FOSSIL ENERGY

DOE/PC/91008-0226
(OSTI ID: 6058)

INVESTIGATIONS ON THE STRUCTURE, TECTONICS, GEOPHYSICS, GEOCHEMISTRY, AND HYDROCARBON POTENTIAL OF THE BLACK MESA BASIN, NORTHEASTERN ARIZONA

Final Report
March 1996

By
T.K. Reeves, Jr.
Michael Szpakiewicz
Bijon Sharma
Genliang Guo
Len Volk
Colin Barker
Richard Erickson
Steve George
Herbert Carroll

April 1999

Performed Under Contract No. DE-AC22-94PC91008
(Original Report Number NIPER/BDM-0226)

BDM-Oklahoma, Inc.
Bartlesville, Oklahoma

National Petroleum Technology Office
U. S. DEPARTMENT OF ENERGY
Tulsa, Oklahoma

Available to DOE and DOE contractors from the Office of Scientific and Technical Information, P.O. Box 62, Oak Ridge, TN 37831; prices available from (423) 576-8401.

Available to the public from the National Technical Information Service, U.S. Department of Commerce, 5285 Port Royal Rd., Springfield, VA 22161

DOE/PC/91008-0226
Distribution Category UC-122

Investigations on the Structure, Tectonics, Geophysics, Geochemistry, and Hydrocarbon Potential of the Black Mesa Basin, Northeastern Arizona

By
T.K. Reeves, Jr.
Michael Szpakiewicz
Bijon Sharma
Genliang Guo
Len Volk
Colin Barker
Richard Erickson
Steve George
Herbert Carroll

April 1999

Work Performed Under Contract DE-AC22-94PC91008
(Original Report Number NIPER/BDM-0226)

Prepared for
U.S. Department of Energy
Assistant Secretary for Fossil Energy

National Petroleum Technology Office
P.O. Box 3628
Tulsa, OK 74101

Prepared by:
BDM-Oklahoma, Inc.
P.O. Box 2565
Bartlesville, OK 73005

TABLE OF CONTENTS

FIGURES

TABLES

ACKNOWLEDGMENTS

This work was sponsored by the U.S. Department of Energy under Work Request Number AC/15044/BC/42. The authors wish to thank Rhonda Lindsey (BPO) and Dr. Arfon H. Jones, former Vice President, Petroleum Technology, under whose guidance the project was initiated, for their support, counsel, and encouragement. The authors also wish to acknowledge the contributions of the following BDM-Oklahoma employees: Bill Johnson and Gene Larson, as well as the Library Services group, Bonnie Mitchell, Josh Stroman, and Jack Chidester.

1.0 INTRODUCTION

The U.S. Department of Energy (DOE) has instituted a basin-analysis study program to encourage drilling in underexplored and unexplored areas and increase discovery rates for hydrocarbons by independent oil companies within the continental United States. The work is being performed at the DOE's National Institute for Petroleum and Energy Research (NIPER) in Bartlesville, Oklahoma, by the Exploration and Drilling Group within BDM-Oklahoma (BDM), the manager of the facility for DOE. Several low-activity areas in the Mid-Continent, west, and southwest were considered for the initial study area (Reeves and Carroll 1994a). The Black Mesa region in northeastern Arizona is shown on the U.S. Geological Survey 1995 oil and gas map of the United States as an undrilled area, adapted from Takahashi and Gautier 1995 (see Fig. 1–1). This basin was selected by DOE as the site for the initial NIPER-BDM survey to develop prospects within the Lower-48 states (Reeves and Carroll 1994b).

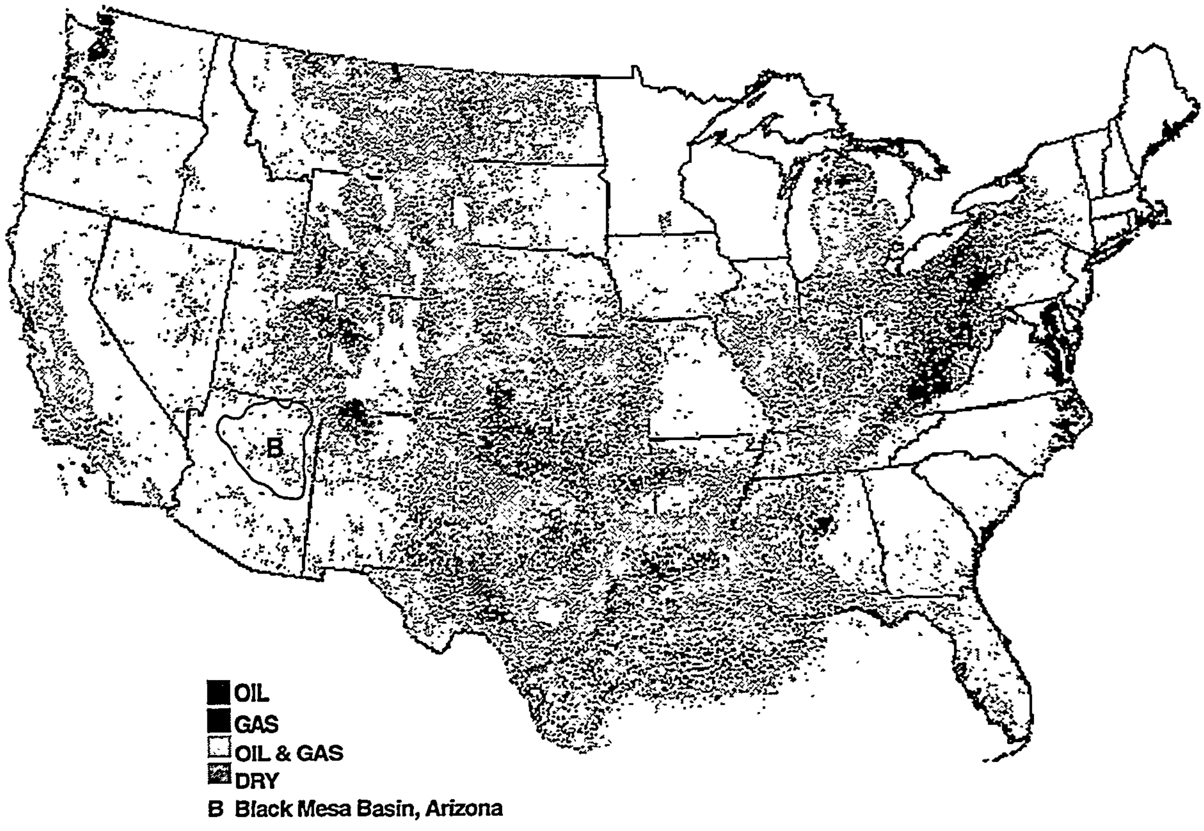


Figure 1–1 USGS 1995 Oil and Gas Field Map of the USA

The Black Mesa basin is a significantly underexplored region. In northern Arizona, as a whole, there is only one well per 155 mi^2. This includes a concentration of wells in the far northeastern portion of the state, in and around a string of oil fields near the Utah border. Outside this productive region, the drilling density is closer to one well per 420 mi^2. Only six wells have been drilled in the deepest, central-portion of the basin. These wells were all located on or adjacent to the 1.5 million-acre Hopi Reservation. An additional six wells have been drilled nearby, at sites somewhat farther from the basin axis (Matheny 1964; Dwights Energydata CD-ROM; Takahashi and Gautier 1995), mostly on Navajo lands. The Hopi wells were all drilled during a single surge of oil-exploration activity during 1965. Due to a flare-up in a long-standing series of land and grazing-rights disputes in the area, there was no follow-up testing or offset well activity around the original exploratory holes. The study area includes the topographic Black Mesa, the ancestral homeland of the Hopi nation, and the surrounding region, with a large number of geologically-contiguous, potential reservoir formations and structures, beneath the southwestern portion of the Colorado Plateau. Much of this surrounding area is included within the Navajo reservation.

Work on the Black Mesa was inaugurated during the early fall of 1994, with the purchase of support equipment, the start of an extensive literature search, data collection, and plans for a scouting, orientation, and planning trip to the study area. Several members of the team visited the region in October 1994, (Szpakiewicz, Reeves, and Volk 1994) with the intent of planning for a series of noninvasive sampling, mapping, and surface studies. Meetings were held with key local officials and representatives of the Hopi and Navajo nations and local industry. A large number of promising contacts were made at a convention of the American Institute of Professional Geologists in Flagstaff. The intent was to return to the field in the Spring of 1995 for detailed sampling and studies.

These plans ran into significant roadblocks when necessary access approval and permission for field work were not granted to the reservation lands on and around the Black Mesa, Kaibab plateau, Defiance uplift, and Four Corners area. This significantly cut into plans to collect hard data numbers for the area. In addition, it proved to be impossible to locate whole-core sections from a series of wells that were drilled in the center of the study area during the mid-1960s. These cores appear to have been lost or dumped during the succeeding decades. These difficulties clearly demonstrated some of the factors that have inhibited oil and gas prospecting in the northeastern corner of Arizona in past decades.

The primary approach to the study shifted from direct sampling and laboratory analysis to indirect, remote-sensing studies and geophysical surveys, along with an expanded literature review (Reeves et al. 1995). Publications, maps, logs, and well data were gathered for the area, including published stratigraphic, structural, geophysical, and geochemical data. An oil well database was purchased, and show and production analyses were run and maps generated. Lithofacial, paleogeographic, and tectonic information, along with well logs and maps of gravity and magnetic anomalies, were studied and became important factors in the identification of prospect areas. Documented oil shows in the Paleozoic and, occasionally, the Mesozoic section in exploratory boreholes also focused attention on promising target regions and stratigraphic units. The NIPER BDM-Oklahoma library services played a key role in a massive literature review of classic and current geoscience articles, monographs, studies, reports, theses, dissertations, and maps relevant to the petroleum prospects for the area.

The final results have painted a very optimistic picture of potential source beds in conventional sediments within the lower Paleozoic section, as well as less conventional possible deep sources that could have supplied large quantities of oil or gas to shallower reservoir formations in the region, due to unusual characteristics of the unique geologic history of this area. Several sequences have been identified where deeper source beds are overlain by potentially porous reservoirs, topped by fine-grained units that would make good cap rocks. Local faulting and structural features have provided migration routes, favorable conditions for stratigraphic and structural traps, and zones with excellent settings for secondary porosity development. Hydrocarbon shows and unusually rich and pure accumulations of commercial-quality helium are widespread across the region, being found in almost every local area that has been tested by the drill, and within almost every coarse-grained clastic unit from the Cambrian, and even possibly in Precambrian beds, through shallow through very shallow sediments. The largest field in the region, the most prolific field discovered to date in Arizona, was located in a presumed "impossible" reservoir formation, a Tertiary volcanic unit, demonstrating the wide range of possibly productive reservoirs in northeastern Arizona.

The following report discusses the results of the research project and the hydrocarbon potential of the greater Black Mesa region, and provides support for the assessment of the area.

2.0 DEFINITION OF THE STUDY AREA

As defined for this study, the greater Black Mesa region involves a much broader area than the restricted topographic feature for which the study is named. It encompasses an extensive block in northeastern Arizona (see Fig. 2–1). The area of interest includes the central basin, as well as surrounding monoclines, shelves, benches, and slopes, stretching out to a surrounding ring of uplifts, divides, and structural highs. The region is named for the centrally-located, dominating topographic/geomorphic feature, the Black Mesa of Hopi lore and legend. The study area is located in the structurally-deep southwestern corner of the Colorado Plateau, west, southwest, or south of a series of structural divides, extending from the Defiance uplift, through the Tyende saddle, Monument upwarp, Shonto plateau and Kaibito saddle, to the Grand Canyon. The southern and western limits of the study area are formed by the gorge of the lower Grand Canyon and the steep slopes and outcrops of the Mogollon Rim. As shown in Figure 2–1, the structural greater Black Mesa region, as defined here, covers nearly one quarter of the state of Arizona.

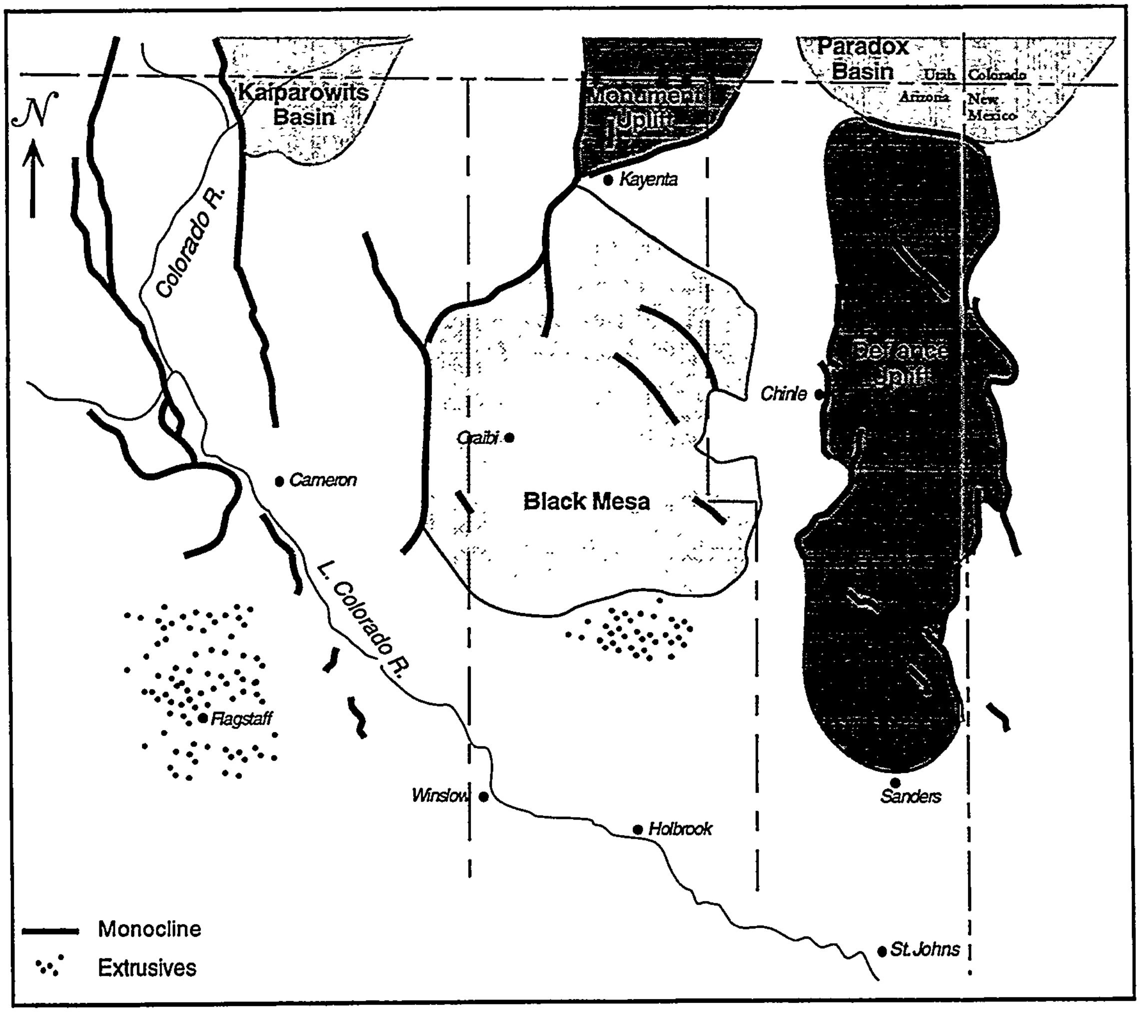


Figure 2–1 NE Arizona Base Map

The study of the Black Mesa region began with literature surveys to identify the relevant geological, geophysical, and engineering characteristics of the region and surrounding productive areas. Hydrocarbon exploration success ratios around the Four Corners-area of Arizona, Colorado, New Mexico, and Utah have generally been low. Within Arizona, minor production has been established from various Devonian, Mississippian, and Pennsylvanian formations within the Paleozoic section. This production was discovered largely through stepout exploration and drilling, with the assist of seismic surveys during recent decades. The fields have been limited to two general areas,

- a series of small fields in the extreme northeastern corner of Arizona,
- a single, relatively large field producing from a highly-unusual reservoir, in fractured Tertiary volcanic rocks, on the Defiance uplift near the New Mexico border.

Drilling around these areas has been relatively dense. Within the Black Mesa basin proper, very few wells have been drilled, and no commercial production has been identified. Extensive drilling has taken place in one additional area, southeast of the central Black Mesa as shown on the Takahashi and Gautier 1995 (see Fig. 2–2), east and northeast of the town of Holbrook, much of it on privately-owned land along or near the railroad right-of-way.

The oil fields that have been found thus far in Arizona are located well up on structural saddles and uplifts, in areas that are generally perceived of as being relatively unfavorable for the generation of hydrocarbons. Source beds are thin or lacking in many of these areas, and depth-of-burial and thermal maturity of the beds in this corner of the state have been suspect, when compared to the deeper portions of the central Black Mesa basin. This may account for the small size of the fields that have been discovered thus far and for the large number of dry holes that accompanied the discoveries in northeastern Arizona. The large number of wells in this hostile area can be attributed to the facts that

- Discoveries, although small, were being made on a continuing basis,
- Operators were able to maintain a feeling of security in stepout drilling in relatively familiar land,
- And to the comparative ease of drilling there, relative to the difficulty of leasing on contested lands in the deeper portions of the Black Mesa.

The area of extensive drilling to the south, on or near the railroad-lands, is also in an area with a thin lower Paleozoic section. Much of this drilling east of Holbrook was done primarily in an attempt to locate commercial helium accumulations or for potash, rather than for hydrocarbon exploration. Ease of physical access in the relatively flat lands of this region, as well as a simplicity of obtaining leases, accompanied by a desire to identify mineral assets on railroad properties, may have fostered a certain amount of promotional activity that would not have been justified with a pure petroleum-exploration program. The DOE program is intended to determine if larger resources exist in the deeper, more thermally-mature portions of the study area, where thicker source beds may have had an opportunity to accumulate.

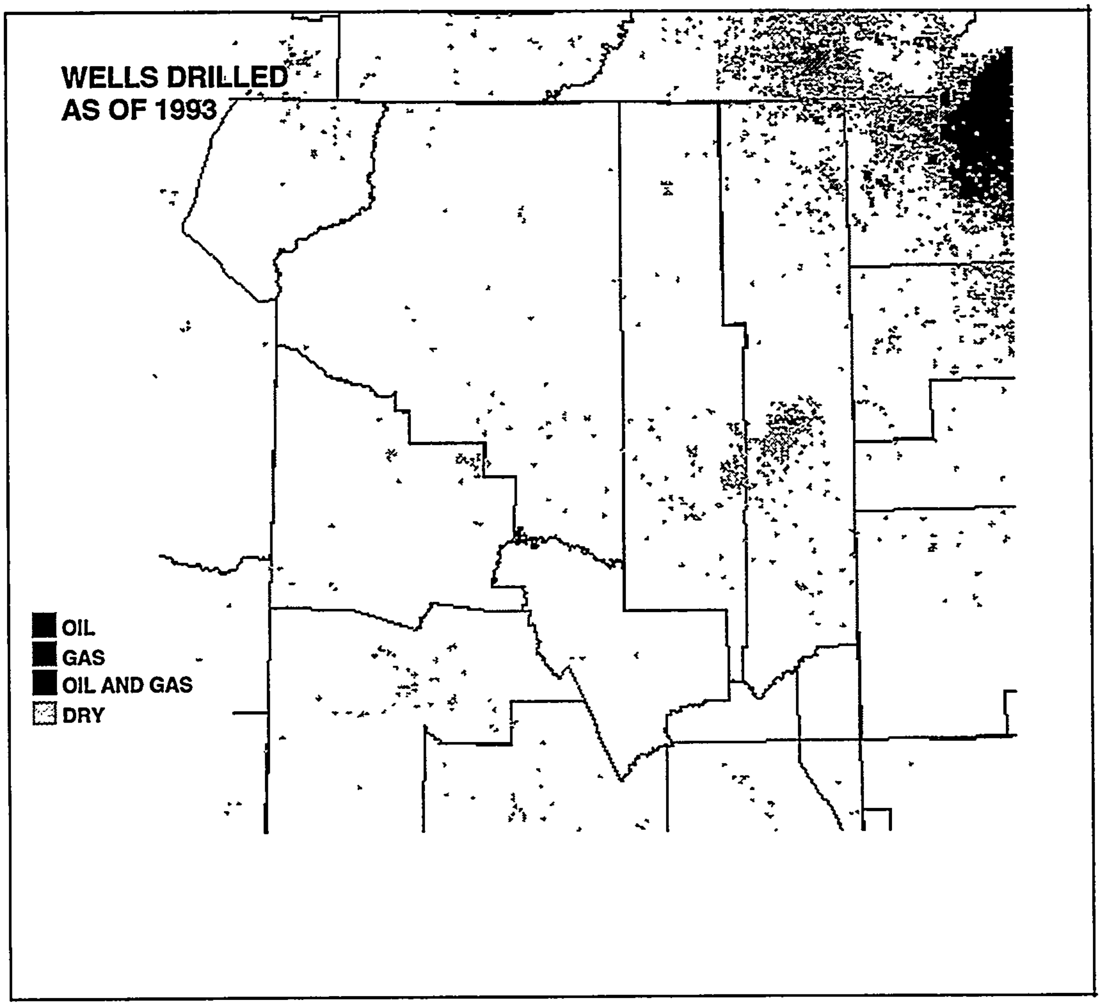


Figure 2–2 USGS Base Map of Oil and Gas Drilling in Northeastern Arizona

The productive wells in the extreme northeastern corner of Arizona are located along the southern margin of the Blanding basin, a minor embayment on the southwestern edge of the Paradox basin. Most of the production that has been discovered in this region comes from porosity within small reefs. These bioherms grew in shoal waters that followed, and were controlled by, a series of reactivated basement faults which underlay the shallow-water fringes of the basin (Brown and Lauth 1957, 1958; Byington 1957; Picard 1960; Matheny 1964; Schneider, Tohill, and Taylor 1971). The regional structural pattern suggests that there may be many additional sites with similar settings within northeastern Arizona, along with several more-promising features that have not yet been identified and drilled.

Publications, maps, logs, and well drilling, completion, and production data were gathered for the study area. With limited time for the project, it was necessary to limit the focus of the study. This led to the identification of several specific target areas within the region for more-detailed work. These target areas were sites where conditions appear to have been particularly favorable for the accumulation of hydrocarbons in commercial-sized traps, some potentially much larger than those found to date around the Blanding basin.

The well databases (Pierce and Scurlock 1972; Dwights) document numerous promising shows of oil and gas across a wide geographic area in northern Arizona. The majority of the holes that have been drilled across the region have had multiple shows. These shows include oil, natural gas, and unusually-rich, commercial-quality helium, and have been encountered in many different stratigraphic units, from the Cambrian through the Jurassic section. Most of the twelve wells drilled on or immediately around the Hopi reservation during the mid-1960s had multiple shows of oil (Pierce and Scurlock 1972; Dwights CD-ROM), but there was no follow up to that activity due to the renewal of a series of land disputes that had persisted in the region for many years. Tensions associated with drilling and mining aggravated the situation and tensions between the Navajo and Hopi peoples around the mesa during the mid-1960s (Cabeen 1958; Barwin 1971; Waters 1977).

In 1966, the year following the drilling of the Hopi wells, a large coal mine was opened by the Peabody Corporation on the northern portion of the Black Mesa (Pierce et al. 1970). The inevitable disruptions of the land around the mine and, more critically, in the arid northeastern Arizona climate, of local water supplies, were very upsetting to the Hopi residents of the mesa (Science & Technology Week 1994). At exactly the same period, long-standing conflicting claims over reservation boundaries and grazing rights between the Hopi and Navajo flared up again (Barwin 1971). Legal suits were filed between the Hopi and the Navajo, and even between Hopi factions and the elected Hopi Tribal Council over the right of the tribal council to grant leases for mining or drilling and the responsibility of the council to protect the people's land. These legal actions, which moved in and out of court throughout the late 1960s and 1970s, inhibited the oil companies from following up on the 1965 programs. Only recently have court settlements have been reached on many of these legal questions, offering renewed opportunities for cooperation between corporations and the two dominant Native American nations in the Black Mesa study area.

The Black Mesa region totally encompasses the Hopi reservation. It also includes the western portion of the Navajo reservation. Surrounding the reservations, and at a few sites within the Navajo reservation, are lands under National Park, National Monument, National Forest, Bureau of Land Management (BLM), and state of Arizona jurisdiction. Much of the region south of the reservation is privately held, including large parcels of railroad lands.

2.1 Identification of Prospective Regions for Hydrocarbon Exploration

The study area was quite large, and the work period was limited, so the initial task was the identification of top priority targets for more-detailed analysis (Reeves and Carroll 1994a, b). Six specific prospective regions (see Fig. 2–3) were identified within the Black Mesa study area. It was felt that each of these areas had a particularly attractive setting or favorable series of characteristics for the accumulation of hydrocarbons. The target areas were selected by a review of:

- well data, particularly indications of abundant oil-shows,
- published data on geology, structure, geophysical information, and geochemical information,
- information gathered during an initial reconnaissance field trip to the Black Mesa and northeastern Arizona, and
- aerial and high-altitude photographic studies.

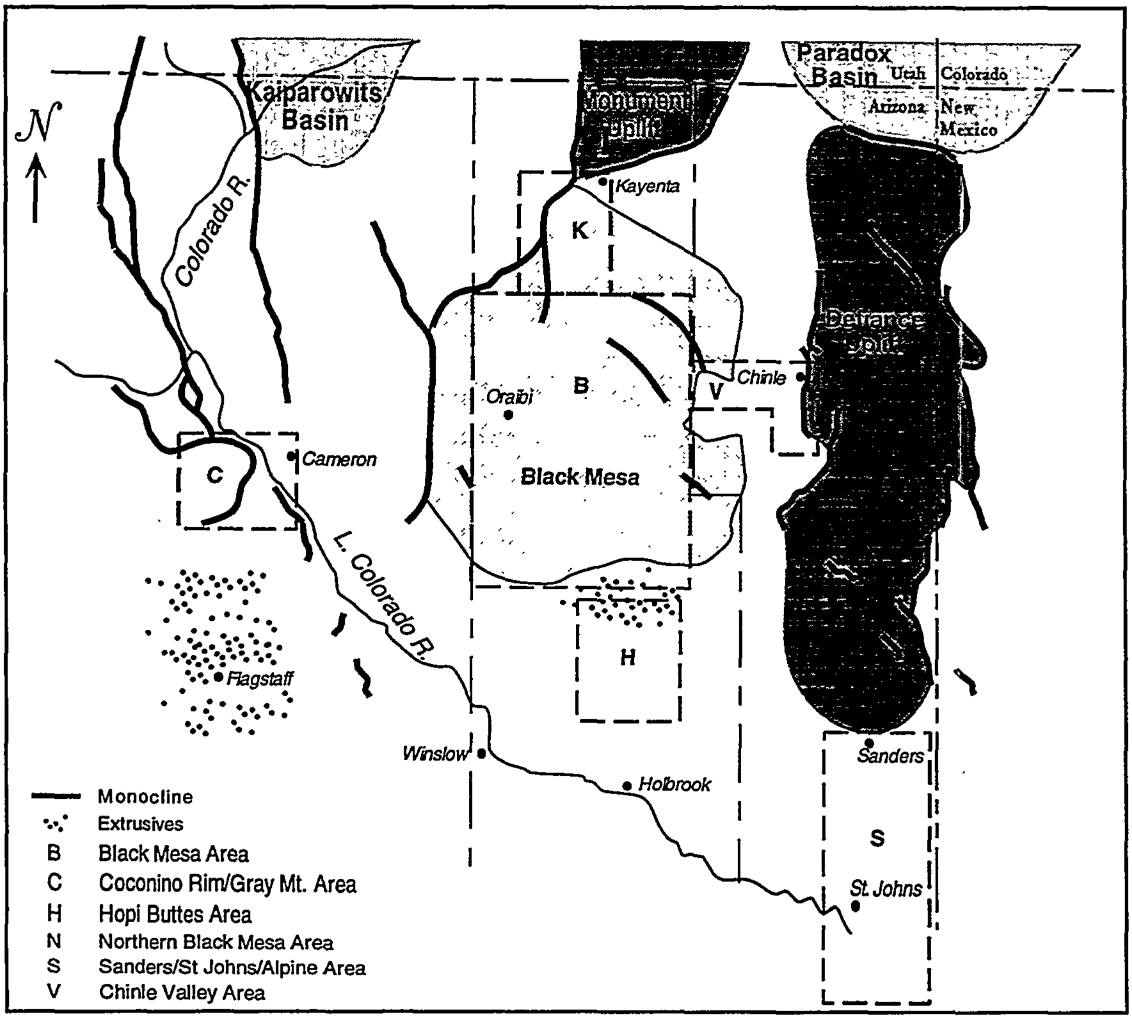


Figure 2–3 NE Arizona Study Areas

Stratigraphic, lithofacies, paleogeographic, and structural information, along with aerial photographs, well logs and maps of gravity and magnetic anomalies, were important factors in the selection process. Gutman and Heckmann (1977) provided a discussion of several areas which they interpreted as being highly prospective for hydrocarbons. Documented oil shows (Pierce and Scurlock 1972; Dwights CD-ROM) in the Paleozoic and, occasionally, the Mesozoic sections in exploratory boreholes were especially useful in focusing attention on promising target regions and stratigraphic units.

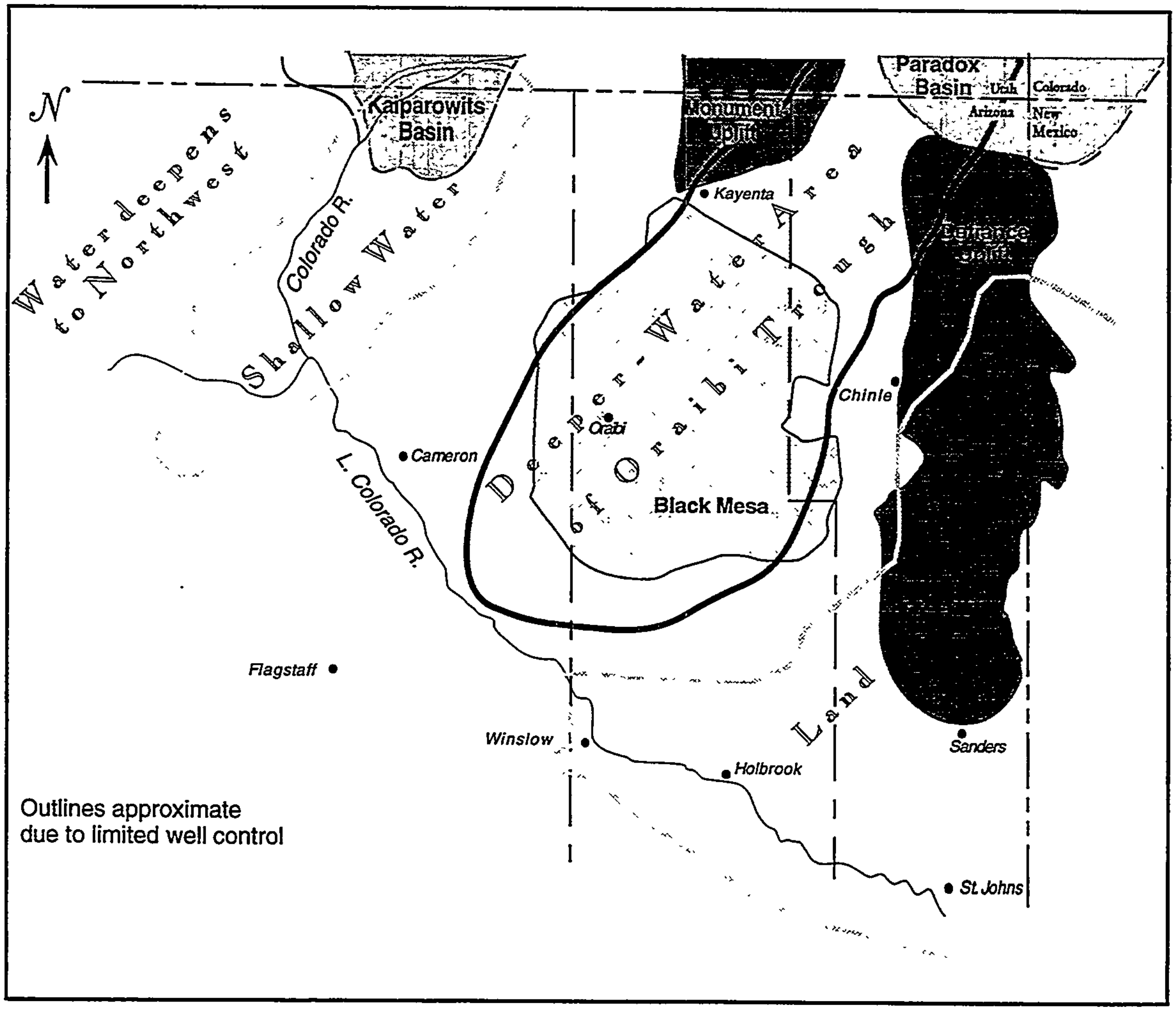
The six prospective regions which were identified are:

- The **central Black Mesa** region. This area encompasses the structurally-deepest portions of the Laramide-age structural Black Mesa basin. It includes the site of a much older, Paleozoic depression, known as the Oraibi trough (see Fig. 2–4). This was the site of locally thick accumulations of lower Paleozoic beds, which included potential source rocks. The trough fill is known to include Devonian and Mississippian fine-grained, dark carbonates and shales, similar to what have been shown to be source rocks in more-extensively tested nearby areas. The beds in the central portion of this area are believed to be the most thermally mature in the region. An exceptionally-well-developed parallel drainage system crosses the mesa, indicating that fracturing is well developed here. This area includes the Hopi reservation and a portion of the Navajo reservation.
- A structurally-complex area along the border between the **northern** portion of the topographic **Black Mesa**, and the southeastern Shonto Plateau, including Skeleton Mesa and Tsegi Canyon. Three large monoclines intersect in this region, and several of the local anticlines reach their greatest closure here. Fracturing along the monoclines may offer excellent trapping conditions. This area encompasses mostly Navajo reservation lands, along with Peabody Coal leases, and several sites comprising portions of the Navajo National Monument.
- An area at **Gray Mountain** and the **Coconino Rim** on the Coconino plateau, well to the west of the Black Mesa and southeast of the Grand Canyon, where large, local structures could form high-quality, conventional reservoirs. A potential prospect area has been created at the intersection of five large monoclines, where a basement trapdoor structure has produced a local uplift of the normally flat-bedded Paleozoic and Mesozoic rocks of the plateau (Barnes 1974, 1987; Barnes et al. 1974; Reches 1978). The interaction of the various monoclines here has created a bubble-shaped structural high with significant closure. Extensive, highly-fractured zones around the periphery of the feature could also provide structural traps, with oil accumulating updip in the knee areas of the flexures, in zones of secondary-porosity. This region is located west of the town of Cameron. This prospect includes Navajo lands.
- The **Chinle Valley**, between the Black Mesa and the Defiance uplift. A significant change in surficial and deep structural orientations occurs in this region, and the thick sediments of the central Black Mesa basin thin rapidly and pinchout against high

basement rocks on the Defiance structure. A large number of exposed volcanic rocks and buried basalt intrusives have penetrated the crust along the Holbrook Line and at the northern end of the Defiance structure. The primary study area begins along the edge of the monocline, west of the town of Chinle. It follows an east-west lineament from the mouth of Canyon de Chelly to Cottonwood gap, at the easternmost point on the Black Mesa. The interest area continues to the south, up the Chinle Valley, to Beautiful Valley, where a closely-spaced anticline-syncline couplet provides an excellent possibility of the development of a structural trap. This prospect includes Navajo lands, the western part of Canyon de Chelly National Monument, and, potentially, some Hopi lands.

- The **Hopi Buttes**, a region of large intrusive bodies and maar collapse structures, where Kimberlite plugs have intruded the local country rock, south of the Black Mesa and northwest of the town of Holbrook. This is a region of apparent ultra-deep-seated zones of weakness, where diatreme Kimberlite plugs and associated collapse structures were intruded into the local country rock, following a trend in the deep crust. Much of the Hopi buttes region is located on the ancient Defiance-Zuni structural high, and is underlain by a shallow basement, compared to surrounding regions. The lower Paleozoic sedimentary section is thin or missing in much of the Hopi Buttes area. Around the northern Hopi Buttes, along the southern edge of the Oraibi trough, the basement is deeper, and the lower Paleozoic section may have hydrocarbon potential. Stratigraphic traps and pinchouts should be common along the southern edge of the Oraibi trough. The surface of the basement rises by 4,000 ft from the central Black Mesa basin, north of the buttes, to the highest areas, at the larger buttes. Due to the shallow depth of burial, thermal maturity of the sediments has been a concern on this basement high. The intrusive activity at the Hopi Buttes was viewed as a possible source of heat which could have aided maturation in the sediments in that area. This prospect includes Navajo, BLM, and Arizona state lands.

- A region on the Mogollon Slope, south of the town of **Sanders**, through **St. Johns**, to **Alpine**, in the southeastern corner of the study area. The area is located near the southern end of the Defiance uplift. This land includes BLM, National Forest, and Arizona state lands. Attention was drawn to this area by oil shows encountered in a recent geothermal test on the Slope (Rauzi 1994). The shows were encountered in beds that had previously been assumed to be too shallow and immature to produce oil. Once the Black Mesa study started, it became evident that there was extensive other governmental and industry interest and activity in this area. It was decided that this no longer could be classified as an "underexplored" area, and no further effort would be made at Sanders/Alpine, to avoid overlap with existing programs.



Outlines approximate
due to limited well control

Figure 2–4 Deepwater Section of the Oraibi Trough

3.0 GEOLOGIC SETTING, SOURCE ROCKS AND TECTONIC HISTORY

3.1 Candidate Source Rocks Within the Black Mesa Region

An early concern of the project was the existence and thermal maturity of potential source beds in the study area. Hydrocarbon shows are common around the Four Corners area, particularly within the Black Mesa basin, proper. Source material was apparently common in the Paleozoic sediments, especially within the fine-grained clastics and many of the carbonates. At the Black Mesa, it appears that the carbonates were much more common, and more prolific sources of hydrocarbons, than the shales. The Mesozoic beds have included several shows, but these beds are primarily terrigenous, and do not have the same overall potential for the sourcing of hydrocarbons as is seen in the Paleozoic rocks.

The following section does not attempt to provide an exhaustive discussion of the complex stratigraphy of northeastern Arizona. The scope is limited to the source rock potential of the region. As the study of the Black Mesa region started it was recognized that the stratigraphy within the deep portion of the basin was poorly documented. The literature contained a limited discussion of potential source beds within the region. Many of the existing articles were not written from a petroleum perspective. More detailed reading, however, suggested that there were several potential source units within the Paleozoic section. In addition, several unconventional source beds were recognized. Initially, four general classes of possible or potential hydrocarbon sources were recognized for this region with its extensively faulted basement. These classes include, from deepest to shallowest:

1. Unonventional, ultra-deep-sourced hydrocarbons, hypothetically generated by complex endogenic processes within the Earth's deep crust or mantle, which escape to the shallow crust through exceptional faults or fractures,
2. Deep-sourced, conventional hydrocarbons, generated within a fine-grained, organic-rich Upper Proterozoic sedimentary sequence, the Chuar Group, which has been shown by testing (Palacas and Reynolds 1989; Rauzi 1990) to have a very high hydrocarbon source potential,
3. Conventional hydrocarbons transported into the Black Mesa region, by hydrodynamic forces, from source rocks or reservoirs in adjacent areas,
4. Conventional hydrocarbons, generated in situ within the Black Mesa basin from organic-rich Paleozoic or Mesozoic sedimentary source rocks in the study area,

A discussion of the primary possible source rocks follows.

3.1.1 Class 1 - Ultra-Deep Sources

The concept of ultra-deep hydrocarbon-sourcing from the mantle is still considered to be hypothetical, and is somewhat controversial in the United States, although it is more broadly accepted in parts of Europe and Asia. Widespread, high-quality helium accumulations and diatreme intrusives throughout much of the Four Corners region lend credibility to the idea that various ultra-deep, mantle-sourced materials have penetrated to the surface or near-surface geologic column in this area (Turner 1968). The history of the assemblage of the continental crust beneath Arizona (Karlstrom, Bowring, and Conway 1987; Karlstrom and Bowring 1991, 1993) and basement structure studies have shown that the basement in the northeastern Arizona region is highly faulted (see Fig. 3–1). These faults have produced extensive fractures in the shallow sediments. A series of repeated collisional orogenies and continental accretionary events during the Early Proterozoic produced a large number of massive, through-crust faults beneath Arizona that periodically have been reactivated during the Phanerozoic. These faults could have acted as a conduit for mantle-derived hydrocarbons. The BDM-Oklahoma Exploration and Drilling Group conducted a remote-sensing study to better analyze this deformation and associated hydrocarbon resources.

