are based on present knowledge as to morphological variations (Bandy, 1960) and community-type variations (Natland, 1933) with depth among modern foraminiferal faunas.

Late Narizian shelf-sea depths are indicated for deposition of the upper Coaledo and lower and middle Bastendorff beds from which samples A-7992, A-7993, A-8000, and A-8003 were collected, though not necessarily for the intervening unexposed portion of the lower Bastendorff. This interpretaion is based on the presence of the very finely costate and smooth-walled buliminids (microcostata var., schencki, and ovata), the common coiled lagenid (Lenticulina inornata), and the biconvex Eponides (gaviotaensis). Possibly shallower, more turbulent conditions may have been represented by the cross-bedded, channel-scoured, sandstones of the uppermost Coaledo, in keeping with Baldwin's (1973, p. 27) interpretation of marine regression for that interval.

A middle or lower bathyal environment is indicated for the Bastendorff Formation above the middle sandstone, as suggested by the predominance of costate uvigerinids and buliminids, thick-tested plectofrondicularids and strongly plano-convex gyroidinids. The upper Bastendorff mudstone thus represents a period of maximum marine transgression in the Coos embayment during late Narizian and Refugian time. Slight shallowing, to perhaps upper bathyal depths, may be suggested for late Refugian time, for the forms mentioned above as indicating deep-water conditions are less conspicuous near the top of the Formation.

Abundant diatoms and radiolarians at many horizons of the middle and upper Bastendorff testify to strong open-ocean influences during latest Narizian and Refugian time.

Correlations

Figure 9 summarizes the age correlation of the Bastendorff Formation with the type Refugian section in southern California, and with selected foraminiferal sequences in the Pacific Northwest. Chronologically, the Bastendorff is most closely equivalent to the Keasey Formation of northwest Oregon and to the Gaviota Formation of California.

Ecologically, the Bastendorff foraminiferal assemblages are most reminiscent, not of correlative faunas in the Pacific Northwest, but of deep-water faunas in California, such as the type Refugian of the western Santa Ynez Mountains (Kleinpell and Weaver, 1963) and the subsurface Tumey Formation of the San Joaquin Valley (Cushman and Simonson, 1944). With their abundant costate and hispid uvigerinids, heavily costate buliminids, thick-tested plectofrondicularids, and a diversity of straight-tested lagenids, the Gaviota, Tumey, and Bastendorff deep-water assemblages are all but indistinguishable.

In contrast, late Narizian-Refugian foraminiferal assemblages in the Cowlitz (Beck, 1943) and Lincoln Creek (Rau, 1948, 1951, 1966) Formations of southwestern Washington are of a dominantly neritic aspect, including a diversity of coiled lagenids, common miliolids, Siphonina, Sigmomorphina, and other forms inferred to have a shelf-sea optimum. Typically deeper-water forms are present, such as costate uvigerinids, but in proportions suggesting somewhat shallower conditions than indicated for the Bastendorff. McDougall (1975, oral comm.) reports that foraminiferal assemblages of the Keasey Formation are also indicative of moderate depths, shallower than indicated by the Bastendorff fauna.

Among correlative faunas of the Pacific Northwest, the Bastendorff is perhaps closest in ecologic facies to assemblages from the middle Twin River Formation of the northern Olympic Peninsula (Rau, 1964, pp. G12-G13), interpreted as indicating "deep, cold water".

The absence of the species of Sigmomorphina in the upper Bastendorff, as well as in all published records of Refugian sequences in California contrasts strikingly with common occurrences of this lineage during Refugian as well as Zemorrian times in Washington and northwestern Oregon (S. schencki, S. pseudoschencki, S. undulata, and S. sp. A, in Lincoln Creek, Blakeley, and Keasey Formations; see Rau, 1948, 1951, 1958; Fulmer, this volume; Cushman and Schenck, 1928). This faunal difference may be due to 1) a preference of Sigmomorphina for the relatively cool waters of northern Oregon and Washington, vis a vis southern Oregon and California, or 2) the preference of Sigmomorphina for the shelf-sea environment apparently present in southern Washington during deposition of the Lincoln Creek Formation, rather than the deeper-water habitat present during deposition of the Bastendorff, Gaviota, and Tumey Formations.

SERIES	WEST COAST STAGES*	FORAM. ZONES CALIFORNIA*	FORAM. ZONES WASHINGTON**	THIS REPORT — BASTENDORFF BEACH	MODIFIED FROM KLEINPELL & WEAVER, 1963 — TYPE SECTION REFUGIAN STAGE SOUTH. CALIF.	RAU, THIS VOLUME — CENTRAL OREGON COAST	MCDOUGALL, THIS VOLUME — NORTHWEST OREGON	RAU, 1958, 1966, 1967 — SOUTHWEST WASHINGTON	FULMER, THIS VOLUME — PUGET SOUND
OLIGOCENE	ZEMORRIAN	U. sparsicostata	upper "U. vicksburgensis zone"	HIATUS	RINCON FM.	YAQUINA FM.	SCAPPOOSE FM.	LINCOLN CREEK FM.	TYPE BLAKELY FM.
		U. gallowayi	lower "U. cocoaensis zone"		VAQUEROS FM.; ? HIATUS ?	ALSEA FM.	PITTSBURG BLUFF FM.		
	REFUGIAN	upper	E. kleinpelli C. galvinensis	TUNNEL POINT FM.	ALEGRIA FM.				
--?--		lower	S. schencki	BASTENDORFF FM.	GAVIOTA FM.		KEASEY FM.		
EOCENE	NARIZIAN	A. jenkinsi	B. schencki P. cf. jenkinsi	sandstone	SACATE FM.	NESTUCCA FM.		? SKOOKUMCHUCK FM.	(NOT EXPOSED)
		B. corrugata	U. cf. yazooensis	COALEDO FM.	COZY DELL FM.		COWLITZ FM.	NORTHCRAFT FM.; MCINTOSH FM.	

* Mallory, 1959; Schenck and Kleinpell, 1936; Kleinpell, 1938
** Rau, 1958, 1966

Figure 9. Foraminiferal correlation of type Bastendorff Formation with type section of Refugian Stage, Santa Ynez Mountains, California, and selected sections Pacific Northwest.

The first-named hypothesis, implying latitudinal differentiation, would not by itself explain the rarity of Sigmomorphina in the Twin River Formation of northern Washington (see Rau, 1964), for the Twin River exposures are at even higher latitudes than the Sigmomorphina-rich Lincoln Creek Formation. It seems more likely that depth may have been the dominant factor in restricting the Refugian occurrences of Sigmomorphina to exclude California and the Coos Bay area, where continental shelf environments were not developed. Alternately, several factors, zoogeographic or ecologic, may have worked together in a manner difficult to delineate in these instances of extinct taxa.

The close similarity of the Bastendorff foraminiferal fauna to correlative faunas of California and the northern Olympic Peninsula, in addition to most elements (excluding Sigmomorphina) in common with Lincoln Creek and Keasey assemblages, implies that during Refugian time a single zoogeographic province for Foraminifera stretched from southern California at least as far north as northern Washington. Foraminiferal taxa that have in the past been recorded only in the Pacific Northwest (e.g. Bulimina schencki, Valvulineria menloensis) or only in California (e.g. Uvigerina vicksburgensis) have been recently identified by the author in Refugian faunas of California and the Pacific Northwest, respectively. Few faunal differences remain to distinguish the two regions. This absence of latitudinal differentiation among West Coast Refugian foraminiferal faunas contrasts with the marked provincialism of contemporaneous West Coast molluscan faunas of the "Lincoln Stage", as noted by Addicott (1970 a, b).

References to Checklisted Species

Species	Reference
Alabamina kernensis Smith	Tipton, Kleinpell, and Weaver, 1973, p. 61, pl. 10, fig. 5.
Anomalina californiensis Cushman and Hobson	Cushman and Hobson, 1935, p. 64, pl. 9, fig. 8.
Bathysiphon eocenica Cushman and Hanna	Cushman and G.D. Hanna, 1927, p. 210, pl. 13, figs. 2, 3.
Bolivina basisenta Cushman and Stone	Cushman, Stewart, and Stewart, 1947b, p. 102, pl. 13, fig. 6
Bolivina jacksonensis var. tumeyensis Cushman and Simonson	Kleinpell and Weaver, 1963, p. 176, pl. 9, fig. 7.
Bolivina cf. B. kleinpelli Beck	Cushman, Stewart, and Stewart, 1974a, pl. 8, fig. 8.
Bolivina sp	Characterized by sharply angled periphery, moderately compressed test, and fine striae.
Bulimina corrugata Cushman and Siegfus	Cushman and Siegfus, 1942, p. 411 pl. 16, fig. 38.
Bulimina microcostata Cushman and Parker n. var.	Differing from the typical in being larger and more elongate, with more nearly parallel sides in mature specimens.
Bulimina ovata d'Orbigny	Tipton, Kleinpell, and Weaver, 1973, p. 53, pl. 5, fig. 10.
Bulimina schencki Beck	Beck, 1943, p. 605, pl. 107, figs. 28, 33.
Bulimina sculptilis Cushman	Cushman, 1923, pl. 3, fig. 3, p. 23.
Bulimina sculptilis var. laciniata Cushman and Parker	Cushman and Parker, 1937, p. 38, pl. 4, fig. 4.
Cancris joaquinensis Smith	Smith, H.P., 1956, pp. 98-99, pl. 15, figs. 5, 6.
Cibicides cushmani Nuttall	Mallory, 1959, pp. 264-265, pl. 31, fig. 3.
Cibicides haydoni (Cushman and Schenck)	Kleinpell and Weaver, 1963, p. 181, pl. 14, fig. 3.
Cibicides hodgei Cushman and Schenck	Cushman and Schenck, 1928, p. 315, pl. 45, figs. 3-5.
Cibicides lobatulus (Walker and Jacob)	Beck, 1943, p. 611-612, pl. 109, figs. 17, 18, 21
Cibicides natlandi Beck	Beck, 1943, p. 612, pl. 109, figs. 1, 5, 13.
Cibicides cf. C. pseudoungerianus var evolutus Cushman and Hobson	Smaller, having more abundant shell material at the umbilucus than is typical.
Cyclammina clarki (Hanna)	Kleinpell and Weaver, 1963, p. 167, pl. 2, fig. 9
Cyclammina pacifica Beck	Beck, 1943, pp. 591-592, pl. 98, figs. 2, 3.
Dentalina consobrina d'Orbigny	Wilson, 1954, p. 135, pl. 14, fig. 7.
Dentalina dusenburyi Beck	Beck, 1943, p. 599, pl. 105, figs. 20, 23.
Dentalina cf. D. dusenburyi Beck	Beck, 1943, p. 599, pl. 105 fig. 14.

Dentalina pauperata d'Orbigny	Kleinpell, 1938, p. 213, pl. 11, figs. 6.
Eggerella elongata Blaisdell	Tipton, Kleinpell, and Weaver, 1973, p. 42, pl. 1 figs. 9, 10.
Ellipsonodosaria (?) sp. B	Cushman and Simonson, 1944, p. 200, pl. 33, fig. 8, 9.
Ellipsonodosaria cf. E. cocoaensis (Cushman)	Beck, 1943, p. 608, pl. 108, fig. 10.
Epistomina eocenica Cushman and Hanna	Cushman and Schenck, 1928, p. 313, pl. 44, fig. 9.
Eponides duprei Cushman and Schenck	Cushman and Schenck, 1928, p. 313, pl. 44, fig. 8.
Eponides gaviotaensis Wilson	Wilson, 1954, p. 143, pl. 16 figs. 11, 12.
Eponides yeguaensis Weinzierl and Applin	Beck, 1943, p. 608, pl. 108, figs. 1, 4.
Globigerina cf. G. wilsoni Cole	Differing from G. wilsoni in being more trochoid, and in consisting of four rather than the typical five chambers.
Globigerina spp	Poorly preserved individuals
Globigerinatheka index index (Finlay)	Blow, 1972, pp. 124-126, pl. 1, figs. 1-4, 6, 7.
Globobulimina pacifica Cushman	Beck, 1943, p. 606, pl. 107, fig. 16.
Globobulimina pacifica var. oregonensis Cushman, Stewart, and Stewart	Cushman, Stewart, and Stewart, 1974b, p. 101, pl. 12, fig. 13.
Globocassidulina globosa (Hantken)	Fairchild, Wesendunk, and Weaver, 1969, pl. 22, fig. 15.
Globocassidulina margareta (Karrer)	Tipton, Kleinpell, and Weaver, 1973, p. 62, pl. 11, fig. 1.
Guttulina problema d'Orbigny	Beck, 1943, p. 602, pl. 106, figs. 11, 17, 20.
Gyroidina condoni (Cushman and Schenck)	Kleinpell and Weaver, 1963, p. 179, pl. 11, fig. 3.
Gyroidina orbicularis var. planata Cushman	Sullivan, 1962, pp. 280-281, pl. 18, fig. 1.
Haplophragmoides sp	Poorly preserved individuals
Lenticulina chirana (Cushman and Stone)	Tipton, Kleinpell, and Weaver, 1973, p. 44, pl. 2, fig. 2.
Lenticulina inornata (d'Orbigny)	Tipton, Kleinpell, and Weaver, 1973, p. 45, pl. 2, fig. 9.
Lenticulina welchi (Church)	Robulus welchi Church, Mallory, 1959, p. 143, pl. 7, fig. 8.
Nodogenerina sanctaecrucis Kleinpell	Kleinpell, 1938, p. 246, pl. 4, fig. 22.
Nodosaria anomala Reuss	Wilson, 1954, p. 136, pl. 14, fig. 11.
Nonion applini Howe and Wallace	Mallory, 1959, p. 180, pl. 36, fig. 14.
Plectofrondicularia garzaensis Cushman and Siegfus	Mallory, 1959, p. 212, pl. 18, fig. 1.

Plectofrondicularia packardi var. multilineata Cushman and Simonson........Cushman and Simonson, 1944, p. 197, pl. 32, figs. 2, 4.

Plectofrondicularia packardi var. packardi Cushman and Schenck............Kleinpell and Weaver, 1963, pl. 174, pl. 8, figs. 5-7, 10, 14.

Plectofrondicularia packardi var. robusta Kleinpell and Weaver............Kleinpell and Weaver, 1963, p. 174, pl. 9, fig. 1.

Plectofrondicularia vokesi Cushman, Stewart, and Stewart..........Kleinpell and Weaver, 1963, p. 174, pl. 9, fig. 2.

Pseudoglandulina ovata (Cushman and Applin)...........Kleinpell and Weaver, 1963, p. 171, pl. 7, fig. 7.

Quinqueloculina sp..................................Rare and poorly preserved representatives of the genus.

Spiroloculina wilcoxensis............................Detling, 1946, p. 352, pl. 46, fig. 3.

Uvigerina atwilli Cushman and Simonson...............Cushman and Simonson, 1944, p. 200, pl. 33, figs. 2-4.

Uvigerina cocoaensis Cushman..........................Cushman and Schenck, 1928, p. 312, pl. 43, figs. 17, 19.

Uvigerina gallowayi Cushman...........................Cushman and Simonson, 1944, p. 200, pl. 32, fig. 18.

Uvigerina garzaensis Cushman and Siegfus.............Cushman and Siegfus, 1939, pp. 28-29, pl. 6, fig. 15.

Valvulineria jacksonensis var. welcomensis Mallory...........Mallory, 1959, p. 231, pl. 20, figs. 3, 5.

Valvulineria tumeyensis Cushman and Simonson..........Cushman and Simonson, 1944, p. 201, pl. 33, figs. 13, 14.

Virgulina bramlettei Galloway and Morrey.............Sullivan, 1962, p. 275, pl. 15, figs. 1, 2.

Locality Descriptions

The following locality descriptions were recorded by John Browning and William Grier, who collected samples A7994 through A8079 during the summer of 1950. All sample localities are those of the Museum of Paleontology, University of California, Berkley.

A7994 through A8079, were collected in the type Bastendorff Formation in the Coos Bay area, Coos County, Oregon, between parallels 43 degrees 20' and 124 degrees 23'W Longitude. The Bastendorff Formation is exposed in sea cliffs (slumps common), in an approximately east-west direct along Bastendorff Beach. Individual beds average in strike N15W and in dip 60E.

A-7992 and A-7993 were collected from the Coaledo Formation which underlies the Bastendorff Formation and is separated from it on Bastendorff Beach by an area of slump approx. 700' in width. The samples are from a thinly bedded shale which is 280' stratigraphically below the contact of the Coaledo Formation with the slump area (see Weaver, 1945, plates 6, 7).

A-7994 thru A-8000 collected from beds of fine brown platy shale which are interbedded with a grayish massive feldspathic sandstone.

A-7994 is 8' stratigraphically above the contact of the lower Bastendorff with the slump.

A-7995 is	2'	stratigraphically	above	A-7994
A-7996 is	3'	"	"	A-7995
A-7997 is	12'	"	"	A-7996
A-7998 is	13'	"	"	A-7997
A-7999 is	115'	"	"	A-7998
A-8000 is	7'	"	"	A-7999

A-8001 thru A-8005 were collected from light brown sandy shale stringers within gray, laminated, fine-grained feldspathic sandstone beds which are interbedded with a brown shale.

A-8001 is 182' stratigraphically above A-8000 and 6' above the lower contact of the first laminated sandstone.

A-8002 is	5'	stratigraphically	above	A-8001
A-8003 is	10'	"	"	A-8002
A-8004 is	20'	"	"	A-8003
A-8005 is	65'	"	"	A-8004

Sandstone is platy at A-8005 and becomes gradually less so, increasingly more concretionary, as you move up the column to A-8011.

A-8006 is	85'	stratigraphically	above	A-8005
A-8007 is	8'	"	"	A-8006
A-8008 is	6'	"	"	A-8007
A-8009 is	2'	"	"	A-8008
A-8010 is	9'	"	"	A-8009
A-8011 is	2'	"	"	A-8010

Near A-8012 the sandstone disappears except for rare stringers and samples A-8012, and A-8013 and A-8019 thru A-8022 were collected from a fine brown siltstone which is the dominant formation. A-8014 thru A-8018 were collected from a shale bed contained within the siltstone.

A-8012 is 15' stratigraphically above A-8010 and 1' above the sandstone-siltstone contact.

A-8013 is	15'	stratigraphically	above	A-8012
A-8014 is	60'	"	"	A-8013
A-8015 is	4'	"	"	A-8014
A-8016 is	2'	"	"	A-8015
A-8017 is	2'	"	"	A-8016
A-8018 is	2'	"	"	A-8017
A-8019 is	7'	"	"	A-8018
A-8020 is	5'	"	"	A-8019
A-8021 is	10'	"	"	A-8020

There is a general slump area between A-8021 and A-8040. Samples were collected from a few restricted areas that remained in place. A-8023 and A-8029 were collected from shales that, with interbedded tuff, form a bed about 35' thick within the siltstone.

A-8022 is	30'	stratigraphically	above	A-8021
A-8023 is	215'	"	"	A-8022
A-8024 is	6'	"	"	A-8023
A-8025 is	1'	"	"	A-8024
A-8026 is	1'	"	"	A-8025
A-8027 is	2'	"	"	A-8026
A-8028 is	3'	"	"	A-8027
A-8029 is	3'	"	"	A-8028
A-8030 is	55'	"	"	A-8029
A-8031 is	7'	"	"	A-8030
A-8032 is	2'	"	"	A-8031
A-8033 is	47'	"	"	A-8032
A-8034 is	75'	"	"	A-8033
A-8035 is	60'	"	"	A-8034
A-8036 is	3'	"	"	A-8035
A-8037 is	10'	"	"	A-8036
A-8038 is	3'	"	"	A-8037
A-8039 is	5'	"	"	A-8038
A-8040 is	8'	"	"	A-8039

A-8041 thru A-8044 were collected from a brown sandy shale which is interbedded with tuff and fine grained sandstone.

A-8041 is	175'	stratigraphically	above	A-8040
A-8042 is	3'	"	"	A-8041
A-8043 is	4'	"	"	A-8042
A-8044 is	17'	"	"	A-8043

A-8045 thru A-8047 were collected from a well consolidated fine brown siltstone.

A-8045 is	18'	stratigraphically	above	A-8044
A-8046 is	68'	"	"	A-8045
A-8047 is	7'	"	"	A-8046

A-8048 thru A-8059 were collected from tuffaceous brown shales interbedded with sandstone.

A-8048 is 7' stratigraphically above A-8047
A-8049 is 30' " " A-8048
A-8050 is 4' " " A-8049
A-8051 is 11' " " A-8050
A-8052 is 32' " " A-8051
A-8053 is 18' " " A-8052
A-8054 is 3' " " A-8053
A-8055 is 10' " " A-8054
A-8056 is 4' " " A-8055
A-8057 is 7' " " A-8056
A-8058 is 2' " " A-8057
A-8059 is 105' " " A-8058
A-8060 is 85' " " A-8059 and was collected in a tuffaceous brown shale.

A-8061 thru A-8079 were collected from a massive brown mudstone (mapped as tuffaceous shale by Weaver, 1945).

A-8061 is 22' stratigraphically above A-8060 and 3' above the contact of the mudstone and last sandstone.
A-8062 is 8' stratigraphically above A-8061
A-8063 is 2' " " A-8062
A-8064 is 3' " " A-8063
A-8065 is 34' " " A-8064
A-8066 is 3' " " A-8065
A-8067 is 6' " " A-8066
A-8068 is 2' " " A-8067
A-8069 is 10' " " A-8068
A-8070 is 8' " " A-8069
A-8071 is 20' " " A-8070
A-8072 is 4' " " A-8071
A-8073 is 120' " " A-8072
A-8074 is 6' " " A-8073
A-8075 is 7' " " A-8074
A-8076 is 5' " " A-8075
A-8077 is 77' " " A-8076
A-8078 is 47' " " A-8077 and 2' below the contact of the upper Bastendorff with the Tunnel Point sandstone.
A-8079 is about 2 inches below the above contact.

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RELIABILITY OF C-14 DATING IN DETERMINING LATE PLEISTOCENE CORRELATION AND RATES OF DEFORMATION: BALDWIN HILLS - RANCHO LA BREA, LOS ANGELES, CALIFORNIA.

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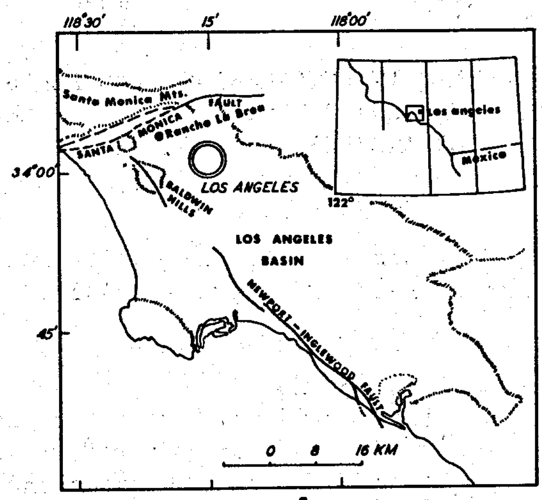
ABSTRACT -- Radiocarbon dates of 36,000 $\pm$ 2,750 years from marine shells, and 28,450 $\pm$ 2,600 years for fossil wood were used by previous authors to correlate late Pleistocene events in the Baldwin Hills, western Los Angeles Basin, with similar events known 5 km to the north, at Rancho La Brea. Numerous published Carbon-14 dates of fossils at Rancho La Brea, radiometric dates of marine faunas comparable to those of the Baldwin Hills and Rancho La Brea, and stratigraphic evidence, are presented to show that if such correlation exists, the reported Baldwin Hills shell date is far too young, and that resultant calculated rates of uplift in the Baldwin Hills of 0.5 to 0.8 m per 100 years, during the past 36,000 years, are excessive. An average rate of uplift in the Santa Monica Mountains foothills, in the vicinity of Rancho La Brea, for the past 100,000 years appears to have been between 0.04 and 0.05 m per 100 years, or about one order of magnitude less than that determined from the Baldwin Hills, for the past 36,000 years.

INTRODUCTION

In the Baldwin Hills area of the northwestern Los Angeles Basin, recent stratigraphic studies, together with radiocarbon analyses of marine shells and fossil wood have provided quantitative estimates concerning both the rates of sedimentation during a part of late Pleistocene time, and the rate of uplift along one known active tectonic feature, the Newport-Inglewood structural zone. The results of this recently published study depend on two critical factors; the reliability of Carbon - 14 dating of shells from the marine strata, and correlation of these sediments with an uppermost, late Pleistocene marine biozone known 5 km to the north at Rancho La Brea, in the Santa Monica Mountains foothills.

Because different depth factors appear to be involved, direct comparison, and thus undisputed correlation of the marine faunules is not possible. While the comparable stratal sequences determined at both localities lends some support for correlation of marine and non-marine events, numerous reliable Carbon-14 dates from Rancho La Brea, and radiometric datings of equivalent marine horizons from elsewhere in southern California suggest that the marine shell date is far too young. If this is so, both postulated rates of sedimentation and uplift in the Baldwin Hills are too high. Present evidence indicates that latest marine invasion of the northwestern Los Angeles Basin occurred in Sangamonian, and not middle Wisconsin time, as has been proposed. An assumption that



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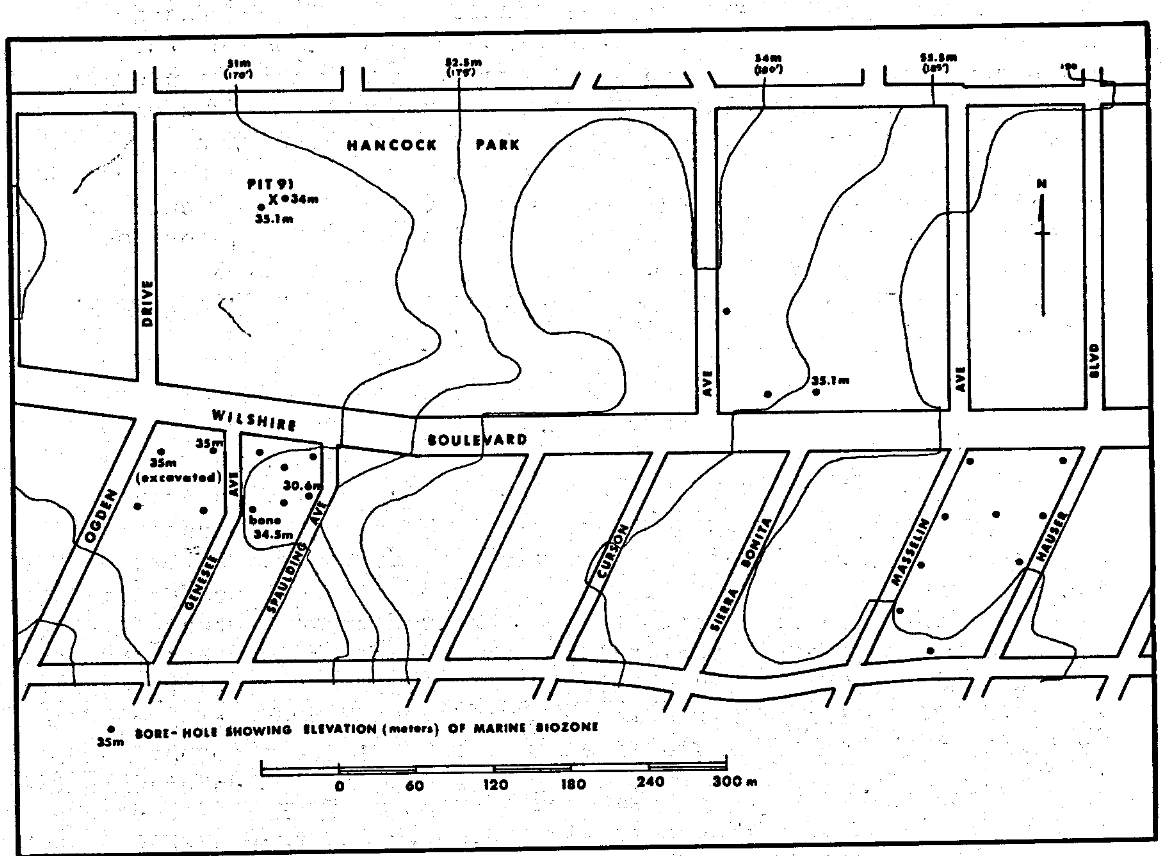

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Figure 1. Location maps showing (a) Baldwin Hills-Rancho La Brea, and (b) street map in the vicinity of Rancho La Brea showing Pit 91 and bore-hole sites pertinent to this study.

the Rancho La Brea fossil deposits should be younger than 28,000 years, at which time it has been inferred that marine submergence ceased in the northwestern Los Angeles Basin, cannot be correct. Numerous radiocarbon dates of fossil wood and bones at Rancho La Brea are in excess of 35,000 to 40,000 years old.

STRATIGRAPHIC EVIDENCE : BALDWIN HILLS - RANCHO LA BREA

In the Baldwin Hills (34° N., 118° 20' W.), western Los Angeles Basin (Fig. 1), Bandy and Marincovich (1973) reported late Pleistocene marine and terrestrial sediments which they suggested to be correlative with marine and terrestrial depositional equivalents, five kilometers to the north, at the Hancock Park Scientific Monument (Rancho La Brea). Radiocarbon analysis of marine shells excavated from the west side of La Cienega Boulevard, west of the Newport-Inglewood fault zone at an elevation of about 78 m yielded a reported age of 36,000 $\pm$ 2,750 years. In the summit of the hills carbonized fossil wood samples taken from an elevation of 145 m yielded an age of 28,450 $\pm$ 2,600 years. Based on these dates, together with paleoecological interpretation of the marine faunules, and deposition accompanying fluctuating sea-levels during late Pleistocene time, they concluded that marine deposition in the Baldwin Hills area of the Los Angeles Basin had concluded less than 28,000 years ago, and that rates of tectonic uplift in the Baldwin Hills were of the order of 0.5 to 0.8 m per 100 years, during the past 36,000 years.

At Rancho La Brea, a phase of warm, shallow-water marine deposition in the northwestern Los Angeles Basin is evidenced from the occurrence of twenty-two species of marine gastropods and pelecypods, together with associated foraminiferan, radiolarian, and ostracod faunules (Valentine and Lipps, 1970), at an elevation of 35 m above sea-level, or 15.3 m below the present land surface. Drilling records of the L. T. Evans Corporation, Consulting Foundation Engineers, Los Angeles, show that marine shells were encountered at a depth of 21.3 m (30.6 m above sea-level) 54 m south of Wilshire Boulevard at Spaulding Avenue, and approximately at 16.5 m depth (35.1 m above sea-level), 100 m east of Rancho La Brea at Sierra Bonita Avenue. At the site of Pit 91 (elev. 48.6 m; 1914 survey), the marine strata occur at depths between 13.5 and 15 m (35.1 - 33.6 m above sea-level). The upper limit of the marine biozone is thus well established at altitudes ranging between 30.6 and 35.1 m above sea-level in the vicinity of Rancho La Brea. The asphaltic fossil mammal deposits excavated by the University of California at Berkeley, and the Los Angeles County Museum of Natural History were confined to the upper 7.9 m of sediments at altitudes greater than 41.6 m (Woodard and Marcus, 1973). The intervening 6.4 to 11 m of tar impregnated quartzose sand, gravel, and pebble conglomerate, which have not yielded marine fossils, record the transition from marine to non-marine depositional environments, and pre-date widespread alluviation that was accompanied by surface exudation of oil, and accumulation of the well-known late Pleistocene Rancho La Brea fossils.

In recent years, numerous Carbon-14 dates have been determined for both fossil wood and bones from various of the Rancho La Brea sites (Howard, 1960; Berger and Libby, 1966; 1968). The most reliable dating

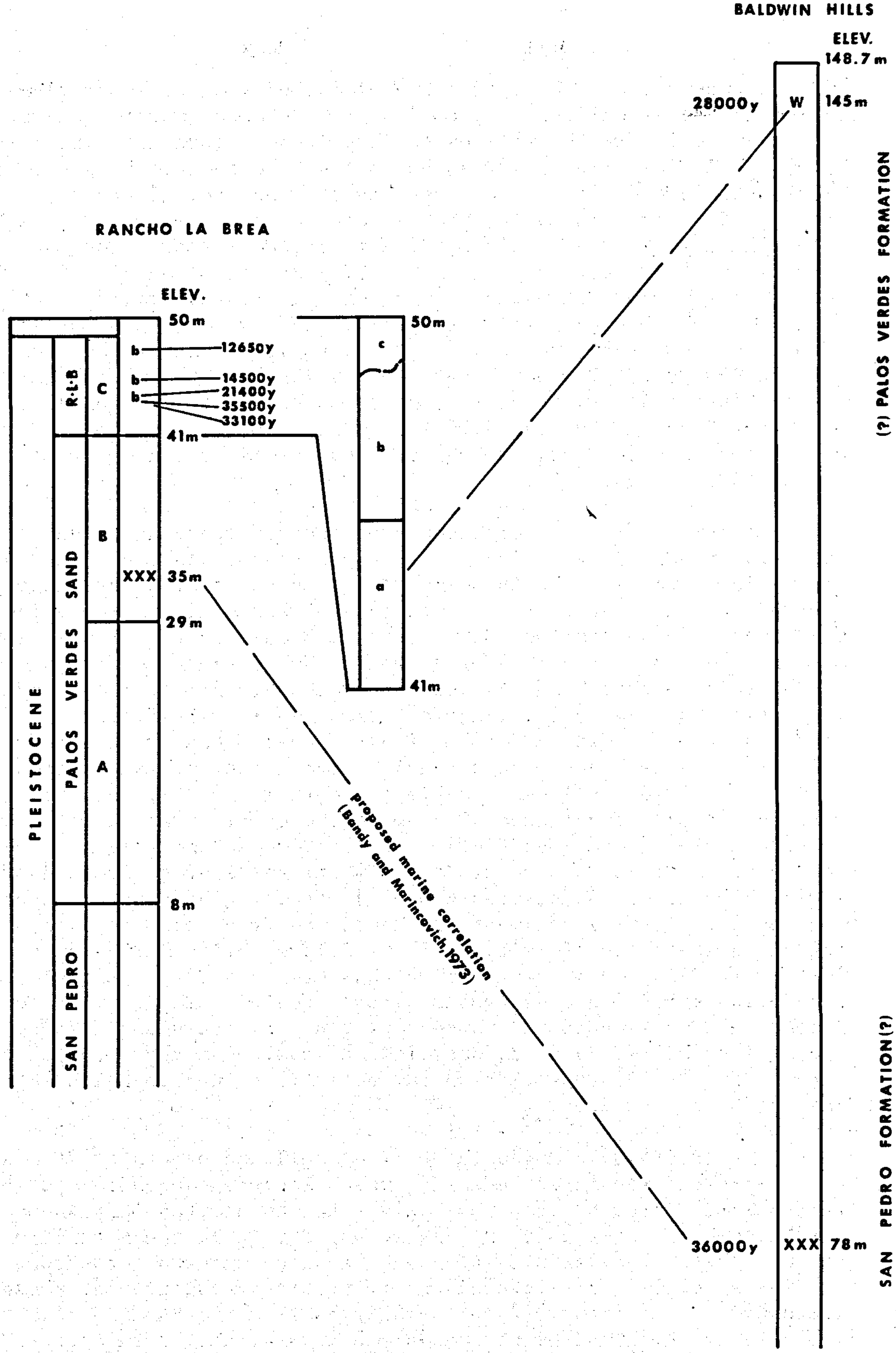

Figure 2. Comparison of stratigraphic columns at Rancho La Brea and the Baldwin Hills showing previously suggested correlation.

of bone has followed the perfection of techniques for separating purified amino acids derived from collagen from bones impregnated with isotopically dead petroleum compounds (Ho, 1965; Ho, Marcus, and Berger, 1968). Collagen amino acid residue dates have in part suggested that the Rancho La Brea fossil deposits may show an overall gross stratification. Presently the oldest bones dated by the amino acid residue method have yielded ages of 33,100 ± to 35,500 ± years from depths of 5 to 5.5 m (R. Berger; pers. comm., 1975) in Pit 4, and 32,600 ± 2,800 years from the current excavation of Pit 91 (T. Downs; pers, comm., 1972). A fossil wood specimen, UCLA-773C, from Pit 77 was dated at 37,000 ± 2,660 years, while four other samples appear to be greater than 40,000 years old (Berger and Libby, 1966). Thus, accumulation of fossils in the asphaltic sediments at Rancho La Brea is reliably documented at least 32,000 to 35,000 years ago from bone dates, and may have begun much earlier, as suggested by fossil wood dates that are greater than 40,000 years old.