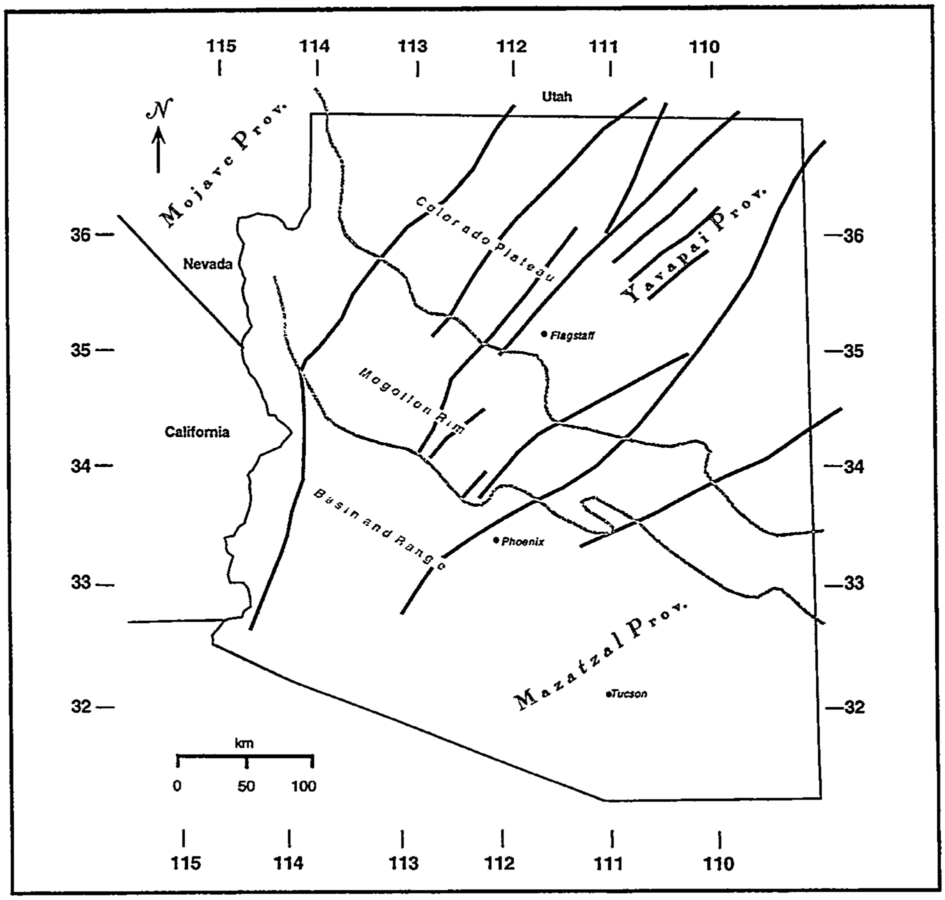


Figure 3–1 **Post-Laramide Tectonic Provinces (Gray) and Proterozoic Suture Zones (Heavy Lines) within the Basement of Arizona**

Many skeptics of the deep-sourced hydrocarbon concept have envisioned the intermittent leakage of very small quantities of hydrocarbons from the mantle which have a tendency to be dispersed widely as they migrate upward through a complex network of relatively vertical faults and fractures. These faults are dispersed comparatively evenly through a hypothetically relatively-uniform upper mantle and the entire crust, rarely concentrating in large, commercial quantities at any one place. An alternative scenario is leakage, from one source region or many, into a complex, deep network of inclined-to-vertical faults and fractures that follow deep structural features, like the remnants of subduction zones. In this model, the hydrocarbons tend to converge as they move toward the surface, ultimately being funneled through a few narrow necks, or fundamental, through-crust faults, in specific tectonic zones, concentrating, rather than dispersing the material during the final stages of migration, above fossil continental sutures and collisional structures.

The Black Mesa basin is a region where the latter scenario makes special sense. The structural history of Arizona includes two major collisional orogenies around 1.6-1.7 Ga, with multiple crustal sutures and through-crust mega-faults. These faults were reactivated repeatedly during a series of extensional events during the Proterozoic and Phanerozoic. The Laramide orogeny has included deep plate-subduction activity extending well into the area beneath Arizona. The Hopi Buttes, in the study area of northeastern Arizona, are diatremes, intrusive bodies with an ultra-deep source, perhaps as deep as the upper mantle. They originate when a subducting plate carries a large amount of water to the level of the Moho, or below. This water eventually flashes to superheated steam. The steam rises, slicing through the overlying rock like a knife. The Hopi Buttes represent the result, where large amounts of steam produced a relatively few eruptions, spread over a limited geographic area. Several other, more isolated diatremes are scattered around the Four Corners.

The overall pattern of diatremes at the Black Mesa and the surrounding areas suggests that a large amount of steam from depth-regions near the Moho erupted in a manner that tended to funnel and concentrate the steam bubbles into a small area, south of the Black Mesa. This suggests that the concentration of ultra-deep-sourced materials en route to the surface can, and does, happen in the real world. Many of the Hopi diatremes erupted carrying a combination of gas and ultra deep-sourced intrusive rocks, known as Kimberlites, to the surface. The Kimberlites have formed the distinctive, high, narrow buttes and extensive lava flows, south of the Black Mesa, many of which have been removed by erosion. Other diatremes had very minor amounts of associated lavas. The vents are largely hollow, in these cases, and the surface has collapsed back into the holes forming a series of sinks. Such tubes would provide an excellent migration path for mantle hydrocarbons. The surface pattern of the diatremes makes it obvious that the deep-sourced resource would concentrate in the same, limited area, south of the Black Mesa. Commercial quantities of helium are common around the area of the Four Corners and near the Hopi Buttes. This helium is also believed to have originated at great depths. The Black Mesa region is one of the prime areas in the United States where geologic structures make it obvious that mantle-sourced hydrocarbons could have been concentrated, rather than dispersed, on the route to the surface.

3.1.2 Class 2 - Deep Precambrian Sources

An unusual, organic-rich sequence, the Upper Proterozoic Chuar Group, has been identified in the Precambrian section at the Grand Canyon and in southern Utah. The Chuar forms the upper portion of the Grand Canyon Supergroup. The consideration of Precambrian rocks as potential source beds is unusual in the United States, although there are many locations in the former Eastern Block in Europe and Asia, China, and Australia where Precambrian oil production has been documented, and is even prolific. In the United States, hydrocarbon signs, shows, and seeps from the Precambrian have been known around the Lake Superior area since 1852 (Dickas and Mudrey 1991, 1992a, 1992b). Live oil has come from the Nonesuch shale of the Oronto Group, along the Mid-Continent rift. Stratigraphic studies, sample dating, and paleomagnetic, polar-wandering evidence indicates that the Oronto sediments of the Mid-Continent were deposited more or less contemporaneously with large portions of the Grand Canyon Supergroup deposits of Arizona (Elston 1986, 1989a, b, 1993). The potential for source beds in wedges of Precambrian sediments between the deep metamorphic and igneous basement of Arizona and the Paleozoic cover led to the determination that gravity and magnetic studies and mapping would be of particular value in the Black Mesa area.

Within the shallow Precambrian section, the source-rock and reservoir potential of dark, fine-grained, organic-rich, portions of the Chuar Group have been studied in detail, in recent years, on outcrops, mostly in the eastern Grand Canyon, and in samples from basement tests. The Chuar was named by Walcott who recognized in his initial report (1883) that the sediments contained what he described as traces of fossils. The 1883 paper assigned the Chuar to the Lower Cambrian, on the basis of the presence of fossils. He later (1886a, b) revised his dating, and assigned the Chuar to the Precambrian. Walcott (1899) describes the fossils in some detail.

The rocks of the Chuar Group were little studied during the early portion of this century. Noble (1914) did work on the Unkar Group, the lower portion of the Grand Canyon Supergroup, which was mapped by Maxson (1961), but the Chuar was largely ignored, other than by Hinds (1933, 1935a, b, 1936, 1938a, b), due to its relative inaccessibility in the upper reaches of side canyons off the Colorado River, west of the point where the Little Colorado enters the Grand Canyon. Van Gundy (1934, 1937, 1946, 1951) refined the boundary between the Unkar and the Chuar. Finally, in 1966, the Museum of Northern Arizona sponsored a helicopter expedition to the upper reaches of some of these tributary canyons to perform the most extensive, systematic study of the Chuar to that date. Ford and Breed (1969, 1972a, 1972b, 1973a, 1973b, 1974a, 1974b, 1974c, 1975) and Ford (1990) subsequently published several landmark articles concerning the Chuar, renewing interest in the formation, and calling additional attention to the fossil remains contained within these ancient beds.

Ford and Breed noted that the Chuar sequence included stromatolitic reefs and other biologic remains, but, at the time, this was apparently considered to be of interest primarily to paleontologists. The Chuar seems to have been largely ignored by the petroleum industry. Elston began work in the region of the Grand Canyon during the 1970s; and, in combination with several collaborators (Elston and Scott 1973; Elston and Gromme 1974a; Elston and Gromme 1974b; Elston and Scott 1976; Elston and Bressler 1977; Elston 1979; Elston and McKee 1982;

Elston 1986; Elston 1989a; Elston 1989b), expanded on the earlier work and produced a significant series of studies and articles. Elston's early work was largely concerned with paleomagnetic data, but his later efforts took more interest in the Chuar Group, specifically, and its stratigraphy. Elston and Scott (1976) updated the terminology for the Grand Canyon Supergroup to the standards of the current North American Stratigraphic Code, and Elston was the authority tapped by the Geologic Society of America to write the Chuar section for the Decade of North American Geology (DNAG) in 1993 (Elston 1993).

New studies and sampling, conducted in the late 1980s-early 1990s, led by Reynolds and/or Palacas, along with Elston and other associates (Reynolds and Elston 1986; Reynolds, Palacas and Elston 1988; Reynolds and Palacas 1988; Reynolds, Palacas and Elston 1989; Palacas and Reynolds 1989; Chidsey, Allison, and Palacas 1990; Palacas 1992; Pawlewicz and Palacas1992; Palacas 1993; Lillis, Palacas, and Warden 1995) have demonstrated that the Chuar includes potential hydrocarbon source beds in both Arizona and Utah, finally attracting the attention of the petroleum industry.

The quality and accuracy of the information on the Chuar has improved steadily since the Museum of Northern Arizona expedition in 1966. The Chuar Group was described again and remeasured during the 1966 field work. Ford and Breed (1973a) reported 6,610 feet (2,013 m) of Chuar in the eastern Grand Canyon. This value has continued to be used in numerous subsequent papers by Ford and Breed, and was cited by Elston in his early papers. The same figure has been referenced by other workers, including Rauzi as recently as 1990. Ford repeats the number in his 1990 paper, although he admits that this figure includes partially eroded Sixtymile Formation redbeds. Elston (1979) and Elston and McKee (1982) reassigned the Sixtymile to independent formation status. The Sixtymile redbeds, variously measured as 100-200+ feet (35-60+ meters) thick, are now believed to be end-of- or post-Chuar. They were deposited under conditions quite different from those which prevailed when the dark, fine-grained Chuar was accumulating. The Sixtymile Formation includes syntectonic, coarse redbed clastics, including sandstones and brechias associated with the early stages of large-scale block faulting. If the reassignment of the Sixtymile formation is correct, then the 1973 Ford and Breed number cannot be accurate. In addition, new work has been conducted in the field that is relevant to this issue.

Reynolds, Palacas and their collaborators have gone back to the field to collect samples for laboratory tests. While there, they have continued to redescribe portions of the Chuar, remeasuring and recalculating new values for the formation thicknesses. In the initial report from this work, Reynolds and Elston (1986) revised the values for the thickness of the Chuar downward. Reynolds, Palacas, and Elston (1988, 1989) again changed their values for the Chuar thicknesses, this time to 5373 feet (1,637 meters). Elston has kept abreast of this ongoing work and modified his values over the years. In 1982, with the Sixtymile Formation removed from the Chuar, Elston and McGee reported 6,223 feet (1,896 meters) for the thickness, still citing Ford and Breed as the authority. By 1989, the value had been updated to 5500 feet (1,676 meters), referencing Reynolds and Elston (1986) and personal communication with Reynolds (1988). Elston uses this number as the definitive value for the Chuar thickness in the DNAG volume (1993).

The following table is adapted from the DNAG volume, Elston (1993):

Table 3–1 Thickness/Environment of Deposition of the Chuar Group

Stratigraphic Unit and Unconformities	Age or Thickness (m)	Environment of Deposition of Formation Members
	Phanerozoic	
"Great Unconformity"		
	Late Proterozoic	
Grand Canyon Supergroup	3,623 (+)	
Sixtymile Formation	59-64 (+)	
Upper and Middle Mem.	37 (+)	Fluvial, Lacustrine?
Unconformity		
Lower Mem.	22-27 (+)	Marine/Subaerial
Chuar Group	1,676	
Kwagunt Formation	632	
Walcott Member	281	Marine or Lacustrine
Awatubi Member	301	Tidal Flat, Marine, or Lacustrine
Carbon Butte Member	50	Subaerial, Fluvial
Galeros Formation	1,044	
Duppa Member	104	Marine or Lacustrine
Carbon Canyon Member	350	Marine or Lacustrine
Jupiter Member	434	Tidal Flat/Lacustrine or Marine
Tanner Member	156	Marine/Marine or Lacustrine
Unconformity		
	Middle Proterozoic	
Nankoweap Formation	113-250 (+)	
Unkar Group	1,775	
"Greatest Angular Unconformity"		
	Early Proterozoic	

Walcott (1895), commenting on the "fresh" appearance of the Chuar, described "... no more evidence of metamorphism throughout ... the Grand Canyon series than there is in the ... Permian, Triassic, and Cretaceous ...." His notes on fossil remains within the Chuar mention "a minute discinoid or patelloid shell, a small Lingula-like shell ..., and a fragment of what appears to be ... a segment of a trilobite .... There is also a Stromatopera-like form that is probably organic." He concluded that "the strata were apparently deposited under conditions most favorable for the development of abundant life." These opinions were remarkably prescient for a geologist working with and under the concepts and prejudices of the nineteenth century.

Reynolds, Palacas, and Elston (1988, 1989) note that more than half of the Chuar sequence consists of organic-rich, gray to black mudstones and siltstones with common to abundant microfossils, interbedded with stromatolites and algal-rich carbonates. Palacas and Reynolds (1989) provide some additional detail on the components of the Chuar in a brief abstract. They list the Walcott Member as a good to excellent petroleum source rock, while the Awatubi and Galeros have a better potential, in general, as a source for natural gas than oil, although they recognize that selected beds within the Awatubi and Galeros could have generated significant quantities of oil.

It had long been assumed that the Chuar shales were marine or coastal tidal flat in origin. The environment of deposition for these units was exceedingly quiet, and persisted for a prolonged period of time. It is clear that water depths were quite shallow, and reducing conditions generally prevailed during the Chuar portion of the Late Proterozoic (Elston 1993). The work by Reynolds, Palacas, and various co-researchers, and by Winston (1990) has suggested that these beds were, at least in part, deposited in intra-cratonic lacustrine, or fluvial, settings. Ford (1990) acknowledges some of the early work of Reynolds and his collaborators, along with Elston (1986) and describes sedimentary features in the various members of the Chuar.

Ford (1990) describes the Tanner as having no identified primary sedimentary structures. He lists this unit as having accumulated in a starved basin, with a rich organic content. This description could fit an intra-cratonic sag or rift setting, although Elston (1993) points out that there should be identifiable stream deposits along the margins of such a setting, and these deposits have not been found. The Jupiter, above the Tanner, includes stromatolitic limestones at the base, becoming increasingly shaley upward. Ripple marks, mudcracks, and raindrop impressions are occasionally found in coarser-grained interbeds in the Jupiter. This unit has been interpreted as a shallow-water, coastal or alluvial plain deposit. The Carbon Canyon consists of interbedded, thin carbonate, shale and sandstone beds. Stromatolites occur in the carbonates, and mudcracks are seen in the sandstones. This could represent a coastal or swamp deposit. The Duppa Member is predominantly an accumulation of shale, with minor limestones. Ford (1990) describes this as an alluvial plain deposit.

Within the Kwagunt Formation, the Carbon Butte Member is distinguished by a thick sandstone at its base, the only thick sandstone in the entire Chuar Group. Cross-bedding and mudcracks are developed within this sand. The upper portions of the Carbon Butte are largely mudstones. The overlying Awatubi Member is once again composed predominantly of shales and mudstones. The Awatubi includes a 12-ft thick, massive stromatolitic layer, with numerous 8- to 10-ft biohermal domes. The uppermost unit of the Kwagunt is the Walcott Member. The Walcott includes dolomites, including algal remains and oolites, which could indicate a well-lit, energetic, oxygenated, environment in the surface and near-surface waters, in which primitive lifeforms could flourish. Black shales are also common in the member. The sediment color and structure indicate that bottom conditions included a reducing environment. This combination of conditions are frequently found in rift settings. Elston (1993) discusses the depositional setting of the Chuar briefly, and concludes that further study is required on these issues.

Just as additional work has refined the thickness information for the Chuar, the accuracy of the value for the organic content of the formation has been improving. Reynolds, Palacas, and Elston (1988, 1989) reported a 5% total organic carbon (TOC), a hydrogen index (HI) of 190 mg HC/g TOC, and a genetic potential ($S_1 + S_2$) as high as 6 kg/ton (6,000 ppm). With additional testing, Palacas and Reynolds (1989) found samples with numbers as high as 7% TOC (averaging ~3% TOC), an HI as high as 204 mg HC/g TOC (averaging 135 mg HC/g TOC), and a genetic potential of nearly 16,000 ppm (averaging ~6,000 ppm), for the lower Walcott. Rauzi (1990), citing personal communication with Palacas (1989), upgrades the TOC for the Walcott to as high as 8%. Chidsey, Allison, and Palacas (1990), cite 10% organic carbon. Reynolds, Palacas, and Elston (1988, 1989) determined a Rock-Eval T_{max} of 430-440°, indicating that the Chuar is thermally mature, within the principal oil-generation window.

Summons et al. (1988), have investigated and confirmed that the organic material in the Chuar is in place, and has not migrated in from younger, outside sources. They have also demonstrated that the organic content has not been significantly degraded or suffered appreciably from weathering, despite the great age of the rocks. The rocks fall into the mature region of the Van Krevelen diagram, and the original material included both type I and II kerogen. On a regional structural basis, the depths of burial and paleothermometry indicate that while the northern Arizona region falls within the oil window, portions of Utah, well to the north, may have reached the natural gas window. Rauzi (1989, 1990) has done much to publicize the potential for hydrocarbons within or sourced from the basement, and concluding that the Chuar has a high potential for hydrocarbon prospecting.

Rauzi has suggested that Chuar sediments may be preserved in a series of half grabens over a broad area of north-central Arizona and southern Utah, north of the Mesa Butte fault and west of the Organ Rock monocline, with particularly thick sections being preserved beneath the Kaibab, Kaibito, and Shonto plateaus. Rauzi states, however, that there is little possibility of the Chuar having been deposited and surviving in the region beneath the topographic Black Mesa. This view is still open to investigation and reinterpretation. Various reports in the literature suggest that Precambrian sediments may be preserved in outcrops as far to the east as the Defiance uplift. Much more work remains to be done on the extent of preservation of the Chuar beneath northeastern Arizona.

The Chuar Group is considered to be a prime potential candidate for hydrocarbon source rock and possible reservoirs under northern Arizona, especially in the western part of the study area. The beds may extend as far east as the structural Black Mesa basin, and beyond. Lineament and fracture studies provided clues to the possible locations of faults bounding the blocks where Chuar might be preserved. Gravity and magnetic studies provided clues as to the lithologic nature of the basement fault blocks, and to a large number of intra-basement and shallow intrusive igneous rocks.

3.1.3 Class 3 - Conventional Shallow Sources Outside the Black Mesa Basin Area

Overlying the late Precambrian Chuar Group sediments is a Paleozoic stratigraphic section with a number of potential source beds and reservoir formations for hydrocarbons. Production from this section is extensive in the Paradox basin, to the northeast of the Black Mesa region. Maps and drill-stem test data compiled by Chuska Energy, and information at the Navajo Nation Minerals Department provide strong evidence that a vast natural water sweep is pushing oil across Colorado, Utah, and New Mexico, toward and into northeastern Arizona. Meteoric waters are continuously entering the exposed ends of upturned porous Paleozoic rocks at high elevations on the western flank of the Rocky Mountains, producing a strong hydrodynamic head into the stratigraphic column on the Colorado Plateau. Fluid movement direction and speed varies from place to place, depending on the local stratigraphy, porosity, and permeability.

The oil front in the Mississippian section, which is exceptionally well-developed, thick, and contiguous over a large area of the Colorado Plateau, has advanced through Colorado, Utah, and New Mexico, and crossed the Four Corners, into Arizona, although it has not been determined how far into the state the front has progressed. The Chuska work has demonstrated that large quantities of oil have been mobilized in the Colorado Plateau region, and migrated toward the study area, validating the general concept that hydrocarbon reserves may have migrated into potential reservoirs in the Black Mesa region. Additional drilling and drill stem testing in the study area will be necessary to expand on the project initiated by Chuska.

3.1.4 Class 4 - Conventional, Local Shallow Sources

Numerous beds within the Paleozoic section have source rock potential in the study area (see Fig. 3–2). These include:

- the Cambrian Bright Angel shales of the Tonto Group,
- the Devonian Aneth shales and carbonates at the base of the Elbert Formation, and stratigraphically-equivalent, dark, fine-grained, organic-rich beds, frequently described as "fetid," within the Martin and Temple Butte Formations, to the south and west of the Black Mesa,
- organic-rich zones within the Mississippian Redwall Limestone,
- possible biohermal buildups within the Pennsylvanian section, and
- organic-rich zones within Permian shale sections.

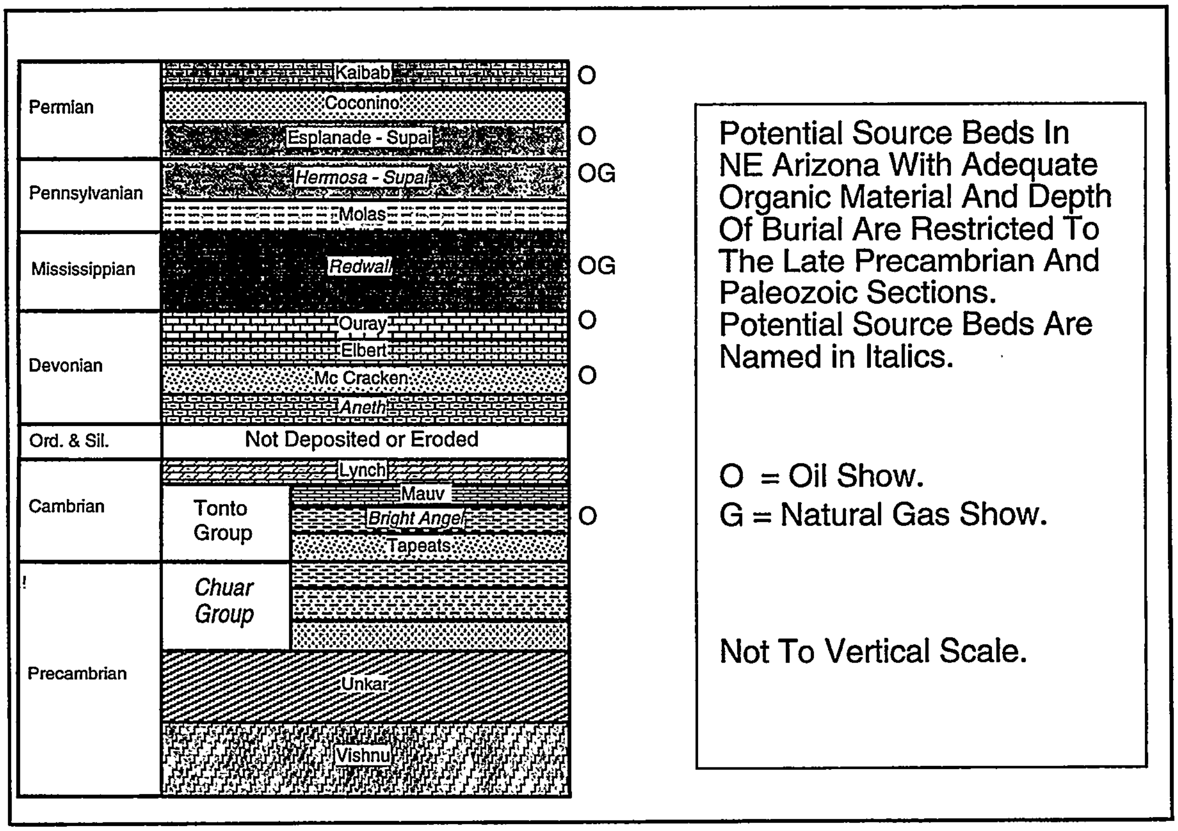


Figure 3–2 Stratigraphic Column

One to several of these zones may be present in any given well, depending on the location of the hole in the Black Mesa region. Most of the beds are exposed at the Grand Canyon. For additional discussion of the work performed by BDM-Oklahoma personnel on the Precambrian and post-Precambrian sediments and structures, see the NIPER FY 1995 Annual Technical Progress Report, and the NIPER Quarterly Technical Progress Reports, January 1995 (p. 91-111), April 1995 (p. 137-160), July 1995 (p. 140-159), and December 1995 (p. 106-115).

The following discussion emphasizes the key stratigraphic units of relevance to the oil and gas potential of the northeastern portion of the northeastern corner of Arizona.

3.1.5 Cambrian

Fine-grained Cambrian clastics are present throughout much of the study area. The erosion surface on top of the Precambrian was quite rugged when the Cambrian sediments were deposited in northern Arizona, and basal Cambrian thicknesses vary greatly across the region. Many low areas were filled with large amounts of fine-grained shale during the Cambrian. In many places the shales are topped by sandstones that could form reservoir beds. The combination of shales overlain by sandstones is ideal for the generation and trapping of hydrocarbons. The deep Cambrian units have experienced the greatest depths of burial of any of the Paleozoic section, and are generally in the oil window of thermal maturity in the study area. The Cambrian Bright Angel shales are up to 640 feet thick at the Grand Canyon. These shales thin, irregularly, beneath an unconformity to the east, toward the Black Mesa, although thick Cambrian sections may be encountered to the east on Precambrian lowlands.

3.1.6 Devonian

The Devonian Aneth and other shaley carbonate lithologies are not present in the Grand Canyon section. Irregular remnants of Temple Butte limestone, preserved beneath another erosion surface, are the only Devonian units identified in the eastern reaches of the Grand Canyon. Further to the west, in the canyon, the Devonian section is 250 ft thick, and is made up predominantly of dolomites and sandstones. The Temple Butte facies grades into the Martin to the southeast and into the Elbert formation and basal Aneth carbonates and shales, to the east.

Thickness and lithologic composition of the Upper Devonian Elbert/Temple Butte/Martin complex varies greatly across the study area. A deep-water crustal sag apparently formed, extending along a southwest-northeast trend from beneath the Black Mesa, into the southeastern corner of Utah, as Upper Devonian deposition began. Up to 200 ft of Aneth, overlain by a thick Elbert section, (Dwights) was deposited in the region beneath the Hopi reservation, known as the Oraibi trough. The unit thins to the west, south, and east of the sag.

Changes in thickness can be quite rapid. Nearby well control on the Coconino Plateau, a short distance west of the mesa, encountered only about 100 ft of Devonian sediments (Heylmun 1990). This section included interbedded shelf and tidal-flat shales, petroliferous limestones, and sandstones. Heylmun also reports that "The Martin contains petroliferous limestones at numerous outcrops in central Arizona, and in many drill holes it has been responsible for live oil and gas shows. Therefore, the Martin must be considered a prime drilling objective in the region." The Devonian section is very thin, or absent on much of the Defiance uplift, to the east of the trough, and on the ancient Defiance-Zuni positive feature, to the southeast of the mesa. Samples of the Martin from the Mogollon region, south of the trough, are also organic-rich, and are often described as "fetid." The Devonian section appears to have high potential as a source rock in this region and may have fed large-scale, conventional-style reservoirs in the overlying McCraken sandstone, also of Devonian age. The close proximity between shale/carbonate source beds and potential sandstone reservoirs is particularly fortuitous in both the Cambrian and Devonian sections around the Black Mesa. Devonian-sourced reservoirs could hold large quantities of resource, in conventional-style traps.

3.1.7 Mississippian

The Mississippian section at the Black Mesa consists of carbonates, primarily the Redwall limestone, across northern Arizona. Despite the name, the Redwall is a dark-colored unit, not a red formation that has been oxidized. The red coloration of the limestone in massive cliffs at the Grand Canyon is due to surface staining by material washing down from above. Dark, organic-rich zones exist within the Redwall, although they have often been ignored academically and in the literature. Many oil shows and some minor production have been recorded in the Redwall limestone around the Four Corners states. Mississippian carbonates have a demonstrated potential as oil source rocks, but have been minimally studied. The Oraibi trough may harbor an exceptionally-rich Redwall section. The variations in lithology within the Redwall appear to be sufficient for the unit to provide both internal sourcing and local reservoir conditions.

Oil in the Redwall could be concentrated in extensive fracture zones developed along monoclinal flexure zones. The Redwall tends to be a massive unit, which would behave in a relatively brittle manner where it is deformed and bent. Relatively few wells around the region have reached the Redwall, and far fewer have been completed in the Mississippian, thus, there is no Mississippian paradigm by which to gauge the "typical" Redwall reservoir size. If the Mississippian carbonate reservoirs resemble the overlying Pennsylvanian carbonate fields, they will be relatively small.

3.1.8 Pennsylvanian

The primary productive units in the Paradox basin, in southeastern Utah and northwestern New Mexico, are Pennsylvanian carbonates. These formations have been producing oil in Utah since 1907. Most of the wells that have been completed in northeasternmost Arizona produce from the Pennsylvanian section along the margins of the Blanding basin, a small peripheral sag on the margin of the Paradox basin. The Pennsylvanian production comes primarily from the Hermosa formation. Hermosa facies include a long string of low, thin, algal reefs which grew in an oxygen-rich, high-energy shelf-margin environment, at the edge of the deeper-basin waters, where abundant sunlight, wave energy, and oxygen encouraged a flourishing biota.

The Hermosa reservoirs have been studied extensively in all of the four states of the region, and the limestone plays have been found to be self-sourced, internally-porous within the reefs, and tightly sealed within surrounding shales. Individual reefs are also quite limited in size. The numerous fields have demonstrated that this type of reservoir, although small, can be quite prolific and economic to produce, even though finding costs/field can be quite high. The Pennsylvanian section has proven oil-generating potential.

The northern Arizona region has several other deeper-water areas similar to the Blanding basin, including the Oraibi trough and a new feature, the Holbrook basin, which began to deepen at this time around the town of Holbrook, south of the Black Mesa. Drilling on the Holbrook anticline, within the Holbrook basin, has been extensive, but the northern, western, and southern shelf edges around this basin are still largely untested. Almost no drilling has taken place on the shelf breaks around the Oraibi trough. Although field size in the Pennsylvanian can be small, most of the reefs are so prolific, when found, that relatively few wells have penetrated the section beneath the Hermosa.

The Pennsylvanian section has obviously been buried deeply enough to generate hydrocarbons in the area, even in relatively shallow regions like the Blanding area in northeastern Arizona. Sourcing from Pennsylvanian rocks is somewhat less expected on the Defiance uplift. There, the local Pennsylvanian rocks are thought to be the source of the oil in the productive intrusive rocks of Dineh-Bi-Keyah, the most-productive field in Arizona. The rocks in this area have seemingly been much more shallow than those in the Blanding basin. Similar conditions have prevailed on the Mogollon slope, near Alpine, where oil shows have recently been encountered in beds that have never been under a massive overburden.

3.1.9 Permian

The Permian section includes dark shales in the Supai and Toroweap formations, which are also considered to have source rock potential. Heylmun (1990) reports that fetid limestones have been encountered within the Permian section in test drilling on the Coconino plateau, west of the Black Mesa. This portion of the Plateau has not been buried as deeply as the Permian section within the central basin. Permian shows are also common in the Four Corners area, although the Permian section there does not have the production potential displayed by the Pennsylvanian rocks. The more-deeply buried Permian of the central basin may hold greater potential that seen around the peripheral areas.

3.1.10 Mesozoic

Some shows have been reported in the Mesozoic section on the southwestern Colorado Plateau, although these may be isolated cases of small, local sources, or they may have been hydrocarbons that migrated into the area where they were found. In general, the Mesozoic section is shallow, and may not have reached thermal maturity in any but the deepest portions of the region, or in special cases of volcanic heating. Much of the Mesozoic section is also of terrigenous origin, and is highly oxidized, making the survival of large-scale Mesozoic hydrocarbons extremely unlikely, according to conventional thinking.

3.2 Paleotectonic History of the Black Mesa Region

The next concern at the Black Mesa was gaining an understanding of the tectonics of the region. This was necessary to identify areas where the Chuar-filled grabens might be preserved, where source beds would have reached maturity, to identify potential migration routes for hydrocarbons, and to identify potential structural traps, including zones of secondary porosity and fracture reservoirs. An extensive study was conducted of existing literature and well records concerning the regional tectonics of the southwestern Colorado Plateau. Structure maps and cross sections were prepared of the study area. Examples of regional tilting and widespread unconformities were identified in the Paleozoic section, although the shallower Mesozoic and younger units are largely undisturbed, as is typical of much of the Colorado Plateau. Basement adjustments during the Laramide orogeny have produced an extensive set of monoclines. These flexures overlie deep-seated ancient faults which were reactivated during the Laramide compression. A few very-low-amplitude folds are also seen in the area.

The primary controlling structures in the southwestern Colorado Plateau area are a series of massive crustal-suture zones that pass beneath the region of the Black Mesa basin. These sutures extend through the entire continental crust and have acted as zones-of-weakness since they initially formed. Repeated movements and adjustments have taken place along these mega-faults, and their pattern has strongly influenced subsequent structures and events on the southwestern portion of the Plateau. The Chuar-filled half-grabens are generally bounded on one side by these breaks. Shallow fracture zones above these deep basement features may act as reservoirs for hydrocarbons. The ultra-deep portions of the weakness zones, penetrating through the lowermost crust, may provide routes for mantle-sourced hydrocarbons to escape to the reaches of the upper crust, allowing the accumulation of unconventional hydrocarbons in the sediments of the study area.

3.2.1 The Yavapai Collision

The sutures were formed during two successive episodes of accretion of suspect terranes against the then-southern continental margin of North America. The first occurred roughly around 1.7 Ga (Karlstrom and Bowring 1991, 1993), the second between 1.66 and 1.6 Ga. At the start of that time, the continental edge apparently ran near the California-Arizona border, then southwest-northeast through central Utah, to the northwest corner of Colorado. The ancestral portion of the North American plate that makes up northwestern Arizona, southeastern California, and northern and western Utah is referred to as the Mojave province of the North American plate.

Prior to the collision and continental-accretionary events, the region around the future Grand Canyon had apparently been a quiet coastal-shelf area with a landmass to the northwest. Shallow water covered the shelf, where fine-grained sediments were accumulating, and deeper offshore waters, with volcanic island arcs lay to the southeast. During the interval between 1.8 and 1.7 Ga, the island arcs collided, in series, with this coast, adding several long, narrow slivers of new material to the outboard edge of the continent. The pattern of peaceful shoreline sedimentation was disrupted, and the fine-grained sediments at the Grand Canyon were lithified, compressed, turned on end, and squeezed again. The contacts between these various island arc crustal slivers, and with the ancient continental slope have never formed a tight bond, despite high temperatures and pressures, and depths of burial.

A sizable mountain range formed at the collision zone. Along the former Mojave-province coast, the muds and shales were transformed into shales and mudstones, then altered further, eventually metamorphosing into the Vishnu schists in the region of the Grand Canyon. Precambrian granites and intrusive bodies were emplaced at many sites along the trace of the broad suture zones. Prior to the collision and metamorphism, the island arcs had been comprised of a number of facies, including volcanic rocks and a large sedimentary section. These rocks were also altered, generally being transformed to schists and associated, equivalent metamorphic facies. This island arc assemblage is exposed at a number of places along the Mogollon Rim. In central Arizona, these metamorphics have been named the Yavapai schist. These schists make up much of the basement block south and east of the Mesa Butte fault. Structurally, this series of elongate, narrow slivers, referred to as the Yavapai province, underlies most of the study area of the Black Mesa basin. The numerous, closely-spaced, parallel sutures in this zone probably account for the strongly-developed parallel drainage, washes and canyons which dissect the Black Mesa region. The sutures here represent zones where the crust has repeatedly adjusted to stresses, large and small, including diurnal tidal forces. Repeated, frequent movements along these fundamental breaks penetrating the crust have shattered the shallow rocks, allowing erosion to occur on traces above the faults.

Several large monoclines, including the Comb Ridge and Cow Springs, just northwest of the Black Mesa, have developed at locations where these suture faults were reactivated on a larger scale. The basement beneath the Shonto plateau, just to the northwest of the Black Mesa basin was uplifted by several hundred feet during the Laramide orogeny. The well control around the Black Mesa is insufficient to thoroughly trace the history of any of the specific basement faults during the Paleozoic era, but indications are that reactivation of the basement breaks were the controlling mechanisms that produced features like the deep, elongate, narrow Oraibi trough. The shape of the trough may closely match the shape of one of the island arc slivers within the Yavapai province. Movement on these same faults may explain some of the abrupt thickness changes in the Cambrian section in the Four Corners region.

3.2.2 The Mazatzal Collision

The highly-faulted Yavapai province rocks extend from northwestern Arizona to the Holbrook line, a geophysical feature made up of a southwest-northeast trending string of gravity and magnetic anomalies that passes close to the town of Holbrook, then to the area of Canyon de Chelly. A second wave of continental accretion began sometime around 1.66 Ga, and continued up to 1.6 Ga. At that time, a mini-continent or other series of large terrane blocks were added to the southern margin of North America. This episode shifted the continental shelf edge from the Holbrook line southeastward, well into New Mexico and the southeastern corner of Arizona. The zone is referred to as the Mazatzal province. A zone of intrusive basalt bodies was emplaced along the zone of weakness that follows the Holbrook line suture zone. Karlstrom et al. (1987) and Karlstrom and Bowring (1991, 1993) suggested that the Holbrook line is part of a transition zone, extending to the Jemez lineament, rather than a simple shear zone.

3.2.3 Suture-Zone Structures

The giant sutures, along the margins of the Mojave, Yavapai, and Mazatzal provinces in northwestern Arizona and the Holbrook line bound individual crustal blocks that were once independent continents, separated by oceanic crust. Slivers of ophiolites, remnants of oceanic crust, frequently get trapped along such suture zones. Most ophiolites tend to be quite dense, and may account for some of the gravity and magnetic anomalies along the Holbrook line and some of the other suture zones in northeastern Arizona. The Payson Ophiolite, which includes pillow basalts, is exposed along the Mogollon Rim, within the Mazatzal block, near the town of Payson. The sutures, in theory, extend through the entire crust, and are bounded by dissimilar rock types. They are of such magnitude in northern Arizona that many have never healed. They have remained as zones of weakness, and have repeatedly failed under stress, forming the loci of massive fault zones. The interior of the Yavapai province, beneath the Black Mesa, is cut by similar zones that once separated elements and blocks within island arc strings.

The sutures generally are assumed to be listric in shape, quite steep near the surface, where the crustal rocks are strong and brittle, but becoming lower and lower in angle with increasing depth, where the crust is subjected to much greater temperatures and pressures. Under high pressures and temperatures, rock strengths decrease, and lithologies become progressively more plastic. The fault angle that can be supported in a rock decreases as the rock becomes more plastic, so the suture zones become flatter with increasing depth. The plane of the great faults forms a ramp. The juxtaposed rock types at these sutures are frequently quite different in type, and can be separated by thin slivers of ophiolites or serpentines, remnants of the ancient seafloor, caught up along the suture zones. Serpentines tend to behave in a soft, plastic manner, and can act as a lubricant between slabs of continental crust. With the listric ramp surfaces lubricated by slippery ophiolites, the sutures become the site of repeated movements. In this configuration, the hanging wall tends to drop down when the region is subjected to tension, while it tends to rise under compressive forces. The structures that originated as sutures, thus, evolve into long-term zones of weakness, and very-large-scale faults, with recurrent movements over vast stretches of time.

The basement faults that are exposed in the Grand Canyon have been extensively studied. These faults demonstrate multiple phases of movement, with many reversals of direction over time. The earliest movements presumably date back to the 1.8-1.7 Ga events, while the most recent major movements are Laramide in age, showing the persistence of these features in structural control for the region. Some of the documented movements have been on the scale of a few feet, while others have been in the range of thousands of feet. A general understanding of this crustal fabric is necessary to comprehend many of the later structural events in northern Arizona. Recognizing that the topographic Black Mesa and the plains to the northeast and southwest are underlain by a different geologic province than the regions to the northwest and southeast is important for the interpretation of basement lithologies, densities, and magnetic character. It also explains the strongly-developed, parallel orientation of the drainage through the area.

3.2.4 The Greatest Angular Unconformity

The northern Arizona region appears to have been relatively quiet, tectonically, following the Yavapai and Mazatzal events. An extended period of erosion reduced the mountain ranges along the sutures to low relief, producing a significant unconformity at the top of the metamorphic section, dubbed, by Noble (1914), the "Greatest Angular Unconformity." At many places around northwestern Arizona, the Vishnu schist and associated granites are overlain by a Proterozoic sedimentary sequence. In these locations the unconformity represents a 400+m.y. gap, stretching from ~1675 Ma to ~1250 Ma (Elston 1989). At other locations, the Proterozoic sediments were never deposited, or have been removed by erosion, and the Vishnu is succeeded directly by Cambrian sediments. Walcott (1894, 1895) depicts the erosion surface beneath the Cambrian as the "Great Unconformity." In areas where the Cambrian directly overlies Vishnu schist, the Greatest Angular and Great Unconformities merge, and the break represents well over a billion year interval of erosion, possible local deposition, and renewed erosion, from ~1675 Ma to ~570 Ma (Elston 1989). In areas where intervening late Middle and late Proterozoic sedimentary sequences intervene between the schists, gneisses and granites and the Cambrian sediments, the erosional gap at the Great Unconformity represents only 200±m.y., from ~800 Ma to ~570 Ma (Elston 1989).

3.2.5 Middle Proterozoic Unkar Deposition

Eventually, deposition resumed in the lowland areas during the late Middle Proterozoic. The Unkar Group sediments were deposited at this time. In general, Unkar rocks are unmetamorphosed or, at most, lightly metamorphosed, but they have little potential for hydrocarbons, due to a lack of organic content.