A number of contradictions are apparent from the evidence cited by Bandy and Marincovich for their suggested correlation of marine and non-marine strata of the Baldwin Hills with the similar stratigraphic record known at Rancho La Brea, if the Baldwin Hills marine unit is as young as 36,000 years old. At Rancho La Brea, and to the east, the uppermost marine invertebrate records are in the sub-surface from sediments of the Palos Verdes Sand (Crowder and Johnson, 1963), at altitudes ranging between 30.6 and 35.1 m above present sea-level (Fig. 2). Sediments recording the transition from marine to non-marine environments lie above the marine biozone to slightly varying altitudes approximating 42 m above sea-level at Rancho La Brea, and rising gently to about 47 m altitude at Masselin Avenue, 0.6 km to the east. Over this distance, the asphaltic sand member B of the Palos Verdes Sand ranges between 9 and 14 m in thickness, and the maximum thickness of sediment above the marine biozone ranges between 6 and 11 meters. The upper contact with the younger alluvial sediments at Rancho La Brea forms a gently undulating surface of disconformity. If the Baldwin Hills marine unit is a part of the San Pedro Formation, as has been suggested, correlation of the marine strata in question is clearly denied. The marine biozone at Rancho La Brea is confined to the lower 6 m of the upper arenite member B of the Palos Verdes Sand, and lies at least 30 m above the upper surface of the San Pedro Formation, as determined in bore-holes south and east of Rancho La Brea.

At the Baldwin Hills the marine shell bed occurs at 78 m altitude, the overlying transition sediments which include equivalents of the Palos Verdes Sand, lying between this height and an altitude of 145 m. This thickness of 67 m of sediment, as compared to only the 6 to 11 m maximum now present in the vicinity of Rancho La Brea appears incongruous with the interpretation of littoral and fluviatile deposition accompanying southward encroachment of coalescing fans from the Santa Monica Mountains. If, as seems likely from sedimentary evidence, the Santa Monica Mountains were a principal source of sediment contributing to late Pleistocene deposition in the northwestern Los Angeles Basin, a greater thickness of sediment might be expected closer to, rather than further from the source area. Correspondingly, unless the area now underlying Rancho La Brea was a topographic or structural high during much of late Pleistocene time, a greater relative rate of sedimentation might be expected in this area lying nearer the Santa Monica Mountains, rather than further from the source area in the vicinity of the present Baldwin Hills. The incongruity presented by thickness data not only suggests that the marine shell beds are not the same, but indicates that the Baldwin Hills shell bed is older than that at Rancho La Brea, despite the young age determination of 36,000 years. Marine sediments of comparable age and depth facies to those known at Rancho La Brea should occur in the Baldwin Hills at a higher elevation than 78 m, but below the level of the carbonized wood sample dated at 28,000 years, at 145 m altitude. Shoaling of the sea by deposition of more than 100 m of sediment in about 8,000 years has been proposed to account for the transition sequence in the Baldwin Hills that lies between 78 and 145 m elevations. This high rate of sedimentation appears altogether disproportionate to minimum rates of accumulation known at Rancho La Brea. Here, Carbon-14 dates independently determined for both wood and bone samples in Pit 3 document less than 4 m of accumulation in about 14,500 years, and about 7 m in 21,000 years. Other estimates for various of the Rancho La Brea excavations suggest an average rate of deposition of about 6 m per 30,000 years.

At the Baldwin Hills, foraminiferans associated with the marine mega-fauna have been used to infer water depths of about 100 m, but less than 200 m (Bandy and Marincovich, op. cit.). While the Baldwin Hills marine horizon may be correlative with that at Rancho La Brea, none of the twenty molluscan species from the Mutual Benefit Building excavation immediately south of Hancock Park, or from below Pit 91, indicate water depths greater than a few meters, at most. The associated foraminiferan and ostracod faunules are consistent with this interpretation, except for a few moderately deep-water foraminiferans that appear to have been reworked from older sediments (Valentine and Lipps, 1970). This local area would seem to approximate closely the zone of littoral deposition along the northern margin of the submerged Los Angeles Basin, or shoaling over a shallowly submerged structural or topographic high. As recently reported (Valentine and Lipps, op. cit.), the consensus of dates for equivalents of the marine biozone at Rancho La Brea is 100,000 years, or more. Although a younger age of the Rancho La Brea marine fossils is not precluded, the shells cannot be as young as 36,000 years, as determined for the Baldwin Hills site. Radiocarbon dates for bone specimens, as much as 11.4 m stratigraphically higher than the marine horizon are in excess of 35,000 years old, and in the case of wood, are greater than 40,000 years.

Olsson (1968) has emphasized that radiocarbon dates of shells older than 25,000 years may be highly unreliable due to low level atmospheric contamination by CO_2.

It cannot furthermore be assumed that the maximum radiocarbon age from the non-marine beds is 21,400 $\pm$ 560 years, or that the Rancho La Brea fossil deposits should be younger than 28,000 years (Bandy and Marincovich, op. cit.). The date of 21,400 years for bone at 6.6 m depth in Pit 3 (Berger and Libby, 1968; Ho, Marcus, and Berger, 1968), indicates only that this was a site of terrestrial fossil accumulation at this time, but does not limit the possibility that a deeper record of fossil accumulation, and thus older dates, might yet be determined from this locality, as they have for other sites at Ranch La Brea.

If an age of 36,000 years for the Baldwin Hills marine shells should be correct, the fossil biozone at Rancho La Brea cannot possibly be correlative. Radiocarbon dating of both wood and bone indicates that terrestrial deposition, subsequent to marine inundation, was already taking place in the Santa Monica Mountains foothills area, at this time. However, correlation of the uppermost Baldwin Hills strata with the Rancho La Brea terrestrial sediments is acceptable. Comparable dates of about 28,000 years, as was determined for fossil wood in the Baldwin Hills, are known from a number of collagen amino acid analyses in various of the Rancho La Brea excavations. At both Rancho La Brea and in the Baldwin Hills, similar transition sequences occur above the fossiliferous marine strata. The notable difference in thicknesses appear to be in part due to inaccuracy of correlation between these two localities, but may also be explained as the result of local changes in paleo-slope, complexities of local uplift, variable sediment supply, and probable sea-leval fluctuations affecting base-level. The individual importances of these factors is not satisfactorily understood.

CONCLUSIONS

Although the stratigraphy reveals a notable similarity of late Pleistocene events at Rancho La Brea and the Baldwin Hills, there is little other evidence that supports correlation of the fossiliferous marine strata. All evidence points to the Baldwin Hills shell bed, reportedly from the San Pedro Formation, being older than the marine horizon at Rancho La Brea, which is confined to the upper Palos Verdes Sand. The marine shell date from the Baldwin Hills appears to be far too young. This in turn indicates that the calculated rate of uplift of 0.5 to 0.8 m per 100 years, during the past 36,000 years, along the Newport-Inglewood structural zone, is excessive. In the Santa Monica Mountains foothills, at Rancho La Brea, an average rate of uplift for the past 100,000 years would appear to be of the order of 0.04 to 0.05 m per 100 years, relative to present sea-level, or slightly less if the marine biozone coincides with a high-level Sangamonian Interglacial stand of the ocean. A maximum rate of uplift along the Newport-Inglewood structural zone, if the Baldwin Hills marine horizon were deposited at about 100 m depth, is less than 0.2 m per 100 years, if marine submergence approximates Sangamonian age. This would not seem excessive in light of the known tectonic activity along this zone of uplift (Barrows, 1973).

ACKNOWLEDGMENTS

I am grateful to the L. T. Evans Corporation, Los Angeles, for bore-hole information in the vicinity of Rancho La Brea, to Dr. R. Berger and Dr. T. Downs for information concerning latest radiocarbon dates from Rancho La Brea, and to Dr. J. G. Vedder, and Dr. W. R. White for critical suggestions regarding an earlier draft of this manuscript.

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THE SANTA BARBARA CHANNEL: TO BE OR NOT TO BE

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The introduction of Hamlet's Soliloquy seems apropos:

> "To be, or not to be, that is the question;
> Whether 'tis nobler in the mind to suffer
> The slings and arrows of outrageous fortune,
> Or to take arms against a sea of troubles,
> And by opposing end them?"

There is little question that the energy and energy related companies operating in the Santa Barbara and Southern California area have received their share of "slings and arrows of outrageous fortune" in the past few years. Figures 1, 2 and 3 show some of the simplistic, emotional, tabloidlike "slings and arrows" which have been launched in various news media. In some cases these reflect a serious concern about safety of offshore operations, about offshore operations as a source of oil pollution, about the consequences of an oil spill, about aesthetics, about geologic hazards, and about supply and demand. In other cases, it seems to me, that these "slings and arrows" are purposely designed to generate anti-industry, emotional reactions. Arnold Toynbee, the British historian, observed that an active minority can control a passive majority. This is especially true in complex matters, such as energy and environment, where emotion causes some to lose sight of the overall problem.

During the past few years, these subjects of concern have been addressed and readdressed at numerous governmental hearings, have been published in numerous environmental impact reports, and some have been synthesized in scientific journals. Figure 4 shows six such compilations about the Santa Barbara Channel and Southern California. These have a 22 inch shelving index and total more than 5400 pages. A problem now is finding time to read and evaluate these masses of information. I agree with a recently made observation that we now are suffering from "paralysis by analysis".

Let's look at some of the issues. How about safety with respect to blowouts while drilling and accidents during producing operations. Table 1 which is based on information contained in the National Science Foundation's RANN (Research Applied to National Needs) report "Energy Under the Oceans" prepared at the University of Oklahoma by 8 non-oil industry related authors-2 political scientists, 2 aeronautical-mechanical-nuclear engineers, 1 zoologist, 1 industrial engineer, and 1 lawyer- reflects the safe and capable technology used in both onshore and offshore operations.

TABLE 1
Safety of drilling and producing operations

OFFSHORE		
	1964-1971 Drilling (w/no blowouts)	99.970%
	1964-1971 Producing (w/no accidents)	99.966%
ONSHORE		
	1960-1970 Drilling (w/no blowouts)	99.961%

From Energy Under the Oceans p. 285-286

These data compiled by a non-industry group of authors are unbiased and obviously refute simplistic statements like "primitive state of technology", "unsafe and untried techniques" and "offshore drilling more hazardous than onshore". The latter is the title of Finding 84 of the California Coastal Zone Commission's Energy Element dated 1-4-75.

How about offshore operations as a source of oil pollution? Figure 5, using data from "Energy Under the Oceans" shows that about 4% of the oil input into the marine environment is estimated to be assignable to offshore operations. The California Resource Agency (1971) refers to a study of 36 oil spills larger than 2,000 barrels during the years 1956-1969 which assigns 5.5% to offshore drilling and producing operations. Stated another way, 94 to 96% of the oil pollution is caused by other than offshore operations.

Notwithstanding this observation, it seems to me that 94 to 96% of the regulatory and legislative efforts are directed toward offshore operations which would seem to be an over kill. In the past 5 years new and revised work practices, regulations, inspection and enforcement procedures, especially by the USGS on OCS leases, have contributed to a reduction in the amount of oil spilled from offshore operations. No significant spills related to offshore drilling and producing operations have befouled any U.S. shoreline since 1969, although three platform accidents with oil spillage occurred in the Gulf of Mexico in 1970 and 1971. No accidents have occurred since then.

What are the consequences of an offshore accident and resultant spill? Since 1969 there have been many research projects directed to the fate of oil in the marine environment with research being carried out at such places as Scripps, Allan Hancock Foundation, U.C. Santa Barbara, College of Marin, Battelle Northwest, Battelle Columbus, Texas A&M, U. of Miami, Woods Hole, Gulf Universities Research Consortium (20 associated universities) and various research centers in foreign countries. These studies strongly suggest the hypothesis, vigorously pushed by anti-industry critics, that oil fractions absorbed by marine animals will be concentrated, be passed up the food web, and be a hazard to human health is not repeat not supported. Rather these studies show, as is illustrated by Figure 6, that the animals will rapidly purge themselves of oil contamination once their exposure to oil is terminated. Because of this purging, the possibility of food web contamination is extremely remote or non-existant. The Gulf Universities Research Consortium (1974) recently completed a two year synoptic study of a 400 square mile oil producing area in offshore Louisiana and adjoining Timbalier Bay with the conclusion that no significant or persistent effects assignable to oil producing operations could be recognized based on the analysis of about 1,000,000 bits of data.

Onsite studies of crude oil spills that have been stranded show no long term damaging effects to the marine biota. Two highly publicized spills of diesel and #2 fuel oil into a small bay at West Falmouth, Mass. and into a lagoon on the coast of Baja California are acknowledged to have had slow recovery. These two spills of refined oil products can not be used, but frequently are, as evidence of the threat to the environment from offshore exploration and production operations. Fuel oil is not crude oil.

Currently there are oil spill clean up cooperatives located at San Francisco, Santa Barbara, and Los Angeles. These cooperatives have an organizational plan which is compatible with both state and national oil spill contingency plans. They have a stockpile of equipment, a complement of trained personnel on call, and a nucleus staff which is also well trained. There is no question that state of the art oil spill clean up and containment technology is readily available in the Santa Barbara channel today. Oil industry associations interested in exploring virgin areas have pledged to the Department of Interior, Council of Environmental Quality and Federal Energy Agency that equipped coop's will be formed prior to exploratory drilling.

An objective analysis of these observations concerning safety, sources of oil spills, consequences of oil spills and clean up and containment technology strongly suggests that continued deferral or prohibition of offshore drilling and producing operations can not be justified on any of these grounds.

I have purposely not discussed the asethetics of platforms or the effect of oil spills on bird life as both these are highly emotional issues. Uniformity of opinion concerning aesthetics can hardly be exepected. However, studies done for Western Oil and Gas Association (1974) indicate that the price of ocean view property is not affected by the presence of platforms. Even though a large number of birds might be involved, the threat to bird life from an oil spill from offshore operations can be no larger than the probability that a spill will occur. With a historic safety record of 99.96 to 99.70% there is only a slight chance that the threat will ever materialize and have a significant impact. If offshore operations are to be denied on these grounds, so be it - but such should be clearly stated so the public can judge the trade off of energy benefits to the local, regional, state and national population versus platform aesthetics and the rare chance of an accidental spill significantly involving bird life.

How about the "to be" portion of the Santa Barbara Channel. For the benefit of the few who know less about the Santa Barbara Channel than I and as a refresher for the experts, needed or not, Figures 7 and 8 will serve as cross-sectional and index map displays for the ensuing discussion.

Structurally the Santa Barbara Channel, which may be classified as a synclinorium, is part of the Transverse Range structural province and is bounded on the north by the Santa Ynez Mountains and on the south by the Channel Islands. The Channel is the offshore extension of the onshore Ventura Basin, and includes about 1750 square miles of which 74% or 1300 square miles are in the Federal domain. Maximum water depth is about 2050 feet Shell Oil Company's recent successful exploratory drilling in more than 2100 feet of water in offshore West Africa shows that the entire Channel needs to be considered explorable. Technology for production from depths greater than about 1,000 feet still has to be developed.

The Channel is characterized by many east-west fold and high angle reverse faults trends. Some major faults, such as Red Mountain, dip to the north while others, like Oakridge, dip to the south. Wave length of folding ranges from as small as 2 to 3 miles to as large as 6 to 8 miles. Maximum fold amplitudes are in the 10,000 to 12,000 foot range. Individual folds have a narrow, steep flank from 2 to 3 miles wide and a more gently dipping broad flank up to 6 miles wide. Reverse faults are commonly associated with the narrow flanks. Individual fold trends on which several culminations may occur extend for distances of 20 to 30 miles. Deep structural resolution of the complex, faulted folds has been a continuing problem in reflection seismic interpretations because of generally poor record quality.

Stratigraphically, the Santa Barbara Channel contains a sequence of clastic rocks ranging in age from Cretaceous to Holocene. Thicknesses in the 40,000 foot range are estimated in the eastern part of the Channel and in the 20,000 foot range in the western part of the Channel. On a gross basis, the section can be subdivided into two basin-filling, transgressive-regressive pulses. The older includes the deep water sands and shales of the Cretaceous and Eocene and culminates in the non-marine Sespe sequence of Oligocene age. The younger sequence starts with the widespread lower Miocene transgressive sediments, expands with the upper Miocene deep-water Monterey shale deposition after which the sand content increases upward through the Sisquoc or Santa Margarita, Repetto, Pico into the Pleistocene and Holocene non-marine beds. Hydrocarbon production is obtained from both sequences with the Pliocene being the major objective in the east central part of the Channel and the Miocene Monterey shale and older units on the north flank of the basin. Curran et al (1971) estimated basin reserves in the 10 billion barrel oil in place range. The California Resource Agency (1971) estimated 4 billion barrels recoverable from the basin in waters shallower than 200 meters.

To date 9 offshore oil fields, 4 offshore gas fields and the offshore extensions of 3 onshore oil fields have been developed in the Santa Barbara Channel. Eight offshore platforms and one drilling island have been sited on State tideland leases and 5 platforms have been erected on OCS leases acquired in the 1966 and 1968 OCS sales. Exploratory and delineation well drilling subsequent to the 1968 OCS sale has indicated at least 8 other probable producing areas most of which still require additional delineation before producing operations can be justified.

Following the blowout in Jan. 1969, all operations on the OCS were suspended pending a review of safety and drilling procedures. Exploratory drilling resumed on selected OCS leases by mid 1969 and more than 35 exploratory and delineation wells have been drilled since that time. From Feb., 1969 until April, 1971, an informal moratorium was in effect on all State tideland leases, at which time operations were formally suspended. In Dec. 1973, the State Lands Commission approved a proposal to allow drilling from existent offshore structures. However their deferral in Jan., 1975, of requests by Arco for operations in South Elwood offshore on the grounds that Arco's environmental statement needed more study and then ruling that Socal's request at Summerland needed a full statement rather than a negative declaration strongly suggests that a de facto moratorium now exists on State tidelands in the Santa Barbara Channel; more than 5 years after its initial inception.