3.2.6 Late Proterozoic Chuar Deposition

The Unkar Group rocks are overlain by another sedimentary series, of Late Proterozoic age, the Chuar Group (Rauzi 1989, 1990; Reynolds and Elston 1986; Reynolds, Palacas, and Elston 1988, 1989). These rocks accumulated in a series of shallow sags or rifts (see Fig. 3–3a) that formed in the southwestern United States, apparently during Keewenawan time, the same period that the Mid-Continent rift was forming through the Great Lakes and Mid-Continent region. The best-developed, ultra-deep portion of the Mid-Continent rift runs through western Lake Superior. When this trend is extended to the southwest, it projects along the axis of the Transcontinental arch, the Colorado Mineral Belt, and directly into the Chuar rift areas of Utah and northern Arizona.

It is unclear how the Mid-Continent rift is related to the depressions of the southwest. The exact timing of the respective extensional events is unknown, but the existence of simultaneous, or near-simultaneous, episodes of rifting on a single trend appears to be more than coincidence. There is, however, a significant difference of scale between the deformation in the midwest and that in the southwest. While the Mid-Continent rift has been described as the deepest, and most-advanced failed rift identified thus far on the planet, the event was much less dramatic in Arizona. The floor of the Lake Superior portion of the Mid-Continent rift has dropped almost to the level of the Moho, nearly cutting through the entire crust, while the thickness of the Chuar sedimentary accumulation indicates that movements in Arizona were only in the range of a few thousand feet. Measurements at the Grand Canyon have recorded less than 7,000 feet of Chuar, insignificant compared to the rift fills of the central states.

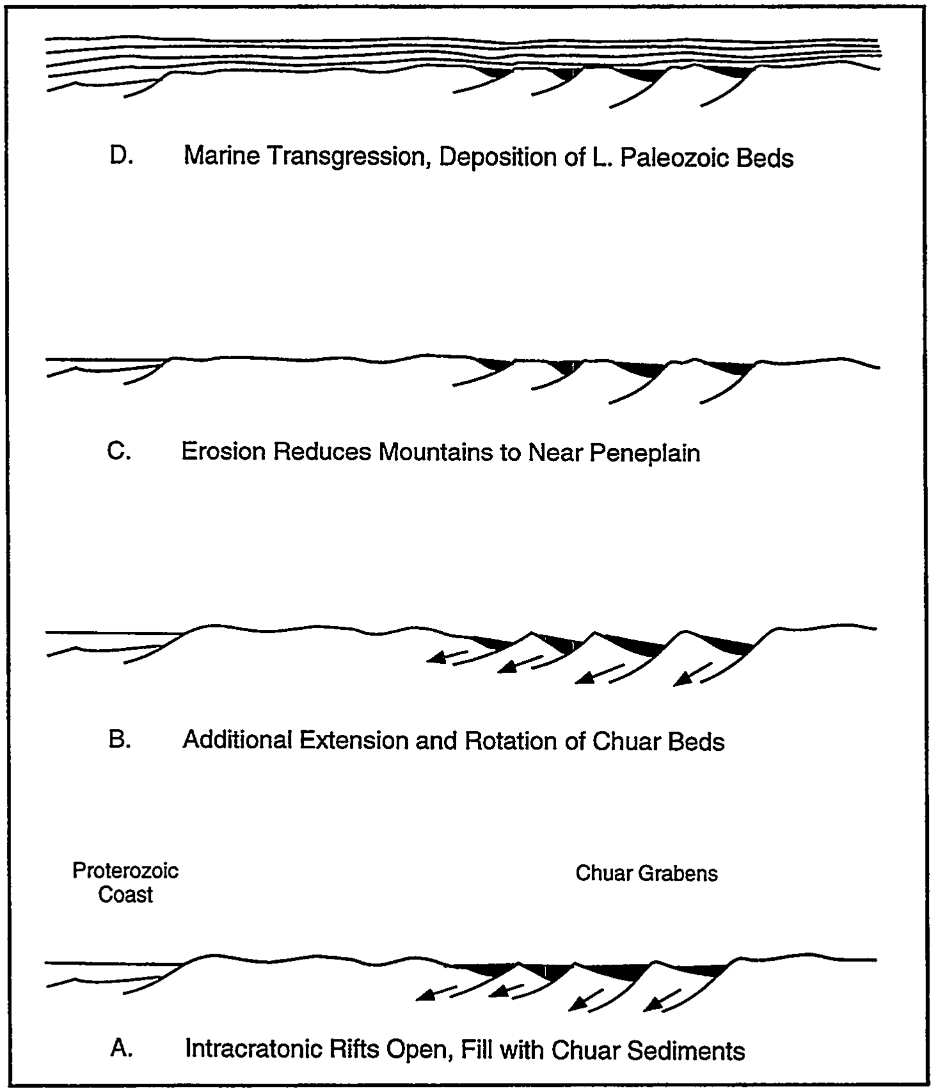


Figure 3–3 Tectonic Setting of the Chuar

Exposures of the Chuar are limited, and the location, orientation, and morphology of the Late Proterozoic depocenters is speculative. The Chuar basins generally formed by reactivation of the suture-zone faults, although it is uncertain if the sediments were deposited in true rifts, in deep valleys between flanking uplands, like the African rift valleys, or if these were simply slight depressions on a low-relief swampland, coastal plain, or lowland surface. Rauzi (1990) has discussed the current state-of-the-art thinking on the extent of the Chuar basins, but there is much more to be learned about this phase of tectonic activity and sedimentation. Gravity and magnetic approaches were used as a means to study the Chuar structure in the Black Mesa region.

The organic material in the Chuar is thought to be primarily the remains of algae and fungi. These lifeforms resemble types that would have flourished in a lacustrine setting. Such lakes are common along the African rifts, but could just as easily have formed on a lowland plain setting with local, small-scale sags. Shallow, sunlit lake waters can support a lavish organic mix in the surface waters and shallow-water algal reefs along well-oxygenated shoals, helping to explain the high organic content of the Chuar. The deeper lake waters are generally quiet, with a reducing environment, allowing the accumulation of abundant source material for hydrocarbons in the lake floor sediments.

3.2.7 Grand Canyon Orogeny Block Faulting

Following deposition of the Chuar, there was a massive-scale reactivation of the now-billion-year-old suture faults, with Basin-and-Range-style block faulting across the Arizona-Utah area (see Fig. 3–3b). These events have been dated at approximately 0.8 Ga. Many of the block faults followed the typical northeast-southwest orientation, although some activity occurred along north-south breaks which also formed part of the ancient system. Offsets on these normal faults have been recorded in the range of 10,000-12,000 feet, although they may have reached 15,000 feet in places.

3.2.8 Southeast-Northwest-Oriented Basement Structures:

At some point during the Precambrian a deep-seated southeast-northwest-oriented structural trend developed in the basement. The origin, structural affinities and age of this trend are unclear. This trend may predate the events discussed above. Several large-scale positive and negative structural trends in the Four Corners follow this orientation. These include the long-lived Defiance-Zuni positive feature, which may have originated during the Precambrian, and which certainly existed as a positive element from Cambrian time well into the Paleozoic, the Circle Cliffs–Monument-Carrizo string of positive structures, the elongate Paradox basin, which developed primarily during the Pennsylvanian period, and several of the Laramide-age monoclines. The Kaibab uplift may represent an intermittently-positive extension of the Defiance-Zuni uplift. The San Juan basin is on trend with the Paradox.

The southeast-northwest structures seem to have an exceptionally deep-seated origin. Several of the volcanic trends of the southwestern Colorado Plateau follow these orientations, most-significantly, the Hopi Buttes diatreme intrusives, which may originate from the depth of the Moho. The Four Corners area is also the site of some of the largest and highest-quality helium fields in the United States. Helium is generally assumed to originate at extreme depths, perhaps within the mantle. The largest helium accumulations are concentrated along the southeast-northwest positive basement trends. Many of the uranium ore concentrations of the Four Corners also follow these trends. The leakage of ultra-deep-sourced materials at the Four Corners is strongly associated with the southeast-northwest-oriented positive areas, reinforcing the concept that these trends are associated with features within the deeper crust or upper mantle. The southeast-northwest orientation parallels a number of continental-scale structural trends which extend across North America from Canada and the Appalachian region, through the Mid-Continent, to the Cordillera. This wide-spread pattern may reflect a global-scale structural grain formed well below the surface in response to tidal forces. Gravity and magnetic maps also show a number of trends and features with this orientation.

3.2.9 Post-Grand Canyon Erosion

The 0.8 Ga events are referred to as the Grand Canyon orogeny. Initially, the latest Precambrian topography should have resembled that of the modern Basin and Range in the western United States, although the Basin and Range is a young geomorphic form, and the Precambrian landscape in Arizona eventually advanced to a super-mature stage (see Fig. 3–3c). Following the block faulting, erosion continued in the region for 200-300 Ma, greatly reducing the elevation of the mountains and hills, eventually eroding even the basin fill. The topography on the erosion surface was apparently quite varied. At places around the Grand Canyon exposures, the erosion surface is described as being remarkably smooth and regular. In other locations, considerable relief can be documented. Drilling has shown that high hills existed on the Precambrian surface to the east, around the Four Corners and near Holbrook, where there has been sufficient drilling to provide some control over relatively short distances, from well to well.

Any Chuar and Unkar sections which existed on the uplifted, Range side of these faults was completely eroded in most or all of this area. The detritus removed from the ranges would have quickly filled the adjacent basins between the ranges with many thousands of feet of post-Chuar, latest Proterozoic sediments composed of mixed, eroded schists, gneisses, and other metamorphics and volcanics, combined with reworked Chuar and Unkar clastics. However, the erosion continued for such a prolonged period, and was so extensive, that this sedimentary section has itself been eroded away in all of the areas that are exposed around the Grand Canyon. This prolonged episode of erosion and removal of massive amounts of material has produced a filter that makes it very difficult to identify the paleogeography of pre-block-faulted Middle and early Late Proterozoic Arizona. On the basin-side of the faults, erosion has cut down to the levels of the Chuar and Unkar sediments which originally floored the downthrown, basin-sides of the faults. The material that was eroded from this area has seemingly disappeared, and was apparently washed from this region to an unidentified Late Proterozoic ocean shore or offshore area.

3.2.10 Latest Precambrian Setting

Basement control in the Four Corners region is extremely limited. Reported basement tops and lithologies are questionable in many of the older wells. It is conceivable that some of the anomalies and irregularities in "Cambrian" sections and basement lithologies may be due to wells that have penetrated some unrecognized latest Proterozoic sedimentary section that is locally preserved in a low on the latest Precambrian land surface. By the end of the Precambrian, the topography throughout the Four Corners region must still have been somewhat rugged. A number of local hills apparently projected well above the plains. While Cambrian or Devonian sediments directly overlie much of the Precambrian, some of the local hills were not covered by sediments until Mississippian or Pennsylvanian time. A larger highland region extended along the Defiance-Zuni positive feature. The irregular topography led to a complicated depositional pattern during the Cambrian period. It could be difficult to distinguish between Chuar and latest Precambrian sediments using gravity and magnetic approaches.

3.2.11 Cambrian Setting

The long period of erosion finally ended, and waters once again spread across northern Arizona during the Cambrian (see Fig. 3–3d). The land surface sloped gently to the west or northwest at that time. Deposition began near the Arizona-Nevada-Utah corner, and spread to the east and south, toward the Black Mesa. The region was apparently part of a relatively quiet, shallow-water shelf at this time, with the water generally deepening regionally to the northwest (see Fig. 3–4). The stratigraphy and supposed depositional environments of the Cambrian throughout northern Arizona are generally based on the interpretation of exposures at the Grand Canyon and their projection over large distances. Well control is generally inadequate to identify facies changes, abrupt thickening or thinning, depositional breaks, or other sedimentary irregularities within the deepest Paleozoic sediments across most of the region to the east of the Grand Canyon. Several wells around the Four Corners have no reported Cambrian sediments, are missing portions of the Cambrian section, or have unusual facies beneath the last easily-identified Paleozoic beds. The anomalies are generally attributed to Precambrian hills, although it is possible that some of these features could represent the effects of lower Paleozoic reactivation of faults that have not been documented in the region. Gravity and magnetic studies could also be used to identify thick accumulations of potential Cambrian reservoirs. At most locations, the Cambrian sediments include a juxtaposition of Bright Angel Shale and overlying Tapeats Sandstone. This is the ideal combination of potential source rocks, the shales, immediately capped by a possible reservoir formation, the sandstone.

3.2.12 Post-Cambrian Setting

Following the episode of Cambrian sedimentation, sea level fell, exposing most of the northern Arizona–southern Utah region, leading to widespread erosion. A regional unconformity developed on the Cambrian sediments, further confusing the interpretation process for the Black Mesa. The Four Corners tilted slightly to the northwest, causing more extensive erosion in the eastern reaches of the study area. It is unclear if the Defiance-Zuni positive feature developed at this time or if it predated this tilting. Well control is inadequate to determine if the ancient faults moved substantially around the Black Mesa at this time period. There appears to have been little or no sedimentation around the study area during Ordovician, Silurian, or Lower Devonian time.

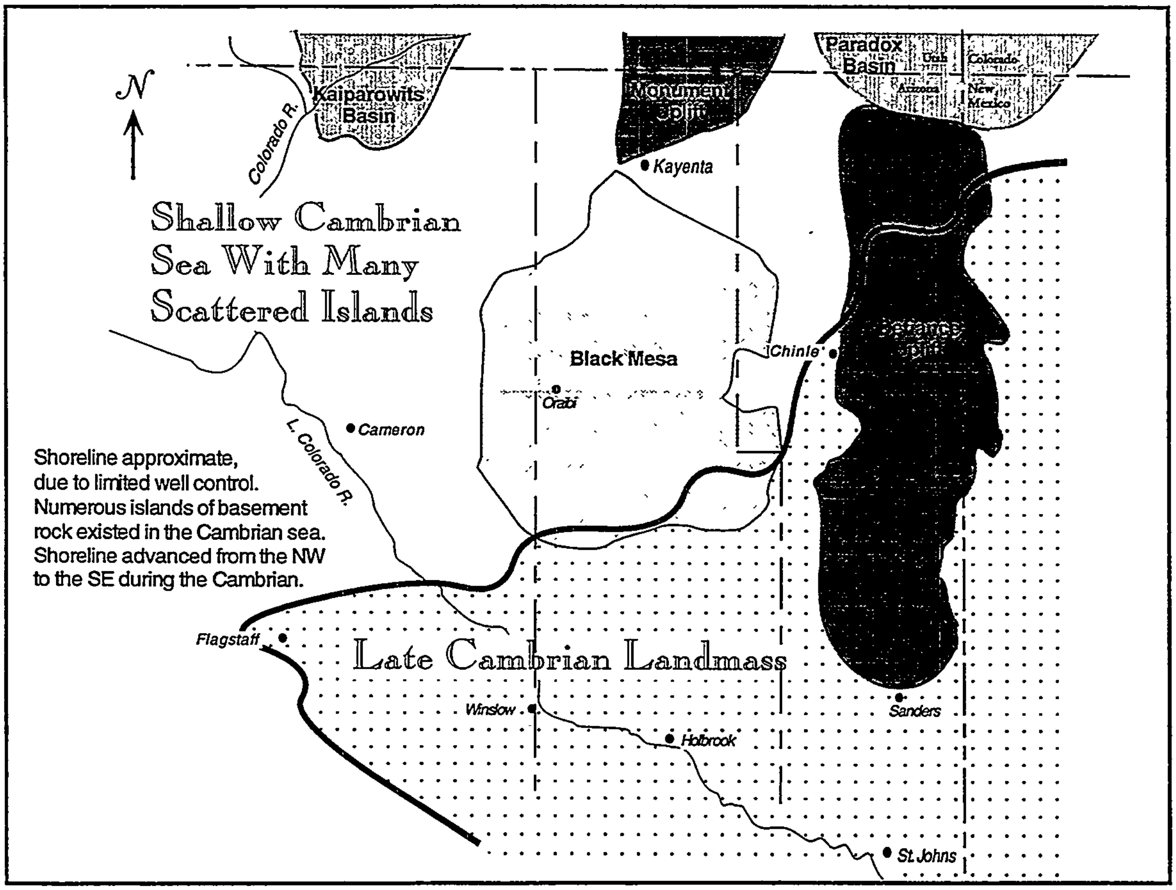


Figure 3–4 Approximate Limit of Cambrian Deposition

3.2.13 Devonian Setting

During the Middle Devonian, the sea spread once again across the study area as the Plateau region tilted farther to the west (see Fig. 3–5). There is some evidence of movements on the intra-basement suture faults at this time. An elongate, narrow sag, the Oraibi trough, developed in the area of the Black Mesa basin. A long tongue of Devonian Aneth sediments were deposited along the axis of this depression, underlying the center of the main study area. The axis of this trough parallels the grain of the basement faults, and the depocenter is just to the southeast of the Cow Springs–Comb Ridge basement fault. Relaxation on this fault may have allowed the block beneath the basin to drop. The process created a shallow, quiet-water depression, with restricted waters and a reducing environment. Large quantities of fine-grained, clastic and carbonate sediments accumulated in this environment. A high organic content has been documented in the Devonian at several locations. In other places, there is no existing well control, but the environment seems to have been similar. The Aneth carbonates and shales have been documented as source beds in the Four Corners area. The Aneth thickness in the trough varies, but reaches between 150 and 200 feet in some wells. The Aneth beds are overlain by McCracken Sandstone, a potential reservoir unit.

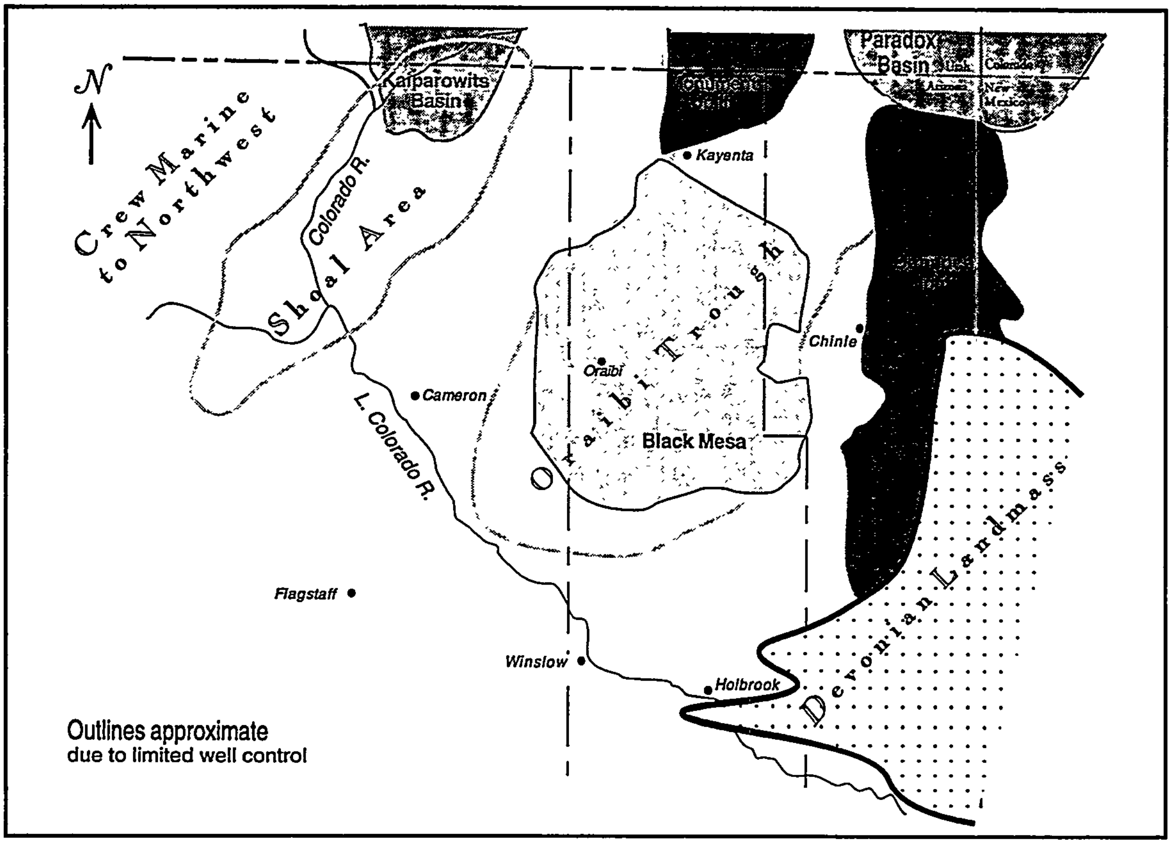


Figure 3–5 Approximate Limit of Devonian Deposition

3.2.14 Post-Devonian Paleozoic Setting

The Mississippian sedimentary section includes extensive carbonates, and represents a relatively quiet tectonic period. Regional tilting at the end of the Mississippian led to the development of another wisespread unconformity.

During the Pennsylvanian, a major crustal sag formed in eastern Utah and southwestern Colorado, following the ultra-deep southeast-northwest orientation. This large depression, the Paradox basin, lies between the Uncompahgre uplands, on the northeast, and a string of positive features, the Circle Cliffs–Monument-Carrizo positive structures on the southwest. The region has become a significant oil- and gas-producing region in the Four Corners, and is on trend with the prolific San Juan basin, farther to the southeast. An additional, smaller, sag, the Holbrook basin, formed in east-central Arizona during the Pennsylvanian. The Defiance-Zuni positive feature was still relatively high through this time period. Several faults that were activated at this time have apparently been identified by gravity and magnetic studies.

Large amounts of sediment continued to accumulate in the Paradox and Holbrook basins during the Permian period. The Defiance-Zuni positive feature was finally covered with sediments during the Permian period. From Permian time on, the basement high has been continuously covered by sediments. The Holbrook basin deepened significantly during the Permian. Permian sediments within this basin are as much as 1,500 feet thicker than would be expected, based on regional isopach trend.

3.2.15 Mesozoic Setting

By Mesozoic time, the Paleozoic seas had retreated, and thick terrigenous Triassic and Jurassic sections were deposited over much of the Colorado Plateau region. The sediments were deposited on a stable basement, therefore, the section was relatively undisturbed during deposition. During the Cretaceous, a seaway spread across the eastern and central portions of the Plateau, to the north and east of the study area.

3.2.16 Laramide Tectonics

At the end of the Mesozoic era, the western portion of the North American continent was subjected to compression, folding, and faulting during the Laramide orogeny. The Colorado Plateau was elevated, with minimal internal deformation, due to complex interactions between regional stresses and an unusually thick crust in the region of the plateau. The general northern Arizona region may have risen by as much as 7,000 feet, at this time. The uplifts, upwarps, saddles, and other positive areas have been elevated by as much as 14,000 feet, leading to the present day pattern of uplifts, divides, and basins. Most of the deformation within the plateau occurred due to reactivation of the Precambrian sutures and fault zones.

Many of the major Yavapai- and Mazatzal-age Precambrian basement faults on the southwestern portion of the Colorado Plateau were reactivated during the Laramide orogeny. The sites of the reactivation are obvious. They form the characteristic monoclines on the Colorado Plateau. Reactivation of the ancient faults has broken the basement floor into a series of steps or shelves. The Paleozoic and Mesozoic beds on these shelves retain very gentle regional dip trends, then abruptly tilt to very high angles, sometimes passing through vertical, as they break over the edges of the monoclines. Figure 3–6 shows a cross section through the Black Mesa region, with steep dips along monoclines at the edge of the Defiance uplift and to the west of the deep, central basin. With the exception of these two areas, the Phanerozoic sedimentary beds are nearly flat, with gentle warping.

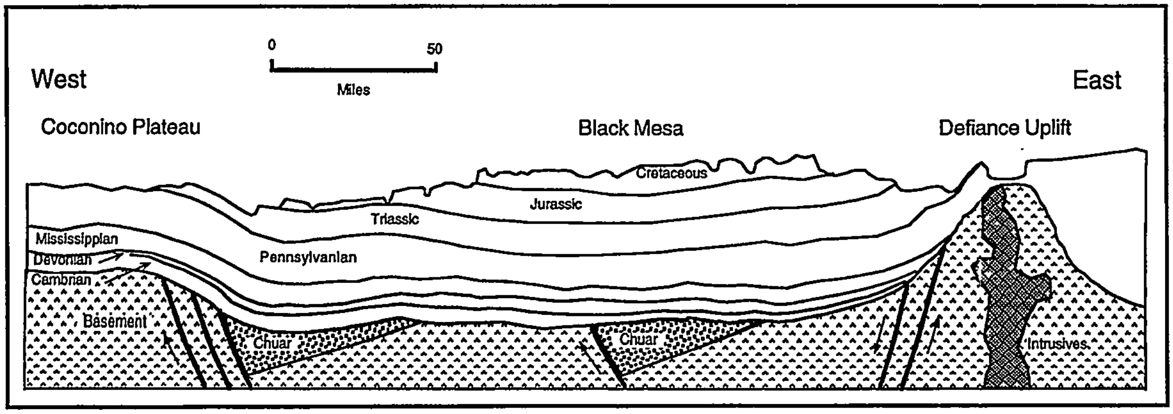


Figure 3–6 **Structural Cross Section of the Black Mesa Region with Hypothetical Chuar-Filled Grabens in Basement**

3.2.17 Post-Laramide Intrusive Activity

The gravity and magnetic signature of the southwestern United States became much more complicated in post-Laramide time. Following the Laramide faulting and folding events, the southwestern Colorado Plateau has been relatively quiet, tectonically. The region has been impacted, however, during the Late Mesozoic and Cenozoic by side effects of plate tectonic events far to the southwest. Subduction of the Farallon plate, off the California-Mexican coast, led to a series of volcanic events throughout the southwestern United States. As the Farallon plate was subducted beneath the North American plate, oceanic crust and associated sediments sank to regions where the material melted and became unstable at depth. A series of deep-seated intrusives, volcanoes, diatremes, and minor dikes developed over a prolonged period across the Four Corners region. In most cases, these intrusive bodies followed the ancient zones of weakness and the southeast-northwest basement trends. The emplacement of recent volcanics into an area which had already been a favored zone for Precambrian intrusions greatly increased the difficulty of accurate interpretation of gravity and magnetic data.

Most of these volcanic features were relatively "conventional," although the diatremes, best-developed around the Hopi Buttes, are quite unusual. The diatremes formed when oceanic crust with an unusually-high water content plunged to tremendous depths, reaching the level of the Moho, beneath the Hopi Buttes area. Water is inherently unstable at these depths and temperatures. In most cases, free water does not reach these depths. When it does, it "explodes" into "bubbles" of superheated steam, and erupts toward the surface. It escapes from these tremendous depths, cutting through the overlying crust in an extremely short period of time, perhaps within as little as twenty minutes.

At the Hopi Buttes, fragments of deep and shallow crustal material, along with surficial sediments, were blown out of the vents at these diatremes. Many of the eruptions were accompanied by basic volcanics, of ultra-deep origin, although other vents released gas, with little associated magma. The gaseous eruptions produced a series of collapse structures, following the eruptions, while the magmatic eruptions produced the high, steep-sided buttes typical of the region south of the Black Mesa. Diatremes are known from other parts of the world. In most places, diatremes are nonmagnetic. At the Four Corners, many of the diatremes can be identified as highly magnetic.

3.3 Additional Studies

In this complex setting, a series of gravity and magnetic studies was undertaken, using information from maps, including trend maps and residual anomalies. Literature searches were conducted, computer programs were developed, and computer analyses and modeling were performed. These are discussed in the following sections.

4.0 GRAVITY AND MAGNETIC MODELING

The analysis and modeling of potential field data, such as gravity and magnetic information, can provide valuable clues to the structure and tectonic deformation of deeply-buried basement rocks. This is due to the fact that metamorphic and igneous rocks within the basement have high densities and magnetic susceptibilities compared to most sediments. The contrasts between the signatures of dense basement rocks and those of sediments give rise to anomalous gravitational and magnetic fields whenever there is a complex distribution of these rocks.

Key targets in the exploration project for the Black Mesa basin include Late Precambrian Chuar sediments which have been preserved in deep half-graben structures within the basement and lower Paleozoic formations which accumulated in sags on the basement. The structure and tectonics of the massive basement suture zones and faults have controlled the configuration and thicknesses of the deeper Paleozoic formations. Thus, gravity and various types of magnetic (ground, airborne, etc.) data may be used for studying structure and faulting in the older sediments. Graben structures in the basement are excellent targets for gravity and magnetic exploration methods.

The gravity anomaly in an area is primarily dependent upon two main factors:

- the depth of the body below a reference datum, and
- the density contrast between the body and the surrounding rock mass.

The accuracy of the interpretation of gravity data is dependent upon the availability of data on lateral density variations. This information can be obtained from various sources like outcrops, sample analysis, wireline logs, geologic projections, etc. The effective integration of information from various sources like magnetic, satellite imagery or other remote sensing data is invaluable in providing depth and density constraints or in removing certain ambiguities in the analysis and interpretation of gravity data.

4.1 Program for Modeling Gravity Data

The extraction of reliable structural information from gravity data requires the application of rigorous modeling of gravity data. An understanding of the gravitational attraction of local geological structures is necessary for this work. To aid in this work, new, original computer code has been written specifically for use in this study.

FORTRAN was used to write a useful algorithm and computer codes for a program which can be used to calculate the gravitational attraction of two-dimensional bodies of arbitrary shapes. This program is based on the formula for the gravitational effect of two-dimensional bodies which was developed by Hubbert (1948) in the form of a line integral. To make Hubbert's formula more useful in practical application and actual calculations, Talwani, Worzel, and Landisman (1959) transformed the line integral to the form of an integral around the periphery of an "n"-sided polygon. Using this transformation, the exact attraction of a two-dimensional body, described by the sides of an n-sided polygon, may be obtained by numerical integration along the periphery of the polygon. The number of sides of the polygon, "n", can be increased in order to describe the causative body as precisely as desired.

This new gravity modeling program, called Gravanom, can simultaneously calculate the gravitational effects of a large number of beds or other geological bodies (like intrusive rocks at various depths) and sum their individual contributions to obtain the total effect of all the geologically-modeled objects at the point of calculation. The required input data for the program consists of a density value for each bed, coordinates for each corner of the polygon describing the geological body, the intervals at which the calculations are to be performed, the total number of structures in the model for calculations, and any regional gravity corrections that need to be added to the calculated values for a comparison of the calculated and the observed values.

The computer program was tested and verified using the gravitational attraction of simple geological structures such as a horizontal cylinder and a vertical fault for which known, standardized analytical expressions of gravitational attractions are available. The program was written with double precision arithmetic for maximum accuracy. The most time-consuming step in gravity modeling is the determination of the input to the coordinates of the large number of polygons used to describe the geological formations. A digitizer was adapted to input the polygon coordinates for the program. This reduced the time and labor required for data input.

4.2 Modeling of Black Mesa Gravity Data

Gravanom was used to model geologic structures along four profiles (see Fig. 4–1) based on observed residual Bouguer gravity data at the Black Mesa basin. The gravity-anomaly values were taken from maps published by Gutman and Heckmann (1977), who obtained the data from various sources and reduced it to a common datum. The lines follow the following courses:

- A 175 km, NE-SW-trending profile (A-B on Figure 4–1), running from Red Lake, in the southwest, to the Chinle Valley, in the northeast,
- A 187.5 km, N-S-trending profile (C-D), running from Kayenta, in the north, to Holbrook, in the south,
- A 187.5 km, NW-SE-trending profile (E-F), running from the Kaibito plateau, in the northwest, to Ganado, in the southeast,
- A 287.5 km, SW-NE-trending profile (G-H), running from the Cameron area, on the Coconino plateau, to the Four Corners area, in the northeast.

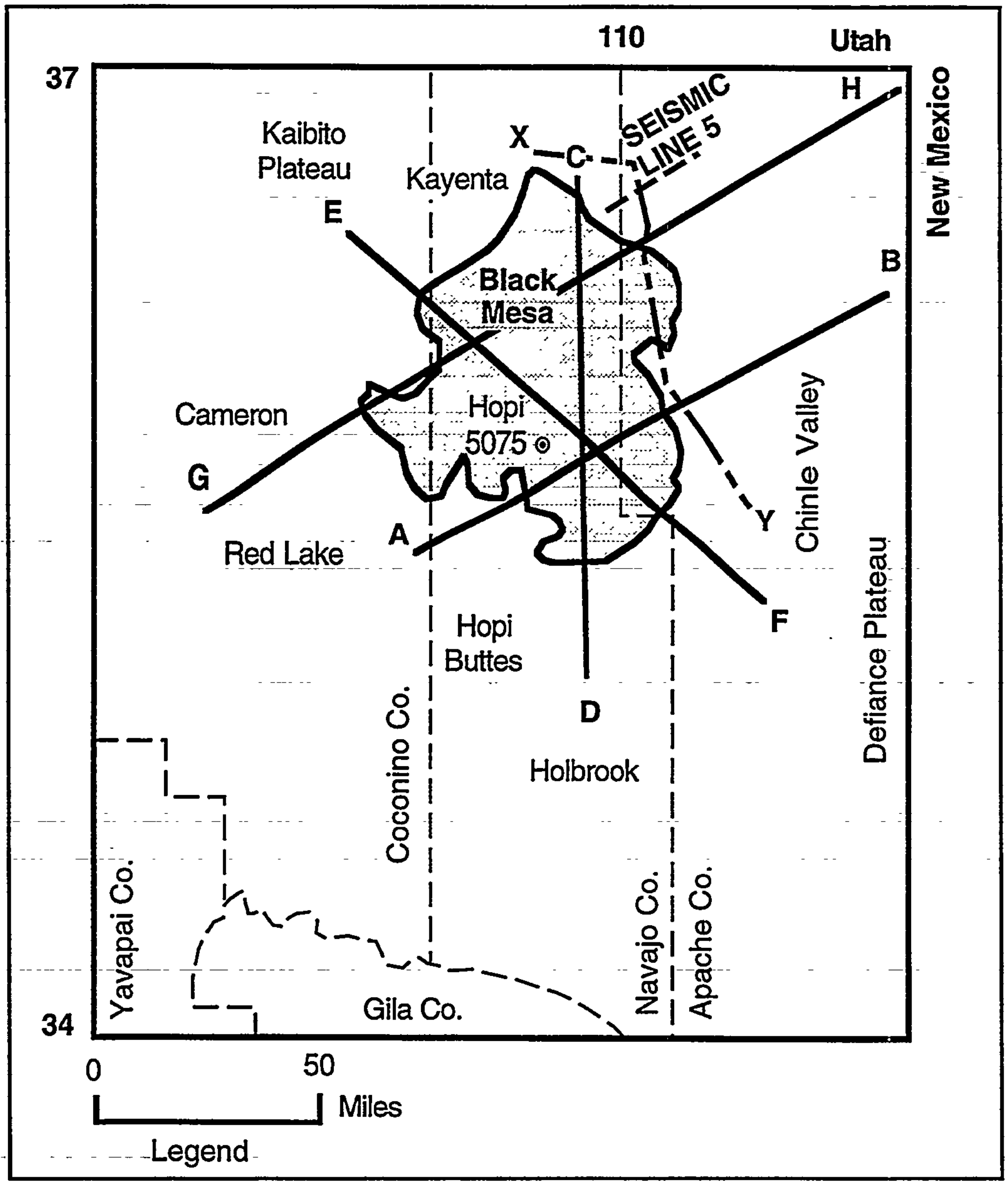


Figure 4–1 Base Map of Geophysical Lines, NE Arizona

Before initiating the model studies, it was necessary to gather data concerning density distributions in the various formations from wells drilled close to the profile. Data were obtained from Aiken and Sumner (1972), Jenkins and Keller (1989), and Pierce, Keith, and Wilt (1970). The density data were obtained primarily from wireline density logs, with some additional values from laboratory measurements of core samples and the literature. After examining the vertical distribution of densities, the sedimentary section from the Cambrian to the Mesozoic was divided, for modeling purposes, into five layers, roughly representing the geological sequences in Table 4–1.

Table 4–1 Density Zones

General Age of Formations	Average Bulk Density (g/cm^3)
Upper Mesozoic	2.35
Lower Mesozoic	2.40
Permian & Pennsylvanian (Shallow)	2.55
Permian & Pennsylvanian (Deep)	2.60
Lower Paleozoic	2.65
Basement	2.70

These density zones do not correspond directly to either stratigraphic formations or age groups. The densities of the model layers have been influenced by a combination of:

- lithology, generally directly equivalent to the stratigraphic layers, and
- the degree of compaction, generally related to depth of burial.

The formations of the northern Black Mesa basin are relatively shallow on the Shonto plateau, then abruptly deepen across the Cow Springs monocline, and are buried beneath several hundred additional feet of cover within the deeper Black Mesa basin. Rock density patterns will not necessarily conform to bedding at such a monoclinal structure. As a given formation abruptly deepens and is covered by much more overburden, the rock may be compressed by the additional overburden and become more dense in the deep portion of the basin. It is important to realize that the model is following rock-density layers, rather than specific formations. The overall trend of density variations in the rocks at the Black Mesa is an increase in density with depth, due to the effects of increasing compaction.

The basement rocks in the study area are composed mainly of Yavapai-province schists (Sumner 1985) and granites (see Fig. 3–1), but locally, quartzites, "metasediments," and undifferentiated metamorphics have been reported at total depth in wells. The primary focus of this study has been to locate structures within the basement in which Chuar sediments could be preserved. The basement density in the study area generally vary between 2.65 and 2.80 g/cm^3. The most common basement rocks should have an average density value of 2.70 g/cm^3.

By experimentally varying the parameters of the model units (thickness and configuration) an attempt was made to match the observed gravity data with the computed values. In constructing the geological model, the depth information from wells in the vicinity of the studied profiles has been used to constrain the thicknesses of the various stratigraphic intervals. The models used a reference datum level of 6,000 feet above mean sea level. This datum is representative of the approximate average surface elevation in the study area.

Approximately 25 model runs were made to gain familiarity with the system and to obtain a good match between the observed and the computed profiles (see Figs. 4–2 through 4–5). In order to match sharp anomalies seen on certain parts of the gravity profile, high density (around 3.0 g/cm^3) mafic intrusive bodies were required. This is realistic in the context of the geology of the region. Intrusive rocks are quite common around the greater Black Mesa region, both within the basement and penetrating the younger sediments. The basement can be viewed in detail at the Grand Canyon. In the inner gorge of the canyon, the Vishnu schists have been extensively intruded by granites, and Proterozoic lavas can be seen cutting younger Precambrian beds. Volcanism was common along the Mesa Butte fault zone and the Holbrook line during the 1.8–1.6 Ga cycles of continental accretion. Slivers of ophiolites may account for some of the large anomalies seen along the Holbrook line suture zone.