In August 1974, the U.S. Geological Survey approved development of the Santa Ynez unit by Exxon after lengthy environmental impact hearings. The Santa Ynez Unit which includes 3 of the 8 indicated productive areas found on OCS leases has an estimated recoverable oil potential of 0.7 to 1.1 billion barrels and gas potential of 370 to 550 billion cubic feet. The Hondo field in the eastern part of the unit is to be developed from a 28 well platform sited in 850 feet of water on the north side of the indicated producing area. Further development of the unit may require 3 to 5 additional platforms or the usage of submerged production systems. Oil and gas has been tested at commercial rates from the Eocene Matilija sand, the Gaviota-Aegria-Sespe sands, the lower Miocene Vaqueros sand, the middle to upper Miocene lower Monterey sand, and the upper Miocene fractured, siliceous shales of the Monterey formation. This latter unit which is the primary reservoir in the Hondo field, ranges in thickness from 1250 to 2500 feet and is composed of interbedded diatomaceous, siliceous, cherty, calcareous phosphatic, and dolomitic "shales". Some siliceous units have favorable matrix porosity created during the recrystallization of the original diatomaceous material. Chert zones tend to have fracture porosity formed by recrystallization of opaline material to calcedonic chert. Good reservoir continuity is suggested by production testing. Oil gravities range from 12 to 26 API with GORs of 200 to 600. Sulfur content is between 3.5 and 4.0%.

Permits have been requested for an onshore facility on a 15 acre site in La Flores Canyon, 6.7 miles from the Hondo field, and for a marine loading terminal 3500 feet offshore. Initial capacity of the onshore treating facilities is to be 40,000 BOPD with expansion capabilities to 80,000 BOPD. Gas production is estimated to peak at 77 million cubic feet per day and will be sold after removal of sulfur. If state and local permits for the onshore facilities and offshore marine terminal are not received, oil handling facilities will have to be constructed on the offshore platform and gas production will have to be reinjected.

In 1969, the same year that the Hondo accumulation was discovered, Arco started recompleting existing wells in the South Elwood offshore field into the Monterey formation. The lithologic sequence there is very similar to that described at Hondo. By the end of 1973, 4 oil producers, and 1 gas injection well had been recompleted from the Monterey and 5 additional wells were scheduled for recompletion. Upon the so-called removal of the moratorium on operations on State tideland leases, permits were requested for the drilling of an additional 17 wells from the existing platform. As the plans were formulated for installation of gas handling facilities on an existing 4.46 acre onshore facilities site. Again produced gas will be sold after sulfur removal if permits are obtained. If not, gas will have to be reinjected into the Monterey. Producing rates are estimated at 12,000 BOPD if gas reinjection is necessary, and 20,000 BOPD if gas can be cleaned and sold.

The offshore operations at South Elwood and the pipeline and marine terminal construction in State tidelands to support Hondo require permits from both the State Lands Commission and from the California Coastal Zone Commission. Onshore facilities require permits from the California Coastal Zone Commission and the County of Santa Barbara. The initial application for renewed operations at South Elwood was approved by the Coastal Commission by an 8-3 vote after consideration of an Attorney General's opinion that Arco's prior activities and expenditures which started in 1964, gave them a vested right for operations. This ruling was immediately challenged in the Superior Court by GOO, a 1500 member organization, on the grounds that the State Lands commission had not given approval of individual well applications at the time Arco was granted an exemption. That is, the "last discretionary" approval had not been granted. The court agreed with GOO's interpretation. The State Lands Commission is also reconsidering Arco's 3 volume environmental impact report. In Exxon's operations, a lawsuit has been filed concerning their proposed pipeline construction across state lands, and the State Lands Commission, in Jan., 1975, requested the Attorney General to determine the validity of Exxon's lease of State lands for the pipeline and marine terminal construction. Further action by the Lands Commission will be delayed until the lawsuit has been tried.

While these regulatory mazes are being traversed, gas production from Santa Barbara Channel fields as shown in Figure 9 has been declining at rates of 15 to 30% per year since production peaked at 58 billion cubic feet per year in 1967. The 1974 estimated rate is only 18.5 billion cubic feet. Naturally state royalties and county ad valorem taxes have declined commensurately. The bulk of the decline is attributable to the exhaustion of the dry gas fields on the north flank of the basin. With the prohibition of new drilling activity on state lands there is no way to explore for new accumulations which might slow or reverse the decline. Gas production from Hondo and South Elwood which may range from 7 to 25 billion cubic feet per year would make a significant contribution to the Channel's production.

As you would expect, oil production from Channel fields as shown in Figure 10 also is declining at rates of 15 to 25% per year from a peak production of 34.9 million barrels per year in 1971 to an estimated rate of 20 million barrels in 1974. The portion subject to state royalty and county ad valorem taxes has declined from an estimated peak of 9 million barrels in 1968 to an estimated 3 million barrels in 1974. Oil production from Hondo and S. Elwood would effectively double the 1974 rate of production from Channel fields. Added production is possible at Dos Cuadros where at least 2 additional platforms are needed for development drilling. Permits for these structures requested by the operators, were denied by the Department of Interior in 1971, and are currently being litigated.

The establishment of Eocene pay zones in the Santa Ynez Unit and of the Monterey fractured "shale" in both the Santa Ynez Unit and at South Elwood highlight the north flank of the Channel as an attractive area for additional exploration for these sparsely explored objectives. On the south flank of the basin, regional geologic relationships indicate that the Eocene and Oligocene beds probably have not been buried as deeply nor have undergone as severe tectonic deformation as in the north flank fields. Reservoir capacity consequently may be improved.

Before concluding, I'd like to make a few observations about a new antiindustry argument which appeared in several comments in the S. Elwood Environmental Impact Report. This argument in essence is -- S. Elwood's production will only be 2% of the state's total and this is such a small amount it isn't important and can easily be foregone. Table 2 shows that only 10 of the state's 185 oil fields product at rates greater than 2% of the state's producing rate (878,000 BOPD in Oct. 1974). In fact, 35 to 40% of the state's production is obtained from fields which individually produce at rates less than 2%. If we follow the anti-industry logic, then 95% of the state's existing fields can be shut in as they aren't large enough to be significant. This is obvious foolishness.

TABLE 2
California oil fields classified by
Percent of State's Production Oct. 1974

Percent of State's Prod.	Number of Fields	Percent of State's Prod.	Number of Fields
0-1	163	10-11	0
1-2	10*	11-12	1
2-3	2**	12-13	0
3-4	2	13-14	0
4-5	2***	14-15	0
5-6	1	15-16	0
6-7	0	16-17	0
7-8	0****	17-18	0
8-9	1	18-19	0
9-10	0	20-21	1

* S. Elwood at 12,000 BOPD
** S. Elwood at 20,000 BOPD
*** Hondo at 40,000 BOPD
**** Hondo at 70,000 BOPD

In conclusion, the time for discussing the question "to be or not to be" is passed. The oil gas potential of the Santa Barbara Channel must be developed. Regulatory and legislative decisions must be based on recognition of energy needs and a realistic assessment of documented factors of safety, sources of pollution, consequences of spills, and oil spill clean up technology rather than on worst-case analysis and on emotional, simplistic, tabloid-like generalizations. Governmental agencies rather than industry must be held accountable for energy shortages which directly result from prohibitive regulations and policies. More knowledgeable legislation, regulations and policies are needed which recognize that oil operations are not incompatible with environmental protection and which will provide clear guidelines to governmental agencies and to the courts. The industry can develop the oil and gas resources in the Channel without raping the land; devastating the coastline; creating jungles of tank farms, refineries, pipelines, drilling rigs; or disrupting the economy or lives of millions. The Channel has the potential to be and must be allowed to be a significant contributor to the energy requirements of the local, regional, state and national population.

L.A. TIMES Aug. 6, 1974 page 1

Oil Leases Could Result in 50 Platforms Off Southland Coast

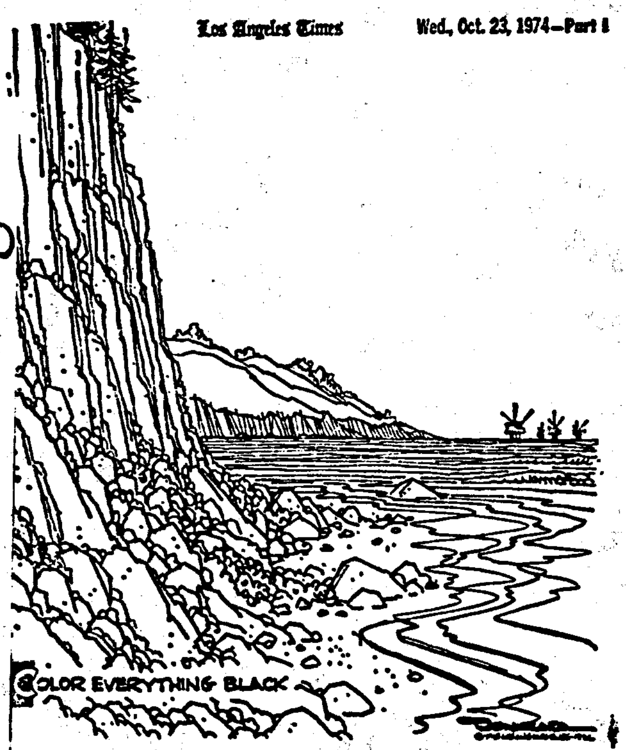
BY PHILIP FRADKIN
Times Staff Writer

Los Angeles Times Wed., Oct. 23, 1974—Part I

Drilling Would Destroy Unique Southland Coast

Thurs., Nov. 14, 1974 ☆ S.F. Examiner—Page 66

Support wanes for offshore drilling



A Page From the U.S. Interior Department's Coloring Book

Tues., Oct. 22, 1974★★★ San Francisco Chronicle 7

Offshore Drilling Spills 'Inevitable'

Figure 1


Fri., July 26, 1974 ★★★ San Francisco Chronicle 3
Channel Oil Drilling Move
S.F. EXAMINER
July 31, 1974
Page 7
Land 'rape' worries governors
By Sydney Kossen
Examiner Political
2 Part II—Thurs., Aug. 1, 1974 Los Angeles Times
Assembly Panel Urges Offshore Drilling Delay
Calls for National Energy Policy Before ... of Federal Leasing Proposals
Antitrust charge
Calif. oil companies accused
SAN FRANCISCO EXAMINER
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Page 4
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Channel Blowout Oil Suit Settled
Los Angeles Herald-Examiner Sunday, August 4, 1974
Viewpoints:
Should the Nation Proceed Quickly In Off-Shore Oil Exploration?
THE CHRISTIAN SCIENCE MONITOR
December 23, 1974
Foes of offshore oil facing stiffer battle

Figure 2

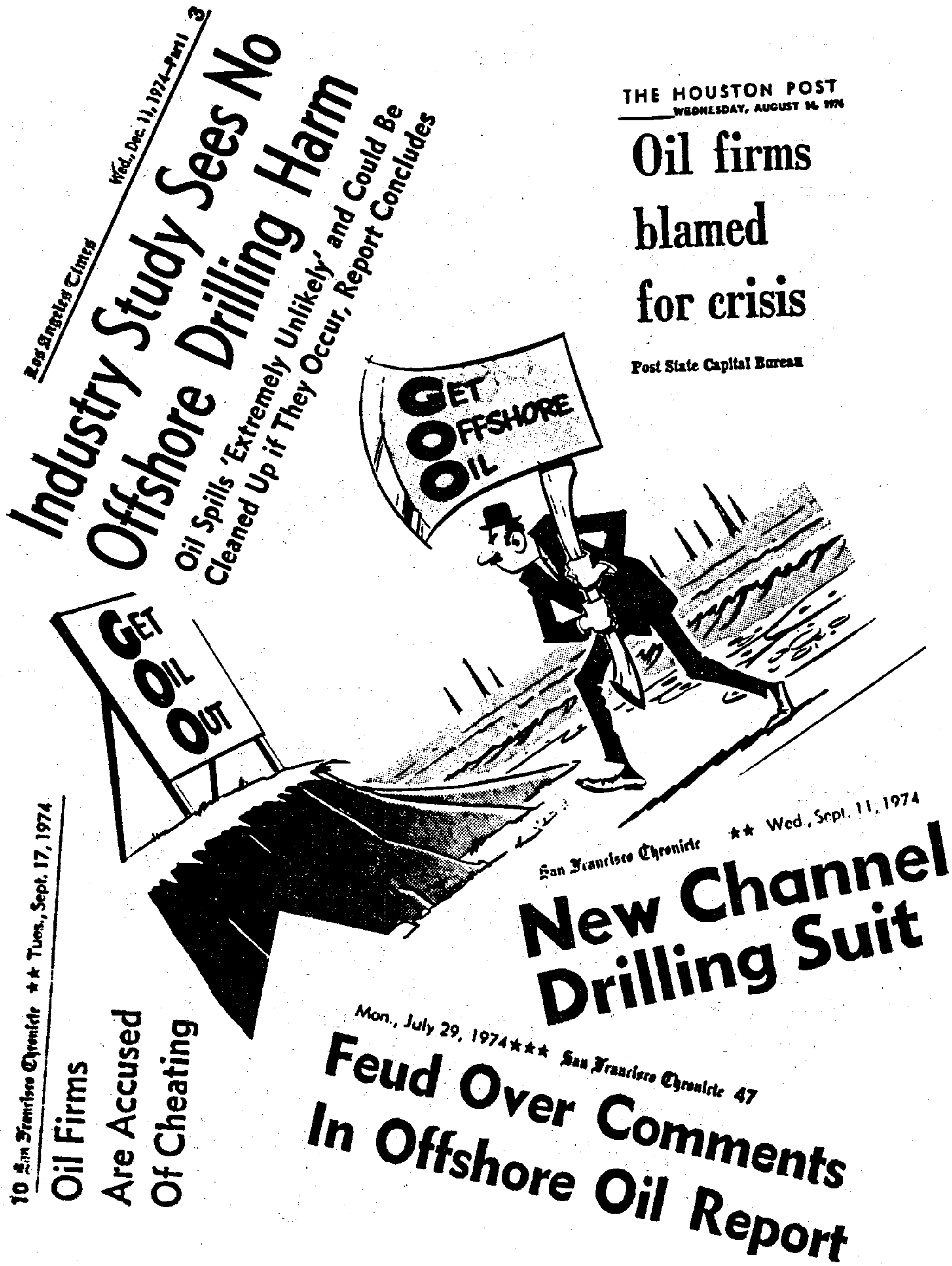

Los Angeles Times Wed., Dec. 11, 1974—Part I 3
Industry Study Sees No Offshore Drilling Harm
Oil Spills 'Extremely Unlikely' and Could Be Cleaned Up if They Occur, Report Concludes
THE HOUSTON POST
WEDNESDAY, AUGUST 14, 1974
Oil firms blamed for crisis
Post State Capital Bureau
GET OFFSHORE OIL
GET OIL OUT
10 San Francisco Chronicle ★★ Tues., Sept. 17, 1974
Oil Firms Are Accused Of Cheating
San Francisco Chronicle ★★ Wed., Sept. 11, 1974
New Channel Drilling Suit
Mon., July 29, 1974★★★ San Francisco Chronicle 47
Feud Over Comments In Offshore Oil Report

Figure 3

Figure 4

SOME OF THE ENVIRONMENTAL AND RESOURCE REPORTS ON SANTA BARBARA CHANNEL AND SOUTHERN CALIFORNIA

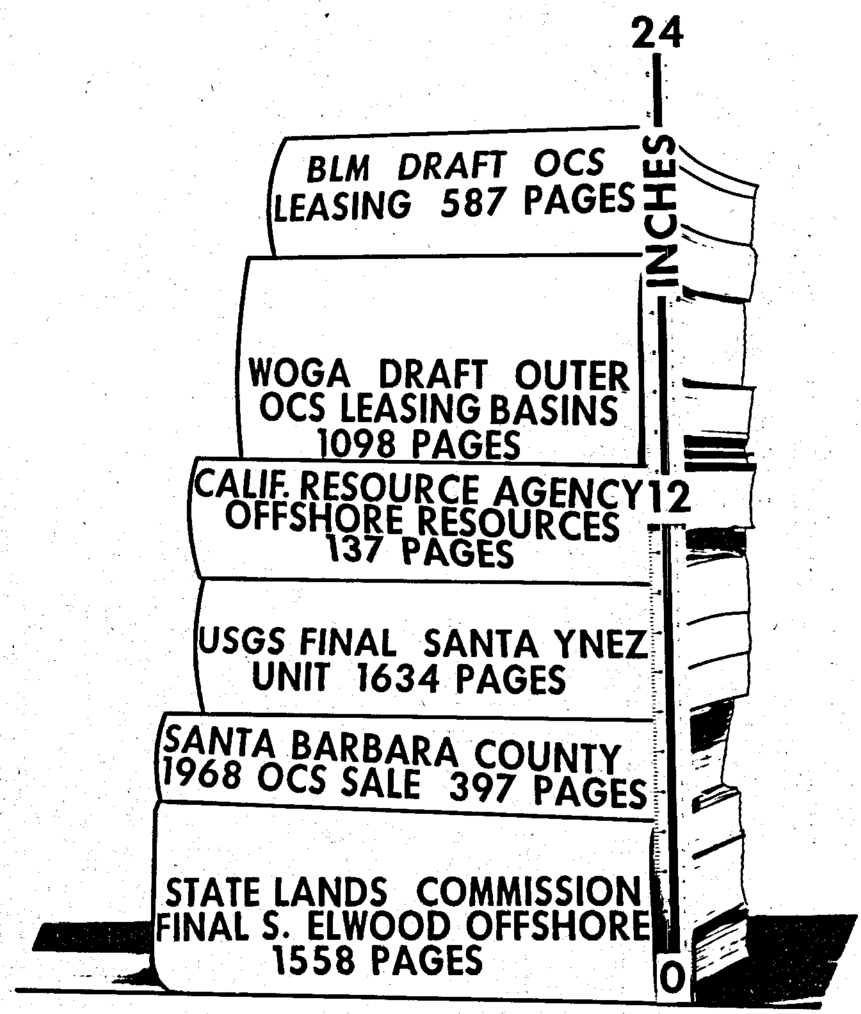
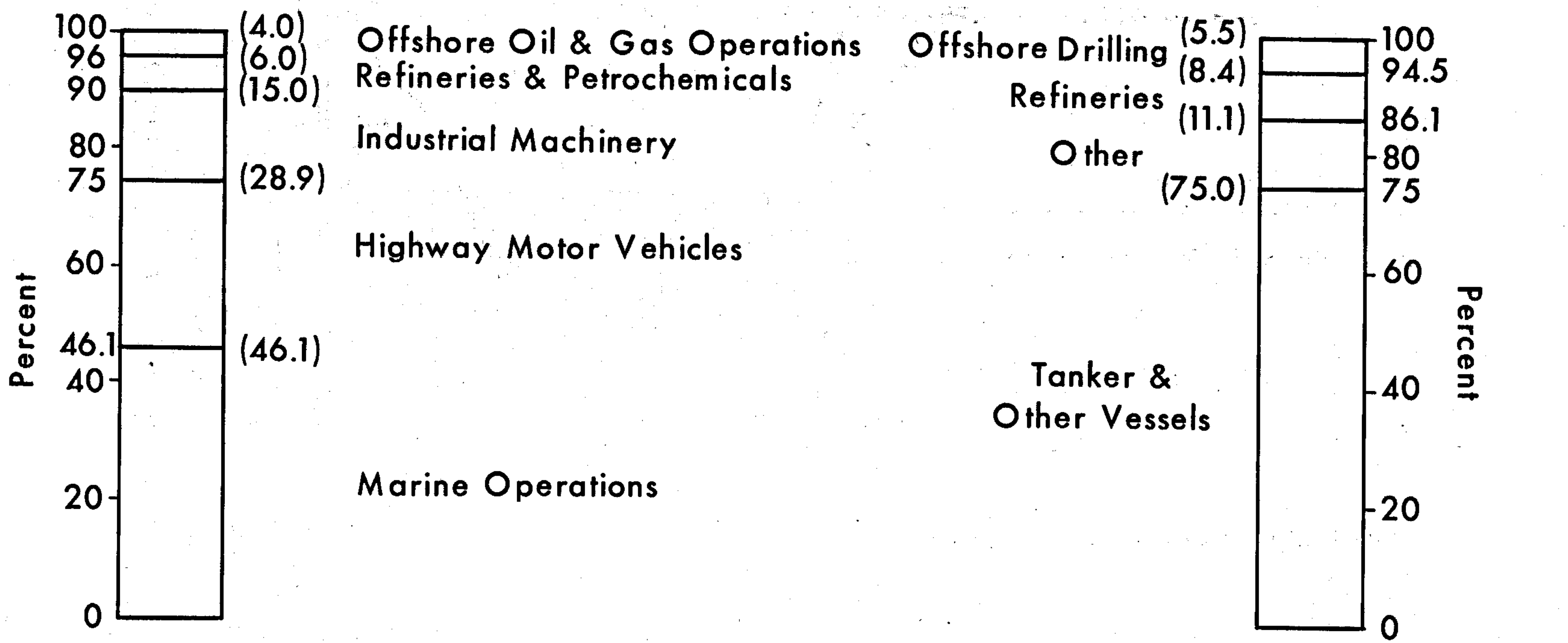