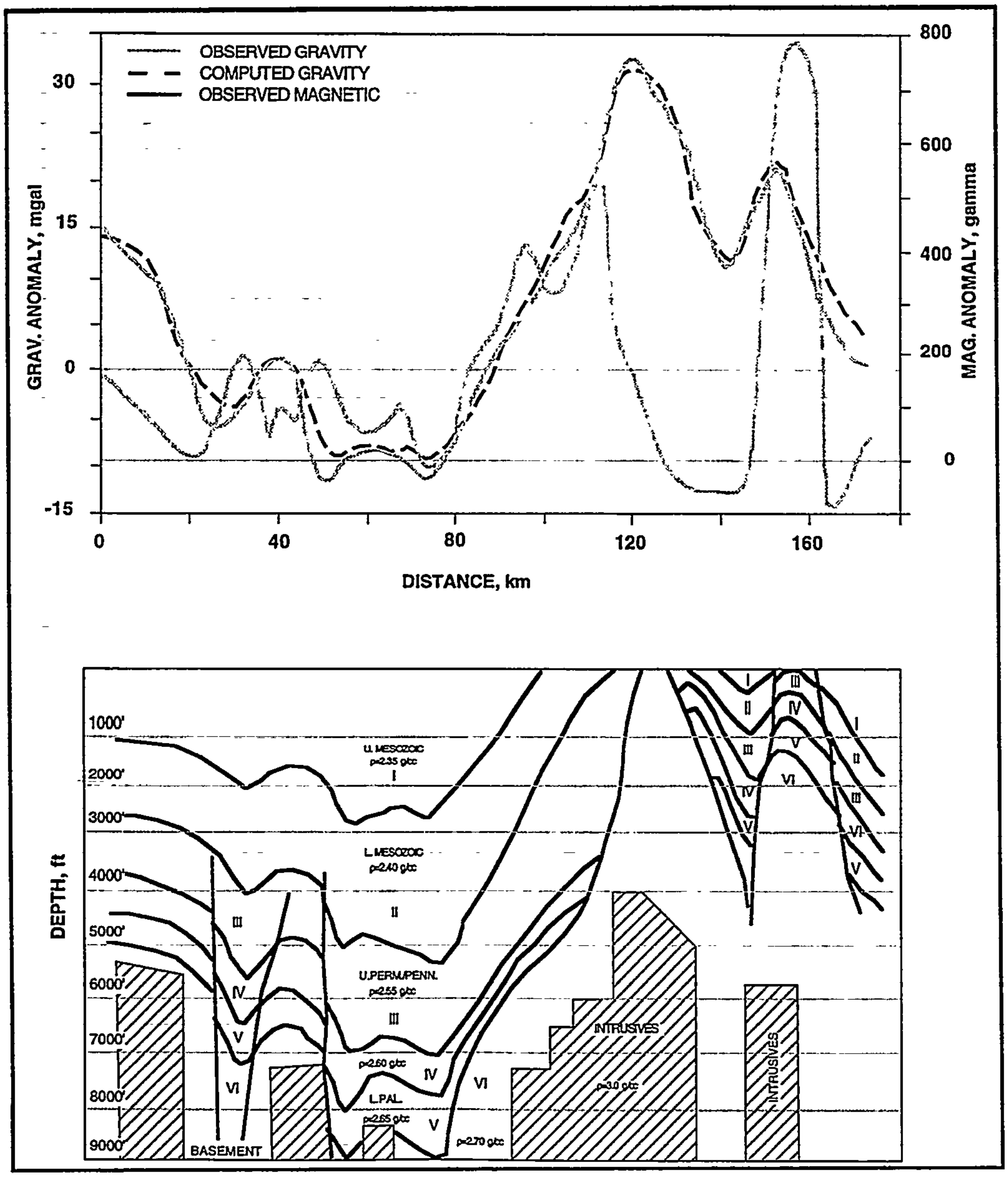


Figure 4–2 Gravity-Magnetic Profile A–B

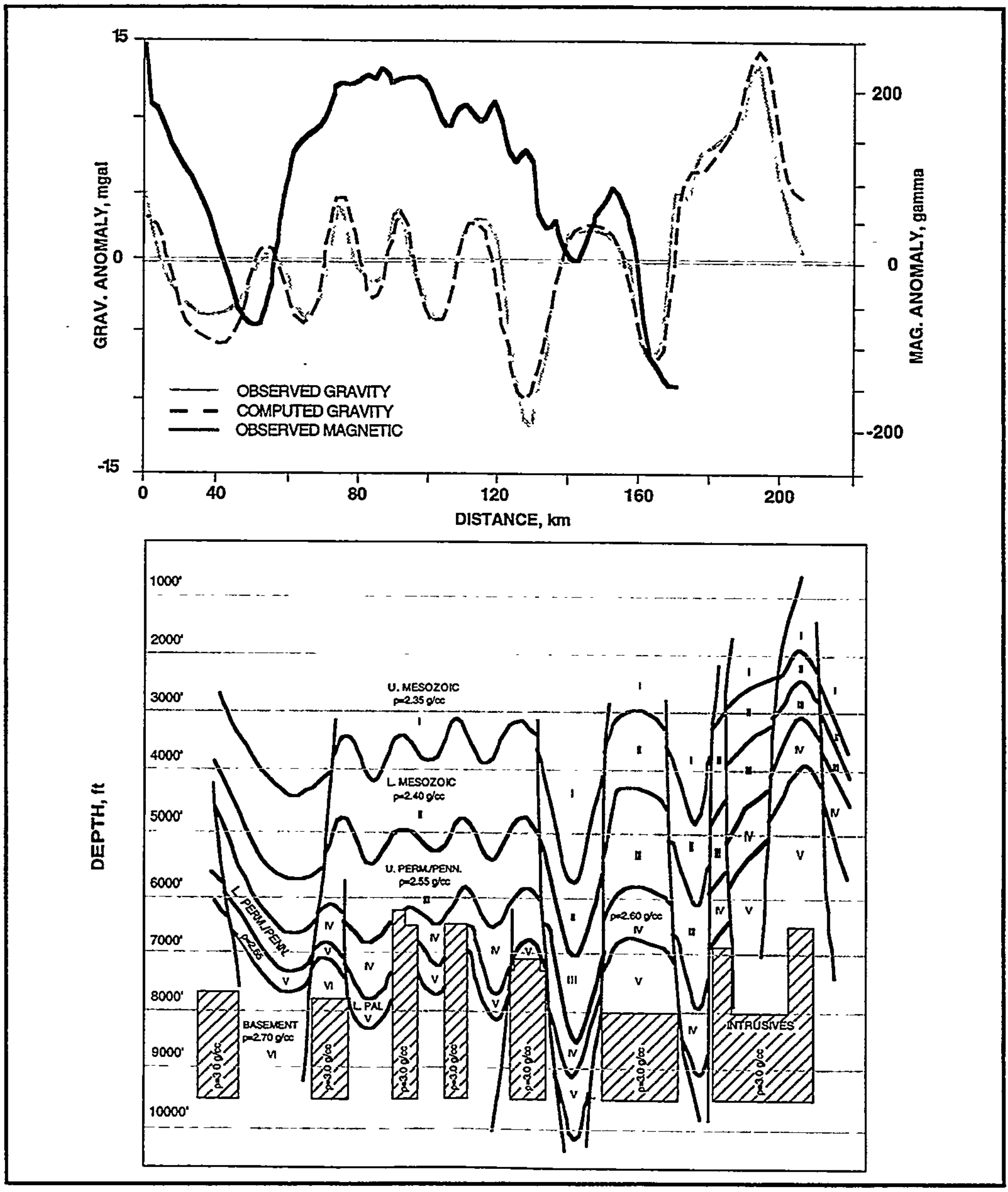


Figure 4–3 Gravity-Magnetic Profile C–D

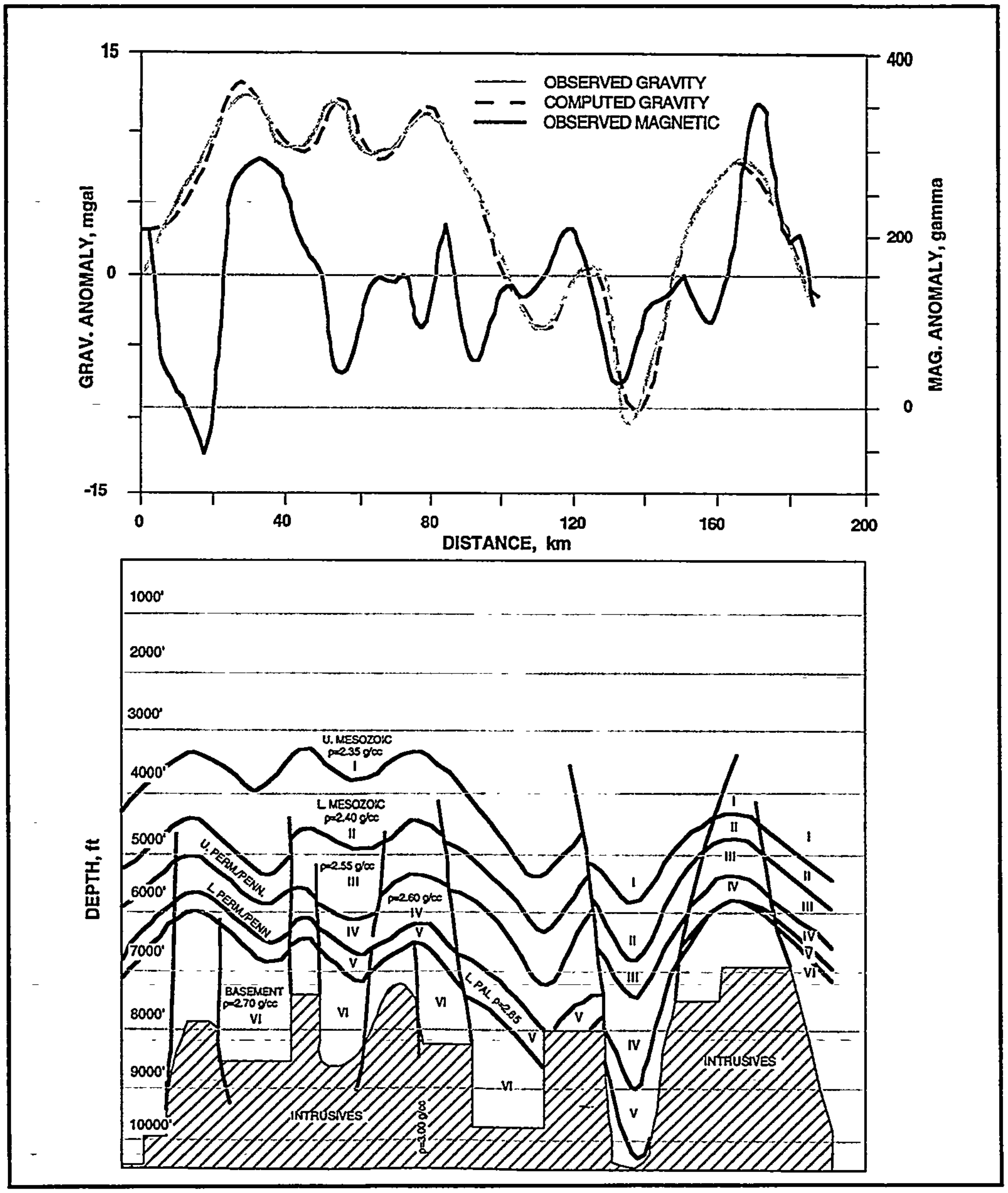


Figure 4–4 Gravity-Magnetic Profile E–F

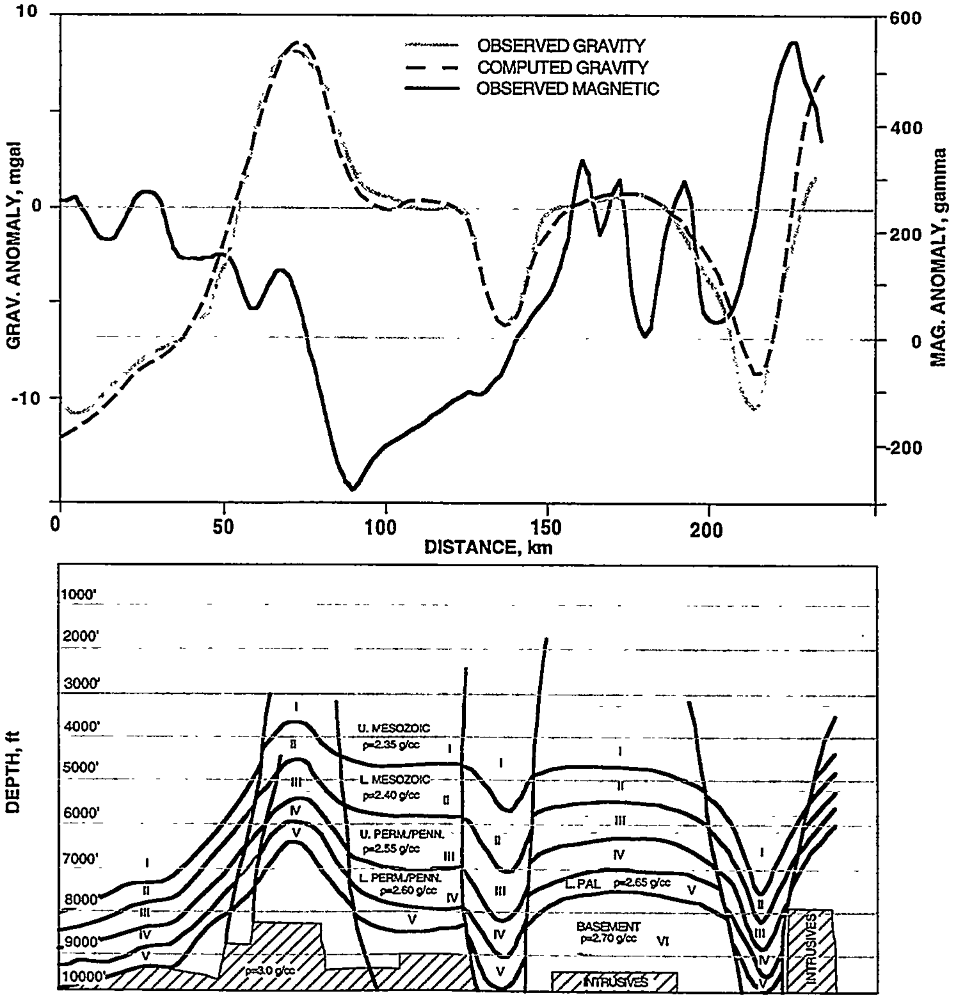


Figure 4–5 Gravity-Magnetic Profile G–H

Several waves of volcanic and intrusive activity swept across the southwestern Colorado Plateau during the Late Cretaceous and Tertiary, in association with the Laramide orogeny and subduction of the Farallon plate beneath the southwestern United States. At this time, large volcanic cones like the San Francisco and White mountains, smaller volcanoes, like the Carrizo peaks, diatreme eruptive features, like the Hopi Buttes and Mule Ear diatreme, numerous dike swarms and lone dikes, and a variety of subsurface intrusive features were emplaced around the area. Intrusive bodies of various rock densities in the study area have been mentioned by several authors, including Sumner (1985), Ander and Huestis (1982), and Shoemaker, Squires, and Abrams (1978). A prime example of the successes of modeling can be seen at a 30-milligal gravity high near the town of Chinle, in the Chinle Valley. Modeling predicted that this could only be a moderate-sized mafic intrusive (see Fig. 4–4). Geologic studies have confirmed that this is a basalt body, intruded along the suture zone between the Yavapai and Mazatzal provinces.

4.3 Modeling of Black Mesa Magnetic Data

Uncertainties about the lithologies of the various intrusive bodies have caused some ambiguity in the interpretation of the gravity data. The mean density of granite is 2.667 g/cm^3. Syenite runs 2.757 g/cm^3; diabase, 2.965 g/cc; and basalt is greater than 3.000 g/cm^3 Some of the problems present in the interpretation of the gravity data were resolved by simultaneous modeling of magnetic data and integration of the modeling with seismic interpretation.

Figures 4–2 through 4–5 show total magnetic intensity values, obtained from the maps by Gutman and Heckmann (1977), along the aeromagnetic profiles. Although there is considerable overlap in the magnetic susceptibility for many different rock types, the average magnetic susceptibility of most common sedimentary rocks is usually very low, typically in the range of 0–50 x 10^{-6} C.G.S. units, compared to a susceptibility for typical acidic igneous rocks, like granite, of 1000 × 10^{-6} C.G.S. units, and for basic igneous rocks, like diorite or diabase, of 15,000 × 10^{-6} C.G.S. units (Nettleton 1973). In general, it can be assumed that an observed magnetic anomaly is caused by a body(s) with high magnetic susceptibility within the basement or to magnetic intrusive or extrusive rocks in the shallow section.

It may be noted in Figures 4–2 through 4–5 that for each magnetic anomaly in the four model sections there is a corresponding intrusive body, although there is usually a shift in the relative locations of the gravity and the magnetic anomalies. This is because, unlike gravity values, magnetic intensity is a vector quantity. The total magnetic intensity vector at a particular location is dependent upon an interaction between the shape, dip, and strike of the causative bodies with the inclination and declination of the Earth's magnetic field.

4.4 Integration of Gravity and Magnetic Data

The main objectives of the gravity and magnetic modeling procedures is to obtain information on regional structure and tectonics, and to identify areas where hydrocarbons may accumulate. These model studies are expected to provide reliable estimates of:

- the structure and configuration of the basement surface,
- the thickness of the sedimentary cover overlying the basement rocks,
- major faults affecting the basement and the overlying sediments,
- the size, depth, and configuration of intrusive bodies,
- anomalous conditions within the sedimentary rocks, potentially favorable for the entrapment of hydrocarbons.

The integration of aeromagnetic data with gravity data in model studies provides information from two independent sources, one based on lateral variations in rock densities, and the other on variations in the magnetic susceptibility of the rocks. When the structural interpretations based on two different rock properties agree, the synergy reaffirms the reliability of both of the structural interpretations.

Results from the gravity/magnetic modeling for the Black Mesa (see Figs. 4–2 through 4–5) produced several findings:

- The models suggest that the deepest portion of the basin has not yet been tested by the bit. The thickest measured sedimentary section identified thus far in a well is around 7,800 feet in the Amerada #1 Hopi well (29N-19E, Sec. 8), where oil shows have been reported in the Upper Devonian McCracken Sandstone. The modeling suggests that the sediment thickness increases to a maximum of 9,000 feet in the center of the basin. This area is approximately 12 mi southeast of the Amerada well. The area of maximum sediment accumulation is undrilled, but is typified by a much lower gravity value than that around the Amerada #1 Hopi. This area may contain a large thickness of lower Paleozoic sediments, including rich source rocks, but from gravity modeling alone it will be impossible to resolve this.
- The basement appears to be divided into numerous, narrow, fault-bounded blocks that generally trend northeast-southwest. A large number of magnetic, intrusive bodies appear to be associated with the faulting. The model studies suggest that the intrusives penetrate to varying depths in the sedimentary section, and that several types of intrusives may exist in the region. If the intrusives are composed of dense, mafic rocks, then a relatively small penetration is sufficient for a match between the observed and the computed profiles.
- The gravity high near Chinle can be modeled with a large mafic intrusive body that has penetrated a granitic or metasedimentary basement. The model suggests that the postulated intrusive has penetrated almost to the surface. The existence of this particular intrusive has been verified through geologic studies, confirming the validity of the model. It is a large basalt body beneath the surface, associated with the Holbrook line. The prospects for hydrocarbon accumulations are low on the top of the structure. On the other hand, the model indicates that favorable stratigraphic trapping conditions may be present in pinch-outs just west of the structure.

4.5 Prospective Areas With Favorable Gravity and Magnetic Characteristics

The gravity and magnetic modeling studies have identified several prospective areas which merit additional investigation by advanced techniques, including seismic, geochemical, satellite or aerial photo imagery, etc. These prime target areas include the following:

- The presence of extensive faulting, and possible intra-basement graben-type structures, filled with considerable accumulations of low-density, nonmagnetic material, observed in the models present prime opportunities for detailed exploration for hydrocarbons. These confined structures may contain extensive deposits of Chuar Group sediments.
- The prominent magnetic low at the western end of profile E-F in the study area coincides with the location of a Late Proterozoic Chuar Group remnant identified by Rauzi (1990). The low magnetic intensities of the Chuar sediments would be expected in nonmagnetic mudstones and shales with thin to medium-thick beds of intercalated dolomite, sandstone, and stromatolitic carbonate beds (Reynolds, Palacas, and Elston, 1988). Local intra-basement structures, covered by Cambrian sandstones could form an ideal environment for the development of traps.
- Similar thick deposits of organic-rich Chuar Group sediments may have been preserved at several areas on the northern Kaibito plateau where low gravity and magnetic values have been mapped.

Several areas with abrupt changes in basement depth are located around the fringes of the deep central Black Mesa basin. Local well control is inadequate in many areas to identify where these slopes on the basement surface are located. The sedimentary section above these steep basement slopes includes many stratigraphic pinch-outs and potential updip attic traps. Particular target areas surrounding the deep portion of the basin include:

- The Chinle Valley region, including the area to the west of the large basalt intrusive feature located 100 km from the origin of Profile A-B (see Fig. 4–2). Well control has demonstrated that dips in the sedimentary section are particularly steep here, and particularly favorable structural and stratigraphic trapping conditions should be present at this site. Similar structure is seen on the model at the east end of Profile E-F (see Fig. 4–4).
- The Hopi Buttes region, to the south of the topographic Black Mesa. The south end of Profile C-D (see Fig. 4–3) shows a basement cross section that could indicate the existence of excellent structural and stratigraphic trapping conditions. The basement beneath the Hopi Buttes is part of the Defiance-Zuni positive area, and is generally located between 3,500 ft and 3,900 ft beneath the surface in most of the wells that have been drilled north and west of the town of Holbrook. To the north of this is a wide band that has not been tested by drilling. The six Hopi wells drilled in the mid-1960s provide control near the center of the structural Black Mesa basin. Beneath the Hopi reservation, the basement is as deep as 7,700 feet, i.e., 4,000 feet deeper than in the wells near Holbrook. The zone where the basement rises 4,000 ft is the target zone. As at the Chinle Valley, beds are pinching out, tilted, and possibly faulted or fractured.

  In general, the basement surface beneath the Hopi Buttes area is considered to be structurally high, and this has been confirmed, near Holbrook, by drilling. However, two gravity lows in the region of the buttes could indicate the existence of an intra-basement graben with a thick sedimentary accumulation on this portion of the Defiance-Zuni structural feature. The gravity lows indicate the possible preservation of several thousand feet of intra-basement sediments which could have been source rocks for extensive hydrocarbon generation. This area of interest is located 20–80 km from the origin of Profile A-B (see Fig. 4–2), and 100–150 km from the origins of Profiles C-D (see Fig. 4–3) and E-F (see Fig. 4–4).

A second location of interest on the Defiance-Zuni structure was selected by Gutman and Heckmann (1977). This area is near the south end of Profile C-D (see Fig. 4–3), in the Hopi Buttes area, located 125 km from the origin in profile. Gutman and Heckmann have noted the presence of numerous structural lineaments in the area. These correspond both spatially and in trend with the basement faulting interpreted from the gravity and magnetic data. This suggests that the faults may cut the entire sedimentary section, providing shallow traps for hydrocarbon accumulations. It should be noted that although the Paleozoic sedimentary section in this area is thin, there is a potentially thick petroliferous Permian section.

- The gravity high associated with Monument Valley, the Skeleton mesa portion of the Shonto plateau, and the Tyende saddle area, located close to the origin of Profile C-D (see Fig. 4–3). This area may include suitable source beds, either locally or in the nearby Oraibi trough. Stratigraphic pinch-outs and steeply-dipping structural traps may provide reservoirs. The monoclines which run through the area include extensive zones of fracturing which could provide elongate zones of secondary reservoirs.

5.0 SEISMIC STUDIES IN THE BLACK MESA BASIN

The Phillips Petroleum Co. was active in the Four Corners area to the northeast of the Black Mesa during the 1960s. Contact was made with the Phillips geophysicists, and they were able to locate nineteen seismic lines in their files which they had shot in the area of interest during 1963. They agreed to provide these data, including sections, films, and tapes, totaling approximately 240 line mi, to the NIPER Exploration and Drilling Group for reprocessing and more detailed interpretation.

Examination and reprocessing of the data has been completed on the best of the data. The overall data quality is "fair" at best due to the vintage of the data and a lack of sophistication and modern techniques during the early 1960s. Some prominent reflectors, such as the top of the basement surface, however, are easily mappable, and with reprocessing, the signal-to-noise ratio was improved.

Line 5 (shown in Figure 4–1), has been significantly improved through reprocessing. The interpretation of Line 5 shows interesting structures within the basement and in the overlying reflectors from the sedimentary section. These include intra-basement faults and sharp flexures in the shallow sediments.

6.0 COMPARISON OF GRAVITY/MAGNETIC MODELS AND SEISMIC INTERPRETATION

An approximate configuration of the basement surface has been obtained from an interpretation of Line 5 (shown in Figure 4–1). Although the quality of the seismic line is only moderately good, the top of the basement surface is mappable. Two apparent faults show up on the line. A graben structure has developed between the two faults. This structural interpretation is consistent with structural patterns identified in the gravity and magnetic modeling. Figure 4–5 shows the interpretation of Profile G-H, and Figure 6–1 shows an interpretation of the basement structure along Line 5.

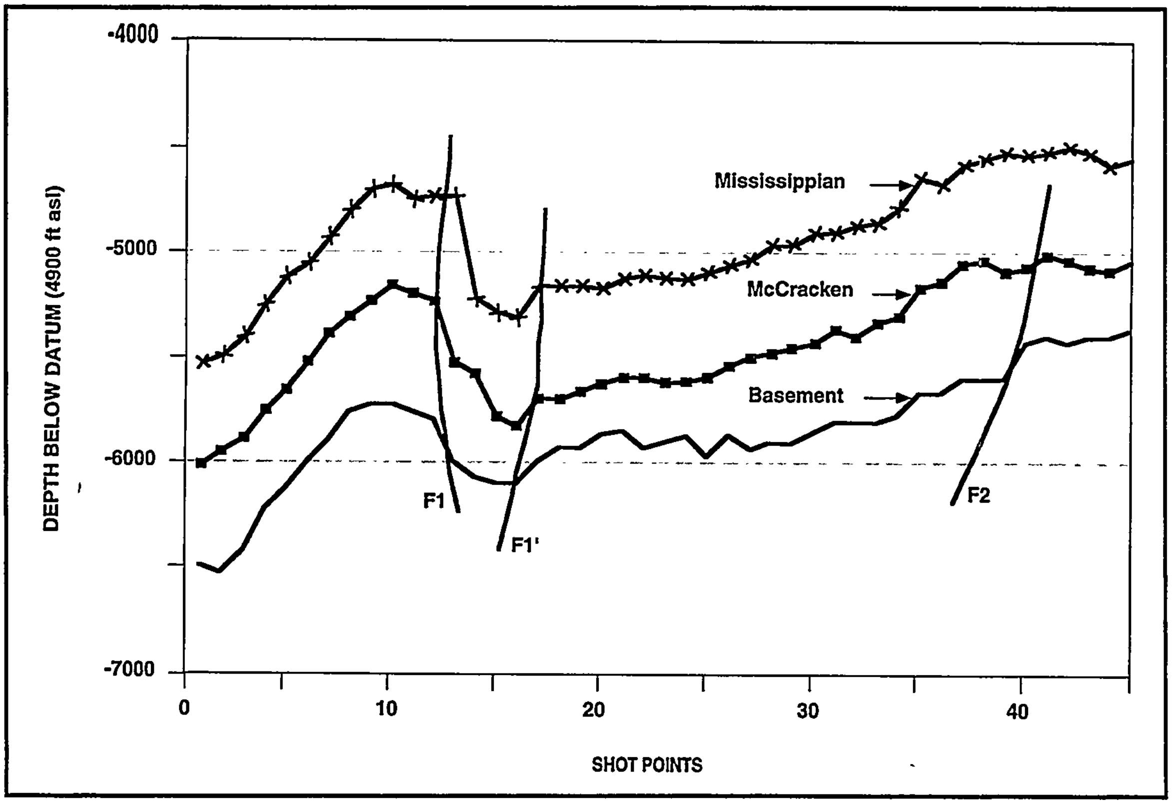


Figure 6–1 Interpretation of Geology Along Seismic Line 5

7.0 COMPARISON OF BASEMENT STRUCTURE WITH SATELLITE IMAGING OF SURFICIAL FEATURES

The basement structure identified on seismic Line 5 (see Fig. 6–1) shows a close correspondence to surficial features identified on satellite imagery (see Fig. 7–1). The locations of the Line 5 shot points have been superimposed on Figure 7–1. A strong association can be seen between the locations of the Chilchinbito anticline–Church Rock syncline axes and basement faults. This type of deformation is typical of the Colorado Plateau. Fault F2 from Figure 6–1 corresponds to the erosional cut of the Chinle Wash. This suggests that the drainage is following the line of faulting and fracturing, and that many of the surficial features in Black Mesa are probably controlled by basement tectonics.

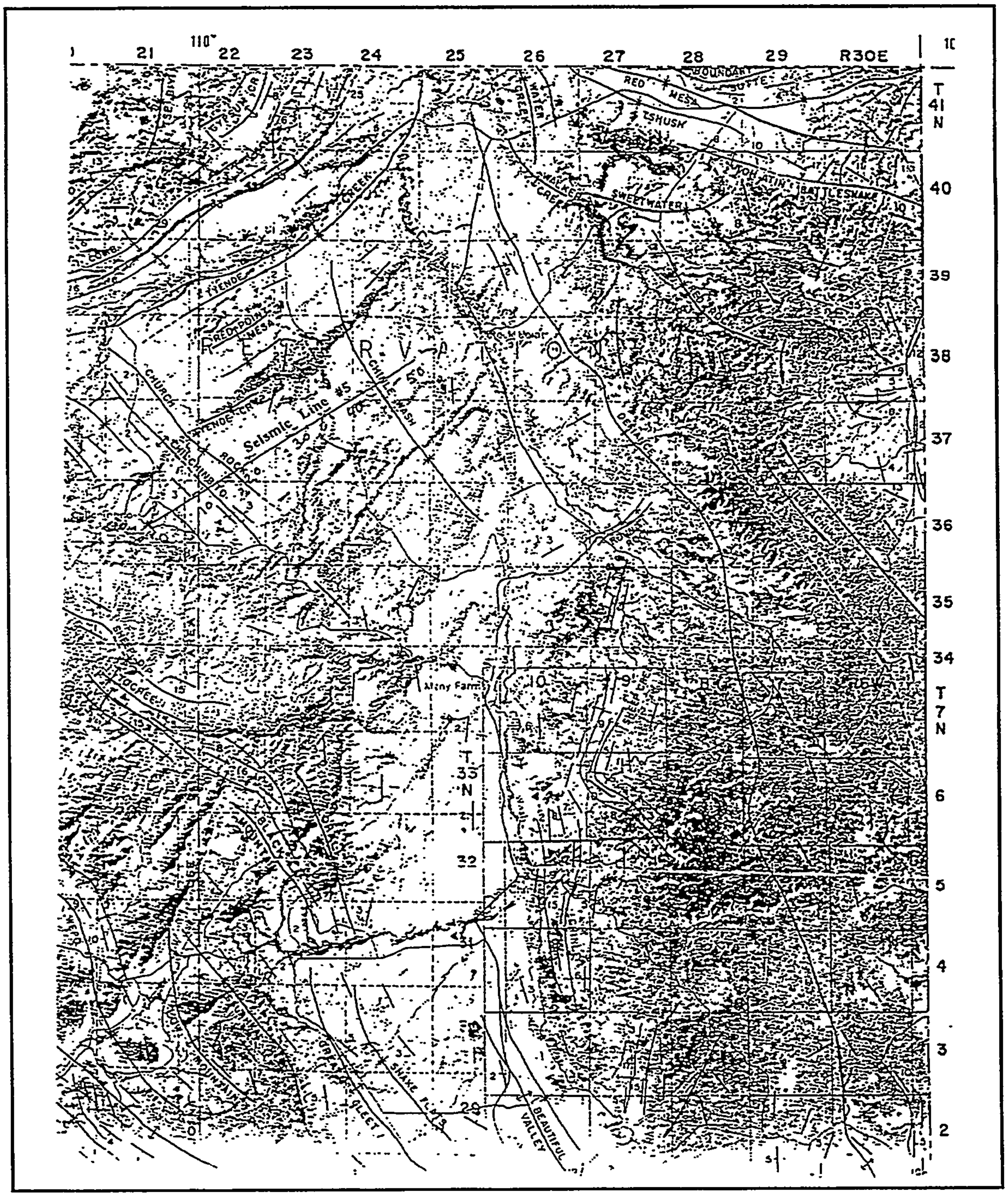


Figure 7–1 Satellite Image and Surficial Structures of Northeastern Arizona.

8.0 DEVELOPMENT OF A COMPUTER PROGRAM TO MODEL TWO-DIMENSIONAL BODIES ASSOCIATED WITH MAGNETIC ANOMALIES

A computer program, Maganom, has been written for the modeling of magnetic data for two-dimensional structures, such as a basement fault or a buried basement ridge. This program can be used to model the total-intensity aeromagnetic data, or to model vertical magnetic intensity data, such as that obtained from a ground survey using a hand-held magnetometer. The effect of remnant magnetization is not considered in this program as remnant magnetization is not of importance for most of the study area. Within the program, the magnetization readings are all attributed to the magnetizing field of the earth. For the interpretation of aeromagnetic data at the Black Mesa, the total field intensity, the vector sum of the Earth's field and any field associated with a buried source, is modeled. Magnetic computations are much more complicated than gravity modeling because of the presence of positive and negative poles and because the strike of the buried body also affects the total intensity vector. Maganom is based on the formula derived by Talwani and Heirtzler (1964) for a body of polygonal cross section and infinite length.

Talwani and Heirtzler have shown that the magnetic attraction caused by an elongate body of polygonal cross section, KNPQRK, can be obtained by adding up the attraction due to prisms like KLMN. The vertical (V) and horizontal components (H) of magnetic attraction for prism KLMN is given by:

$$V = 2\int_{z_1}^{z_2} \frac{J_x z - J_z x}{x^2 + z^2} dz$$

$$= 2\sin\phi\left[J_x\left\{(\theta_2 - \theta_1)\cos\phi + \sin\phi \log\frac{r_2}{r_1}\right\} - J_z\left\{(\theta_2 - \theta_1)\sin\phi + \cos\phi \log\frac{r_2}{r_1}\right\}\right]$$

$$H = 2\int_{z_1}^{z_2} \frac{J_x x - J_z z}{x^2 = z^2} dz$$

$$= 2\sin\phi\left[J_x\left\{(\theta_2 - \theta_1)\sin\phi - \cos\phi \log\frac{r_2}{r_1}\right\} + J_z\left\{(\theta_2 - \theta_1)\cos\phi + \sin\phi \log\frac{r_2}{r_1}\right\}\right]$$

where

J = Total intensity of magnetization,

J_x, J_z = The horizontal and vertical components of the intensity of magnetization,

θ_1, θ_2 = The angle subtended by the end points of a line segment on the observation point,

r_1 = $\sqrt{x_1^2 + z_1^2}$,

r_2 = $\sqrt{x_2^2 + z_2^2}$,

x_1, x_2 = x-coordinate of the end points,

z_1, z_2 = z-coordinate of the end points,

ϕ = A variable that indicates the angle subtended by a line drawn from an observation point on the surface of the ground to an arbitrary point on the surface of the object.

The definitions of J, J_x, and J_z, with respect to magnetic and geographic north, and the inclination (I) and declination (D) of the Earth's field, is explained in Figure 21. From Figure 21,

$$J_x = J \cos I \cos (C - D); \text{ and}$$
$$J_z = J \sin I$$

If the magnetization is by induction:

$$J = \mu F$$

where:

μ = *the magnetic susceptibility,*

F = *the magnetic field of Earth,*

C = *the angle between geographic north and the positive X axis, measuered in degrees, clockwise, from geographic north,*

I = *inclination of the Earth's field, and*

D = *declination of the Earth's field.*

When evaluating a total intensity anomaly (T), then, for very small anomalies with respect to the total field (F), T is the sum of the projections of H and V along the direction of F, i.e.,

$$T = V \sin I + H \cos I \cos (C - D)$$

The Maganom program is based on the above mathematical formulas and definitions. When using Maganom, the shape of the modeled body may be approximated as an n-sided polygon. By increasing the value of "n," the shape of the body may be modeled to any desired degree of precision.

It should be noted that for most sedimentary rocks, the magnetic susceptibility value is very close to zero. Thus, it can be assumed that when an anomaly is found, it is almost entirely due to a feature within the basement or to an intrusive body in the shallow section. For magnetic modeling, therefore, it is not necessary to model effects of the sedimentary cover, as must be done in the case of gravity modeling.

8.1 Verification of the Maganom Program

The Maganom program was tested and verified against anomalies of simple geological structures for which known, standardized analytical expressions of magnetic values are available.

8.2 Interpretation of Aeromagnetic Data from the Black Mesa Basin

The Maganom program was used to compute the total-intensity magnetic anomaly along the basement profile of seismic Line 5 (see Fig. 8–1). The basement rocks were modeled using a susceptibility value of 0.002 C.G.S. units, which is typical for the susceptibility of granitic rocks. The strike of the basement surface was taken as 70° from magnetic north, based on structure maps of the area. The magnetic inclination in the study area is around 60°, based on values in the literature, and the Earth's total field 60,000 gammas.

When the computed total-intensity anomaly was compared to the observed aeromagnetic anomaly (see Fig. 8–1), it was obvious that the computed anomaly was much too small. This strongly suggested that there must be additional igneous sources within the basement or sedimentary section contributing to the observed anomaly. This corresponds to the conclusion drawn from gravity modeling. To obtain a satisfactory match, high-density, magnetic, mafic igneous rocks must be included in the model. The proper location of faults, and dense, high-susceptibility bodies within the basement, along with post-Laramide igneous intrusive rocks, can provide a satisfactory match between the computed and the observed data.

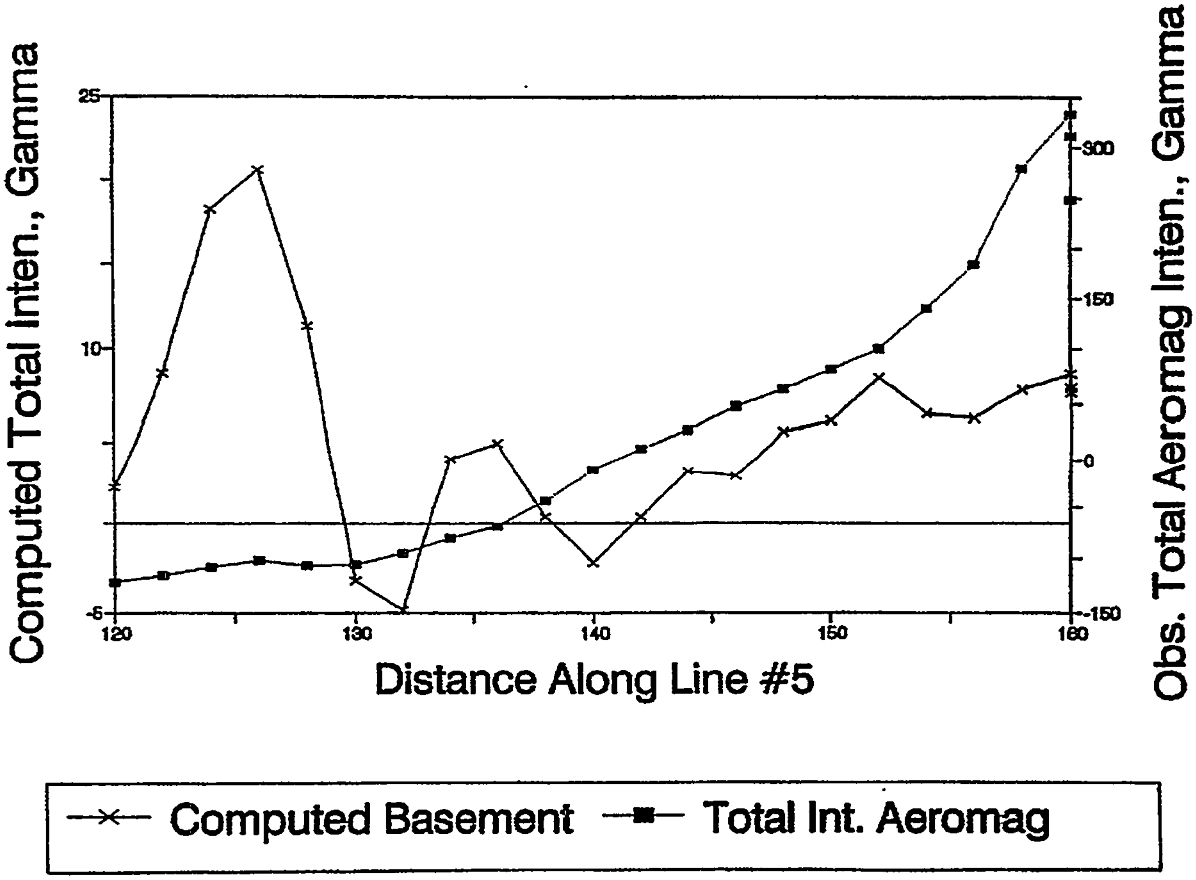


Figure 8–1 Observed Aeromagnetic and Computed Basement Anomaly Along Seismic Line 5

9.0 STRATIGRAPHIC CROSS SECTIONS FROM WIRELINE LOGS

Forty-five wireline logs were obtained for the primary target area within the Black Mesa. Two stratigraphic cross sections were constructed using wireline logs. The first trends NE-SW, and the other trends N-S across the morphological Black Mesa and Hopi Butte areas. Gamma ray, density, neutron, induction, SP, sonic, and resistivity logs were used for detailed investigation of the lower Paleozoic section. The main objective of the stratigraphic cross sections is the study of the distribution and the lateral variations in the quality of the source, reservoir and caprocks in the study area.

Figure 9–1 shows a roughly north-south trending stratigraphic section (Profile X-Y from Figure 4–1) for the lower Paleozoic interval. This section is hung on a datum at the top of Mississippian section, and is constructed with gamma ray logs. The pinch-out of the Cambrian against the Defiance-Zuni positive structure can be seen, along with thickness variations in the Aneth and McCracken Devonian units.

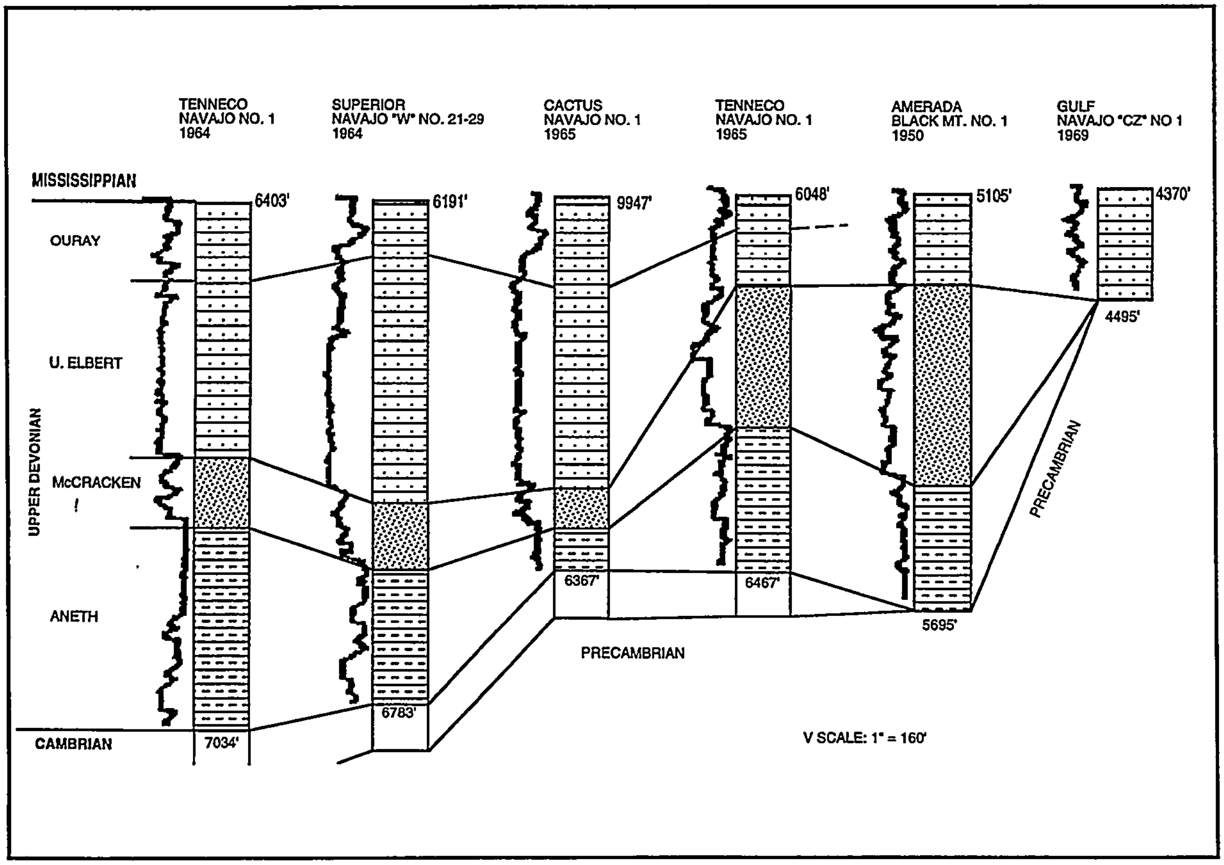


Figure 9–1 Wireline Log Correlation Along Profile X–Y

Figure 9–2 displays the gamma ray and sonic transit-time plots for well Hopi 5075. The location of this well in the Black Mesa basin is shown in Figure 4–1. This well had hydrocarbon shows in the McCracken Sandstone and, also, in the Chinle Formation. The large scatter in log values in the McCracken Sandstone interval indicates rapid lithologic variations within that unit. The sandstone in this well is apparently interbedded with large amounts of shale, causing the high gamma-ray readings. The average sonic transit time is moderately high, indicating modest porosity development, although thin streaks in the sandstone may have fairly high porosities.

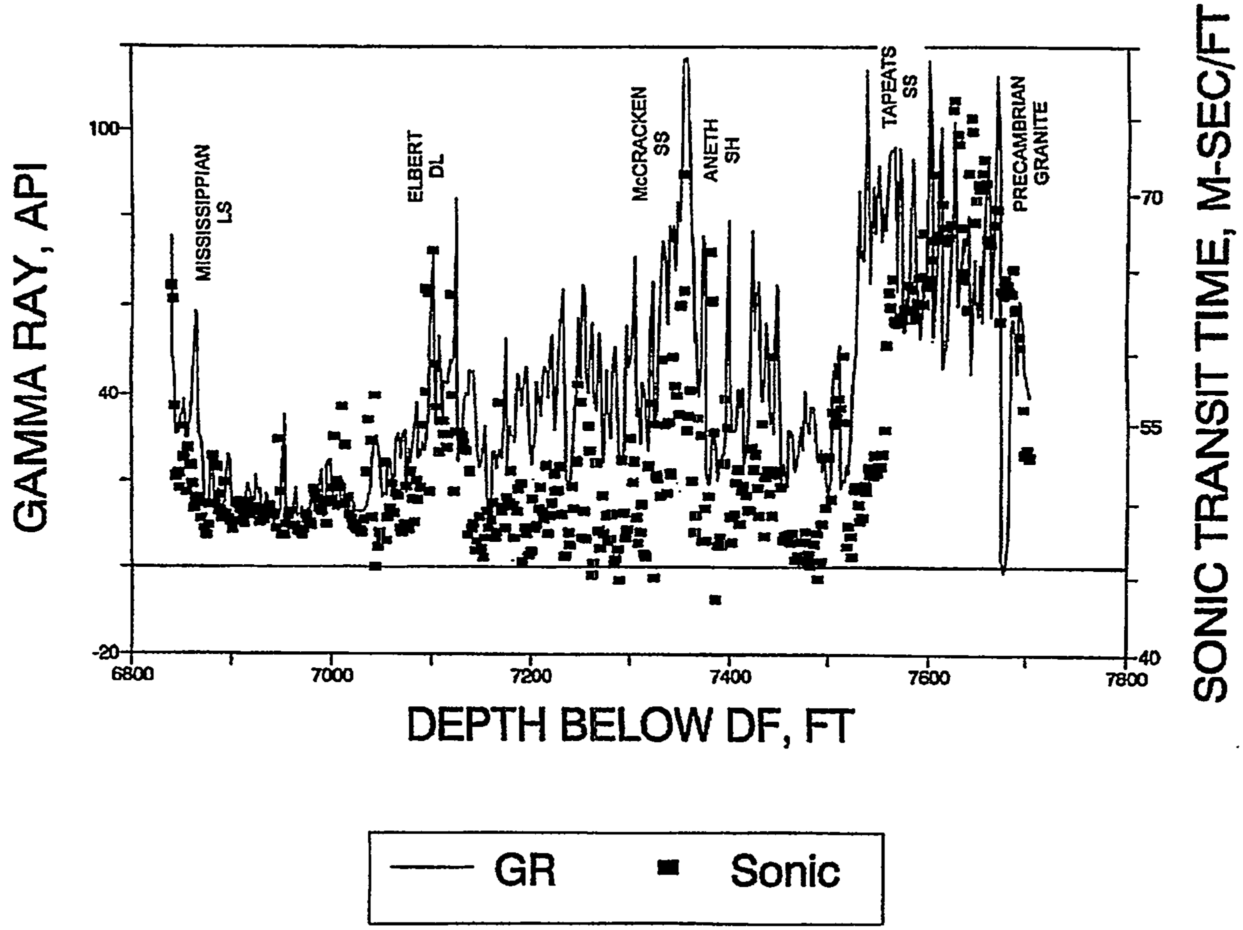


Figure 9–2 Distribution of Source and Reservoir Rocks in the Lower Paleozoic Interval in Well Hopi 5075

10.0 REMOTE-SENSING STUDIES

The geomorphology of the Black Mesa region demonstrates an exceptionally-well-developed pattern of parallel drainage. A literature search made it evident that this drainage pattern has been controlled by a series of large basement faults. These basement faults divide the deep crust beneath the Black Mesa into three geologic provinces. The Black Mesa region lies above two major continental-scale sutures. It was determined that an understanding of this suture/fault/fracture system would be crucial to this study. Remote sensing studies were added to the geophysical tools for a more-detailed analysis of the structure of the region.

Large areas can be quickly studied with aerial or satellite photos to identify especially promising target zones. A USGS publication, "An Integration of Landsat and Geophysical Data in Northeastern Arizona" was prepared by S. I. Gutman and G. A. Heckman in 1977. This publication combined remote sensing with other tools to identify several areas which were interpreted as being highly prospective for hydrocarbon exploration. This reference was helpful in identifying prospective areas, although some of the features identified by Gutman and Heckmann held more potential than others.

Each of the six specific prime prospective regions shown in Figure 2–3 was reviewed to see how fractures and lineaments might relate to hydrocarbon trapping.

- At the **central Black Mesa** region, the strongly-developed parallel drainage system suggests that deep-seated structures like the through-crust faults shown in Figure 3–1 are controlling shallow fracturing in this region. This was considered to be a prime area for remote-sensing analysis.
- At the **northern Black Mesa,** fracturing along the monoclines may offer excellent trapping conditions. Figure 10–1, from Reches and Johnson 1978, shows typical extensional fracture patterns associated with the knee area of a monocinal structure. Fracture studies along the monoclines were deemed to be important.
- The complexity of structures at **Gray Mountain,** may be partially unraveled through this type of work. Remote-sensing here is useful to identify knee-area fractures and fracturing patterns on the high, to focus on migration pathways, as well as possible reservoir locations.
- Reservoirs along the **Chinle Valley** may be concentrated in the deeper areas, in stratigraphic pinchouts. The primary focus for fracture studies here is to decipher the structural relationships in the complex area where the northeast-southwest trend at the Black Mesa changes to the north-south trend seen along the Defiance uplift.
- Around the **Hopi buttes,** the greatest interest is in the deeper beds to the north of the central buttes. Remote sensing here could help to identify structural changes along the southern edge of the Oraibi trough, and identify possible fractured reservoirs.
- The **Sanders, St. John,** and **Alpine** area was considered to be outside the scope of this study, and was not reviewed in this phase of the project.

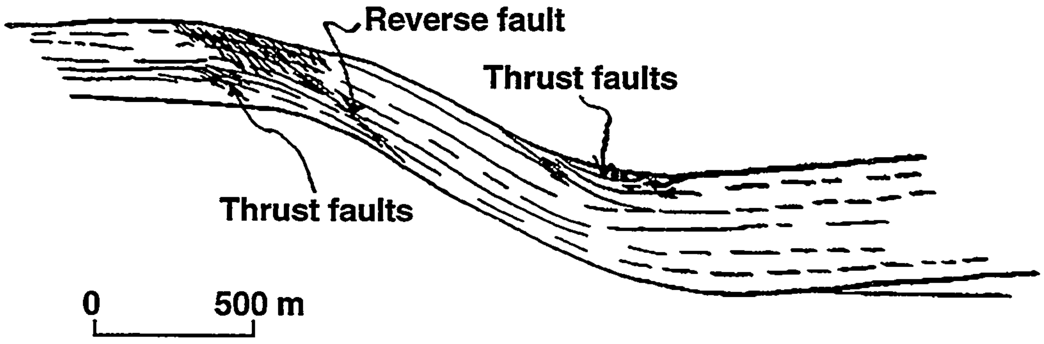


Figure 10–1 Example of Fracturing/Faulting at Knee Area of Monocline

10.1 Morphology of the Black Mesa Region

The general morphology and the drainage pattern at the Black Mesa is highly unusual. The Black Mesa forms a relatively regular polygonal figure, with relatively straight edges on the west, northwest, northeast, and southeast sides (although the east side has been broached by a gap at Cottonwood/Black Mountain, and the southeast side has been partially inundated by recent volcanic activity). However, the southwest margin is deeply dissected by modern drainage features, a series of wide, straight, parallel washes. This suggests two things:

- The geomorphic pattern at the topographic mesa is due to deep-crustal structural control of the surface morphology, with persistent basement-fault-trend features oriented,
  - southeast-northwest,
  - north-south, and
  - southwest-northeast,
- The most-persistent, more-recently-activated fractures are oriented southwest-northeast, following many of the lines shown in Figure 3–1

The bedding on the valley floors in the washes is relatively undisturbed, and does not appear to be faulted or folded. Walking the valley floors provides no obvious clues to the existence of any major deformation that would have led to such massive erosion. Recent structural movements along the southwest-northeast-oriented features apparently have not been large, in terms of amount of each offset. Instead, they represent the site of very frequent, repetitive movements.

They may have been caused by diurnal tidal forces, with the Black Mesa region shifting up and down in syncronicity with tidal forces, twice a day, every day, over the expanse of geologic time. The effect of the tidal forces may be exceptionally large here due to abrupt, sharp variations in the density of the deep crustal rocks beneath the sediments in this region.

The crust beneath the Black Mesa has been formed by the aggregation of a patchwork of many narrow crustal slivers, sutured together during the accretion of a series of island arcs along the southern margin of North America between ~1.8 and ~1.7 Ga. These slivers included a wide variety of rock types and densities. Where bands of highly contrasting density in the deep crust abut, the overlying shallow beds will be affected differentially by Earth tides. The sediments will be tidally shifted by a slightly greater amount above very dense deep crustal blocks than they will above much less dense deep blocks. Even if these variations are extremely slight, there will be noticeable side effects over geologic spans of time. Tidal rise and fall occurs two times each day, every day.

This constant flexing and repeated differential movements in the shallow sediments above such a boundary zone in the basement tend to affect the integrity of the intergranular cement and some crystal types, weakening the rocks, and leading to fracturing in the shallow beds. This type of process can propagate vertical zones of fracturing which are also zones of weakness, susceptible to subsequent deformation when the area is subjected to stress. It is above these types of features that the monoclines of the Colorado Plateau have formed. Where the basement has not actually been displaced, such as in the central Black Mesa, there are no monoclines, but the fracture trends can be identified by the unusual, straight, regularly-spaced, parallel drainage trends, reflecting regularity in the width and spacing of the elongate island arc slivers that comprise the deep continental crust. The general trend parallels the 1.8 Ga coastline and accretion trend. Occasional wiggles along these trends show up as bends in the monoclines or washes. When one sliver ends and another begins, the bands can narrow abruptly, taking brief north-south doglegs. This control of shallow flexing, monoclines, and fractures makes it easy to trace the outlines of the 1.8 Ga basement blocks and to determine where the weakest sutures, bounding crust of highly-contrasting density, are located.

The fracture zones have additional significance, beyond leading to erosion along the washes. Well-developed fractures can provide migration routes from deep source beds to more-shallow reservoirs. Fractures tend to develop best, and stay open, in hard, brittle beds, including potential reservoirs, like sandstones. Fractures are much less likely to form, or survive and stay propped open in potential cap rocks, like shale, which are much softer and more plastic. Potential reservoir rocks at shallow depths tend to fail, break, and stay open, while potential shale cap rocks tend to flow and reseal, even at shallow depths. This structural relationship favors the development of fracture zones and overlying reservoirs. The reservoirs can be in porous, brittle units, but it is also possible for the fractures themselves to form reservoirs, under certain conditions. Where the fractures are well developed, and have formed a migration pathway over geologic time, fractures within otherwise-tight rocks can form reservoir zones.

The Cretaceous beds which support the heights of the mesa, well above the surrounding plains, are quite strong and resistant to erosion. Despite this, they have collapsed and been eroded away along the series of parallel washes which cut deeply, from southwest to northeast, into the Black Mesa. These washes are remarkably straight, as can be seen when one drives along one, in a straight line, with minimal twists and turns, along a jeep trails through one of the drainage trends. The tough, resistant Cretaceous units would not have been eroded in such a uniform pattern unless they were much more highly fractured along the trend of the washes.

Arid-country geomorphology is exceptionally sensitive to slight differences in rock strength and its related corollary, regional fracturing.

It was recognized that the parallel drainage at the Black Mesa was so well developed that it must have a deep-seated cause. quickly noted that the southwestern Colorado Plateau is known for having an unusually thick, stable crust, which has undergone minimal deformation through Mesozoic and Cenozoic time. The Mesozoic beds are typically nearly flat-lying in the study area, with a gentle dip toward the Four Corners. Exceptions are found at the Colorado Plateau monoclines, where the beds have sharply flexed over deep-seated offsets. These structures were produced by Laramide-age movements on ancient (1.8 Ga) faults that were reactivated as the Colorado Plateau area was compressed toward the northeast.

Studies of the tectonic framework of the southwestern United States showed that the crust beneath Arizona is strongly segmented into a series of slivers, most of which follow an ancient southwest-northeast orientation, parallel to an ancient coastline of North America that ran close to the California-Arizona border, through the area of the Grand Canyon, then through western and central Utah. At approximately 1.8 Ga, a series of island arcs began to collide with this coastline. Band after band of new material was added to this coastline, shifting it progressively farther to the southeast.

Each of the contact zones has remained as a zone of weakness within the deepest crust. The island arc sliver's were apparently relatively regular, linear features, creating a series of exceptionally straight contact zones through the region beneath the Black Mesa.

10.2 Application of Surface Fracture Analysis to Hydrocarbon Exploration

The use of surface fracture analysis as a tool for hydrocarbon exploration requires:

- an understanding of regional structural styles and basement structures,
- a reliable mapping of surface lineaments, fracture traces, and circular and arcuate anomalies,
- geological and statistical analysis of the mapped surface features.

The objective is to identify potential locations of subsurface hydrocarbon traps.

In preparation for this study, previous investigations in mapping surface major lineaments using satellite images and monoclinal analysis in northeastern Arizona were reviewed and analyzed. The significance of the mapped surface lineaments is discussed in the following section. Also discussed are the detailed photogeological study which was conducted to map surface fracture traces, plus circular and arcuate anomalies in the restricted Black Mesa basin and its adjacent areas, and the surface-fracture analysis which was performed to provide priority locations for potential subsurface hydrocarbon traps in northeastern Arizona.

The investigation of surface lineaments mapped from monoclinal analysis and Landsat imagery interpretation covers all of northeastern Arizona (see Fig. 10–2), ranging from the Mogollon Rim in the south to the Arizona-Utah border in the north, from the Kaibab Uplift in the west to the Arizona-New Mexico border in the east. This area comprises approximately 32,000 mi^2. Well-known physiographic and topographic features in this study area include the restricted Black Mesa basin, Defiance Uplift, Tyende Saddle, Piute folds, Kaibito Saddle, Preston Bench, Cameron Bench, Echo Cliffs Uplift, Kaibab Uplift, and Little Colorado River.

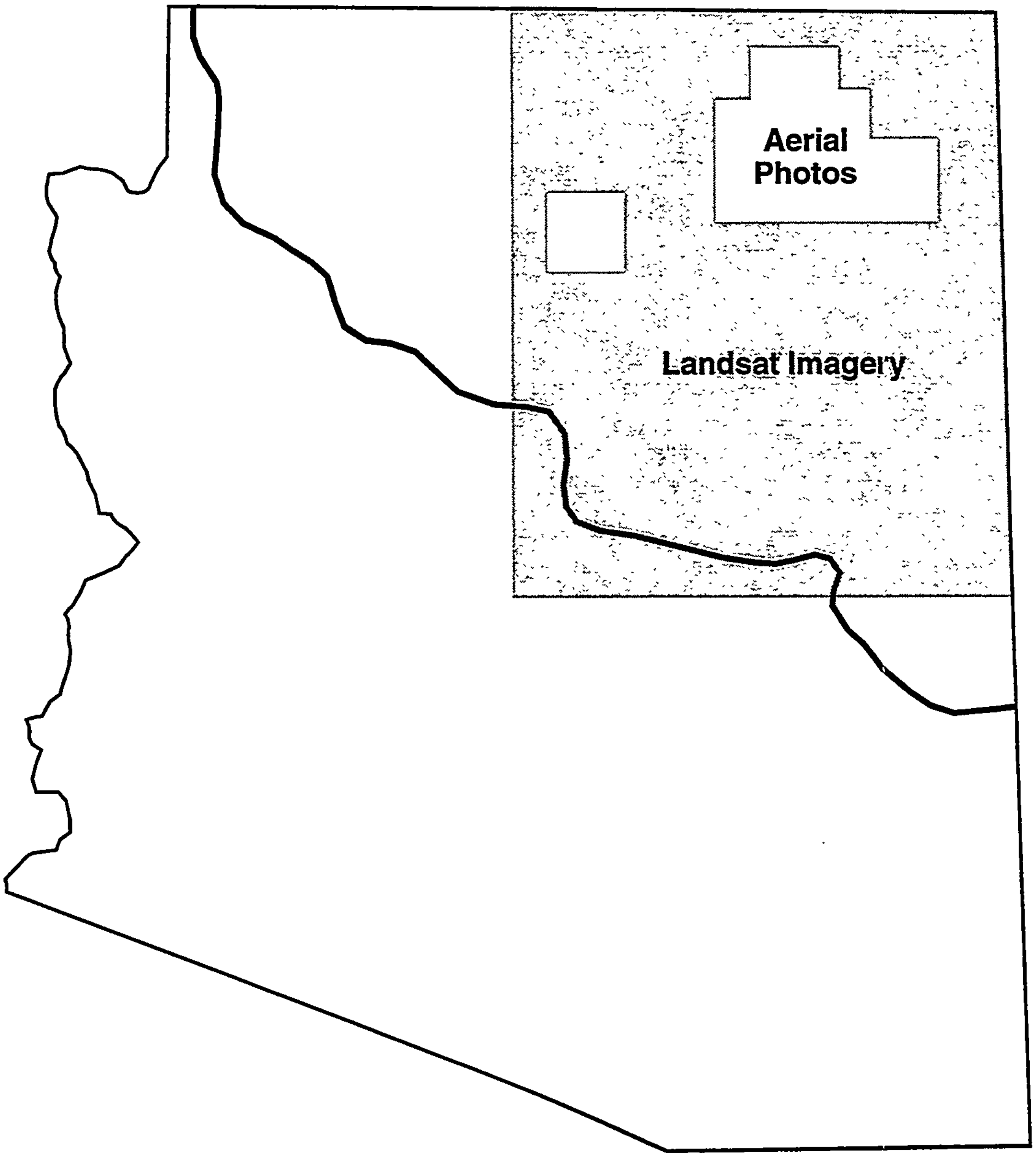


Figure 10–2 Aerial-Photo and Landsat-Image Coverage Areas in Arizona

The photogeological analysis was done on two separate areas (see Fig. 10–2). The smaller, westernmost area commonly called the Cameron area comprises roughly 775 mi^2 in Coconino County. The larger area includes the northern two-thirds of the restricted Black Mesa basin, the northern extension of the Black Mesa basin (Kaibito Saddle), and the Chinle Valley in the east. This area comprises approximately 4950 mi^2 in parts of northern Apache and Navajo counties. It includes parts of Navajo and Hopi Indian reservations.

10.3 Structural Styles and Basement Structures in Northeastern Arizona

An understanding of regional structural styles and basement structures is fundamentally important to any exploration effort because different types of oil and gas trapping mechanism are associated with different structural styles (Berger 1994). Structural styles are classified as detached or basement-involved. Basement-involved structural styles are further categorized as arches and domes, compressional blocks, extensional blocks, and wrench faults. Salt domes, detached normal faults, and thrust-fold belts are types of detached structural styles.

Northeastern Arizona, located in the southwestern part of the Colorado Plateau, has been the focus of numerous geological investigations for hydrocarbon and other mineral potentials (Holm 1938; Arizona Development Board 1961; Pye 1967; Pierce, Keith, and Wilt 1970; Turner 1968; Gutman and Heckmann 1977). As has been previously discussed, the structural style of this region appears to be that of a basement-involved extensional fault block. Characterized by extensive extentional faulting, the Precambrian basement rocks in the northeastern Arizona were exposed in the Grand Canyon area, Mogollon Rim, Four Corners area, and Defiance Uplift (Turner 1968; Werme 1981). Both northeast- and northwest-trending block faulting exists with the northeast-southwest as the predominant orientation of the basement structural grains (Pierce, Keith, and Wilt 1970).

The basement-faulting period was followed by deposition, emergence, erosion, regional tilting, and basin formation during the Paleozoic and Mesozoic (Pierce, Keith, and Wilt 1970). The basic structural grain of the formations formed during this relatively stable period is in a northwest-southeast direction, with a few exceptions oriented in a northeast-southwest direction (Davis 1975; Jenkins and Keller 1989). After that, the Laramide orogeny occurred across the region between the Cretaceous and Eocene causing massive folding, monoclinal flexturing, uplifting, and formation of the Black Mesa basin under compressive stress conditions (Pierce, Keith, and Wilt 1970; Turner 1968; Lucchitta 1978). Laramide deformation reflects a north or northeast orientation, which may represent a reactivation of major Precambrian zones of weakness (Turner 1968; Lucchitta 1978). The region is believed to have been subjected to tensional stress conditions from the Miocene up to recent time (Lucchitta 1978).

The Precambrian basement structures of northeastern Arizona has been investigated through outcrop observations, surface lineament analyses, gravity and aeromagnetic surveys, and surface monoclinal analyses (Gutman and Heckmann 1977; Werme 1981; Davis 1975; Jenkins and Keller 1989; Lucchitta 1978; Shoemaker, Squires, and Abrams 1978). Figure 10–3 shows one interpretation of the basement faulting systems in northeastern Arizona, which was obtained through an integration of Landsat, gravity, thermal gradient, and aeromagnetic data (Gutman and Heckmann 1977). The Precambrian basement rocks appear to be divided into regular, fault-bounded blocks, which trend predominantly northeast-southwest. The average width of these blocks is approximately 25 mi, and they tend to be truncated or terminated by north-south and northwest-southeast trending faults (Gutman and Heckmann 1977; Davis 1975). In addition, there are three basement arching systems corresponding to three volcanic areas: San Francisco Mountains, Hopi Buttes, and White Mountains (Gutman and Heckmann 1977).

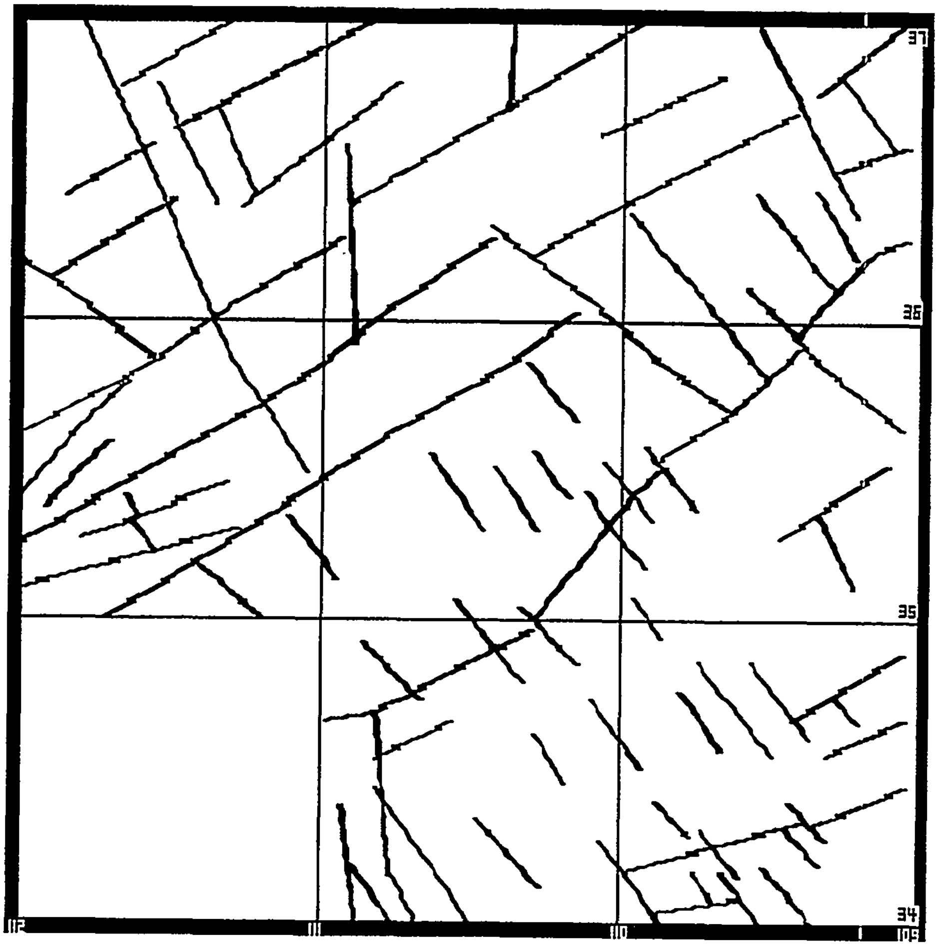


Figure 10-3 **Basement Fault Systems Interpreted from an Integration of Landsat and Geophysical Data in Northeastern Arizona**

Many investigators have described basement control of Phanerozoic deformation in northeastern Arizona. In the Grand Canyon region, many basement faults have been reactivated many times, and propagated upward to the surface (Lucchitta 1978; Shoemaker, Squires, and Abrams 1978; Hodgson 1965). Many of the major monoclines (e.g., Comb, Echo Cliffs, and Cow Spring monoclines) indeed are associated with faulting in the Precambrian basement (Gutman and Heckmann 1977; Davis 1975). The monoclines in the region are believed to have developed as a response to differential movements of basement blocks along high-angel faults (Davis 1975). In the eastern Grand Canyon region, all of the monoclines exposed to the crystalline basement are underlain by Precambrian normal faults (Huntoon 1981).

Further evidence supporting the basement control of Phanerozoic structures in northeastern Arizona includes the alignment of many eruptive centers along major fault systems (i.e., Bright Angel and Mesa Butte fault systems) to the west of the study area (Shoemaker, Squires, and Abrams 1978) and of earthquake epicenters along major monoclines (Cow Spring monocline) (Gutman and Heckmann 1977).

The extensively faulted basement, its control of Phanerozoic deformation, and the propagation of the basement fault systems to the surface indicate the applicability of lineament and fracture analysis to hydrocarbon exploration in northeastern Arizona.

10.4 Surface Lineament Analysis in Northeastern Arizona

This section reviews three previous studies on surface-lineament mapping from monoclinal analysis and from Landsat images. The consistencies and/or discrepancies among them are assessed, as is the significance of surface lineaments and surface fracture zones in hydrocarbon exploration in northeastern Arizona. Preliminary priority locations for potential oil and gas entrapment in northeastern Arizona are identified.

10.4.1 Monoclinal Analysis

Based on the hypothesis that monoclines within the Colorado Plateau were developed as a response to differential movements of basement blocks along high-angle faults, one study showed that the surface monoclinal traces can be used as a guide to identify major fracture zones which are believed to divide the Colorado Plateau into blocks (Davis 1975). Surface fracture zones thus defined in the Plateau are shown in Figure 10–4. A rose diagram of those fracture zones is given in Figure 10–5. One can see from Figures 10–4 and 10–5 that there are four preferred directions for the inferred fracture zones in the Colorado Plateau: N20°W, N55°W, N20°E, and N55°E. They were interpreted as the reflection of the Precambrian basement weakness zones in the Colorado Plateau.

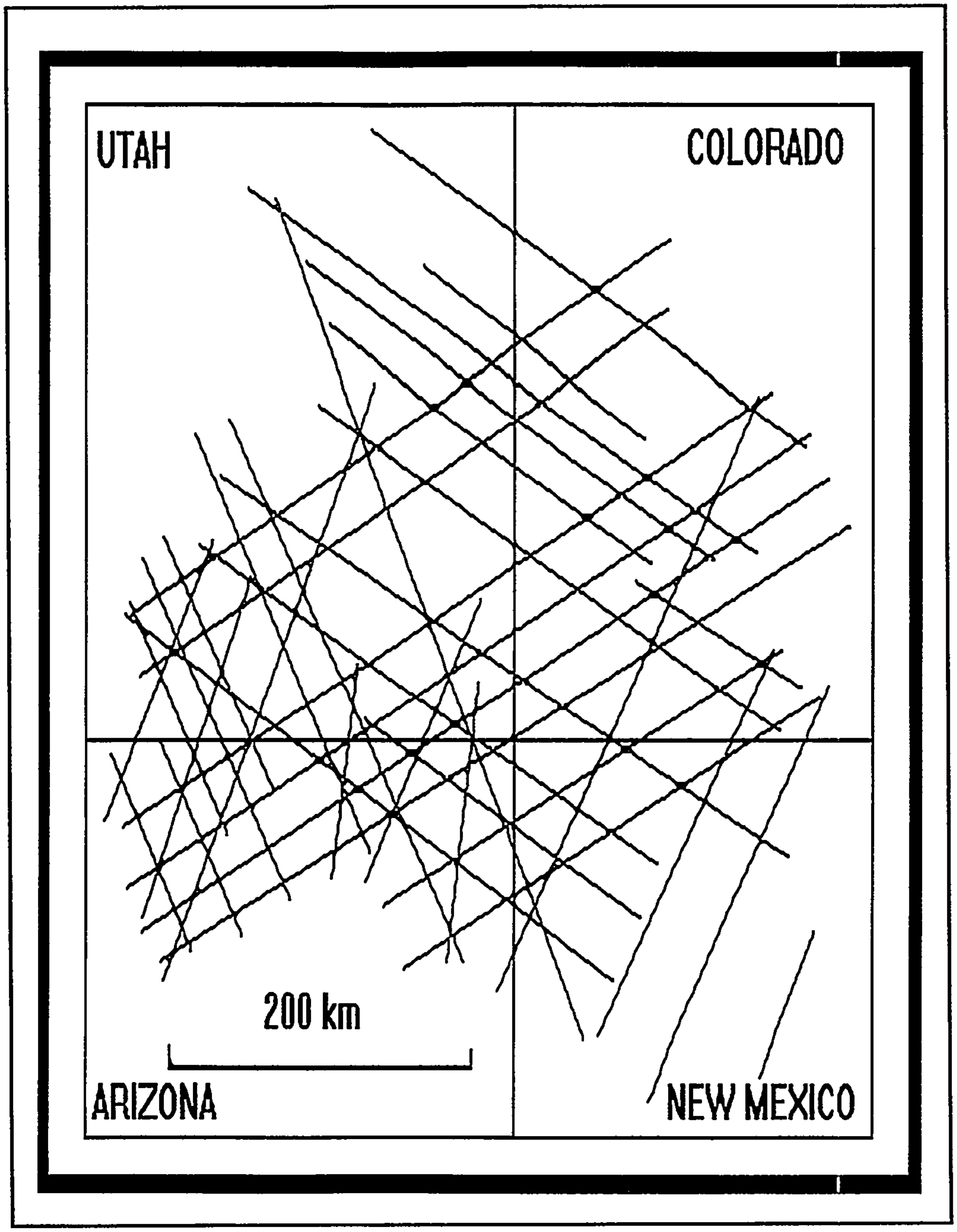
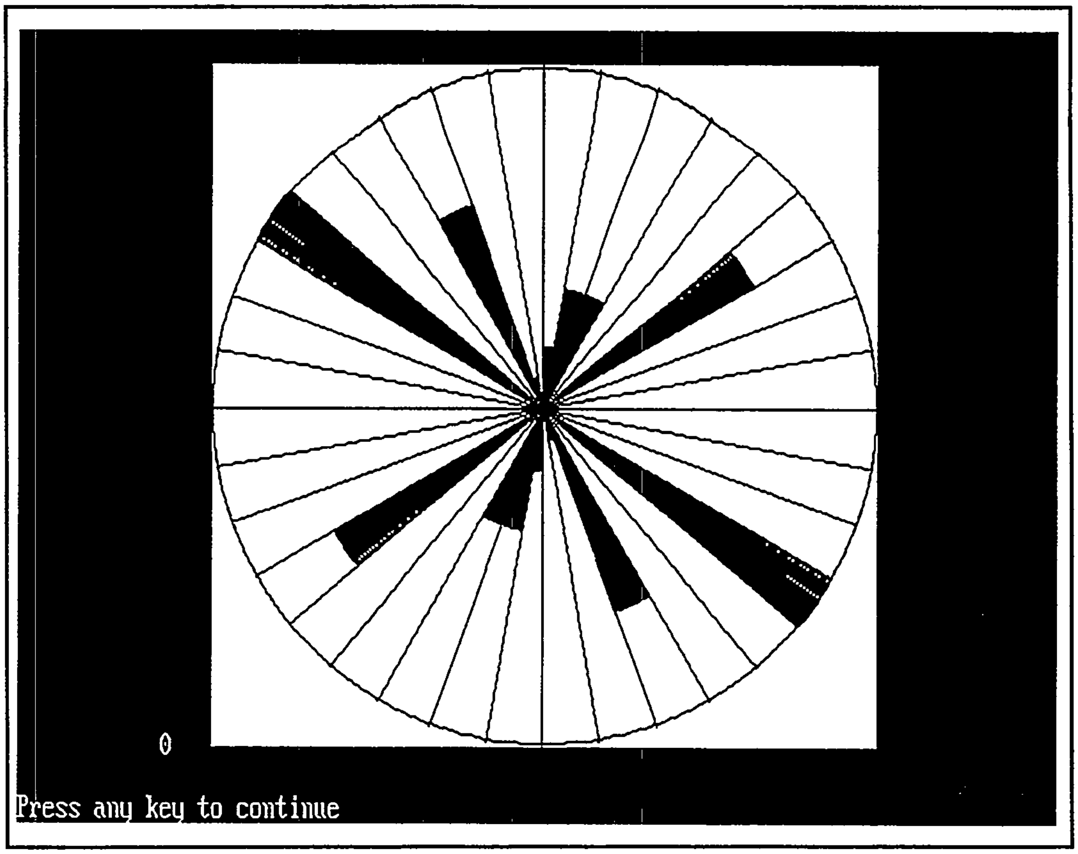


Figure 10–4 Inferred Fracture Zones from Monoclinal Traces in the Colorado Plateau



Press any key to continue

Figure 10–5 Rose Diagram of the Inferred Fracture Zones in the Colorado Plateau

The inferred surface fracture zones for a portion of the Colorado Plateau tectonic province of Arizona are shown in Figure 10–6, which was obtained by integrating monoclinal and aeromagnetic analysis (Davis 1975). The rose diagram of the inferred fracture zones in northeastern Arizona, as given in Figure 10–7, indicates the consistency in trend between those within Arizona and those in the whole Colorado Plateau. The significance of the structural model derived from this study is discussed later.

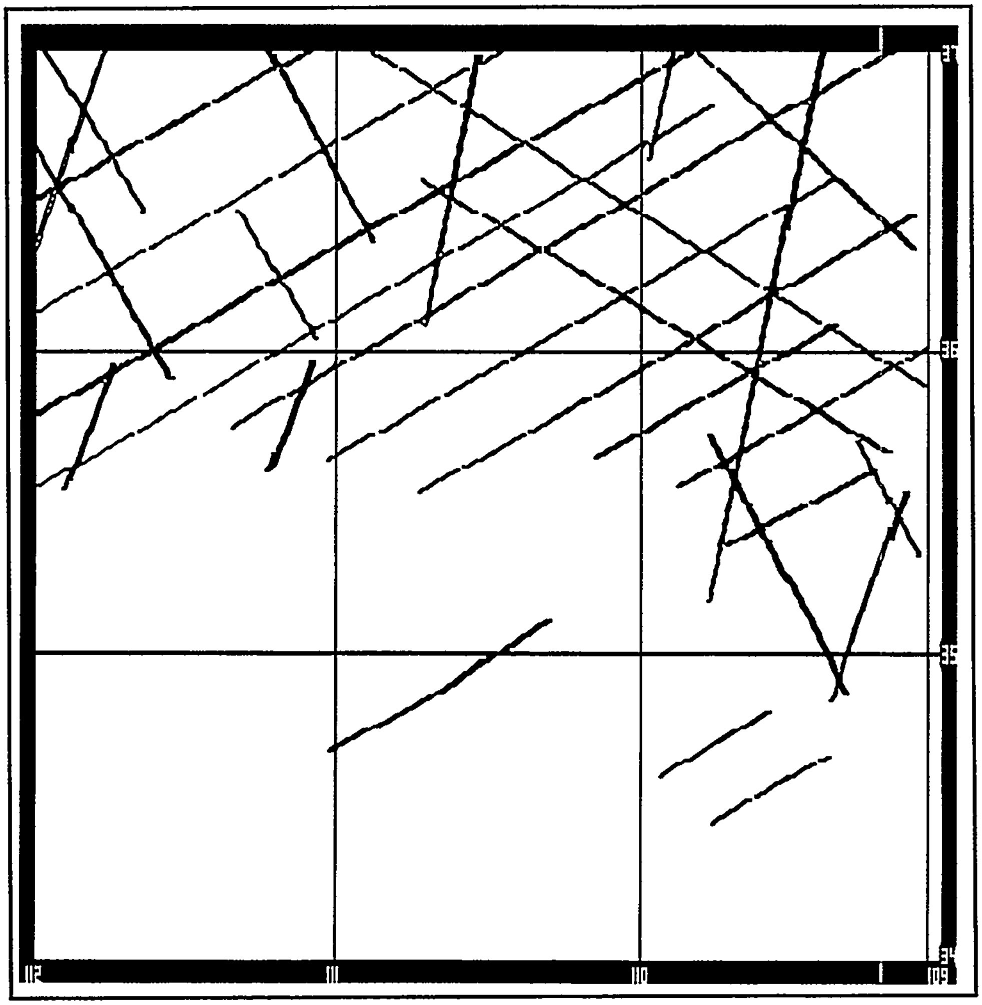
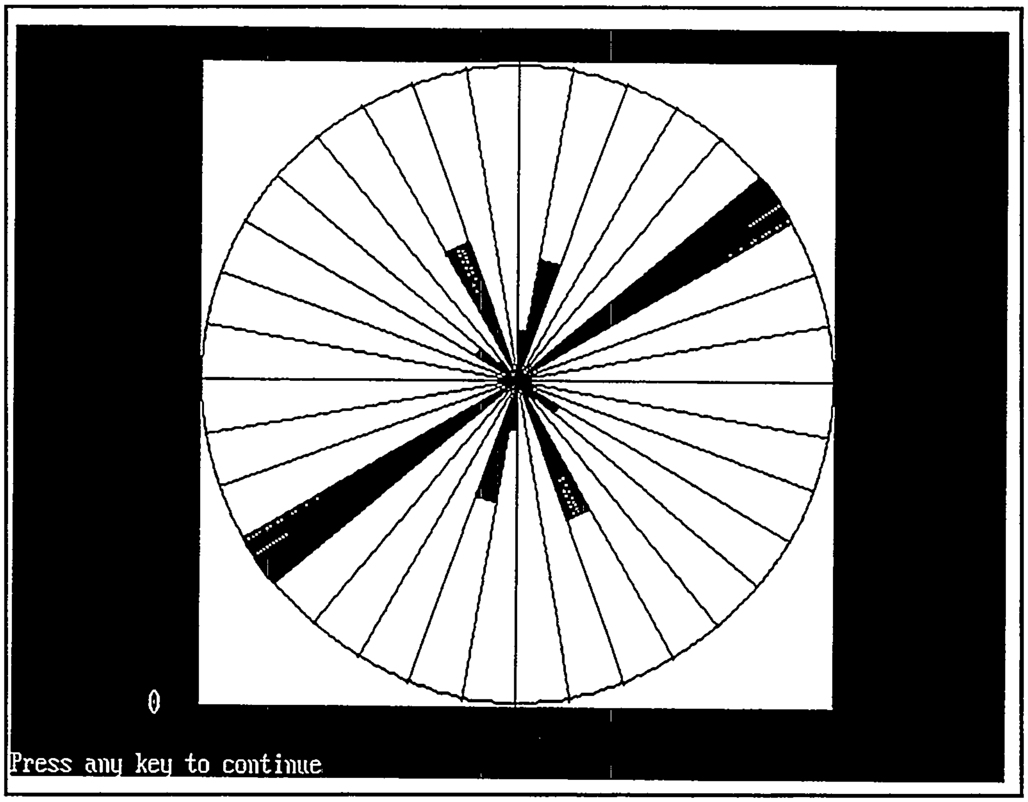


Figure 10–6 Inferred Fracture Zones from a Monoclinal Analysis in Northeastern Arizona



Press any key to continue

Figure 10–7 Rose Diagram of the Inferred Fracture Zones in Northeastern Arizona

10.4.2 Landsat Imagery Analysis

In addition to monoclinal analysis, Landsat images have also been used for mapping surface lineaments and other geological features in northeastern Arizona. A study showed that an integration of Landsat, gravity, and aeromagnetic data may result in a more realistic structural model of northeastern Arizona since these three types of data provide information for different parts of the earth crust: Landsat images to map surface lineaments, aeromagnetic data to detect basement structures, and gravity data to discern anomalies within sedimentary strata (Gutman and Heckmann 1977). The surface lineaments interpreted from Landsat images in the study is shown in Figure 10–8; the corresponding rose diagram is in Figure 10–9. The final Precambrian basement fault systems interpreted from this study, and its corresponding rose diagram are shown in Figures 10–3 and 10–10, respectively. Figure 10–9 indicates that the surface lineaments mapped in the study consist of two major sets oriented in northwest-southeast and northeast-southwest directions, and two minor sets orientated in north-south and west-northwest–east-southeast directions. The basement faults in Figure 10–3, however, consist of only two sets oriented in northwest-southeast and northeast-southwest directions, as indicated in Figure 10–10.