Figure 5

SOURCES OF OIL POLLUTION
(WORLD WIDE)

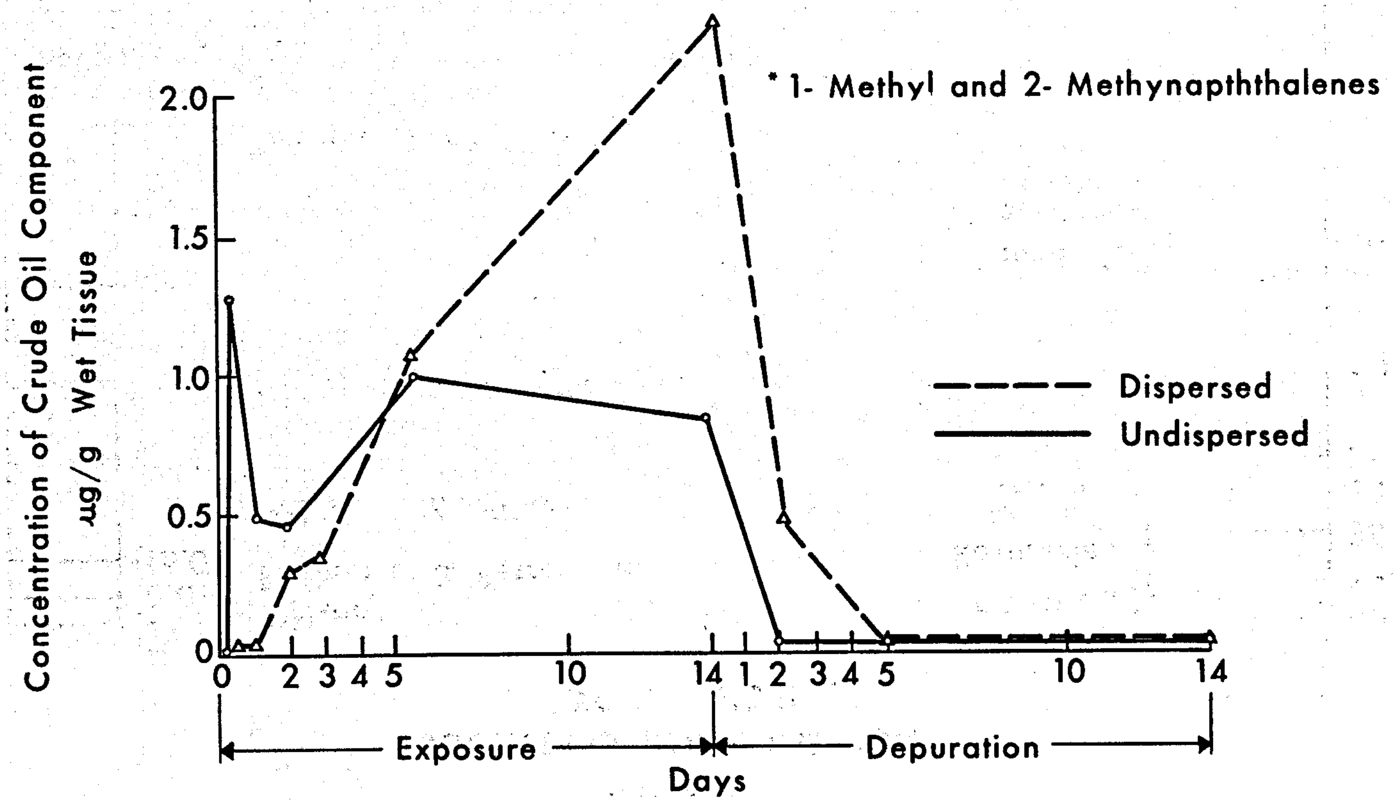


PERCENT OF ESTIMATED OIL POLLUTION
OF WORLD WATERS 1969-70
(Total direct pollution 35,000,000 bbls)
From 'Energy Under the Oceans 1973'

SOURCE OF SPILLS 1956-69
FOR 36 MAJOR INCIDENTS
From California Resource Agency
'The Offshore Petroleum Resource' 1971

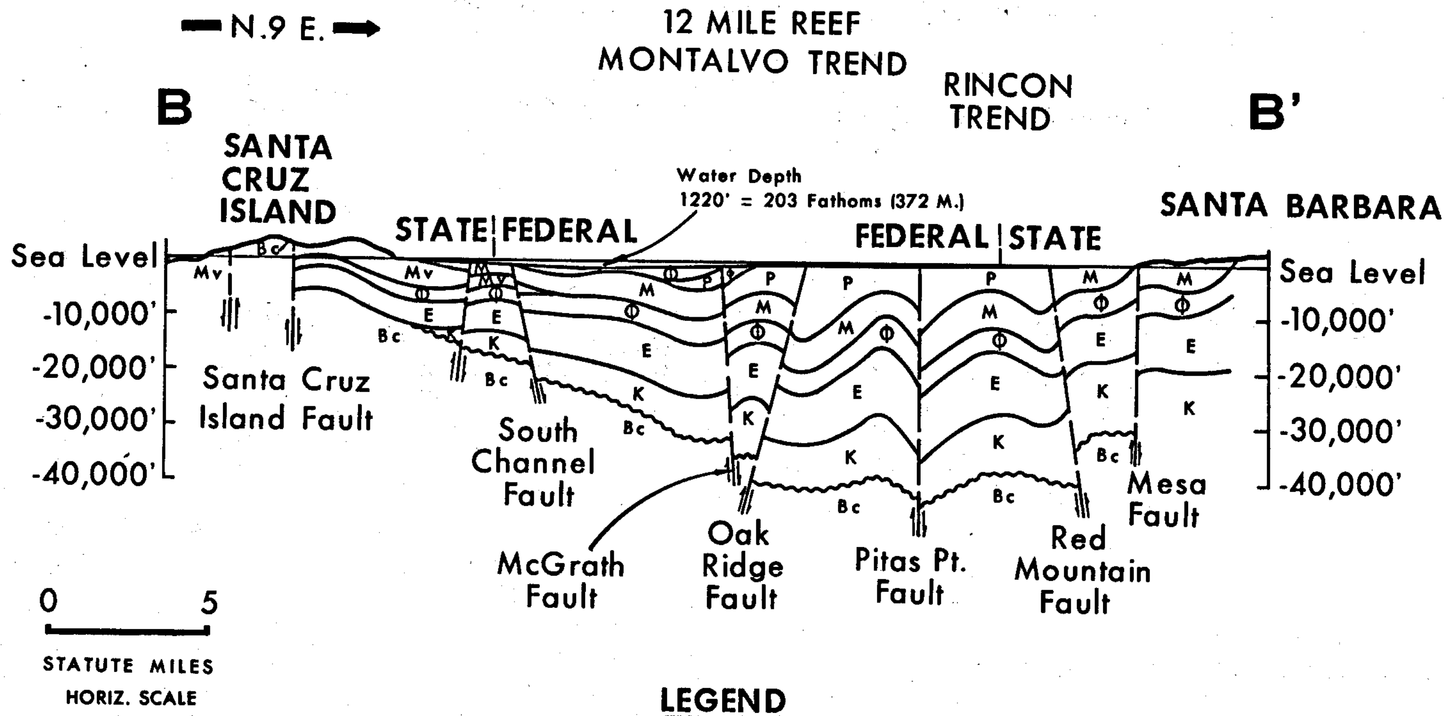
Figure 6

THE UPTAKE AND RAPID PURGE OF KUWAIT CRUDE OIL COMPONENTS* BY OYSTERS



From: E.W. Mertens (1973) Statement at BLM hearing on OCS Leasing Sale #33

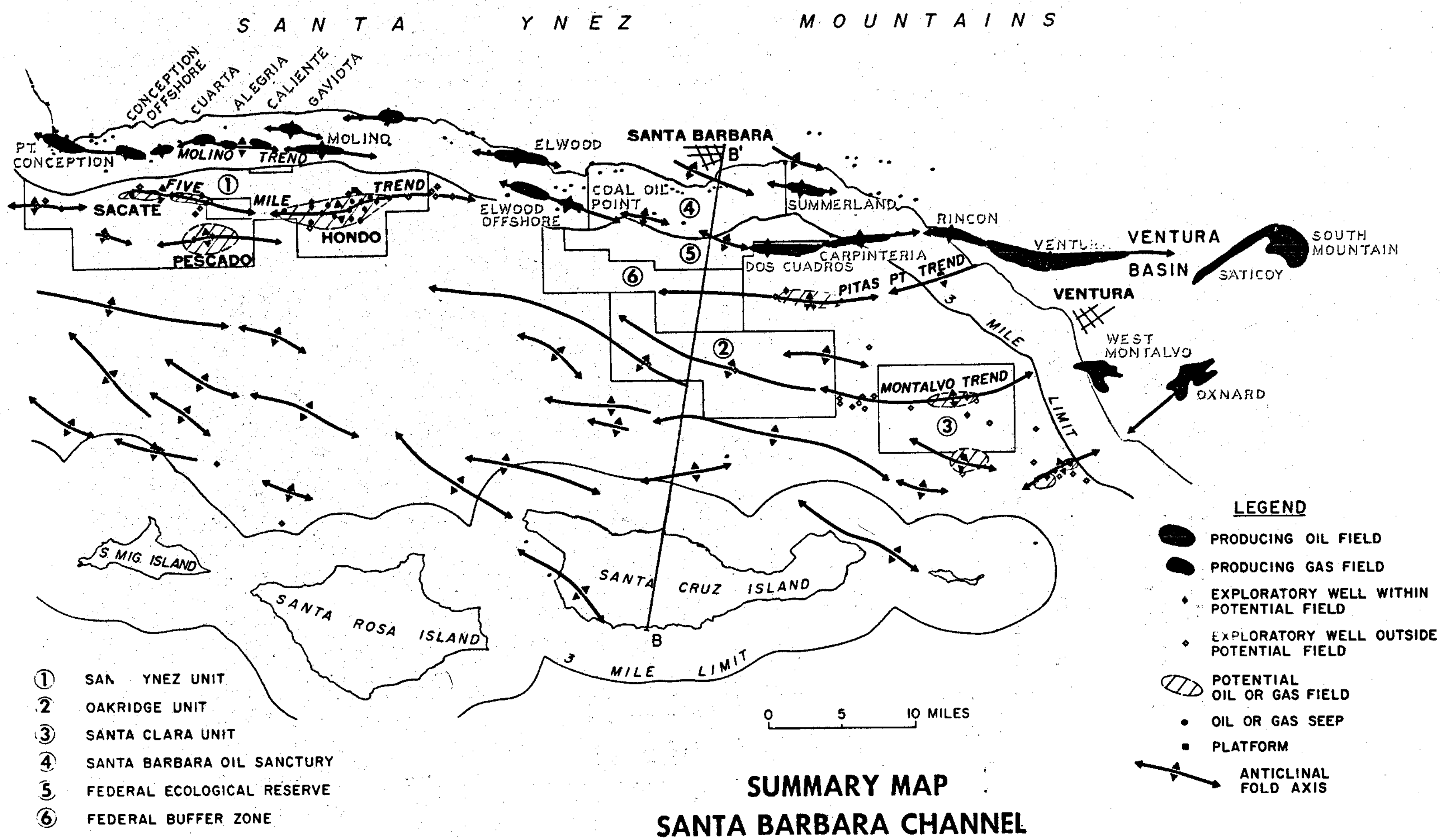
Figure 7



LEGEND

Q	Recent & Pleistocene	Φ	Oligocene
P	Pliocene	E	Eocene
M	Miocene	K	Cretaceous
Mv	Miocene Volcanics	Bc	Pre-Cretaceous

From Curran et al AAPG Mem. 15 1971



SUMMARY MAP
SANTA BARBARA CHANNEL

FIGURE 8

Figure 9

ANNUAL GAS PRODUCTION
OFFSHORE SANTA BARBARA CHANNEL

From Conservation Committee of California Reports
(Excludes Rincon and Montalvo Offshore)

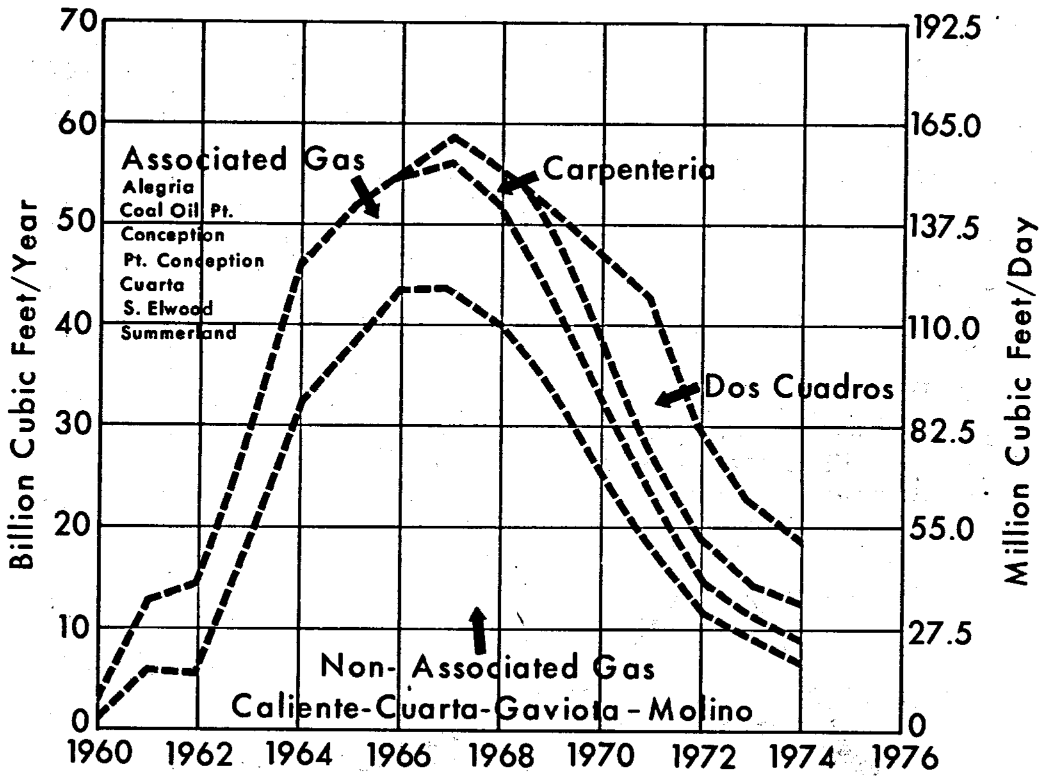
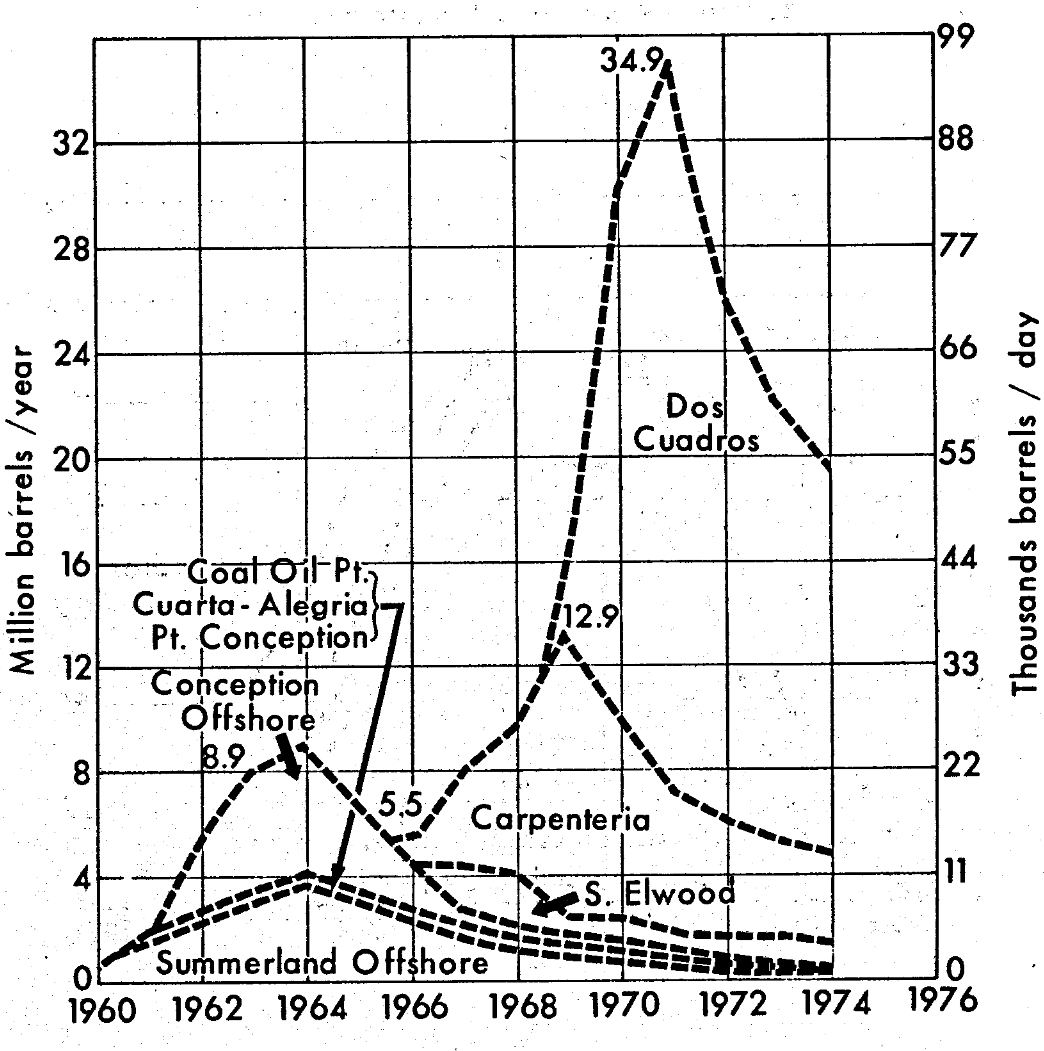


Figure 10

ANNUAL OIL PRODUCTION
OFFSHORE SANTA BARBARA CHANNEL

From Conservation Committee of California Reports
(Excludes Rincon and Montalvo Offshore)



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APPLICATION OF COMPLEX RESISTIVITY MEASUREMENTS TO GEOTHERMAL PROSPECTING

by

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ABSTRACT

Recent field tests have indicated that a new resistivity measuring technique can overcome many of the limitations encountered in deep resistivity surveys. This new approach is based on low frequency transient or complex resistivity measurements similar to those which have been performed in the field for the past three years in the search for economic sulfides.

Basic advantages of CR measurements are (1) the removal of inductive coupling effects which contaminate most resistivity sounding methods, (2) deeper penetration through the use of received electromagnetic reflections in mapping deep subsurface structure, and (3) the ability to identify changes in host rock alteration at depth, and to provide an electrically derived apparent geologic section.

Introduction

Intensified world-wide interest in energy sources has given motivation to the exploration for geothermal fields and their subsequent delineation and evaluation. The main bridge between regional exploration techniques and drilling is geophysics. While physical and chemical characteristics of known geothermal fields are well documented (Kruger and Otte, 1973; United Nations symposium on Geothermics, 1972), most of these characteristics are not particularly susceptible to conventional geophysical prospecting methods. DC resistivity methods can delineate a subsurface conductive zone, but since conductivity is at least a function of temperature, salinity, porosity, and clay content, interpretation is complicated and never conclusive. Gravity and magnetic characteristics differ widely from field to field, and EM methods are limited by skin depth considerations and the same non-discrimination limitations as DC resistivity methods.

This paper proposes the use of a dynamic resistivity measuring technique which has been used successfully in the search for economic sulfides. This system, Complex Resistivity, or CR, combines some of the best aspects of conventional resistivity and ultra low frequency EM systems. Complex Resistivity spectra have been used to delineate areas of differing host rock alteration as well as mineral differentiation. In addition electromagnetic effects have been used as an aid for more accurate interpretation of resistivity pseudosections and apparent geologic structure. Although this system has not yet been used directly in the search for geothermal sources, the advantages of recognizing differing alteration patterns, removing EM coupling effects in low resistivity areas, and using EM reflection data for deeper penetration are all directly applicable to geothermal exploration.

Host Rock Delineation

As discussed in Browne (1972), the zones of highest production quality in geothermal fields are strongly associated with the alteration minerals present. Alteration zoning has been well-documented for the Otake and Komatsu fields in Japan, with the greatest geothermal activity being associated with an alunite zone, hosting alunite and other related clay minerals including kaolin and montmorillonite. When chlorite alteration products are exposed to hot geothermal fluids, large amounts of chloride ions go directly into solution. Kruger and Otte (1973) indicate that "Chloride is the most critical single constituent in distinguishing hot-water systems from vapor-dominated systems.. ..a chloride-bearing water body (Cl $\geqslant$ 50PPM) definitely indicates a hot-water system." Chloritized rocks give a definite spectral signature as will be explained in the following discussion.

Recent laboratory and field research (Zonge and Wynn, 1975) has indicated that the spectral response of mineralized and unmineralized rocks can be loosely grouped into three categories. These "host" responses are shown in Figure 1 in an idealized form as Type A, B and C curves. Almost all rocks seem to have an inherent electrical signature, and the intensity and type of response appears to be closely related to alteration and alteration products.

A portion of some laboratory measurements are summarized in Figures 2 and 3 and represent a suggestive correlation although incomplete in scope. Note from the middle graph in Figure 2, that the chlorite alteration discussed above gives a reasonably consistent Type C response. This trend is also consistently noted in field measurements over chloritized areas.

These host rock signatures are measured with our current system by combining the magnitude and phase responses of rocks measured at 24 discrete frequencies ranging from .01 Hz through 110 Hz. These results are usually plotted in the complex plane, in-phase vs. quadrature or real vs. imaginary, as in Figure 1. Field measurements are typically made with a dipole-dipole array and the data plotted in pseudosection form similar to conventional representations of resistivity data.

A representative set of data over a hydrothermal ore deposit is given in Figures 4, 5 and 6. The Type A host rock response in Figure 5 outlines the clay-sericite alteration North of the fault zone quite well. Figures 7 and 8 show another example of the use of complex resistivity to discriminate between rock types. In this case neither rock type is significantly altered, and no sulfides are indicated. A subsequent drill hole at station 4 confirmed the electrically derived geologic section and intersected fresh volcanics at 1150 feet. As in this case, host rock spectral data often delineates rock type changes missed by resistivity or induced polarization.

Electromagnetic Effects

EM effects are generally considered a problem in normal induced polarization (IP) or resistivity surveys. However, the full spectral measurements of CR permit the complete removal of unwanted inductive coupling and the utilization of reflective coupling for EM sounding measurements (Wynn and Zonge, 1975).

Several investigators have tried using EM reflection techniques to some advantage. One of the more successful attempts is reported by Kinghorn (1967), who obtained limited success in delineating resistive structure to a depth of approximately 1500 meters using a perpendicular bipole-dipole array. The main problems encountered with his system are electrical noise and the inability to remove polarization effects of the ground which would create intolerable errors in depth calculations.

The present CR system provides selective digital filtering and separation of responses due to EM reflections and ground polarization effects. This permits use of EM sounding techniques in areas of low resistivity and intense alteration - a combination which usually renders measurements from conventional resistivity techniques inaccurate.

In order to test the possibilities of EM sounding techniques, the Willcox Playa (a dry lake near Tucson, Arizona) was selected as a test site. The lake bed sediments are believed to be at least 4000 feet thick and very conductive, so this provided a good, extreme test area. These tests were cut short by lack of time and input power, since our system then was capable of putting less than 500 watts into the low resistivity ground. However, these initial measurements look encouraging and two sets are included in the subsequent figures, where the transmitter is a 1500 meter bipole with a perpendicular 60 or 300 meter receiving dipole.

An example of the shallow soundings is shown in Figure 9. This is a typical suite of curves for a layered earth environment with layers at depth increasing in resistivity. Figure

10 displays a set of theoretical two-layer earth curves for constant N-spacing, constant depth to dipole length ratio (D/A), and varying resistivity contrasts. Also shown is the perpendicular bipole-dipole array used for the calculations and for field measurements. Note the strong dependence upon resistivity contrast. Figure 11 shows the results of curve matching four of the six curves in Figure 9. This approach can be considered as a type of resistivity inversion where unique simplistic models can be obtained from suites of curves obtained by varying frequency and N-spacing. Figure 12 again shows field and curve matched data for a deeper sounding in the same area. A good fit was obtained only after an anisotropic layer at 200 meters was included.

It has been observed during the course of normal resistivity surveys that EM reflections are more diagnostic of both shallow and deep resistivity interfaces than standard resistivity sounding methods. Although we are still in the embryonic stage of interpreting reflection data in the course of normal resistivity analysis, the work done so far has been encouraging and rewarding. Due to the complexity of this inversion process, a large amount of computer processing needs to be done for accurate results. However, it appears that rough depth estimates for field data will be possible by constructing sets of "type" curves for EM reflection data.

Using reasonable sized arrays, it appears possible to obtain accurate sounding results to at least 2000 meters. A reasonable sized system would be a transmitter bipole 2000 meters long and a receiver dipole of 400 meters. More experience is needed to find out what can be actually expected in complex geologic areas.

Conclusions

To date, the Complex Resistivity system has been used in mineral exploration over a wide range of environments in the U.S. and Canada, but not yet over an active geothermal zone. The evidence, both field and theoretical, indicates that CR is particularly well suited for delineating and evaluating a geothermal system, filling the gaps left by conventional geophysical and geochemical techniques. It can discriminate between alteration types and intensity of alteration, and between different barren, unaltered rock types as well. In addition, electromagnetic coupling can be used to identify conductors at depth. Instead of being treated as a nuisance and avoided, it can be exploited to augment the effectiveness of the system. Complex Resistivity is a hybrid technique which adds another dimension to resistivity and Induced Polarization, and in the process has been established as a powerful new tool in mineral exploration. We expect it will soon be established as an equally powerful tool in the exploration for and evaluation of geothermal energy resources.

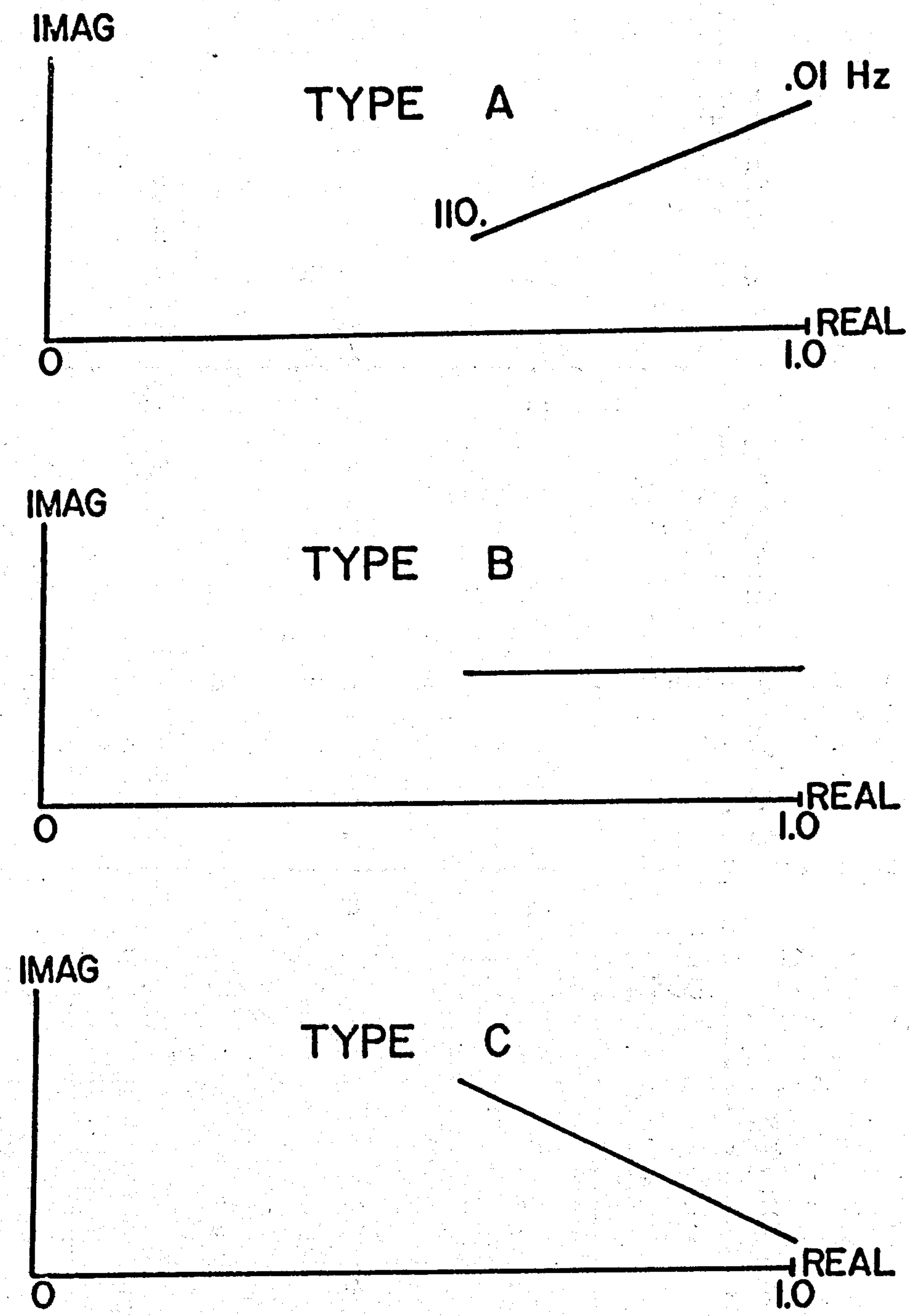

Figure 1. Idealized representation of three basic host rock spectral types.