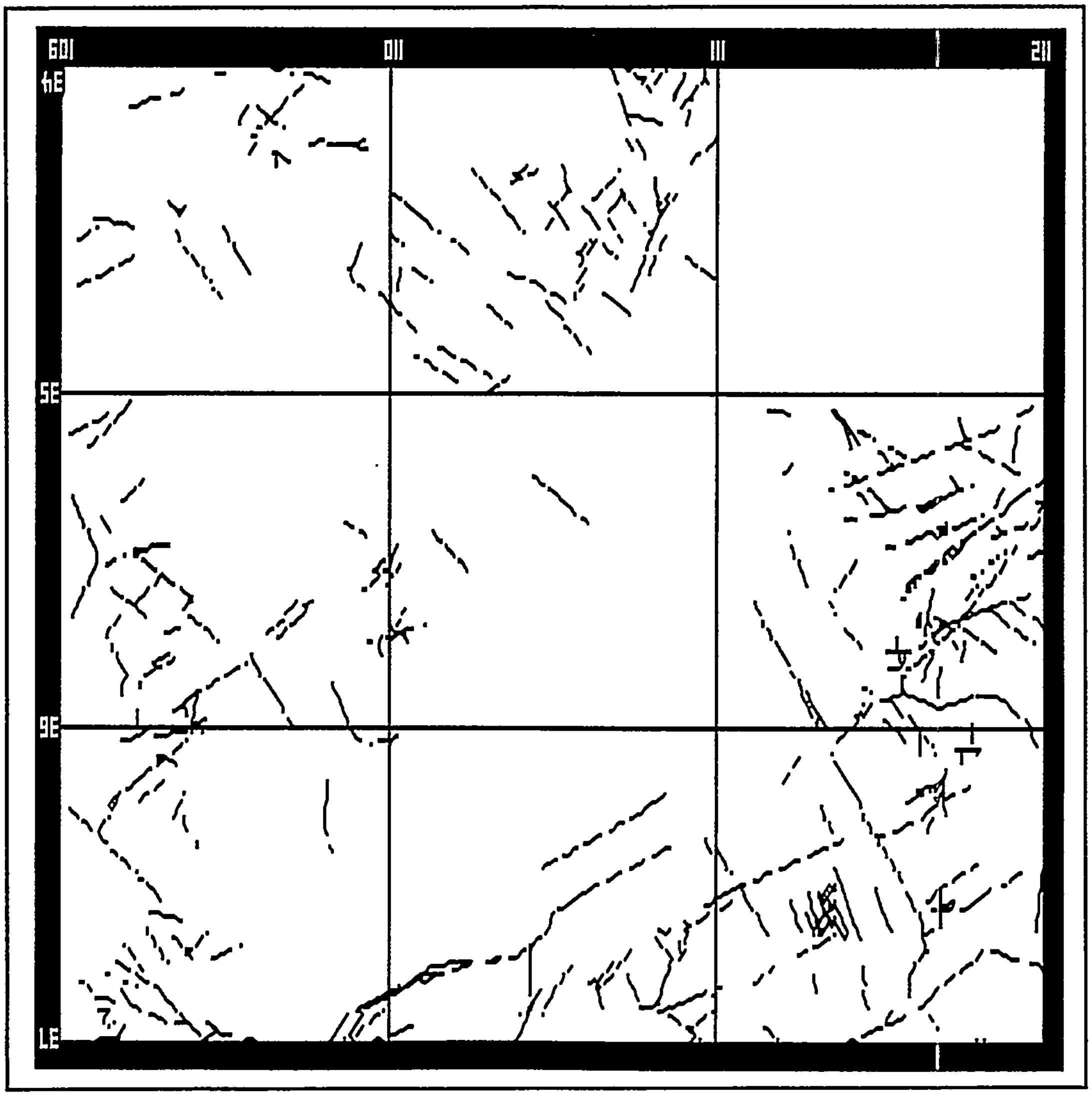
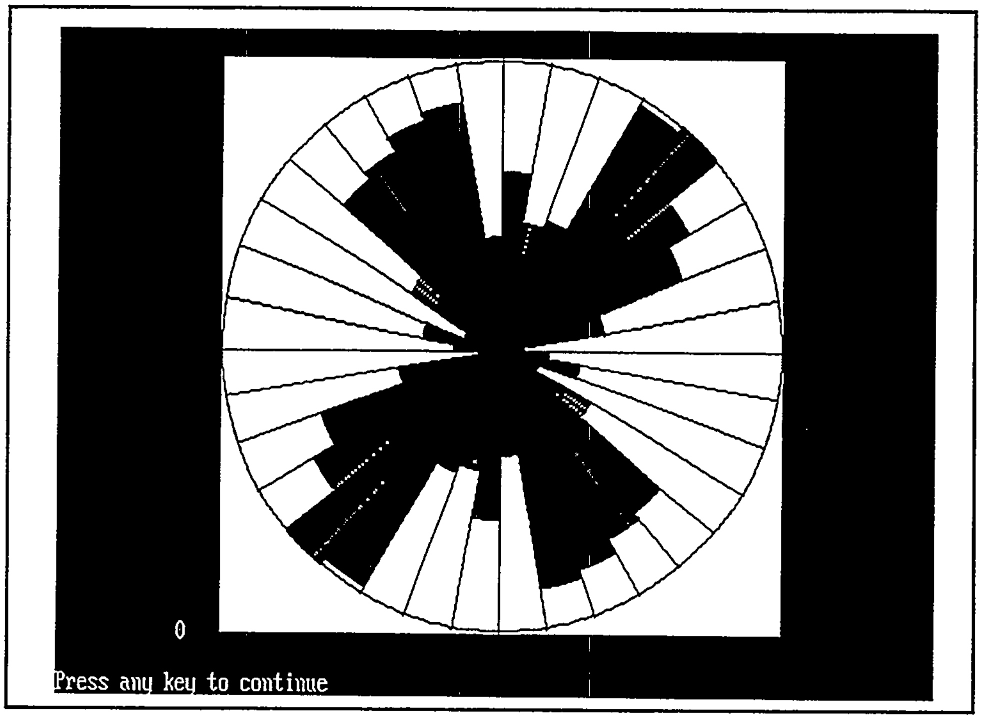
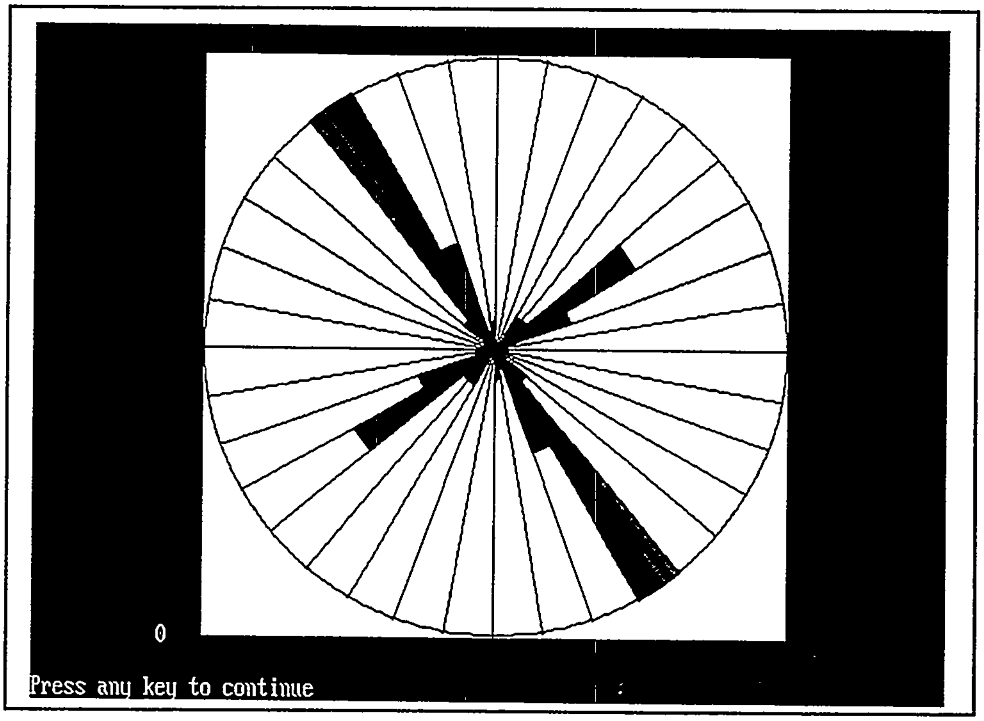


Figure 10–8 Surface Lineaments Interpreted from Landsat Images in Northeastern Arizona



```
Press any key to continue
```

Figure 10–9 Rose Diagram of the Surface Lineaments (in Figure 10–8) Interpreted from Landsat Images in Northeastern Arizona



```
Press any key to continue
```

Figure 10–10 Rose Diagram of the Basement Faults in Northeastern Arizona

Mapping surface lineaments in Arizona using Landsat data was also reported in another study, in which Quaternary fractures were emphasized during image interpretation (Lepley 1977). Surface lineaments for the whole state of Arizona were mapped. Figure 10–11 shows those in northeastern Arizona; Figure 10–12 shows the corresponding rose diagram. It can be clearly seen that the surface lineaments in northeastern Arizona mapped from this study consist of three sets oriented in northwest-southeast, northeast-southwest, and north-south directions. No attempt was made to interpret the basement structures based on these surface lineaments since the emphasis of the study was on Quaternary fractures.

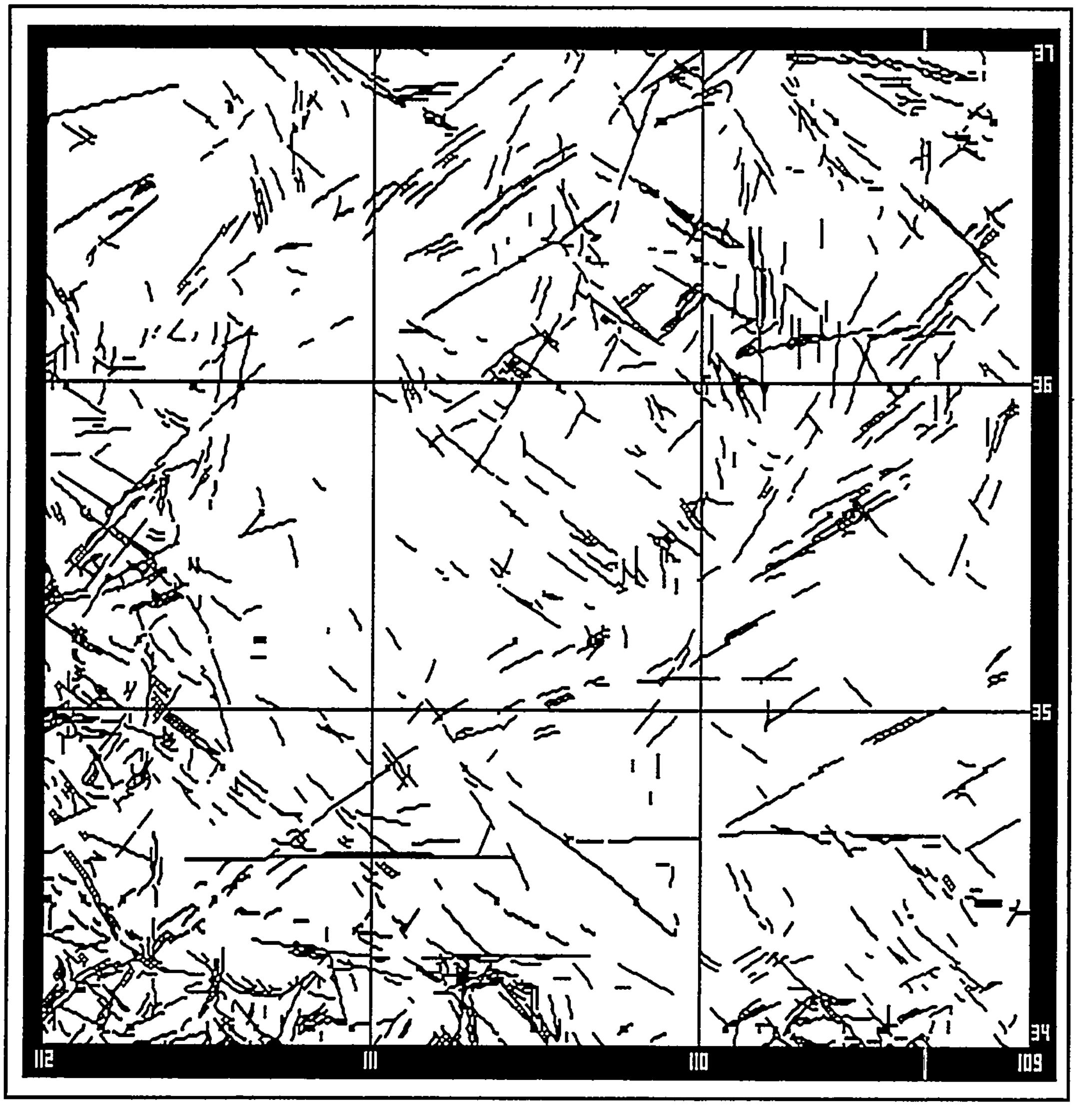
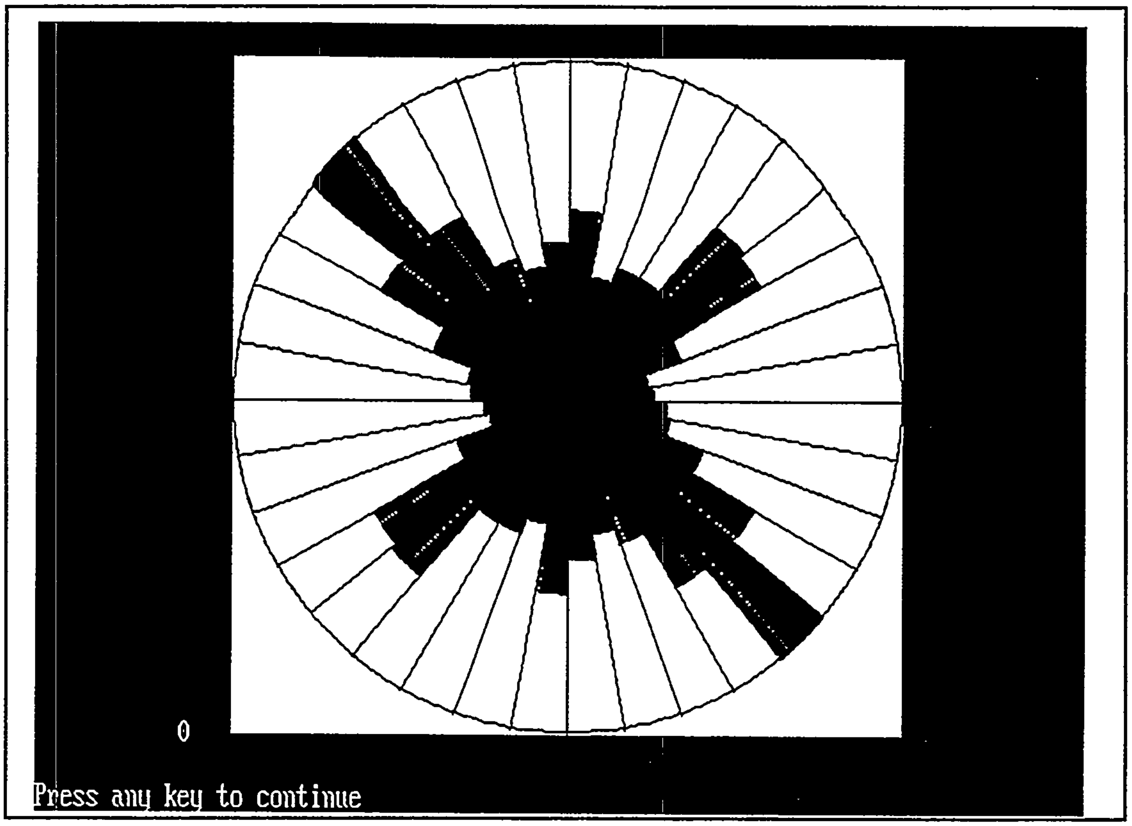


Figure 10–11 Surface Lineaments with Emphasis on Quaternary Fractures Interpreted from Landsat Images



Press any key to continue

Figure 10–12 Rose Diagram of the Surface Lineaments Interpreted from Landsat Images with Emphasis on Quaternary Fractures

10.4.3 Comparisons and Discussions

A comparison of Figures 10–9 and 10–12 indicates that the surface lineaments mapped from the two Landsat image interpretations are very consistent in trend. Both figures portray almost identical structural grains (i.e., northeast-southwest, north-south, northwest-southeast) although the density of lineaments mapped from these two studies is quite different, as can be seen by comparing Figures 10–8 and 10–11. This discrepancy in density can be explained by the fact that the objective of the first lineament study (see Fig. 10–8) was to detect basement weakness zones or fault systems, whereas that of the second lineament study (see Fig. 10–11) was to map Quaternary fractures. Both lineament studies appear to support the interpretation of the basement fault systems given in Figure 10–3.

A comparison of Figures 10–7 and 10–9 shows that both the surface fracture zones identified from the monoclinal analysis and the surface lineaments mapped from a Landsat image interpretation consist of four sets with northeast-southwest and northwest-southeast as the two primary orientations. The two minor sets from these two studies, however, differ slightly in orientation.

In summary, both monoclinal and lineament analyses, as well as gravity and aeromagnetic data, indicates the validity of the basement fault systems given in Figure 10–3 with northeast-southwest and northwest-southeast as the two basic basement structural grains. Additional minor basement fault systems may also exist, although probably less significant. Therefore, a combination of the basement fault systems interpreted from Landsat and geophysical data (see Fig. 10–3) and the surface fracture zones interpreted from monoclinal analysis (see Fig. 10–6) may provide a realistic and more detailed representation of the internal structures of the earth crust rocks in northeastern Arizona. The overlap of the basement fault systems and the surface fracture zones is shown in Figure 10–13.

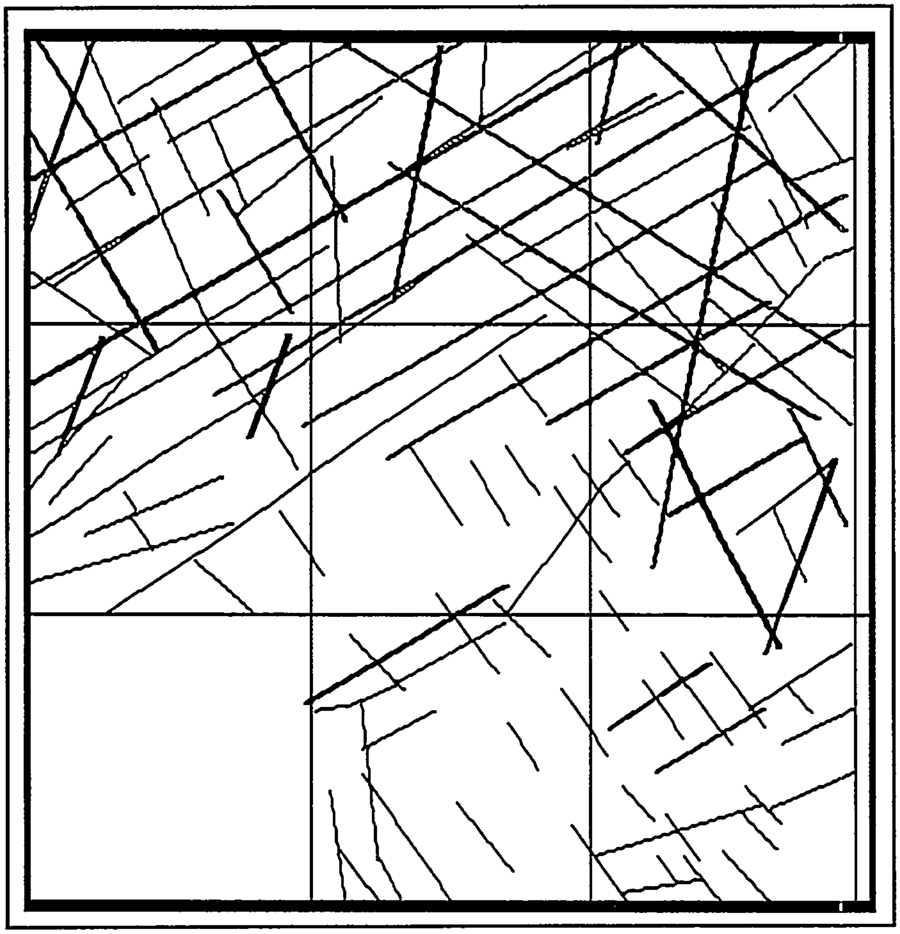


Figure 10–13 **Overlap of the Surface Fracture Zones (Dark Lines) Interpreted from Monoclinal Analysis and the Basement Fault Systems (Light Lines) Interpreted from an Integration of Landsat and Geophysical Data in Northeastern Arizona**

10.4.4 Significance of Surface Fracture Zones and Basement Fault Systems for Oil and Gas Exploration in Northeastern Arizona

Figure 10–14 shows the relationship of the surface major fracture zones inferred from a monoclinal analysis to the distribution of the oil and gas pools and salt anticlines in the Colorado Plateau (Davis 1975). Oil and gas pools are shown in black. Patterned areas are salt anticlines. Circled numbers represent the following oil and gas pools (Davis 1975):

1) McElmo Dome
2) Tohonadla
3) Gothic Mesa
4) Aneth
5) Andy's Mesa
6) SE Lisbon
7) Big Flat
8) Big Indian
9) Lisbon
10) Tocito Dome
11) Table Mesa
12) Rattlesnake
13) Hogback
14) Horseshoe Canyon
15) Many Rocks
16) Bisti
17) Escrito
18) Dineh-bi-Keyah
19) Bita Peak, Teec Nos Pos, Twin Falls Creek
20) East Boundary Butte, North Toh-Atin
21) Dry Mesa, Black Rock

One can see from Figure 10–14 that:

- all the salt anticlines and many of the oil and gas pools are oriented in northwest-southeast, parallel to one of the surface fracture-zone systems,
- some of the salt anticlines and many of the oil and gas pools lie along or at the intersections of the surface fracture zones, and
- virtually all of the oil and gas pools in Arizona are positioned on the traces of the surface fracture zones.

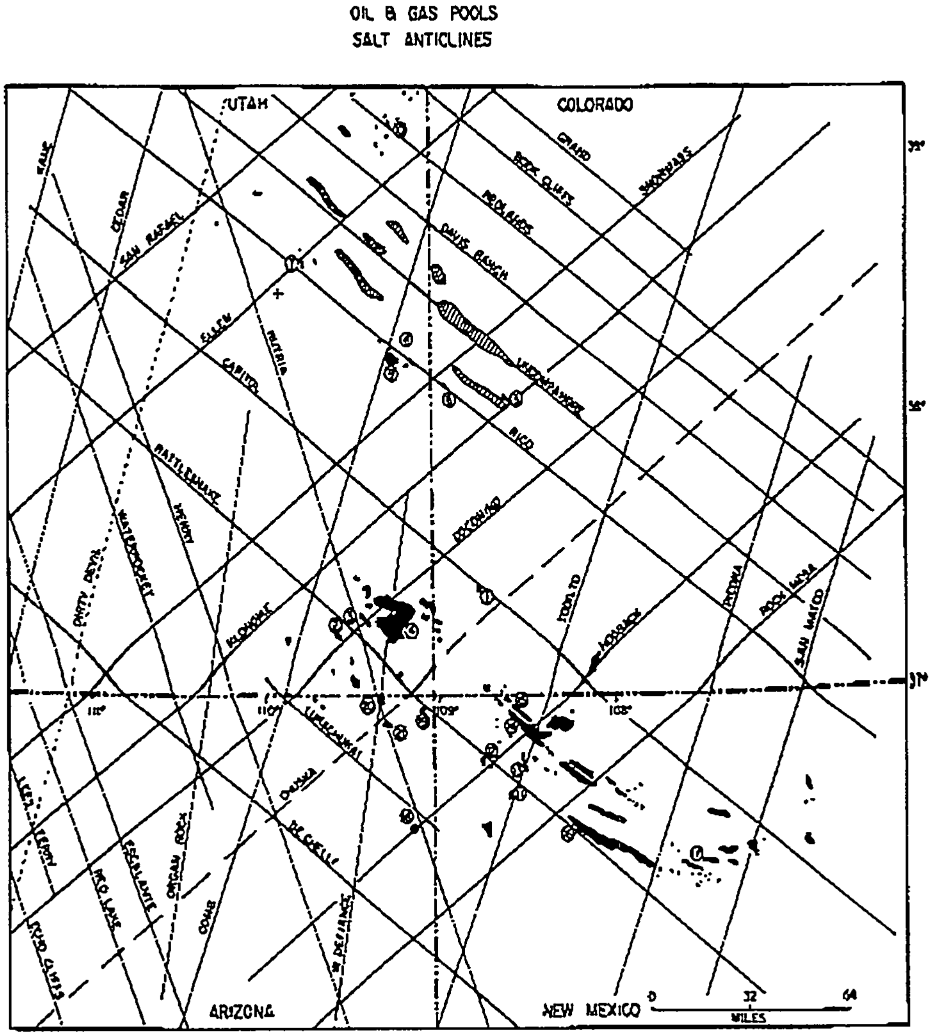


Figure 10–14 Relationship of the Inferred Fracture Zones to the Distribution of Oil and Gas Pools and Salt Anticlines in the Colorado Plateau

These observations tend to confirm the hypothesis that surface fracture zones and/or basement fault systems, as loci of major fracturing, folding, and rapid facies changes, exert some control on the entrapment of oil and gas.

On the premise that this hypothesis is true in the San Juan and Paradox basins (including extreme northeastern corner of Arizona) it is not unreasonable to postulate that oil and gas pools in the rest of northeastern Arizona, if they exist, are likely to be located along the surface fracture zones and/or the basement fault traces. In other words, there is a better chance of striking subsurface structures (i.e., traps) along these surface fracture zones and/or basement fault traces than elsewhere. Therefore, the surface fracture zones and subsurface basement fault systems, as shown in Figure 10–13, can be used as a guide for oil and gas exploration in the region.

10.4.5 Priority Locations for Potential Oil and Gas Traps in Northeastern Arizona Based on Surface Lineament Analysis

Hydrocarbon production in Arizona is currently confined to the Arizona part of the Four Corners area (i.e., extreme northeastern Arizona). As an element of a basin analysis project, the objective of this study is to provide priority locations for potential exploratory drilling and/or further geophysical and geochemical investigations beyond the Four Corners area into the general Black Mesa basin region.

The relationship of the surface fracture zones to the oil and gas pools in the San Juan and Paradox basins (see Fig 10–14) suggests that the fracture zones in northeastern Arizona shown in Figure 10–6 could be used to identify additional oil and gas traps. On the other hand, the basement fault systems, shown in Figure 10–3 and obtained from an integration of Landsat and geophysical data, may provide a more detailed description of Phanerozoic structures in the region. Figure 10–13 shows that only a few surface fracture zones coincide in position with basement faults, although they are generally consistent in orientation. To investigate their relative effectiveness, the surface fracture zones and the basement fault systems were compared with some of the well locations with oil shows identified in northeastern Arizona.

Figure 10–15 shows a distribution of oil shows in northeastern Arizona. Many of the oil shows within the Four Corners area are actual producing wells, whereas no commercial production has been reported in the rest of the region. Although not prominent, those oil shows in the south part of the study area seem to follow a rather weak trend oriented in northwest-southeast direction; those in the north central appear to follow a trend oriented in northeast-southwest direction. These two trends are parallel to the principal orientations of the surface fracture zones and the basement fault systems. However, more data are needed to confirm this observation.

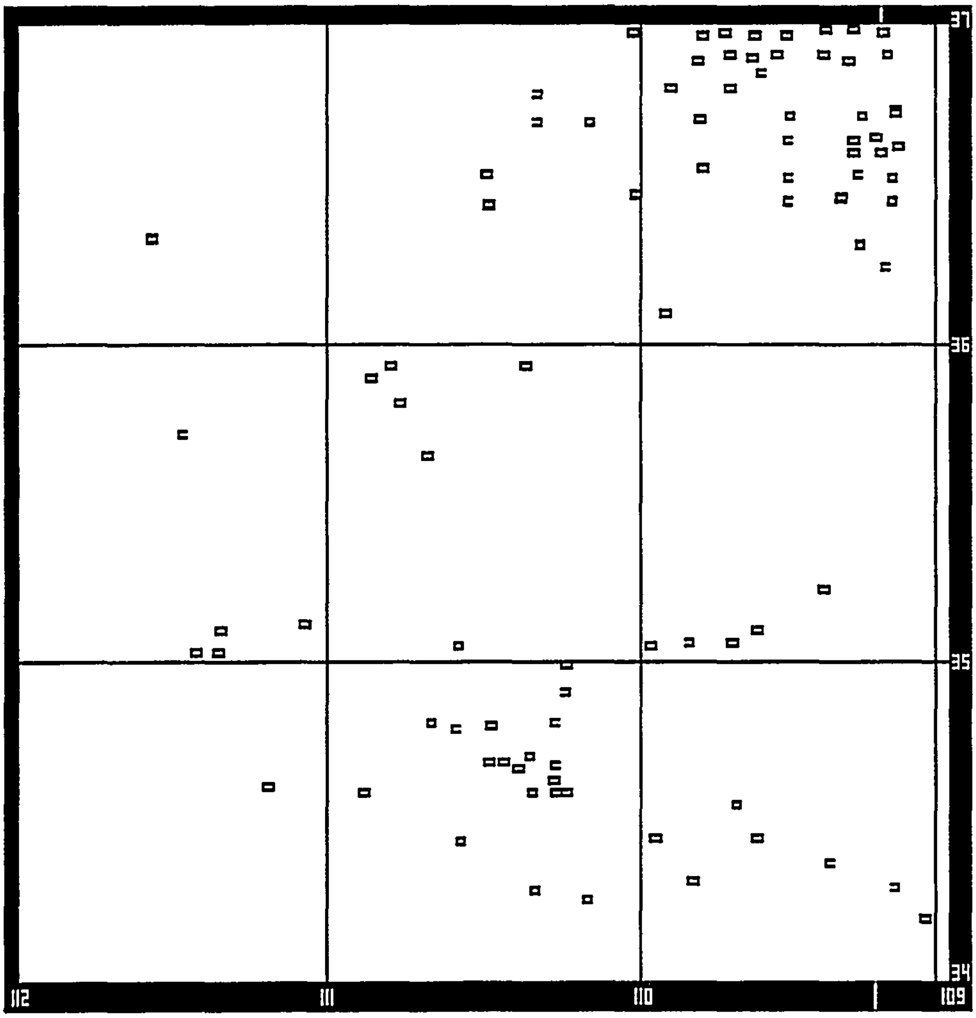


Figure 10–15 Locations of Oil Shows in Northeastern Arizona

Figure 10–16 shows the relationship of the oil shows to the surface fracture zones inferred from a monoclinal analysis. Of 88 oil shows in the region, 20 of the them appear to lie along those fracture zones. Similarly, the relationship of the oil shows to the basement fault traces interpreted from an integration of Landsat and geophysical data is depicted in Figure 10–17. It appears that 31 of the 88 oil shows are positioned along the basement fault traces. It seems that the basement fault systems have a better correlation with the oil shows than the surface fracture zones, although the total length of the basement fault traces is larger than that of the surface fracture zones. This study suggests, therefore, that a combination of the surface fracture zones and the basement fault systems (see Figs. 10–13 or 10–18) be used to infer subsurface oil and gas traps. That is, as the first step in hydrocarbon exploration in northeastern Arizona, exploratory drilling should be located and/or geophysical and geochemical surveys conducted along (or across) these surface fracture zones and basement fault systems.

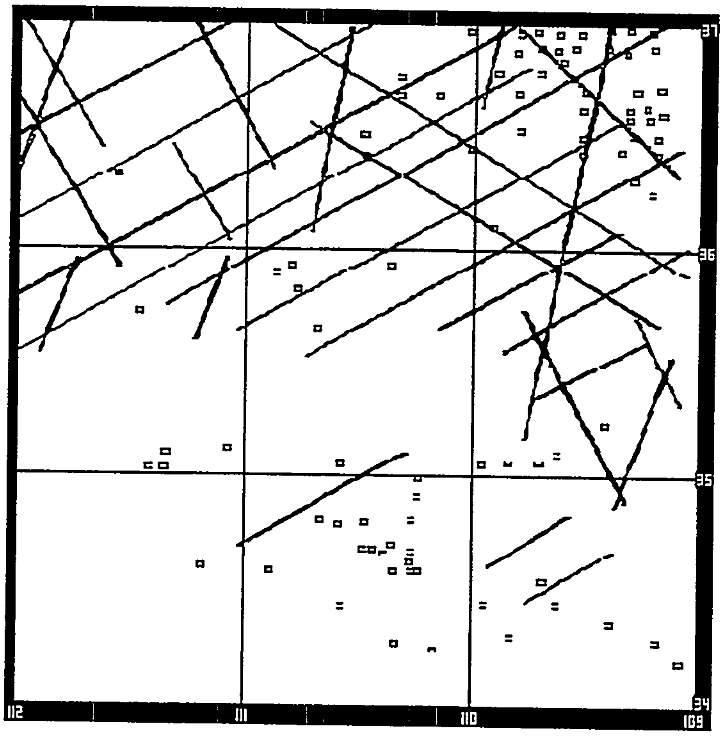


Figure 10–16 Relationship of Oil Shows (Squares) to Surface Fracture Zones in Northeastern Arizona

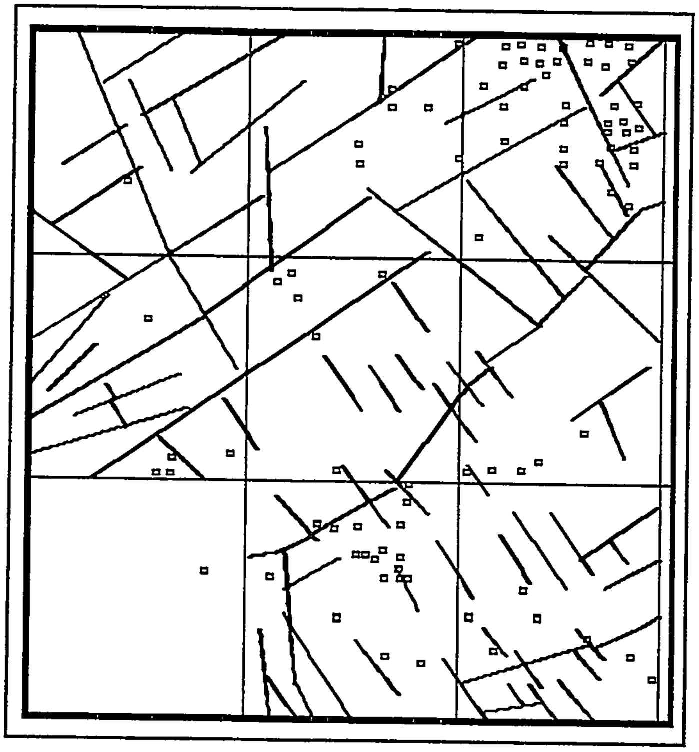


Figure 10–17 Relationship of Oil Shows (Squares) to Basement Fault Systems in Northeastern Arizona

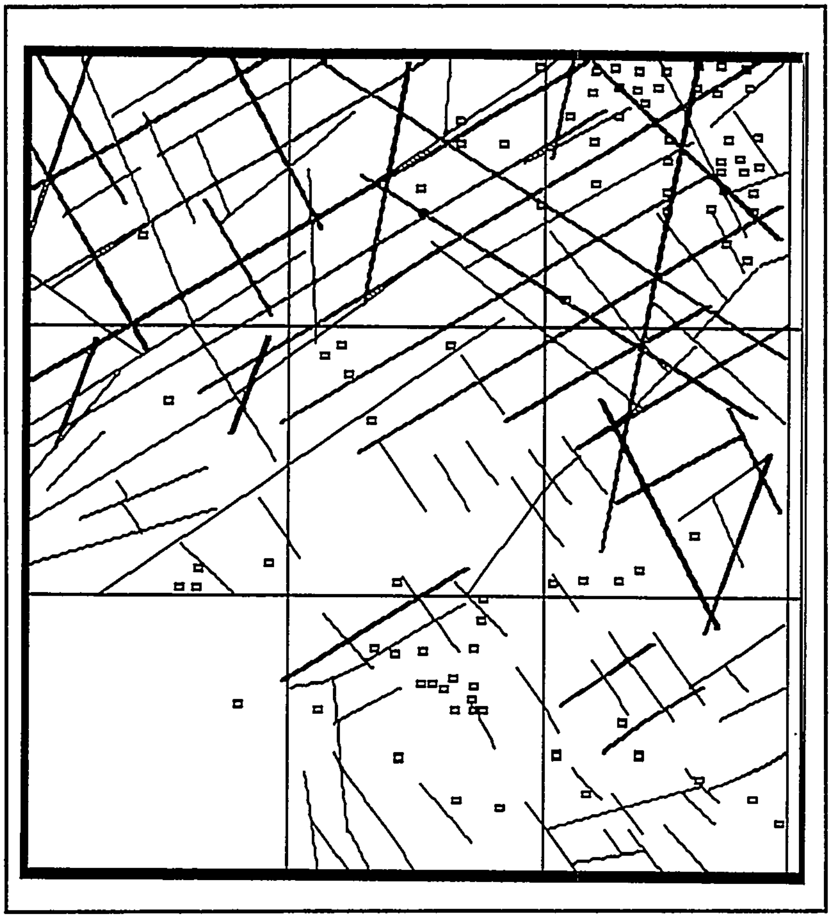


Figure 10–18 **Well Locations with Oil Shows (Squares) on the Overlap Map of Basement Fault Systems (Light Lines) and Surface Fracture Zones (Dark Lines) in Northeastern Arizona**

To further pinpoint the priority locations of potential subsurface oil and gas traps, small-scale surface fracture traces and surface drainage patterns discernible from aerial photographs should be analyzed. The analysis of the small-scale surface fracture traces in northeastern Arizona is discussed in the following section.

10.5 Analysis of Surface-Fracture Traces in Northeastern Arizona

Analysis of surface-fracture traces involved photogeological interpretation of surface fracture traces and circular and arcuate anomalies from aerial photographs, and geological and mathematical analysis of these surface features. The objectives were to provide additional information for constructing a more realistic structural model and to identify more detailed anomalous locations of potential subsurface oil and gas traps in northeastern Arizona.

10.5.1 Photogeological Study

The photogeological study included two separate areas: the Cameron area and the Black Mesa basin area (see Fig. 10–2). Aerial photographs used in this study were purchased from the U.S. Geological Survey (USGS). They are high-altitude, false-color infrared photographs taken from aircraft flown during 1980–1985 as part of the National High Altitude Photography program (NHAP). Forty such 9 × 9 in aerial photographs were acquired to cover the Cameron area. Another 154 were acquired to cover the Black Mesa basin area. The scale of these photographs is supposed to be 1:58,000. However, the actual scale varies ranging from about 1:62,000 to slightly less than 1:60,000. This scale discrepancy created minor problems for photogeological interpretation and map compilation. Some difficulty was experienced during stereoscopic viewing because overlapping aerial photographs in some flight lines were exposed on different dates and at slightly different scales. Overall, the NHAP color-infrared photographs were very well suited to mapping fracture traces in this desert environment. The special properties of the false-color infrared photography enhanced expression of vegetation highlighted fracture traces, and the fine-grained quality of the color photographs emphasized even the smallest details, especially given the small scale of the photographs.

Fractures, faults, linears, curvilinear lines, drainage, and culture were annotated stereoscopically on clear-film overlays of the aerial photographs using a pocket and/or a mirror-type reflecting stereoscope. The 3× magnification of the instruments allowed very accurate and detailed delineation of even the faintest fracture traces. Detailed drainage patterns were also mapped.

The photograph data were compiled to base maps by first determining average photo scale along flight lines for each base map area. Then, photocopy enlargements of the 1:100,000 scale USGS topographic base maps were made at the average photo scales, facilitating and simplifying the transfer of photo data by tracing annotations from the photo overlays directly onto the enlarged 1° × 30′ quadrangles.

The recognition of surface fracture traces on aerial photographs was based on the following criteria:

- Visual identification of actual crevices in the rock outcrops
- Alignments of vegetation growing in erosion-widened fractures
- Straight-line drainage segments initially formed and controlled by fractures in the bedrock surface
- Straight-line tonal or color changes in surface soils and rocks
- Locations of dikes of igneous rock injected into the weak zones in the host rock caused by fractures and faults
- Straight cliff edges

The surface fracture traces in northeastern Arizona were created by many different mechanisms and at various times. Some deep-seated stress system is believed to be responsible for the final gross fracture patterns. It is those surface fractures which originated from deep formations that may bear significance for inferring subsurface oil and gas traps.

10.5.2 Digitization of Surface-Fracture Traces

The surface fracture traces mapped from the photogeological interpretation in the Black Mesa basin and Cameron areas were subsequently digitized for further geological and mathematical analyses. A computer program was developed for the specific purpose of digitizing surface fracture traces and other linear features. Written in QBasic, the program automatically stores the coordinates of the two end points for an individual fracture trace from a digitizing board as soon as a stylus is pressed. In total, 37,914 surface fracture traces were digitized in the Black Mesa basin area, and 6,104 in the Cameron area.

Figure 10–19 shows the 37,914 surface-fracture traces mapped in the Black Mesa basin area. Individual fracture traces can not be seen clearly due to the small scale (approximately 1:820,000). In general, fractures are better exposed in the northern and central parts of this study area. A few of northeast-trending blank strips, visible across the area, are apparently caused by alluvium coverage associated with washes and valleys (from west to east, they correspond to Klethla Valley and Long House Valley, Moenkopi Wash, Dinnebito Wash, Oraibi Wash, Wepo Wash, Polacca Wash, Chinle Wash, and Nazlini Wash). Additional areas of sparse surface fracture traces in the west, southwest, southeast, and northeast of the study area are due to sand-dune coverage.

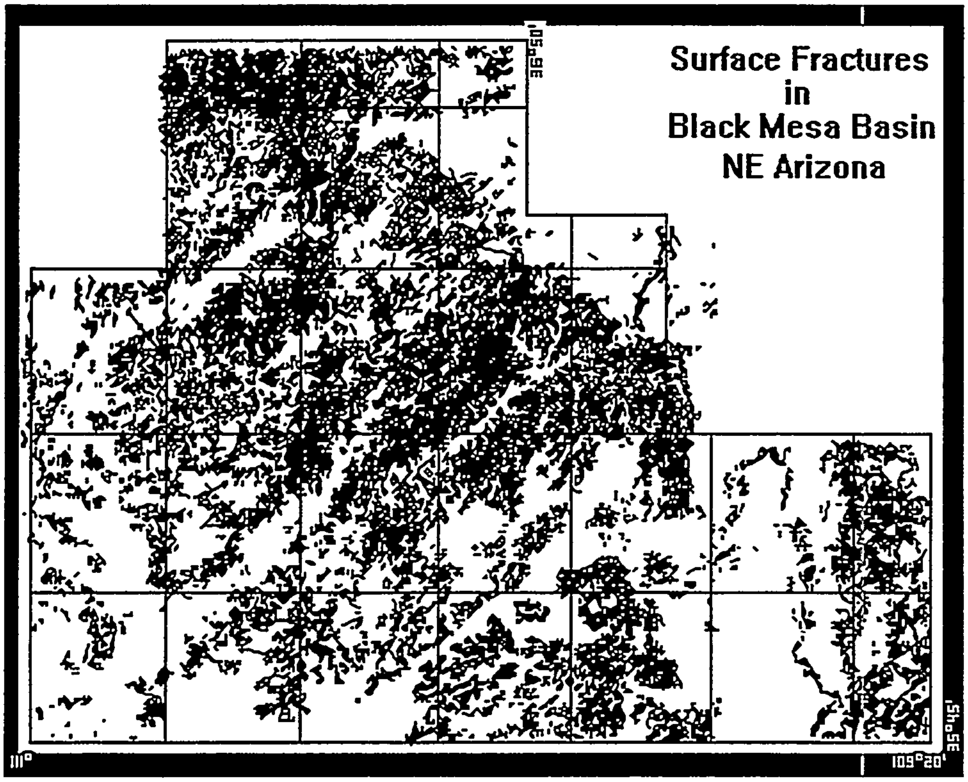


Figure 10–19 The 37,914 Surface-Fracture Traces in the Black Mesa Basin Area

The 6,104 surface-fracture traces mapped in the Cameron area are shown in Figure 10–20. More surface fractures and faults were observed in the northwestern than in the southeastern half of the area. Blank patches in the southwest and south-central are due to coverage by lava flows. The scarcity of surface fractures in the east is largely due to sand coverage associated with the Painted Desert. A small blank area in the northwest reflects cultivation activities. Part of the blank areas in the east and northwest is also due to alluvium coverage associated with the Little Colorado River, which runs across the area from southeast to northwest. The extensiveness of lava flows, faulting, and fracturing reveals the active tectonic history of the area.

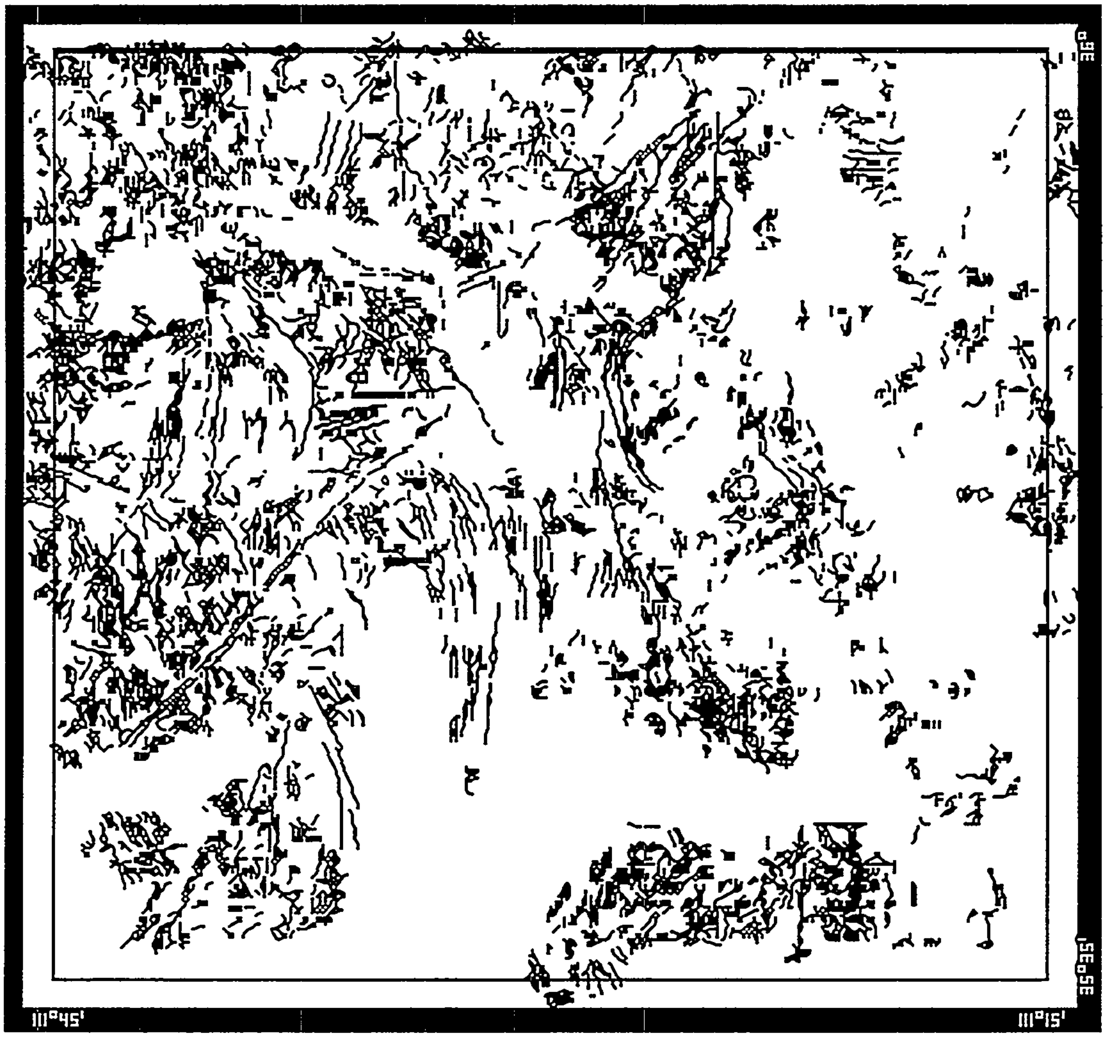
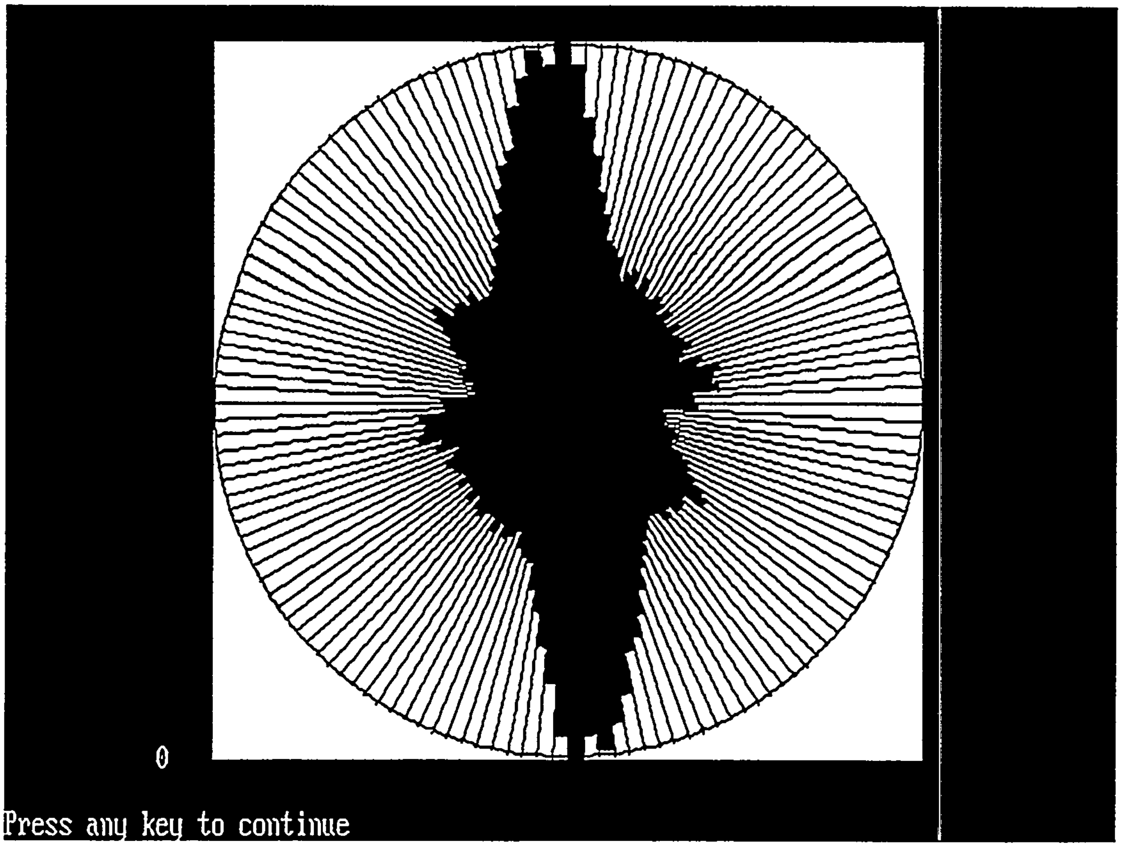


Figure 10–20 The 6,104 Surface-Fracture Traces in the Cameron Area

10.5.3 Orientation Analysis of Surface-Fracture Traces:

A composite rose diagram for the total 44,018 surface-fracture traces mapped in the Black Mesa basin and Cameron areas is shown in Figure 10–21. The surface fracture traces consist of roughly four sets: northwest, north, northeast, and east-northeast. The north-trending set appears to be the most prominent. A comparison of Figure 10–21 to Figures 10–9 and 10–12 shows that the surface-fracture traces in the Black Mesa basin and Cameron areas and the surface lineaments in the whole northeastern Arizona are essentially consistent in orientation. Both surface fracture traces and surface lineaments have northwest, north, and northeast as the three fundamental structural grains.



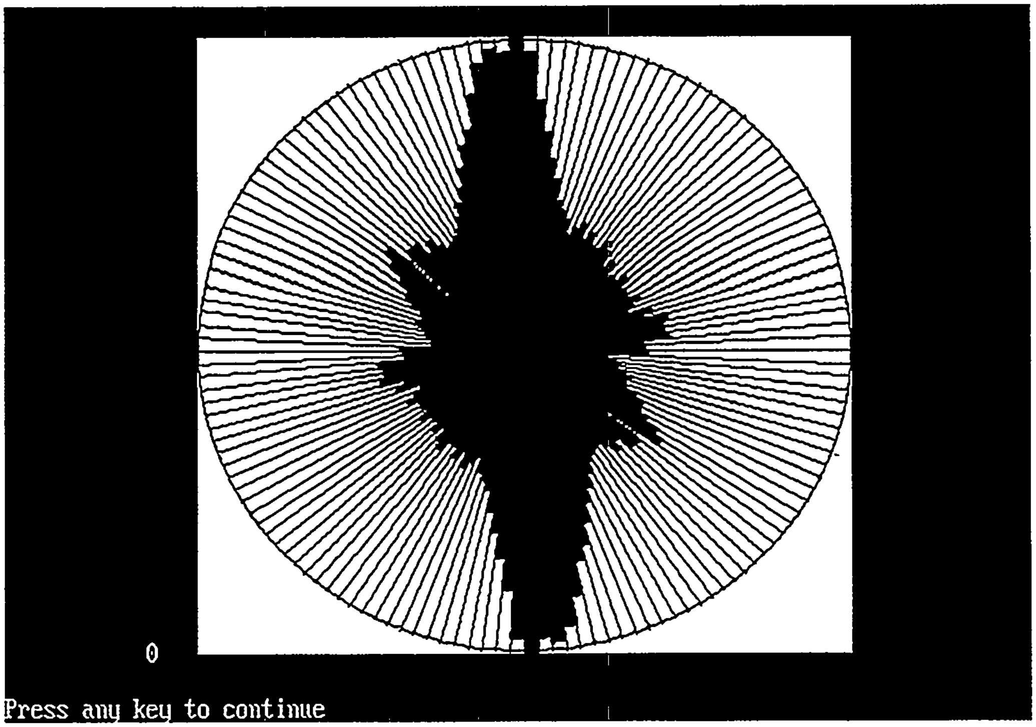
Press any key to continue

Figure 10–21 Composite Rose Diagram of the 44018 Surface-Fracture Traces Mapped in the Black Mesa Basin Area and Cameron Area

However, the rose diagrams for the surface-fracture traces and surface lineaments are far from being identical. In Figure 10–9, there is a minor set of surface lineaments oriented in west-northwest. There is also a minor set of surface fracture traces (see Fig. 10–21), but it is trending east-northeast. This discrepancy is insignificant due to the fact that only small percentages of the total surface lineaments and surface-fracture traces fall into these two minor sets. A more prominent discrepancy occurs in the general shapes of the these rose diagrams. Figures 10–9 and 10–12 show that the northwest- and northeast-trending sets are the two primary sets for the surface lineaments, with the north-and west-northwest-trending sets as the secondary sets. The surface-fracture traces (see Fig. 10–21), however, have the north-trending set as the primary and the northwest- and northeast-trending sets as the secondary. This difference may be explained by the fact that surface lineaments are more likely to reflect tectonic activities that originated from basement and/or other deep zones, whereas surface fracture traces are more likely to have resulted from more recent tectonic events. If this is true, the rose diagram of the surface lineaments (see Figs. 10–9 and 10–12) will depict the structural grains of the basement, whereas that of the surface-fracture traces (see Fig. 10–21) provides a composite profile of both basement and surface structural grains as some of those basement structures propagate to the surface. This explanation is consistent with the discussion of the basement structures in the previous sections.

On the other hand, Figure 10–21 could also imply that there is a significant set of basement fault system oriented north-south in northeastern Arizona. This set apparently has not been prominently identified in various gravity and aeromagnetic investigations. More data are required to confirm this postulation.

Figure 10–22 is the rose diagram of the 37,914 surface-fracture traces mapped in the Black Mesa basin area. It is almost identical to the composite rose diagram (see Fig. 10–21). Similarly, a rose diagram also was generated for the 6,104 surface-fracture traces mapped in the Cameron area (see Fig. 10–23). Different from the composite rose diagram (see Fig. 10–21), Figure 10–23 indicates that the surface-fracture traces in the Cameron area consist of only two sets oriented north-south and northeast-southeast. This orientation anomaly is caused by extensive wrench faulting in the Cameron area.



```
Press any key to continue
```

Figure 10–22 Rose Diagram of the 37914 Surface-Fracture Traces in the Black Mesa Basin Area

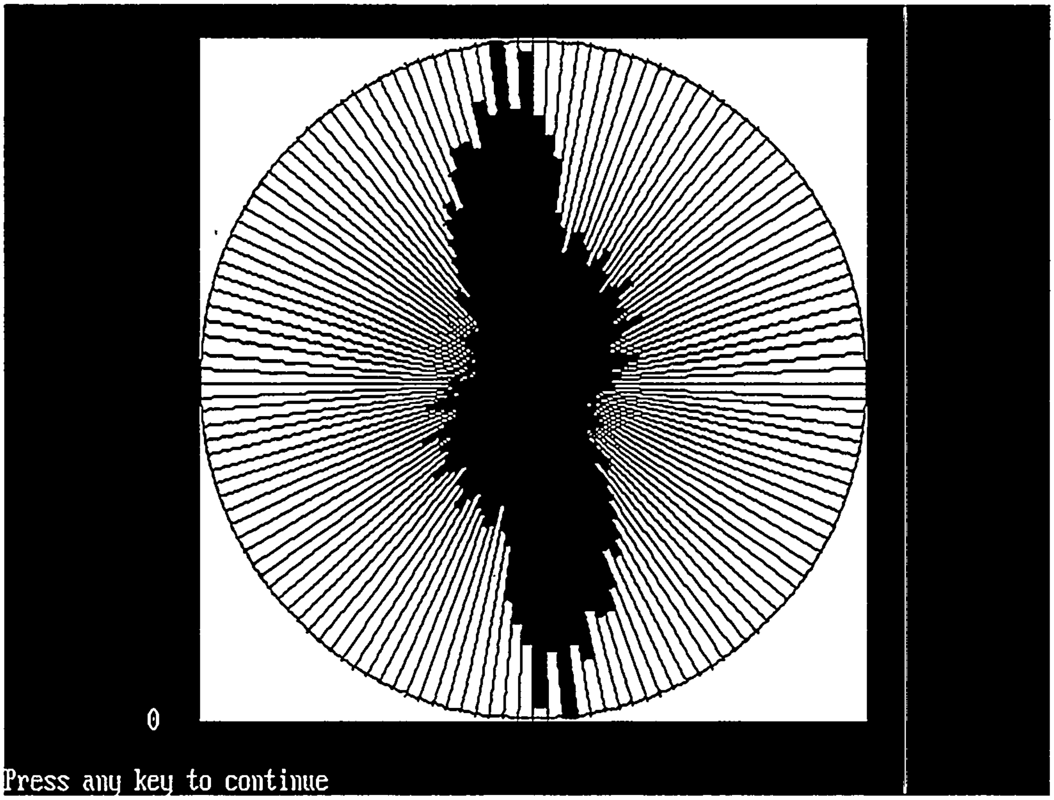


Figure 10–23 Rose Diagram of the 6104 Surface-Fracture Traces in the Cameron Area

10.6 Conclusions and Recommendations

The following conclusions can be drawn from this study of surface lineaments and surface-fracture traces in northeastern Arizona

- The structural style of northeastern Arizona is that of basement-involved extensional fault blocks. The Precambrian basement rocks are divided into regular blocks bounded by northeast- and northwest-trending fault systems. There may be another significant basement fault system oriented north-south. Many of the basement faults have been reactivated and have propagated to the surface. As loci of major faulting, folding, and rapid facies changes, the basement faults may exert some control on the entrapment of oil and gas.
- There is a strong association between the locations of oil and gas pools and surface fracture zones (interpreted from a monocline analysis) in the San Juan and Paradox basins (including Arizona part of the Four Corner area). A subtle relationship appears to exist between oil shows and surface fracture zones and/or basement fault systems in northeastern Arizona. Therefore, this study suggests that these surface fracture zones and basement fault systems (see Figs. 10–13 and 10–18) be used to infer subsurface oil and gas traps in northeastern Arizona. In other words, exploratory drilling should be positioned and/or geophysical and geochemical surveys conducted along (or across) these surface fracture zones and/or basement fault systems.

- A photogeological study was conducted in the Black Mesa basin area and the Cameron area. Surface drainage systems, surface fracture traces, and circular and arcuate anomalies in these areas were mapped from color-infrared aerial photographs. The surface-fracture traces, over 44,000 in total, were subsequently digitized. An orientation analysis of the surface fracture traces, as well as surface major lineaments mapped from Landsat images, showed that surface fracture traces and surface lineaments, although they are from different sources (aerial photographs vs. Landsat images) and differ in scale, essentially portray the same structural grains trending northwest, north, and northeast. These structural grains are generally consistent in trend with the basement fault systems.

The priority locations indicated by the surface fracture zones and basement fault systems (see Fig. 10–13) for potential subsurface oil and gas traps are too general. It is imperative that more detailed locations be identified to pinpoint positions for exploratory drilling so as to reduce the risks associated with the hydrocarbon exploration in northeastern Arizona. To reach this goal, the following further analyses are recommended

- A few prominent washes, oriented in northeast-southwest direction, cut across the restricted Black Mesa basin. Discernible from Landsat images as lineaments, these washes have been claimed by some researchers as merely caused by regional tilting toward the southwest. However, surface fracture mapping from aerial photographs indicates that some of these washes may have originated from basement faults, and consequently may bear significance in oil and gas exploration. Therefore, it is recommended that an analysis be conducted to investigate the origin of these washes.
- Surface drainage systems in the Black Mesa basin area and the Cameron area have been mapped from aerial photographs. A drainage pattern analysis is recommended to identify the locations of surface and subsurface structures. Special attention should be given to areas along and/or at the intersections of surface fracture zones and basement fault systems (see Fig. 10–13). This drainage pattern analysis will aid in delineating more detailed locations for exploratory drilling.
- Characteristics, such as frequency, density, and orientation, of surface fracture traces need to be analyzed. Locations of high residual frequency, high residual density, and anomalous rose diagrams should be identified as potential positions for subsurface oil and gas traps. In addition, a few circular anomalies mapped from aerial photographs in the Black Mesa basin area and the Cameron area need to be analyzed to investigate their significance for oil and gas exploration in the corresponding areas.

11.0 THERMAL-HISTORY MODELING OF THE BLACK MESA BASIN

The region of the Black Mesa basin considered for the thermal modeling is centered in north-central Navajo County. Although no commercial oil or gas production has been established in this portion of the basin, it has as much as 8000 to 9000 feet of sedimentary rocks (Peirce et al. 1970) that include both potential source rocks and potential reservoirs. This investigation relies mainly on published information and is a preliminary evaluation of the source-rock potential in the basin. It addresses two aspects of source-rock potential:

- identifying rock units having sufficient carbon content to have generated commercial quantities of oil or gas, and
- determining if these rock units have experienced sufficient time-temperature exposure to have generated hydrocarbons.

In the literature, and as previously defined in this report, the name "Black Mesa basin" has been applied in a broad sense to a large area of northeastern Arizona, as shown in Figure 2-1. From the point of view of thermal modeling, this definition includes structural features on the flanks of the sedimentary basin. Because this investigation is concerned with source-rock maturation, which is generally greatest in the center of the basin, where potential source rocks have experienced the greatest burial and heating, the use of the term in this section of the report is restricted to the deep portion of the sedimentary basin and excludes uplifts and shallow features around the margins of the basin. For thermal modeling purposes, the basin outline follows the limits of surface exposures of the Cretaceous Dakota Sandstone (see Wilson et al. 1960; Moore et al. 1960). The Cretaceous Mancos Shale and Mesa Verde Group overlie the Dakota and are the surface rocks within the basin.

Using the above limited definition, the Black Mesa basin is restricted to the area comprising townships 28 North through 38 North and ranges 14 East through 24 East. This area is approximately 4350 mi^2. It lies mostly in Navajo County, but extends about 16–17 mi into northwestern Apache County, and approximately 7–8 mi into northeastern Coconino County.

This restricted version of the Black Mesa basin is bounded on the east by the Defiance Uplift, an area that has been part of the Zuni-Defiance structural high since the Precambrian, with additional adjustments and reactivation along a north-south trend since the Devonian (Beus 1989). The Monument Upwarp forms the northern edge of the basin. Between the Defiance feature and the Monument Uplift is a structurally slightly lower area, the Tyende Saddle, which separates the Black Mesa basin from the Paradox basin of southeastern Utah. The northwestern limit of the Black Mesa basin is the Kaibab Uplift, and the southwestern and southern boundary of the basin is formed by the Mogollon Rim.

The above definition of the Black Mesa basin is suitable for modeling the thermal maturation of potential source rocks, and all the oil wells used as the basis for this modeling lie within these strictly defined basin limits. However, the potential source rocks and reservoir rocks that are buried within the basin extend updip to surface outcrops outside the basin. Because these rocks provide important clues about potential source-rock richness and maturity within the basin, they have been included in the study. The hydrodynamic studies and flow of hydrocarbons into the Black Mesa region from sources to the northeast, outside the basin, as discussed at the Navajo Nation Oil and Gas Company, are outside the scope of this portion of the study, and are not considered in this section of the report.

The modern location and structural configuration of the Black Mesa basin are largely a product of movements associated with the Late Cretaceous and Tertiary Laramide orogeny. Depocenters active prior to the Cretaceous were not necessarily coincident with the center of the Black Mesa basin. The deepest portion of the Oraibi Trough of the Devonian and Mississippian, as defined by Beus (1989), covered much of the western and northern edge of the modern Black Mesa basin, although geophysical modeling presented in this study suggests that thick sediments also accumulated southeast of the central mesa. This sag also extended northward into Utah.

The Holbrook basin, developed at a relatively late point, during the Pennsylvanian and Permian periods. It was located to the south of the central Black Mesa, along the northwestern end of the ancient Zuni-Defiance trend. It extended northward, into the modern Black Mesa basin, and wrapped around the southern end of the Defiance Uplift, projecting into New Mexico. The center of the Holbrook basin depocenter lay about 100 mi south of the center of the Black Mesa basin (Blakey and Knepp 1989, their Figure 5).

Because the depocenters of Arizona's Paleozoic basins were not coincident with the center of the modern Black Mesa basin, the maximum thickness, maximum burial, and maximum maturity of Paleozoic source rocks could be either outside the Black Mesa basin, or, at best, along the flanks of the basin. For this reason, the definition of the Black Mesa basin used in this study allows the evaluation of the source rock within the basin, but it does not necessarily identify the most favorable location for oil and gas generation.

11.1 OVERVIEW OF BASIN HISTORY

The Precambrian history of the Black Mesa basin is known from the ten Precambrian well penetrations listed in Table 11–3, from well penetrations in areas surrounding the basin, and by extrapolation from outcrops in the Grand Canyon and Gila County, which is southwest of the southwestern corner of Navajo County. A discussion of the Precambrian history of the basin is beyond the scope of this paper, and the reader is referred to review papers by Anderson (1989), Wrucke (1989), and Elston (1989) for detailed information. Of the ten Precambrian penetrations, well reports from five wells simply refer to "basement" or "Precambrian" without further details. Granite and/or granite wash were reported in the other five wells. Three cores of Precambrian granite were taken in the Amerada Hess Navajo #1, and a total of 8 feet of weathered and unweathered granite were recovered.

During the Cambrian, the Tapeats Sandstone and the overlying Bright Angel Shale were deposited in the Black Mesa basin; both are formations within the Tonto Group. The basal part of the Tapeats contains fluvial deposits in the Grand Canyon area (Middleton 1989) and might also contain fluvial deposits in the Black Mesa basin. The rest of the Tapeats and Bright Angel formations were shallow marine (Hereford 1977; McKee and Resser 1945). The Tapeats and Bright Angel formations are routinely reported on the well reports for wells listed in Table 11–2. The Muav Limestone (the top member of the Tonto Group) is not reported on any of these well reports, and is probably present only north and west of the Black Mesa basin (Beus 1989, his Figure 7).

Ordovician, Silurian, and Lower and Middle Devonian strata are absent in the Black Mesa basin. Deposition resumed in the Late Devonian during two marine transgressions (Beus 1989). At that time, the basin lay on the southwest side of the North American Craton; immediately to the west of the basin was the Cordilleran miogeocline. The sea transgressed from the south and west and reached maximum transgression during the Frasnian. The Temple Butte, Elbert, and Aneth formations were deposited in the basin at this time. South of the basin, the Martin Formation was also deposited during this transgression. Following a withdrawal of the sea during the early Famennian, a second, minor transgression during the late Famennian resulted in the deposition of the Ouray Formation in the northern half of the Black Mesa basin.

The Mississippian Redwall Limestone covers most of northeastern Arizona except for the Defiance Uplift and the southern part of Navajo County just west of the uplift. Although it is commonly considered to be a single formation, the Redwall was deposited during two transgressive episodes. The Whitmore Wash and Thunder Springs members of the Redwall were deposited during a late Kinderhookian and early Osagian transgression. Following a middle Osagian hiatus, a second transgression during the Meramecian resulted in deposition of the Mooney Falls and Horseshoe Mesa members. During the Chesterian, terrestrial environments covered all of Arizona except a small part in the southeastern corner (Beus 1989).

Blakey and Knepp (1989) divided the Pennsylvanian of Arizona into three major depositional packages, which they called phases. The first phase (Morrowan to Atokan) had little or no affect in the Black Mesa basin. The major areas for deposition were in northwestern Arizona, southeastern Arizona, and the Paradox basin of southeastern Utah and the northeastern corner of Arizona (northeast of the Black Mesa basin), where the Molas Formation was deposited. The second phase (Desmoinesian to Missourian) produced the Pinkerton and Paradox formations of the Hermosa Group in northeastern Arizona. The third Pennsylvanian phase (Virgilian) affected most of eastern and northern Arizona, and resulted in the deposition of formations in the upper part of the Hermosa Group.

During much of the Permian, sedimentation in the Black Mesa basin occurred in eolian, fluvial, and sabkha settings (Blakey and Knepp 1989). Some cyclic marine transgressive and regressive sequences are also known. The thickest Permian sequence (about 3500 feet thick) is centered in the Holbrook basin (Peirce 1976; Blakey and Knepp 1989), on the southern edge of the modern Black Mesa basin.

The Triassic and Jurassic rocks of northeastern Arizona are chiefly nonmarine. Triassic rocks include the Lower Triassic Moenkopi Formation, which is mostly redbeds, and the Upper Triassic Chinle Formation. The Chinle is known for its fossil assemblage of plants (e.g., the Petrified Forest southeast of the Black Mesa basin) and vertebrates that lived in fluvial swamps, lakes, and forests (Gottesfeld 1972). Jurassic rocks in the Black Mesa basin are mostly redbeds and cross-bedded eolian sandstones of the Glen Canyon and San Rafael groups and the overlying Morrison Formation (Blakey 1989).

No Lower Cretaceous rocks are present in the Black Mesa basin; however, Lower Cretaceous are present in the southeastern corner of Arizona. A comprehensive review of the Upper Cretaceous rocks of the Black Mesa basin is presented in Nations (1989). The basal Upper Cretaceous unit is the Dakota Sandstone, which grades upward through fluvial, marsh, and nearshore marine deposits. The Dakota is overlain by the marine Mancos Shale. Above the Mancos Shale lie the regressive sequence formed by the Toreva and Wepo formations and the overlying, transgressive shoreline sands of the Yale Point Sandstone (Nations 1989). The final regression of the sea from the Black Mesa area occurred during the late Turonian and was caused by the start of the uplift of the Colorado Plateau during the Laramide Orogeny.

The Wepo Formation contains the coal mined in the northern Black Mesa (Nations and Stump 1981); a discussion of this coal and its implications for basin history is presented later in this report. Although no Cenozoic rocks are preserved in the Black Mesa basin, this coal allows us to estimate the possible thickness of Cenozoic strata that were deposited and subsequently eroded. Figure 11–1 is a generalized stratigraphic column for the Black Mesa area.

PLIOCENE		Bidahochi Fm.	
CRETACEOUS	MESAVERDE GROUP	Yale Point SS	
		Wepo Formation	
		Toreva Formation	
		Mancos Shale	
		Dakota SS	
JURASSIC		Morrison Fm.	Cow Spring SS
	SAN RAPHAEL GROUP	Bluff SS	
		Summerville Fm.	
		Todilto Lms	
		Entrada SS	
		Carmel Fm.	
	GLEN CANYON GROUP	Navajo SS	
		Kayenta Fm.	
TRIASSIC		Moenave Fm.	
		Wingate SS	
		Chinle Fm.	
		Shinarump	
		Moenkopi Fm.	
PERMIAN		DeChelly/Coconino SS	
	CUTLER GROUP	Organ rock Fm.	
		Cedar Mesa SS	
		Halgaito Fm.	
PENNSYLV.	HERMOSA GROUP	Honaker Trail Fm.	
		Paradox Fm.	
		Pinkerton Trail Fm.	
		Molas Fm.	
MISSISSIP.		Redwall Lms.	
DEVONIAN		Ouray Lms.	
		U. Elbert	
		McCracken	
		Aneth	
CAMBRIAN	TONTO GROUP	Muav Lms.	
		Bright Angel Shale	
		Tapeats SS	

Figure 11-1 Black Mesa Generalized Stratigraphic Column

11.2 EVIDENCE FOR THE PRESENCE OF MATURE SOURCE ROCKS

Several types of evidence suggest the presence of mature source rocks within the Black Mesa basin. All the oil and gas fields in Arizona are located along the northern and eastern flanks of the basin. Several wells drilled within the basin had hydrocarbon shows. South of the basin, surface oil seeps and exposures of the petroliferous Martin Dolomite might be the products of oil migrating from the basin. Outcrops of the Supai Group at Promontory Butte (south of the Black Mesa basin) contain carbonized plants fragments; if the carbonized plant deposits extend northward in the subsurface to the Black Mesa basin, they might have become a source rock.

11.2.1 Oil and Gas Production on the Flanks of the Black Mesa Basin

All Arizona oil and gas fields discovered through the end of 1995 are from the northern or eastern flanks of the Black Mesa basin. Four of these fields were producing oil and gas at the end of 1995. The total production through September 1995 from each of the producing fields is given in Table 11–1.

Table 11–1 Arizona Oil Production Through September 1995

Field	Producing Zone(s)	Total Oil (bbl)	Total Gas (mmcf)
Dineh-Bi-Keyah	Hermosa Group	17,812,136	4,660
Dry Mesa	Mississippian Redwall Ls. and Paradox	813,298	995
East Boundary Butte	Paradox	874,445	9,764
Black Rock	Ismay and Akah zones of Paradox Formation	32,362	6,033

Teec Nos Pos, which produced from the Ismay and Desert Creek formations, had no production in 1995, but the field has made 486,329 bbl of oil and 1,428 mmcf of gas (Arizona Geological Survey 1995). Six other fields, all of which are now abandoned, are Bita Peak, Tohache Wash, Toh-Atin, North Toh-Atin, Twin Falls Creek, and Walker Creek. Total production from these six fields and two wells not within these fields is 118,745 bbl of oil; although natural gas might have been produced in these fields, no natural gas production is reported (Nations et al. 1989).

Oil and gas fields at the edges of the Black Mesa basin suggest the presence of mature source rocks within the basin, but the hydrocarbons in these fields could have been generated in the Paradox basin, which lies in Utah just north of the fields, or in the San Juan basin, which lies east of the fields in New Mexico.

11.2.2 Hydrocarbon Shows in Wells Drilled Within the Black Mesa Basin

Although about 350 oil, gas, and helium wells have been drilled in northeastern Arizona, only 25 of these have been drilled within the limits of the Black Mesa basin as defined above (see Table 11–2), giving a well density of only 1 well per approximately 175 mi^2 or one well per 4.8 townships. None of these wells encountered commercial quantities of hydrocarbons, but the few wells certainly do not eliminate the possibility of commercial hydrocarbon reservoirs in the basin.

Table 11–2 Wells Drilled Within the Black Mesa Basin

Operator	Well Name	Location	Total Depth (feet) And Notes
Atlantic Refining	Hopi -9 #1	sec. 9 - T28N - R15E	6640 *
Pennzoil	Hopi #1-11	sec. 11 - T29N - R14E	6944 *
Moore & Miller	Hopi #1	sec. 6 - T29N - R 15E	7000 *
Amerada Hess	Hopi - 5075 #1	sec. 8 - T29N - R 19E	7750 *
Gulf	Navajo - CZ #1	sec. 21 - T29N - R24E	4552 *
Skelly Oil	Hopi Tribe - A #1	sec. 35 - T30N - R 17E	7780 *
Amerada Hess	Navajo #1	sec. 3 - T31N - R23E	5766 * H
Peabody Coal	Navajo #3	sec. 14 - T35N - R18E	3599
Peabody Coal	Navajo #4	sec. 16 - T35N - R 18E	3534
Tenneco	Navajo - 8939 #1	sec. 2 - T35N - R22E	6754
R.Y. Walker	Navajo #1	sec. 20 - T36N - R18E	1270 H
R.Y. Walker	Navajo #1-A	sec. 20 - T36N - R 18E	1258
Peabody Coal	Navajo #1	sec. 20 - T36N - R18E	5745 H
Peabody Coal	Navajo #2	sec. 20 - T36N - R18E	3649
Peabody Coal	Navajo #6	sec. 26 - T36N - R18E	3571
Peabody Coal	Navajo #5	sec. 34 - T36N - R18E	3749
Cactus Drilling	Navajo #1	sec. 14 - T36N - R22E	6689
Cactus Drilling	Navajo 88-18 #1	sec. 23 - T36N - R 24E	5720 H
Sinclair	Navajo #1	sec. 28 - T37N - R14E	7211
Tenneco	Navajo - 8351 #1	sec. 24 - T38N - R19E	7400 * H
Superior	Navajo - W #21-29	sec. 29 - T38N - R21E	7207 * H
McCulloch Oil	Navajo #1-1	sec. 1 - T38N - R22E	5846
McCulloch Oil	Navajo #1-1X	sec. 1 - T38N - R22E	765
Tesoro Petroleum	Navajo - Davis #1	sec. 13 - T38N - R23E	5554
Exxcel Energy	Navajo Tribal #29-1	sec. 29 - T38N - R24E	6020 H

* indicates well drilled to Precambrian

H indicates a known or possible hydrocarbon show

The first well drilled in the Black Mesa basin was the Superior Navajo-W #21-29, which was drilled in 1952. No other wells were drilled in the basin until 1964, following settlement of a land dispute between the Hopi and Navajo tribes. All but two of the wells listed in Table 11–2 were drilled between 1964 and 1972. The most recent well in the basin is the Exxcel Energy Navajo Tribal #29-1, which was drilled in 1979. Although the six Peabody Coal wells were drilled as water supply wells, they are included in Table 11–2 because at least one (the #1) encountered hydrocarbons and all were deep enough to test some potential hydrocarbon reservoirs.

Of the wells shown in Table 11–2, at least four show conclusive evidence of oil in the subsurface of the Black Mesa basin. The gas shows are less conclusive. Gulf Oil's Navajo "CZ" 1 recovered 2680 feet of gas-cut brackish water from porous Devonian dolomite, but the gas was CO_2. Pinta Dome, Navajo Springs, and East Navajo Springs helium fields in Apache county are some of the world's richest helium fields (Fellows 1994). Nitrogen has also been reported from this area (Fellows 1994). Reported gas could be methane or other hydrocarbons, but it could also be CO_2, He, N_2, or a mixture of these gases.

11.2.3 Oil and Gas Shows Outside of Black Mesa Basin

Oil shows have also been reported in wells south of the Black Mesa basin limits used in this report. The wells and nature of the show are given in Table 11–3.

Table 11–3 Wells Reporting Oil Shows

Operator	Well Name	Location	Oil show description
Tucson Oil and Gas	Woodman #1-X	sec. 20-T18N-R20E	drill-stem test recovered some gas-cut mud with oil odor fi Coconino Formation
Pan American	Aztec Land & Cattle #1	sec. 5-T16N-R20E	dead oil in core of Fort Apache Formation
Adamana Oil	Government #1	sec. 4-T14N-R20E	oil shows in Supai and Redwall formations, no tests report
L.M. Lockhart	Aztec Land & Cattle #1	sec. 33-T14N-R20E	oil in cores of Supai Formation, oil and gas cut mud recov on drill stem test of Supai
L. Johnson Trustee	Aztec #2	sec. 33-T14N-R20E	oil show in Fort Apache Formation
Holbrook Oil	Government #1	sec. 23-T15N-R18E	oil show in undisclosed Permian formation
Continental Oil	New Mexico-Arizona Land #1	sec. 34-T15N-R19E	oil odor in two cores of Supai Formation; asphaltic residu core of Naco Formation
Black Canyon Oil	Black Canyon #1	sec. 20-T16N-R17E	oil show in Coconino Formation

In 1993, the Arizona Department of Commerce and the U.S. Department of Energy drilled the Alpine-Federal #1 well in the southeastern corner of Apache County, Arizona. Although this well is southeast of the Black Mesa basin, it encountered oil and potential source rocks that have implications for the oil and gas potential of the Black Mesa basin. The intended purpose for this well was to measure temperatures within Precambrian rocks at 4500 ft below the surface. Drilling was stopped in Permian strata at a total depth of 4505 ft. The well penetrated 3260 ft of Tertiary sedimentary and volcanic rocks, 109 ft of Cretaceous clastics, and 1136 ft of Permian sedimentary rocks, which were cut by three mafic dikes (Rauzi 1994).

Shows of live and dead oil in the Alpine-Federal #1 indicate the presence of a source rock with sufficient organic carbon content and sufficient thermal maturity to generate oil. Rauzi (1994) suggested that volcanism might have caused local maturation of source rocks near the Alpine-Federal #1. Another possibility would be maturation elsewhere and long-distance migration to the well location, but, if this is the case, the location of the source rocks is unknown. If such source rocks were north and west of the Alpine Federal #1 (i.e., nearer the Black Mesa basin), it is possible that such source rocks could have charged Black Mesa reservoirs.

Rauzi (1994) reported two oil shows in the Alpine-Federal #1: (a) possible dead oil at the Cretaceous-Tertiary contact and (b) bleeding oil in cores of the Fort Apache Limestone member of the Corduroy Formation (Permian).

Rauzi (1994) also suggested that gray to black shales within the San Andres Limestone (Permian, above the Fort Apache Limestone) could be similar to possible source rocks located deeper in the well. The San Andres Limestone has interbedded, thin, dark shales and stylolites containing black organic material. Rauzi suggested that nearby volcanic intrusions could have caused the thermal maturation of the shales and the formation of oil.