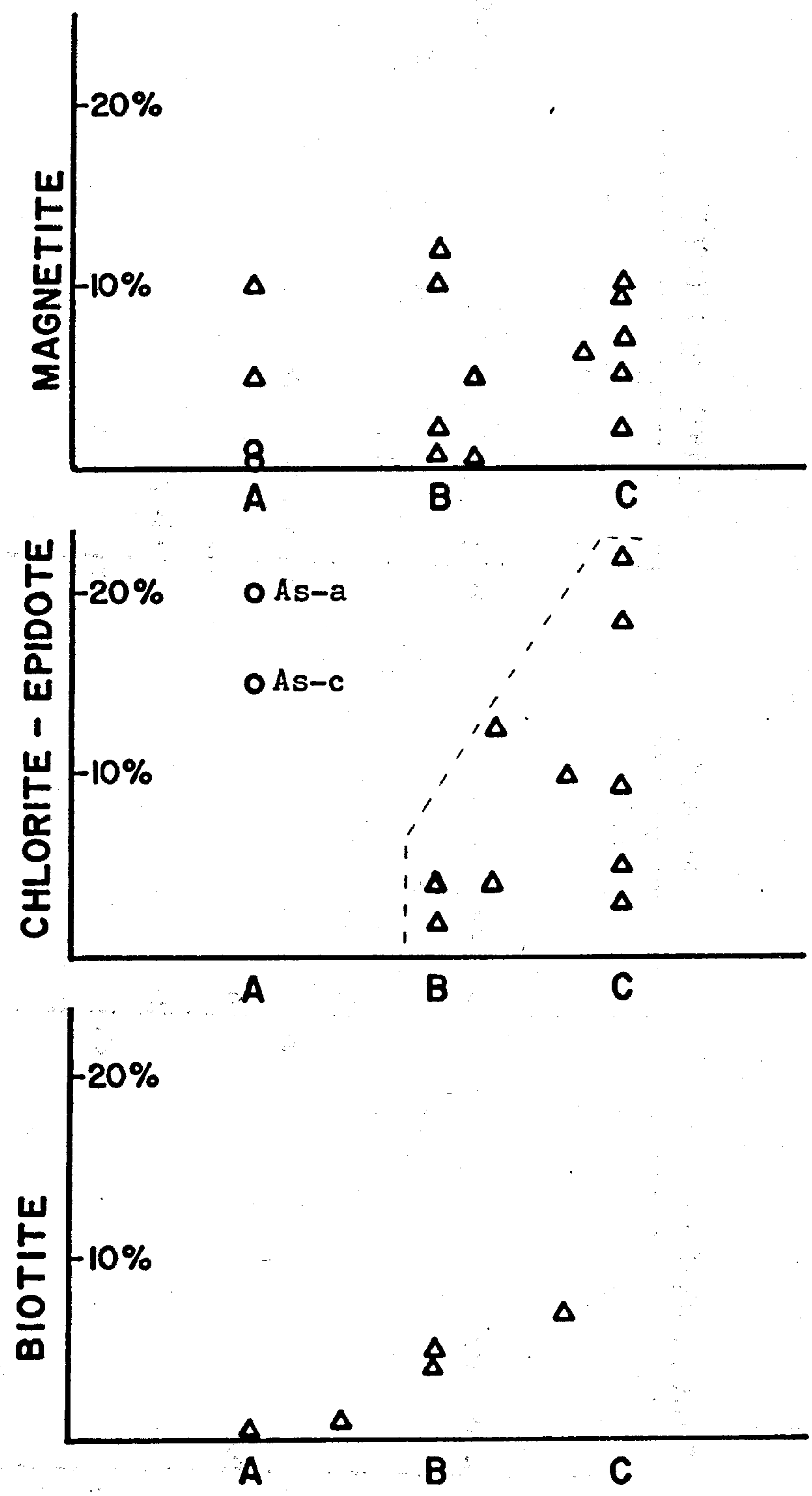

Figure 2. Propyllitic Alteration vs. Spectral Types

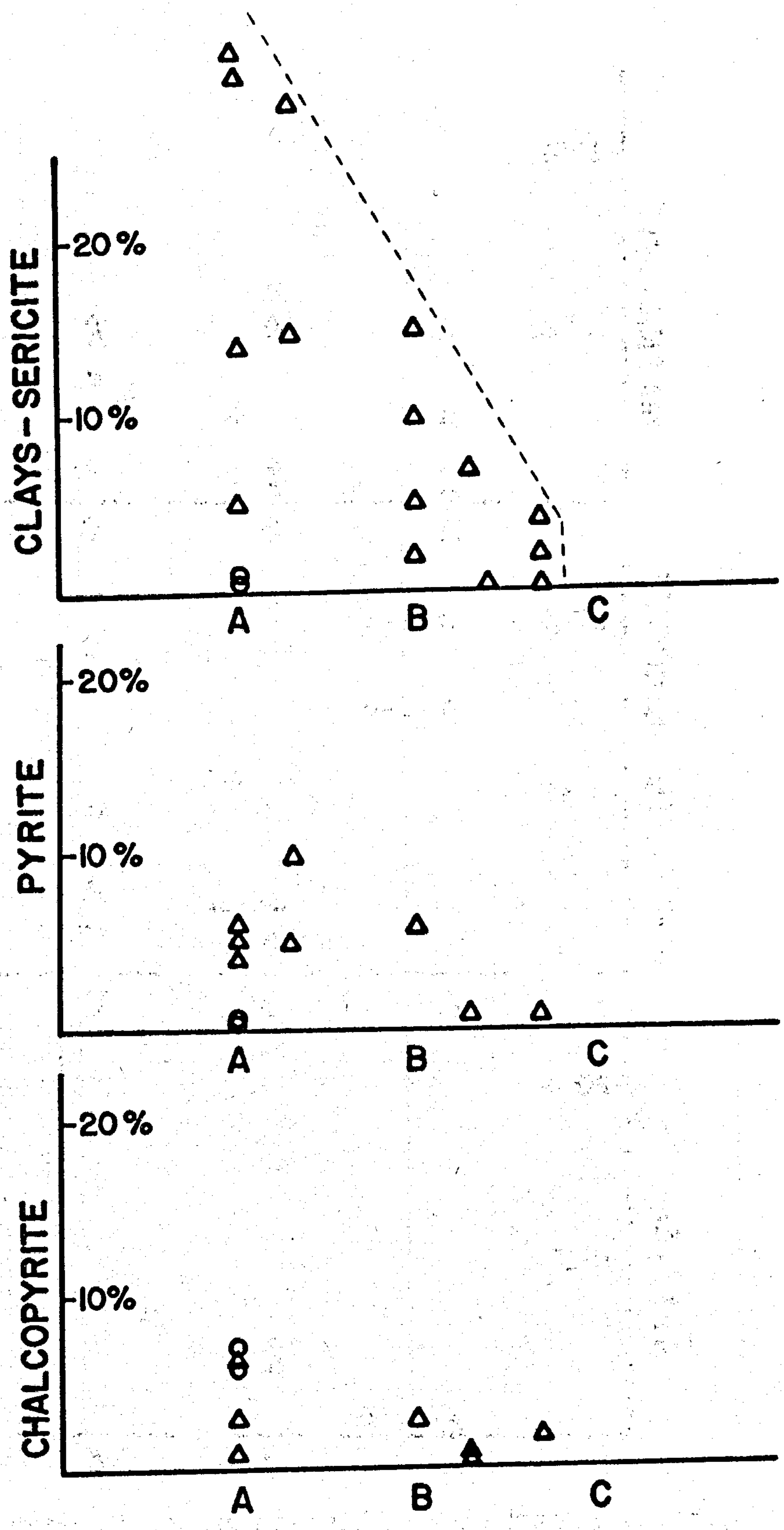

Figure 3. Sericite-Argillic Alteration vs. Spectral Types

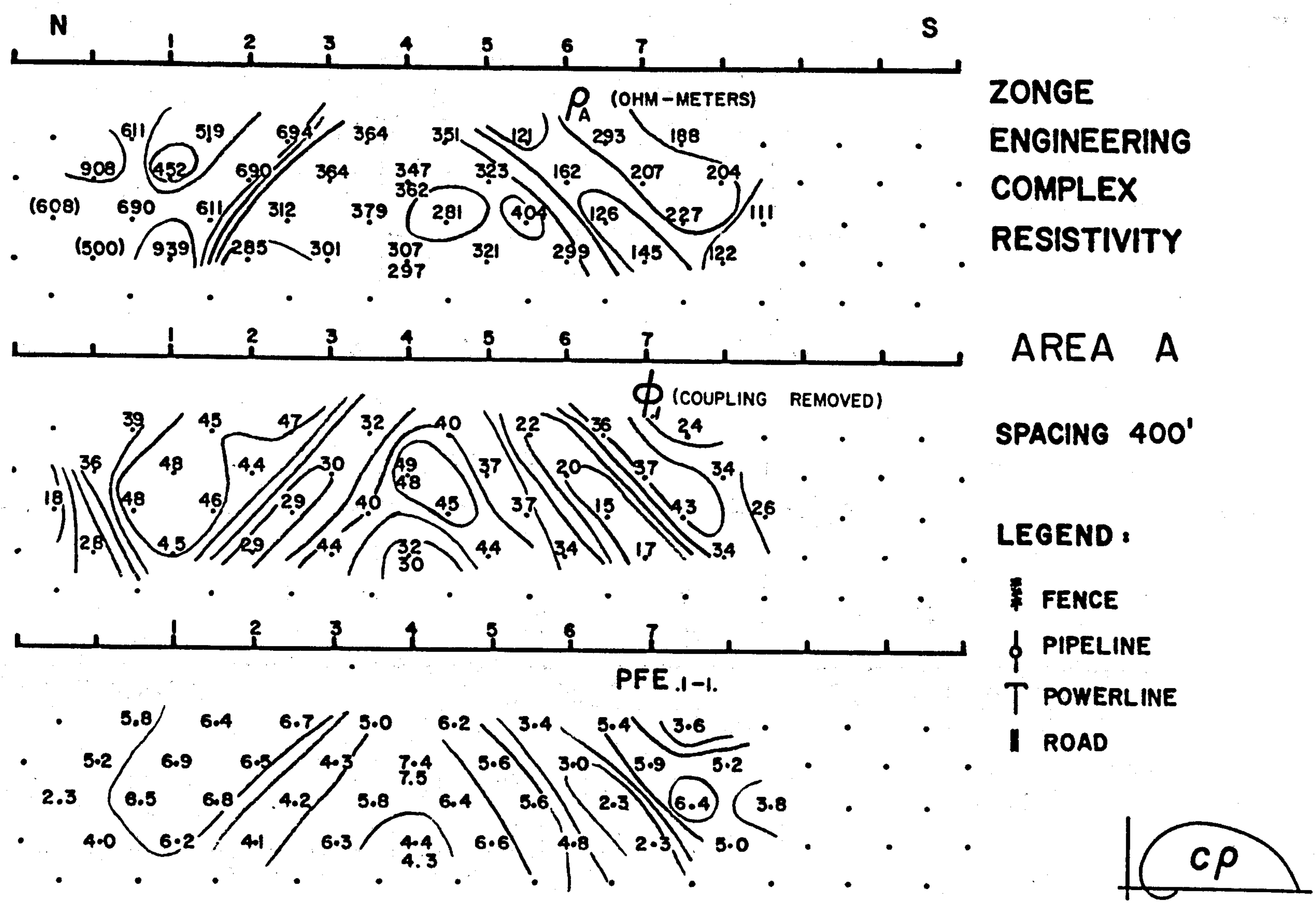

Figure 4. Resistivity, Corrected Phase angle, and PFE for Site A.

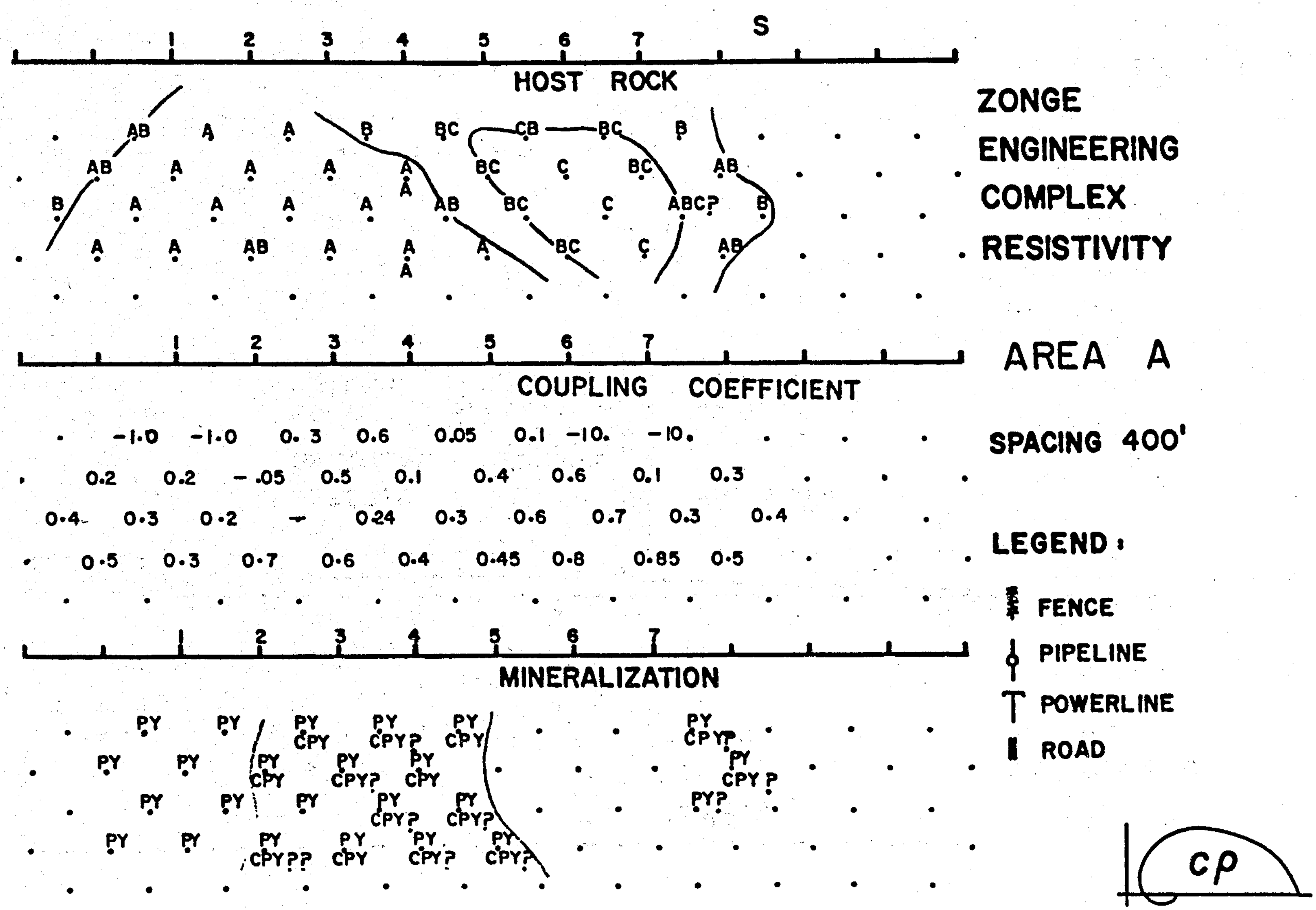

Figure 5. Host Rock (Spectral Type), Coupling Coefficient, and Interpreted Mineralization for Site A.

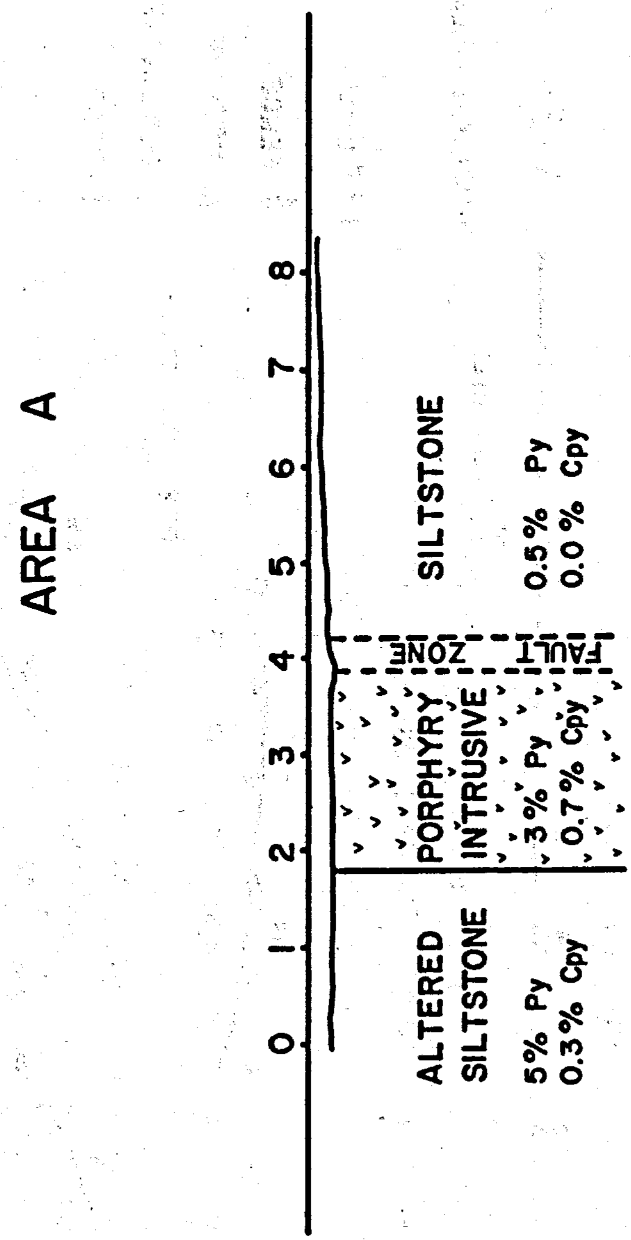

Figure 6. Actual Geology of Site A, as inferred from drill holes.

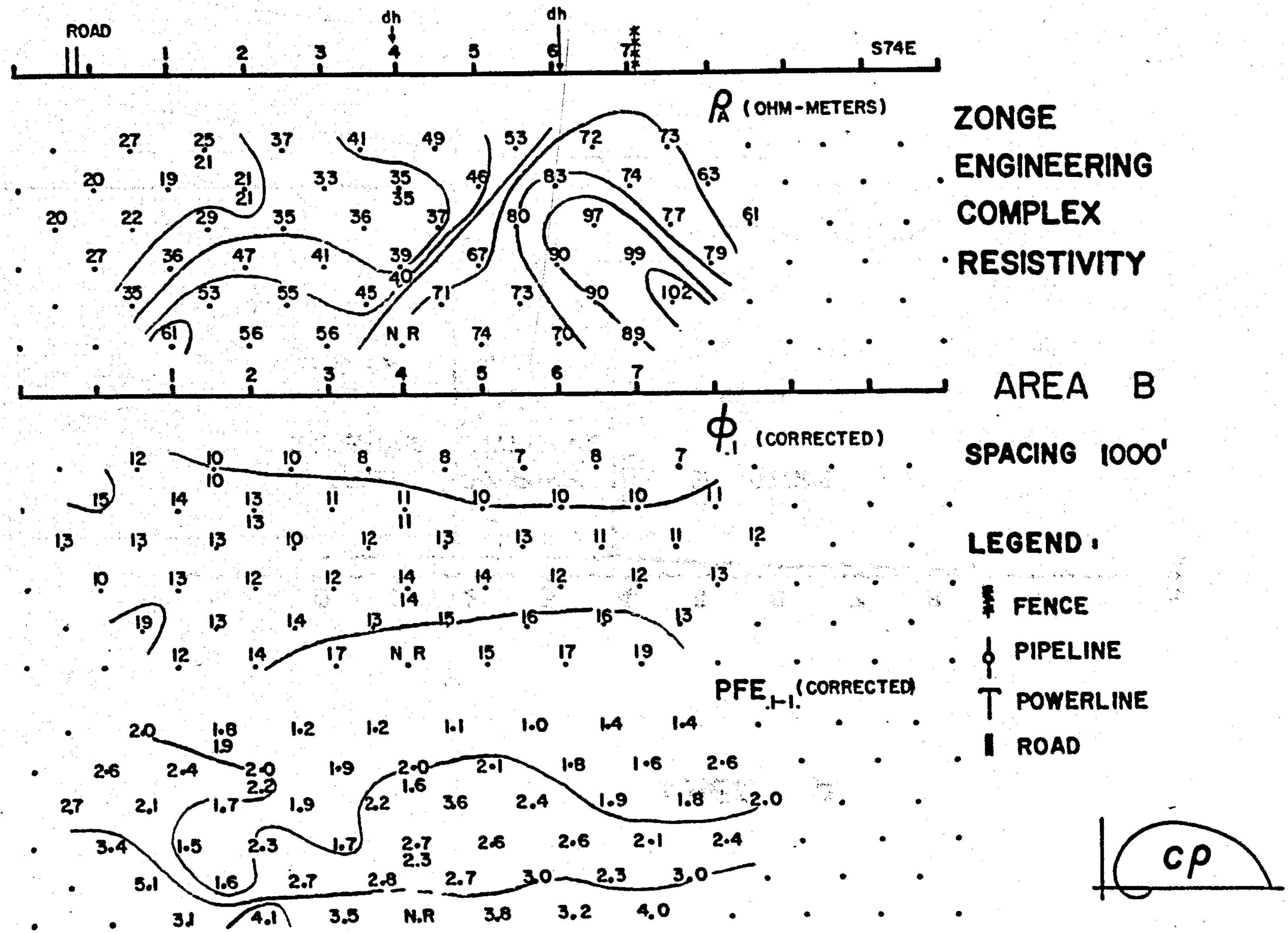

Figure 7. Resistivities, Corrected Phase angles, and PFE's at Site B.

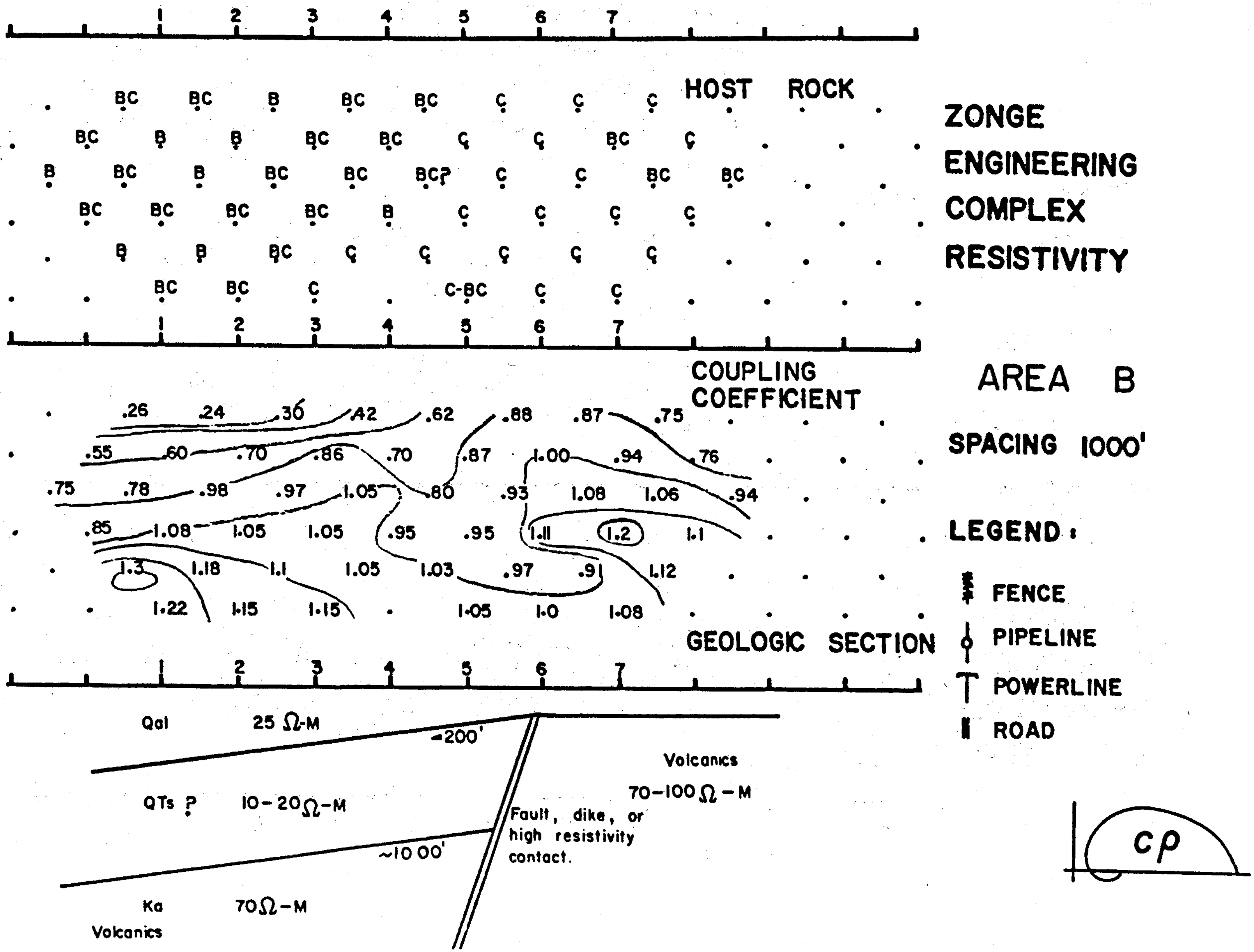

Figure 8. Host Rock (Spectral Types), Coupling Coefficient, and Geology for Site B.

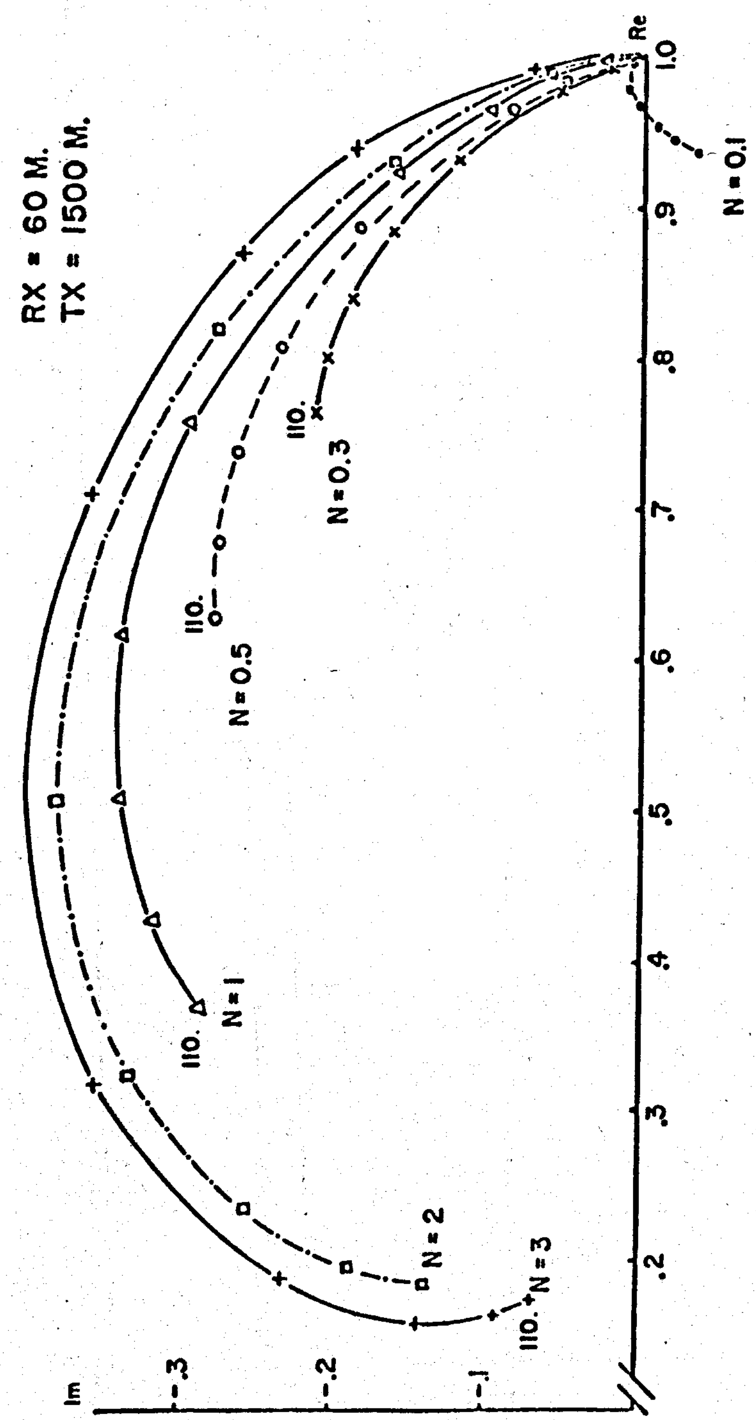

Figure 9. Field Spectra measured in Willcox Playa, Arizona. (Perpendicular Bipole-Dipole)

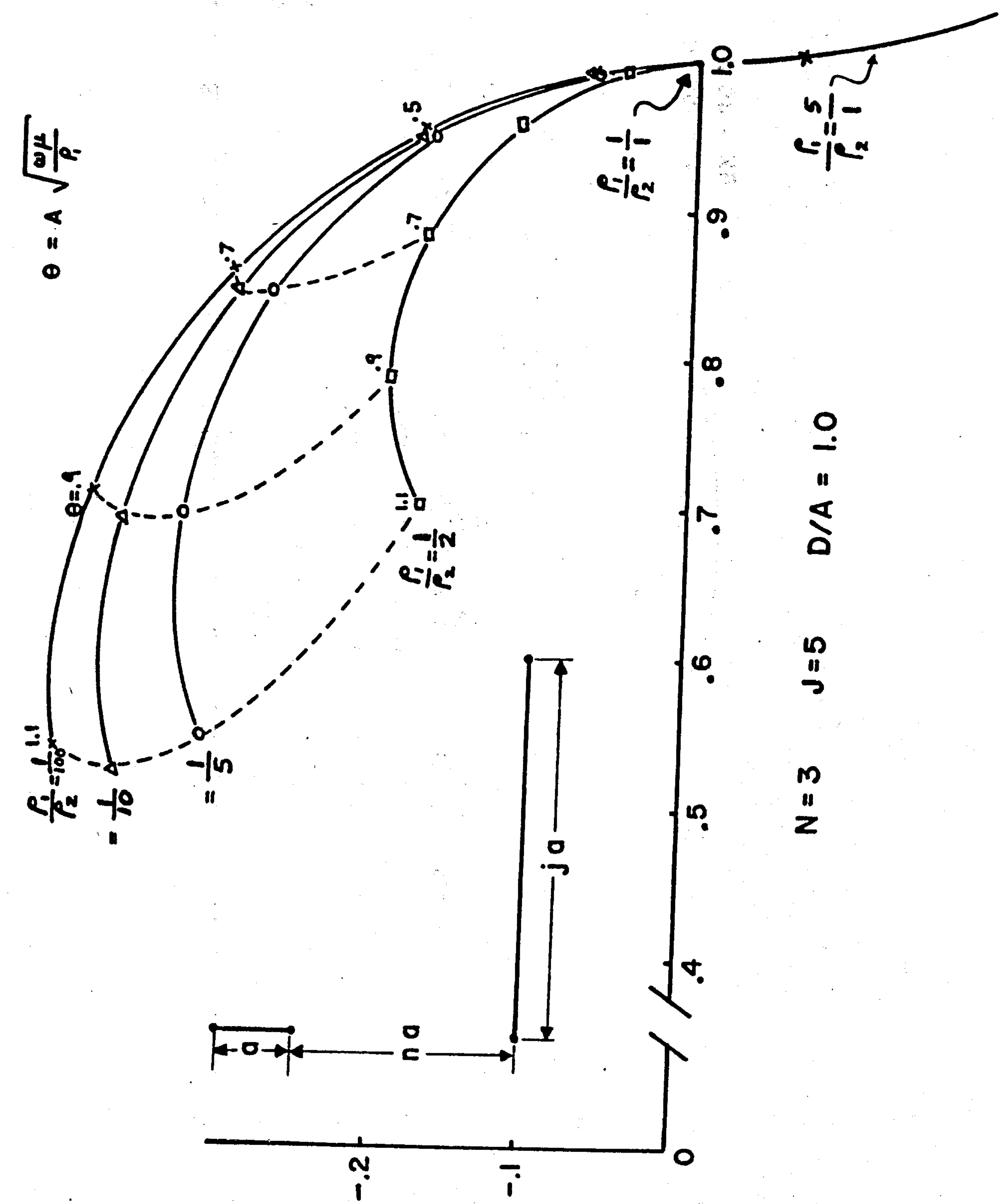

Figure 10. Theoretical Results for the Perpendicular Bipole-Dipole Array (shown), Two-Layer Model.

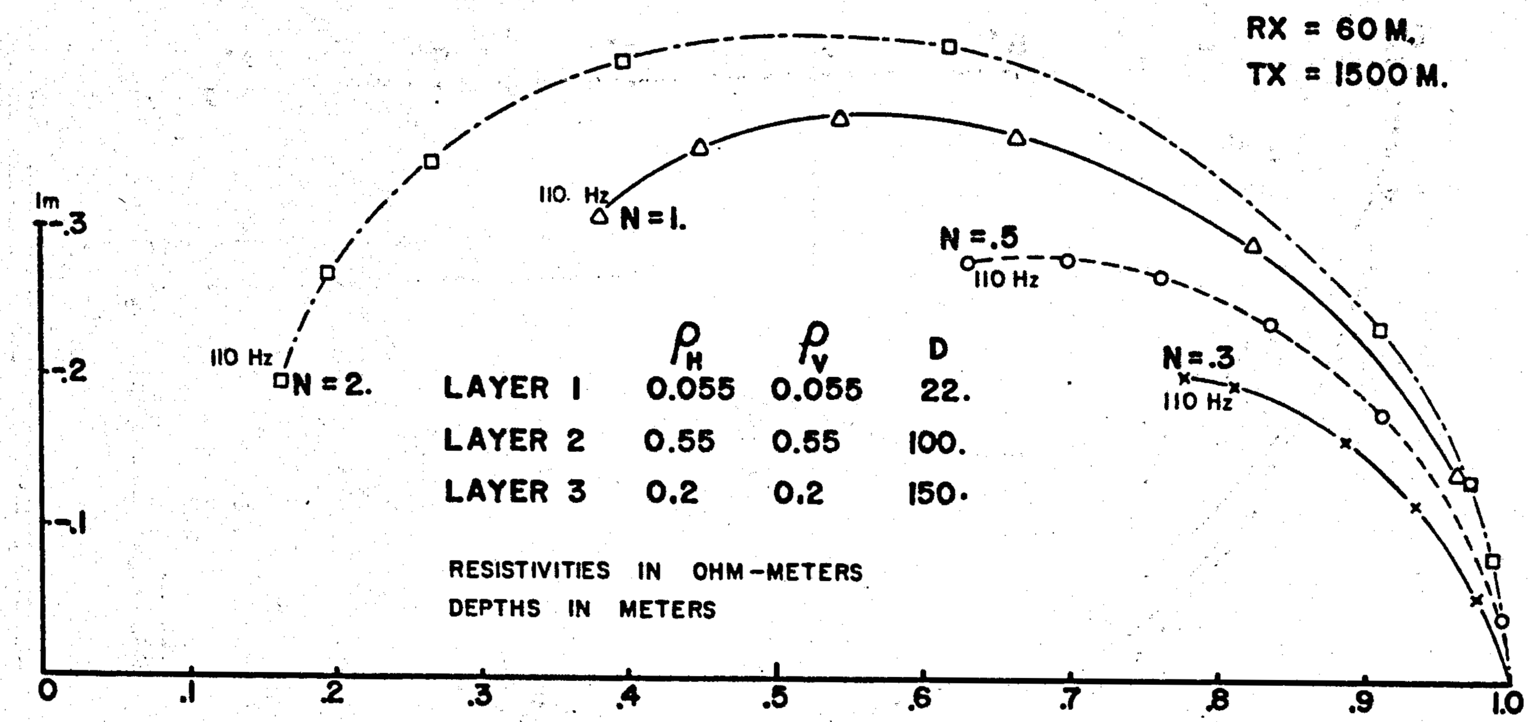

Figure 11. Theoretical Fit to Willcox Playa field data, (with final successful model).

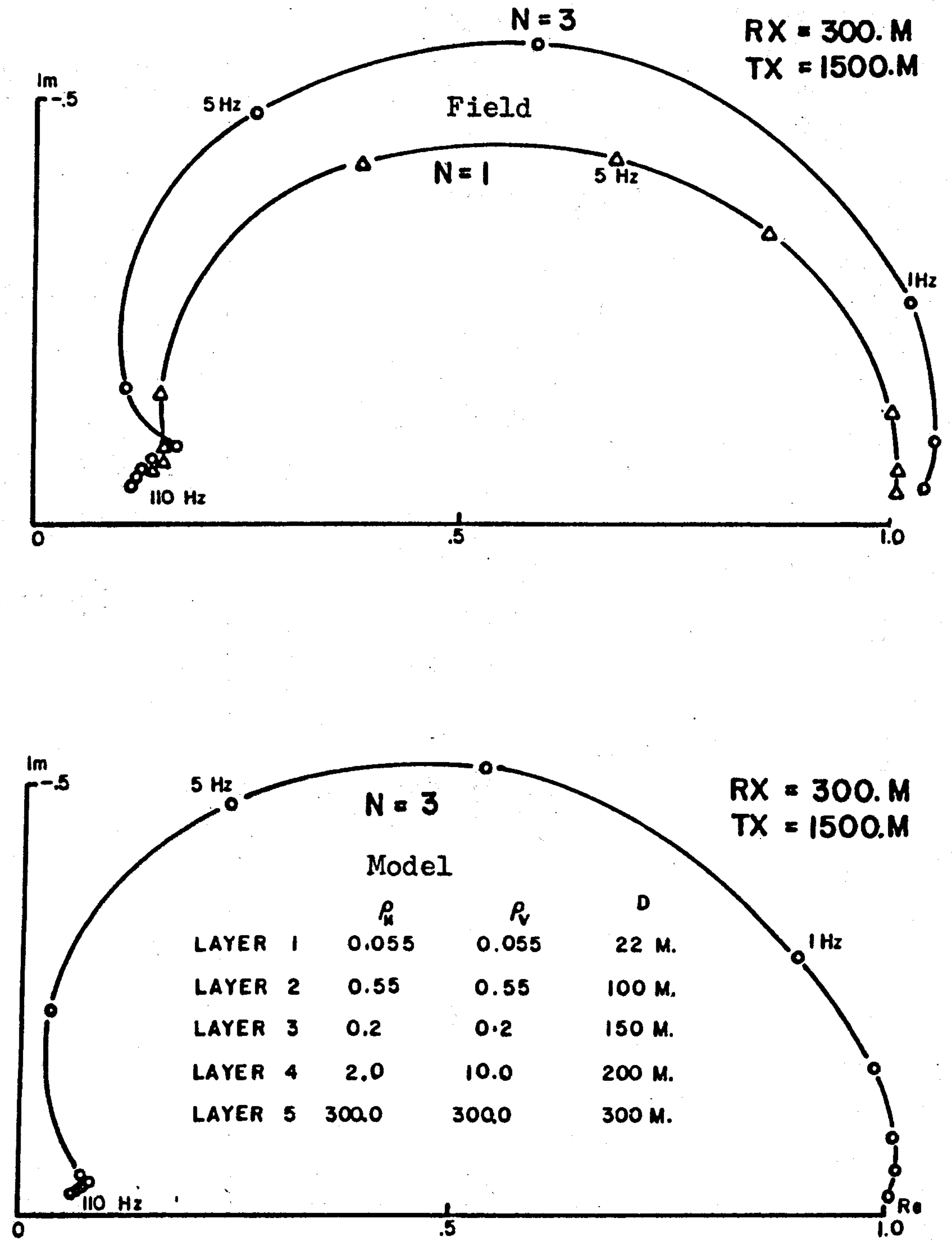

Figure 12. Field Spectra and Theoretical Model for larger Dipole spacing test, Willcox Playa, Arizona.

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