Using samples from the Alpine-Federal #1, Jarvie (1995) found TOC values of 3.11%–8.58% in Cretaceous strata, 3.70%–12.77% in the San Andres Limestone (Permian), values as high as 7.21% in the Corduroy Formation (Permian), and one value of 4.25% in the Fort Apache Member of the Corduroy Formation. These values demonstrate the presence of strata with sufficient organic carbon to be potential source rocks.

Jarvie (1995) also published gas chromatograms of oil extracted from Alpine-Federal #1 core material.

11.2.4 Surface Seeps

Conley (1975) compiled a list and map of known surface outcrops containing hydrocarbons, four of which have implications for Black Mesa basin oil and gas potential. Three of these are Permian outcrops. The Sedona-Vernon outcrop is a 135 mi zone of the Fort Apache Member of the Corduroy Formation; this outcrop runs roughly east-west along the southern margin of the Black Mesa basin. Northwest of the Black Mesa basin, the Soap Creek outcrop of northern

Coconino County contains petroliferous dolomite in the Woods Ranch Member of the Toroweap Formation. In southern Apache County, the St. Johns outcrop contains an oil seep and oil-stained Permian Coconino Sandstone. All three Permian outcrops lie just outside the margins of the Black Mesa basin. Oil generated within the central (and presumably thermally mature) part of the basin would have tended to migrate updip to the basin margins, following migration pathways in permeable strata that extend from the center of the basin to its margins.

Conley's (1975) compilation also included the surface exposures of the Devonian Martin Formation. Traces of oil in the Martin Formation have been reported in Gila County, but little detailed information has been published. The presence of oil in the Martin was studied and the results are reported below.

11.2.5 Martin Formation

The Martin Formation (Upper Devonian, Frasnian) outcrops just south of the Mogollon Rim south of the southern margin of the Black Mesa basin. The Martin probably extends northward in the subsurface, perhaps as far north as the basin, but the stratigraphically equivalent Aneth and Elbert formations replace the Martin in most or all of the Black Mesa basin. Teichert (1965) described the fetid dolomite unit that is present in the basal part of the Jerome Member of the Martin Formation. The fetid odor and an oil seep have been reported from a locality northwest of Payson. On February 12, 1995, one of the authors of this report (Erickson) found this locality and collected samples of the fetid dolomite unit.

The locality is a road cut along both sides of highway 87 approximately 0.6 mile (measured along the road) northwest of the East Verde River bridge. Here the highway follows the northeast side of the small canyon formed by Sycamore Creek, which is shown on the Payson North Quadrangle (7.5 minute) topographic map. Sections, townships, and ranges have not been surveyed in this area, so a satellite global positioning system (GPS) was used to measure the latitude and longitude of the fetid dolomite outcrop. The Eagle AccuNav GPS unit used is limited to C/A code, which limits the unit's precision. To minimize the error, five readings were taken over about 30 minutes, and the results were averaged. The fetid dolomite locality sampled is at 34° 18.566 ' north and 111° 21.813 ' west. The fetid dolomite locality is in a series of several road cuts, all of which are Martin Formation outcrops. The latitude and longitude give here describe the location of the dolomite with the strongest fetid odor found by Erickson.

Although an oil seep has been reported at or near this locality (locality 7-A of Conley 1975; Rauzi personal communication 1995), Erickson found no trace of any oil seep. Erickson visited the locality in February, and the cold weather could have prevented active seepage. Erickson examined part of the series of outcrops carefully, but it is also possible that the reported oil seeps are in a part of the extensive series of road cuts that were not examined by Erickson.

Thin sections of the fetid dolomite show a trace of oil in finely crystalline dolomite, however the oil inclusions are small and do not fluoresce under ultraviolet light. Hydrocarbons were extracted from a 206 g sample of powdered dolomite using dichloromethane solvent and a

Soxhlet extractor. After 24 hr of extraction, the extract was evaporated to dryness, and the amount of oil was so small that it left only a thin ring of oil residue in the bottom of a 2 ml sample vial. A gas chromatogram of the Martin oil residue is shown in Figure 11–2. Compared with most oils generated from Type II kerogens, the chromatogram shows reduced normal paraffins and an enhanced unresolved hump. Both these features are consistent with a somewhat biodegraded oil. The pristane/phytane ratio is slightly below 1.00 and is consistent either with a marine shale source rock or a carbonate source.

Pyrolysis of the fetid dolomite samples indicates that there is almost no kerogen present. Although this could be because the sample is overmature and all kerogen has already been converted to hydrocarbons, it is more likely that the dolomite is simply not rich enough in kerogen to be a source rock. If the Martin Formation in the subsurface of the basin has kerogen content as low as the Martin samples taken from the basin margin, the Martin Formation is probably not a significant source rock in the Black Mesa basin. The trace of oil in the Martin does suggest that the formation might be a reservoir somewhere in or near the basin.

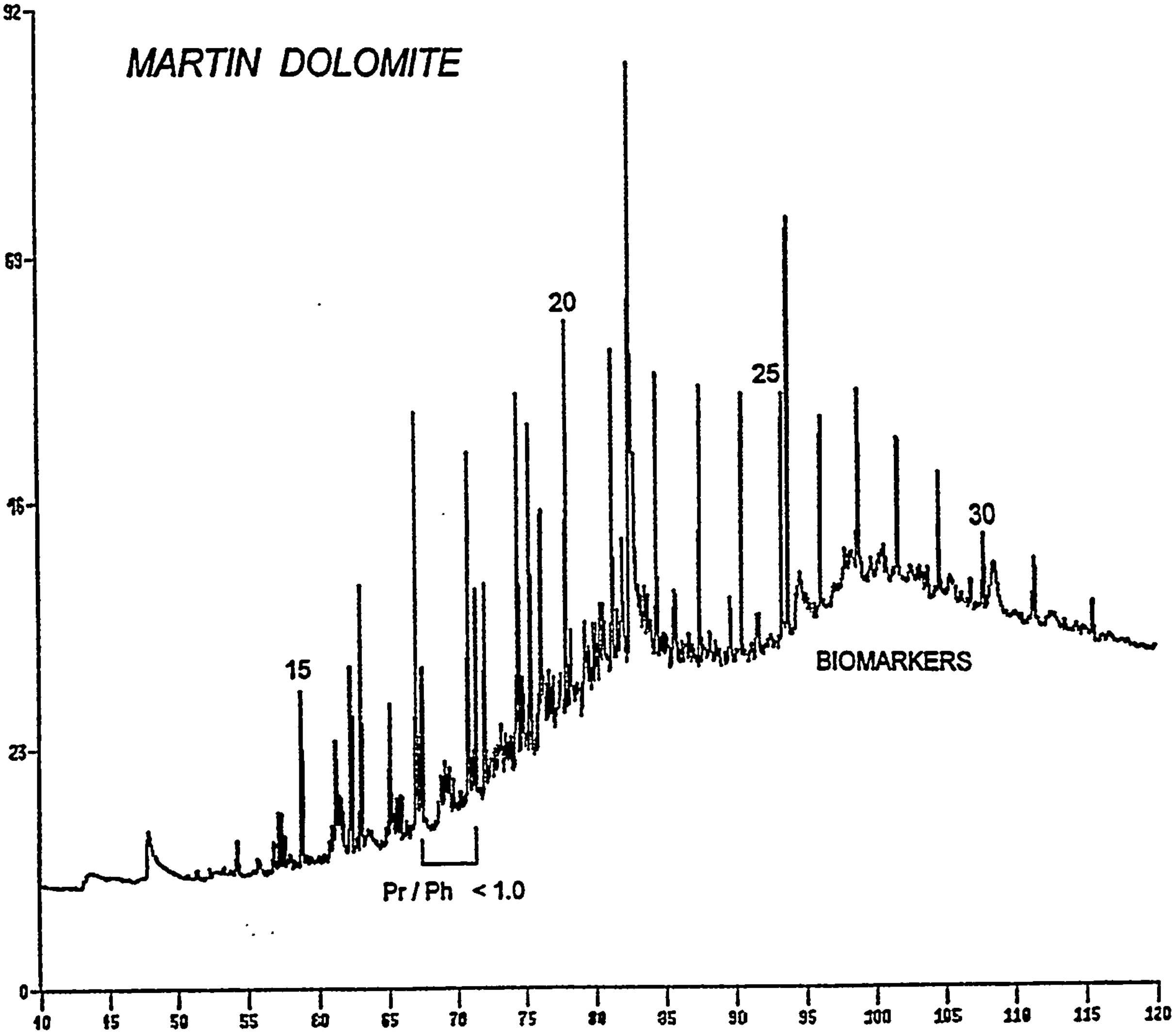


Figure 11–2 Gas Chromatogram of Extract from the Martin Dolomite.

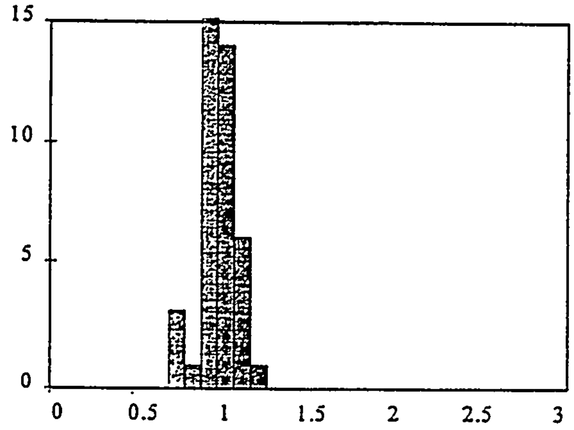
11.3 POTENTIAL SOURCE ROCKS

11.3.1 Promontory Butte

An outcrop at Promontory Butte (north of Payson, Arizona) containing carbonized plant fragments has been correlated to the Pennsylvanian to Permian Supai Group by Wenrich et al. (1989); Figure 11–12 of Wenrich et al. is a photograph of this plant material. Erickson collected specimens of this plant material on February 12, 1995. Detailed locality data for this outcrop has not been published previously; the location is almost in the exact center of the north half of Section 24, T11N, R12E, Promontory Butte Quadrangle (1:24,000 scale, 1973). Access to site is by gravel road extending north and east from Highway 260 at the SE/4 NE/4 Section 26, T11N, R12E. Wenrich et al. (1989) referred to this locality as Promontory Butte, a conspicuous landmark 1 mi north of the outcrop.

Two samples collected by Erickson were selected for vitrinite reflectance analysis by DGSI, Houston, Texas. Both samples came from the same outcrop and had R_o values of 1.00% and 0.86% (see Fig. 11–3). The dominant kerogen is vitrinite, but both samples contain some amorphous kerogen. The sample with 1.00% R_o has amorphous kerogen that fluoresces orange-brown and is associated with moderate to strongly fluorescing liptodetrinite. John Castano (for DGSI) noted that it is unusual to see fluorescence of this intensity at a vitrinite reflectance of 1.00% R_o. The fluorescence of the amorphous kerogen in the other sample is dark brown and weaker, which is more typical for a maturity of 0.86% R_o.

DGSI Project 95/3444 Sample No. 3
OTHER ID: CPF #1



VITRINITE

MEAN	1.00
ST DEV	0.10
VARIANCE	0.01
MINIMUM	0.76
MAXIMUM	1.20
NUMBER	44

BITUMEN

MEAN
ST DEV
VARIANCE
MINIMUM
MAXIMUM
NUMBER

V 0.76 V 0.91 V 0.94 V 0.97 V 0.98 V 1.02 V 1.06 V 1.09 V 1.12
V 0.78 V 0.91 V 0.95 V 0.97 V 0.99 V 1.03 V 1.06 V 1.09 V 1.15
V 0.78 V 0.91 V 0.96 V 0.97 V 0.99 V 1.03 V 1.06 V 1.10 V 1.18
V 0.82 V 0.92 V 0.96 V 0.98 V 1.01 V 1.03 V 1.07 V 1.10 V 1.20
V 0.91 V 0.93 V 0.97 V 0.98 V 1.01 V 1.04 V 1.09 V 1.11

TYPE		
	K/OC	
	TOC	
	TMAX	
	HI	
	V Ro	1.00
	B Ro	-
	VRE	-

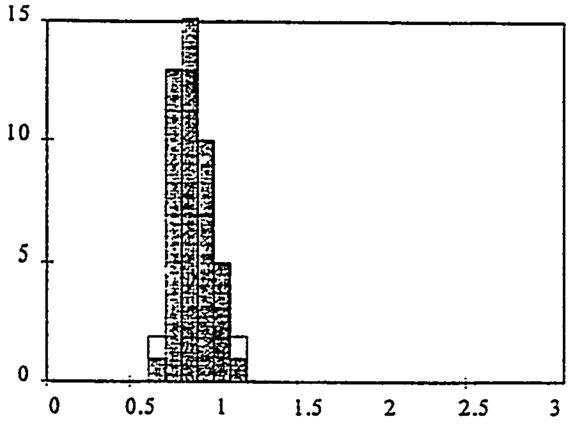
Visual Kerogen Summary

Unstructured Lipids	15
Structured Lipids	-
Solid Bitumen	-
Inertinite	T
Vitrinite	85
Other	0
TOTAL	100

Background Fluorescence	Moderate
TAI Unstructured	2+,2
TAI Structured	2+

COMMENTS:

DGSI Project 95/3444 Sample No. 4
OTHER ID: CPF #2



VITRINITE

MEAN	0.86
ST DEV	0.11
VARIANCE	0.01
MINIMUM	0.69
MAXIMUM	1.11
NUMBER	46

BITUMEN

MEAN
ST DEV
VARIANCE
MINIMUM
MAXIMUM
NUMBER

0.64 V 0.72 V 0.76 V 0.80 V 0.83 V 0.86 V 0.89 V 0.93 V 0.99 V 1.08
V 0.69 V 0.72 V 0.78 V 0.80 V 0.84 V 0.86 V 0.90 V 0.96 V 1.00 V 1.11
V 0.70 V 0.72 V 0.78 V 0.80 V 0.85 V 0.87 V 0.90 V 0.96 V 1.00 1.18
V 0.71 V 0.74 V 0.79 V 0.82 V 0.85 V 0.88 V 0.92 V 0.98 V 1.01
V 0.71 V 0.75 V 0.79 V 0.83 V 0.86 V 0.89 V 0.92 V 0.99 V 1.06

TYPE		
	K/OC	
	TOC	
	TMAX	
	HI	
	V Ro	0.86
	B Ro	-
	VRE	-

Visual Kerogen Summary

Unstructured Lipids	35
Structured Lipids	-
Solid Bitumen	-
Inertinite	5
Vitrinite	60
Other	0
TOTAL	100

Background Fluorescence	Moderate
TAI Unstructured	2+,3-
TAI Structured	2,2+

COMMENTS:

Figure 11–3 Vitrinite Reflectance Histograms for Two Samples from the Martin Dolomite (Data from DGSI, Houston).

The significance of these R_o values is that they place the Supai Group at this location within the oil window of maturity. Although these rocks are now at the surface, they were buried deep enough to have generated oil. Farther north, these rocks are still buried, although it is unknown if they extend into the Black Mesa basin. It is worth noting that terrestrial organic matter generally tends to generate gas or low sulfur, high pour point, waxy crudes.

11.3.2 Source Rocks Within the Black Mesa Basin Subsurface

The Arizona Geological Survey has sets of cuttings from most of the wells drilled in the Black Mesa basin, and they have sample descriptions prepared by AmStrat. Using the AmStrat descriptions, Erickson located shale samples that might be potential source rocks and personally examined the cuttings of these shales. None of the samples were black shales of the type commonly considered to be typical source rocks. It is possible that carbonate source rocks are present in the Black Mesa basin, but no effort was made to locate samples of carbonate source rocks.

In 1992, ARCO analyzed Aneth Shale cuttings from six of the wells listed in Table 11–2 (Atlantic Refining Hopi - 9 #1; Moore, Moore, and Miller Hopi #1; Amerada Hopi - 5075 #1; Cactus Drilling Navajo 85-15 #1; and Cactus Drilling Navajo 88-16 #1) and two other wells near the Black Mesa basin, but outside the basin limits used in this report. ARCO's unpublished data are on file at the Arizona Geological Survey. Of a total of 51 Aneth samples analyzed, only three had TOC greater than 0.3 wt. %, and only 1 had TOC greater than 0.5 %. Based on his examination of the samples ARCO used together with other Aneth Shale samples, Erickson concluded that ARCO had carefully selected the shales that appeared to have the highest carbon content. However, the low TOC values indicate that the Aneth Shale has too little organic carbon to have been a source rock. ARCO also measured R_o on three samples, probably from the Amerada Hopi - 5075 #1, and found R_o values of 0.39 to 0.43%.

11.3.3 Cretaceous Coals

Coals occur in several units of the Black Mesa basin and they are especially prominent in the Upper Cretaceous. Coal is an organic-rich rock with considerable potential to generate natural gas, and in some parts of the world coals have also sourced paraffinic crude oils. Coal beds crop out on the top of Black Mesa and around its edges, and the combined coal thickness in the Dakota Sandstone, Toreva Formation, and Wepo Formation is approximately 515 m (Nations and Stump 1981). Total reserves in the Black Mesa basin have been estimated at 21.3 billion short tons, with coal close enough to the surface to be strip mined accounting for about 1 billion tons. The best quality coal is in the Wepo Formation and coal from this formation is currently being mined by Peabody Coal.

The presence of coal (as opposed to lignite) implies burial, and in this area shows that considerable thicknesses of Tertiary must have accumulated before subsequent erosion exposed the Upper Cretaceous rocks now at the surface (see discussion below).

11.4 THERMAL MODELING OF SOURCE ROCK MATURITY

11.4.1 Introduction

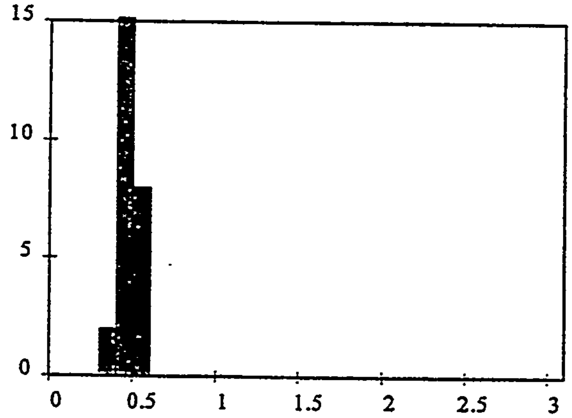
The dominant factors controlling petroleum generation are temperature and time. In evaluating basin evolution the data available are usually geologic age and depth. Clearly age provides time. Temperature is much more difficult to constrain throughout the geologic history but can be derived from depth in a couple of different ways. The usual approach is to develop a burial history plot that shows the depth of each unit of interest as a function of geologic age. This information is then combined with geothermal gradients to give temperature at any time. Alternatively, values for heat flow can be combined with thermal conductivity data for all the units in the section to provide temperature profiles as a function of age and changing lithologic makeup. Commercial computer programs are available that take present-day geological information and combine it with other relevant information (or best estimates) to calculate timing of oil generation and the thermal destruction of oil to give gas. In this project we have estimated organic maturity using the BASINMOD program (Platte River Associates, Denver). Preliminary maturation studies were made using Version 2.95, but when the updated Version 5.00 was released all maturity profiles were recalculated. This also coincided with the availability of vitrinite reflectance data and improved estimates of erosional losses.

11.4.2 Erosional Loss from the Present Day Surface

A major concern in reconstructing burial histories in the Black Mesa basin area is the amount of erosional loss from the present surface. Rocks currently exposed are mostly Upper Cretaceous. These include coals whose rank indicates that they have been buried in the past. Coal rank reflects previous burial/temperature history and can be established by determining vitrinite reluctance, or in other ways. Two coal samples from surface exposures near the Peabody Coal Mine, close to the basin center, were collected and sent to DGSI, Houston, for vitrinite reflectance (R_o) determination. Vitrinite reflectance histograms for both coals are given in Figures 11–4 and 11–5, and in both cases show tight groupings with an average R_o of 0.46%. This is only slightly higher than the ARCO R_o values for the Devonian Aneth Shale. Both coal samples were dominated by vitrinite (35–50%), but also contained appreciable amounts of inertinite (20–25%) and lipid-rich vitrinite (15–20%) (Table 11–4). The high lipid content might have suppressed the vitrinite reflectance.

DGSI Project 95/3444 Sample No. 1
OTHER ID: Coal #1

TYPE	
WR/C	
TOC	
TMAX	
HI	
V Ro	0.46
B Ro	-
VRE	-



VITRINITE

MEAN	0.46
ST DEV	0.04
VARIANCE	0.00
MINIMUM	0.38
MAXIMUM	0.57
NUMBER	50

BITUMEN

MEAN	
ST DEV	
VARIANCE	
MINIMUM	
MAXIMUM	
NUMBER	

V 0.38	V 0.41	V 0.43	V 0.44	V 0.45	V 0.46	V 0.47	V 0.48	V 0.49	V 0.50
V 0.39	V 0.42	V 0.43	V 0.44	V 0.45	V 0.46	V 0.47	V 0.48	V 0.49	V 0.52
V 0.40	V 0.42	V 0.43	V 0.44	V 0.45	V 0.46	V 0.47	V 0.48	V 0.50	V 0.56
V 0.40	V 0.43	V 0.44	V 0.44	V 0.45	V 0.47	V 0.47	V 0.48	V 0.50	V 0.56
V 0.40	V 0.43	V 0.44	V 0.45	V 0.46	V 0.47	V 0.48	V 0.49	V 0.50	V 0.57

Visual Kerogen Summary

Unstructured Lipids	-
Structured Lipids	20
Solid Bitumen	-
Inertinite	25
Vitrinite	35
Other	20
TOTAL	100

Background Fluorescence	Strong,Intense
TAI Unstructured	
TAI Structured	

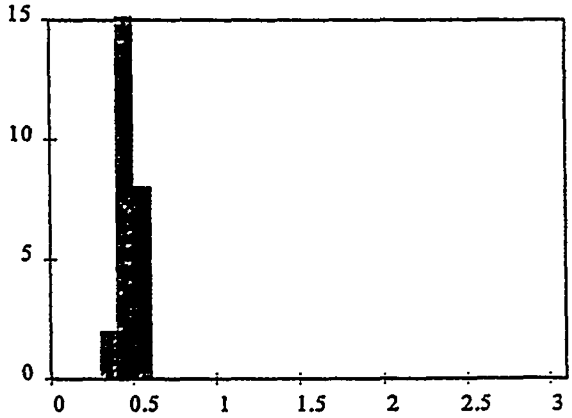
COMMENTS:

Figure 11–4 Vitrinite Reflectance Histogram for Coal Sample No. 1. (Data from DGSI, Houston).

DGSI Project 95/3444 Sample No. 2

OTHER ID: Coal #2

TYPE	
WR/C	
TOC	
TMAX	
HI	
V Ro	0.46
B Ro	-
VRE	-



VITRINITE

MEAN	0.46
ST DEV	0.04
VARIANCE	0.00
MINIMUM	0.38
MAXIMUM	0.57
NUMBER	50

BITUMEN

MEAN	
ST DEV	
VARIANCE	
MINIMUM	
MAXIMUM	
NUMBER	

V 0.38	V 0.41	V 0.43	V 0.44	V 0.45	V 0.46	V 0.47	V 0.48	V 0.49	V 0.50
V 0.39	V 0.42	V 0.43	V 0.44	V 0.45	V 0.46	V 0.47	V 0.48	V 0.49	V 0.52
V 0.40	V 0.42	V 0.43	V 0.44	V 0.45	V 0.46	V 0.47	V 0.48	V 0.50	V 0.56
V 0.40	V 0.43	V 0.44	V 0.44	V 0.45	V 0.47	V 0.47	V 0.48	V 0.50	V 0.56
V 0.40	V 0.43	V 0.44	V 0.45	V 0.46	V 0.47	V 0.48	V 0.49	V 0.50	V 0.57

Visual Kerogen Summary

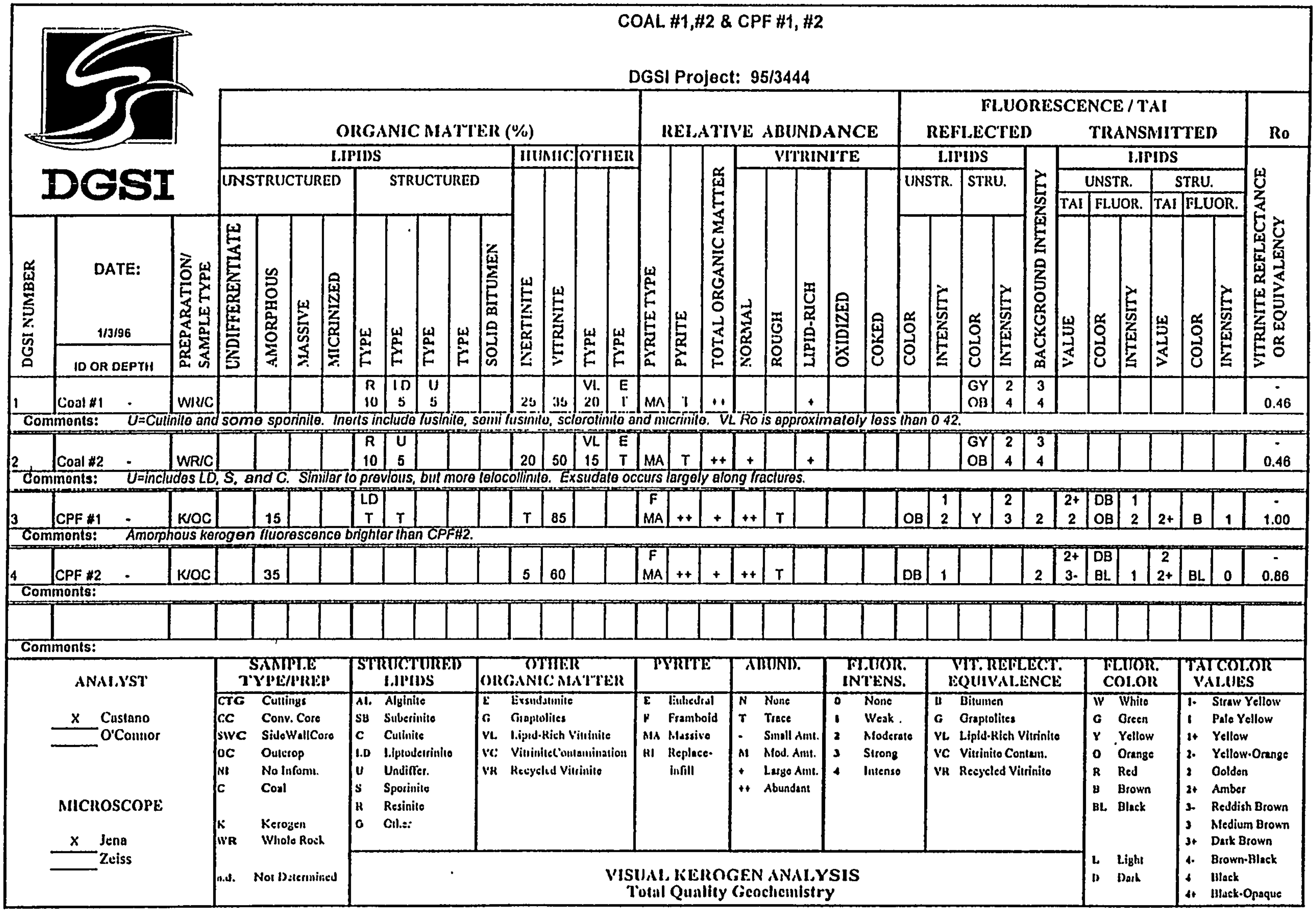
Unstructured Lipids	-
Structured Lipids	15
Solid Bitumen	-
Inertinite	20
Vitrinite	50
Other	15
TOTAL	100

Background Fluorescence	Strong,Intense
TAI Unstructured	
TAI Structured	

COMMENTS:

Figure 11–5 Vitrinite Reflectance Histogram for Coal Sample No. 2. (Data from DGSI, Houston).

Table 11–4 **Visual Kerogen Analysis for Two Coal Samples from Black Mesa (Coal #1, Coal #2), and Two Martin Dolomite Samples (CPF #1, CPF #2). (Data from DGSI, Houston.)**



DGSI

COAL #1,#2 & CPF #1, #2

DGSI Project: 95/3444

			ORGANIC MATTER (%)													RELATIVE ABUNDANCE								FLUORESCENCE / TAI REFLECTED					FLUORESCENCE / TAI TRANSMITTED						Ro
			LIPIDS									HUMIC		OTHER					VITRINITE					LIPIDS					LIPIDS						
			UNSTRUCTURED				STRUCTURED																	UNSTR.		STRU.			UNSTR. TAI	UNSTR. FLUOR.		STRU. TAI	STRU. FLUOR.		
DGSI NUMBER	DATE: 1/3/96 ID OR DEPTH	PREPARATION/ SAMPLE TYPE	UNDIFFERENTIATE	AMORPHOUS	MASSIVE	MICRINIZED	TYPE	TYPE	TYPE	TYPE	SOLID BITUMEN	INERTINITE	VITRINITE	TYPE	TYPE	PYRITE TYPE	PYRITE	TOTAL ORGANIC MATTER	NORMAL	ROUGH	LIPID-RICH	OXIDIZED	COKED	COLOR	INTENSITY	COLOR	INTENSITY	BACKGROUND INTENSITY	VALUE	COLOR	INTENSITY	VALUE	COLOR	INTENSITY	VITRINITE REFLECTANCE OR EQUIVALENCY
1	Coal #1 -	WR/C					R 10	ID 5	U 5			25	35	VL 20	E T	MA	T	++			+					GY OB	2 4	3 4							- 0.46
Comments:	U=Cutinite and some sporinite. Inerts include fusinite, semi fusinite, sclerotinite and micrinite. VL Ro is approximately less than 0 42.																																		
2	Coal #2 -	WR/C					R 10	U 5				20	50	VL 15	E T	MA	T	++	+		+					GY OB	2 4	3 4							- 0.46
Comments:	U=includes LD, S, and C. Similar to previous, but more telocollinite. Exsudate occurs largely along fractures.																																		
3	CPF #1 -	K/OC		15			LD T	T				T	85			F MA	++	+	++	T				OB	1 2	Y	2 3	2	2+ 2	DB OB	1 2	2+	B	1	- 1.00
Comments:	Amorphous kerogen fluorescence brighter than CPF#2.																																		
4	CPF #2 -	K/OC		35								5	60			F MA	++	+	++	T				DB	1			2	2+ 3-	DB BL	1	2 2+	BL	0	- 0.86
Comments:																																			
Comments:																																			

ANALYST

X Custano
O'Connor

MICROSCOPE

X Jena
Zeiss

SAMPLE TYPE/PREP

CTG	Cuttings
CC	Conv. Core
SWC	SideWallCore
OC	Outcrop
NI	No Inform.
C	Coal
K	Kerogen
WR	Whole Rock
n.d.	Not Determined

STRUCTURED LIPIDS

AL	Alginite
SB	Suberinite
C	Cutinite
LD	Liptodetrinite
U	Undiffer.
S	Sporinite
R	Resinite
O	Other

OTHER ORGANIC MATTER

E	Exsudatinite
G	Graptolites
VL	Lipid-Rich Vitrinite
VC	VitriniteContamination
VR	Recycled Vitrinite

PYRITE

E	Euhedral
F	Framboid
MA	Massive
RI	Replace-infill

ABUND.

N	None
T	Trace
-	Small Amt.
M	Mod. Amt.
+	Large Amt.
++	Abundant

FLUOR. INTENS.

0	None
1	Weak .
2	Moderate
3	Strong
4	Intense

VIT. REFLECT. EQUIVALENCE

B	Bitumen
G	Graptolites
VL	Lipid-Rich Vitrinite
VC	Vitrinite Contam.
VR	Recycled Vitrinite

FLUOR. COLOR

W	White
G	Green
Y	Yellow
O	Orange
R	Red
B	Brown
BL	Black
L	Light
D	Dark

TAI COLOR VALUES

1-	Straw Yellow
1	Pale Yellow
1+	Yellow
2-	Yellow-Orange
2	Golden
2+	Amber
3-	Reddish Brown
3	Medium Brown
3+	Dark Brown
4-	Brown-Black
4	Black
4+	Black-Opaque

VISUAL KEROGEN ANALYSIS
Total Quality Geochemistry

R_o values can be used to provide an estimate of past thermal exposure, and Barker and Pawlewicz (1986) have obtained a relation between the maximum temperature experienced, T_{max}, and R_o based on over 600 analyses. The equation is:

$$T_{max} = 104 \ln R_o + 148 \qquad 11\text{–}1$$

Substituting $R_o = 0.46\%$ leads to a maximum subsurface temperature of 67.2 °C. Barker and Goldstein (1991) developed a relationship between R_o and fluid inclusions homogenization temperatures (T_h) for calcites:

$$\ln(R_o) = 0.00811\,(T_h) - 1.26 \qquad 11\text{–}2$$

This expression leads to a temperature of 59.2°C for T_h. A pressure correction is needed to give actual temperatures, but this can only be done approximately since neither subsurface pressure nor salinity is known precisely. Based on a burial depth of 5000 ft (see below) pressure will be approximately 150 bars. This corresponds to a pressure correction of roughly 8°C, leading to a temperature of about 67°C, in very good agreement with the number derived from Equation 11–1. However, Johnsson et al (1993) have claimed that these methods underestimate temperatures, and a somewhat higher temperature of 76.2 °C is obtained from the R_o–T_h correlation proposed by Aizawa for Tertiary samples:

$$R_{max} = 0.352 \exp(0.00976\,T) \qquad 11\text{–}3$$

The temperatures obtained from R_o can be combined with surface temperature and a geothermal gradient to provide an estimate of maximum depth of burial. Present-day surface temperature is about 13°C (Druitt 1976), but in the Upper Cretaceaous the area was slightly further away from the equator (~40°N [Habicht 1979] versus 35–37°N today), and average temperatures may have been slightly lower, although it is difficult to account for elevation above sea level at a time of major erosion. Values for the amount of section lost by erosion have been estimated by combining surface temperatures of 15°C and 10°C with geothermal gradients of 25, 35, and 45°C/km. The results are summarized in Table 11–5. The generalized values used in subsequent modeling are given and more precise values are not justified given the large uncertainties in many of the estimated parameters.

Table 11–5 Erosional Loss During the Late Cretaceous

R_o-derived Temperature	Geothermal Gradients		
	25°C/km	**35°C/km**	**45°C/km**
Maximum subsurface temperature			
67.2°C (ref 1)			
67.2°C (ref 2)			
76.2°C (ref 3)			
Surface temperature: 15°C; erosional loss			
52.2°C (ref 1)	(2.09) 6852	(1.49) 4889	(1.16) 3803
52.2°C (ref 2)	(2.09) 6852	(1.49) 4889	(1.16) 3803
61.2°C (ref 3)	(2.45) 8026	(1.75) 5738	(1.36) 4459
	±7300	±5200	±4000
Surface temperature: 10°C; erosional loss			
57.2°C (ref 1)	(2.29) 7508	(1.63) 5344	(1.27) 4164
57.2°C (ref 2)	(2.29) 7508	(1.63) 5344	(1.27) 4164
66.2°C (ref 3)	(2.65) 8689	(1.89) 6492	(1.47) 4820
	±7900	±5700	±4400
Generalized values of erosional loss used in thermal modeling:			
	±7600	±5450	±4200

11.4.3 Volcanism

Middle to late Tertiary volcanism occurred in the general vicinity of the Black Mesa basin and has left a ring of intrusive plugs exposed around the edges of the basin. This has two consequences for thermal modeling. First, exposure of the volcanic necks (such as the dramatic Shiprock) show erosional loss of Tertiary rocks. Second, volcanism implies high geothermal gradients, at least locally. Intrusives such as dikes and sills have a relatively limited thermal influence that is restricted to about twice the thickness of the intrusion. However, when there are a large number of intrusives in an area, or active volcanism, it usually shows that the geothermal gradient at that time was higher.

11.5 HOPI NO. 1 WELL

The Hopi No. 1 well was drilled in 1965 by Amerada Hess Corp in Navajo County, Arizona, Section 8, Township 29N, Range 19E (see Fig. 11–6). The well reached a total depth of 7750 ft subsurface and bottomed in Precambrian rock. Electric log data provided tops for selected formations and these are summarized in Table 11–6. The general reconstruction of the geology of the Black Mesa basin shows that the Tertiary, Lower Cretaceous, and the Ordovician/Silurian are missing, and as expected these are not reported in the Hopi No. 1 well. The missing Ordovician/Silurian could be due to nondeposition or to deposition with subsequent erosion (unconformity) but has been treated as a hiatus. The choice is not critical because these rocks predate many of the potential source rocks in the section. Even if there are Precambrian source rocks they would have to buried more than about 6000 ft to become mature at this time. The unconformity at the base of the Upper Cretaceous could also be due to erosion of preexisting Lower Cretaceous rocks, or to a hiatus in sediment accumulation. It has been modeled both ways. The present surface for much of the Black Mesa basin is Cretaceous. Although it is possible that no Tertiary was deposited in this area it seems more likely that sediment did accumulate and was later eroded. Erosional loss of Tertiary is supported by the exposed mid-to-late Tertiary volcanics, and by the presence of coal in the Mesaverde Group and Dakota Sandstone. Bituminous coal formation needs the elevated temperatures that come from burial and the vitrinite reflectance data discussed above leads to the erosional losses summarized in Table 11–5. These values have been used in modeling maturity in the Hopi No. 1 well.

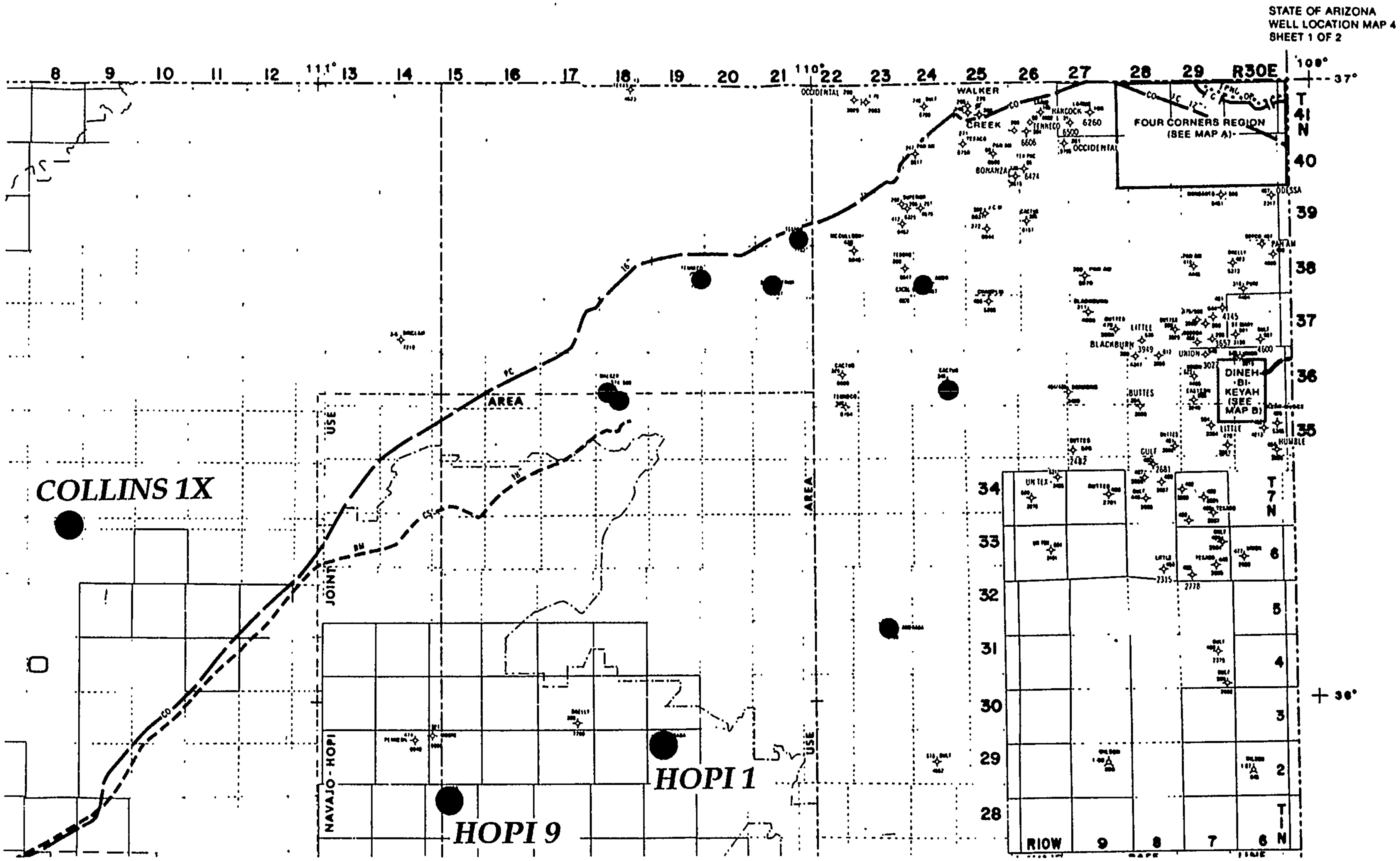


Figure 11–6   Locations of the Three Modeled Wells

Table 11–6 Input Stratigraphy Data for Modeling the Hopi No. 1 Well

Formation or Event Name	Type	Begin Age (Ma)	Well Top (feet)	Present Thickness (feet)	Missing Thickness (feet)
Erosion 2	E	33			-7600
Tertiary	D	66			7600
Mesaverde Group	F	75	0	302	
Mancos	F	85	302	519	
Dakota	F	98	821	791	
Erosional	E	100			-1000
Lower Cret.	D	144			1000
Navajo	F	208	1612	517	
Wingate	F	226	2129	631	
Chinle	F	232	2760	1300	
De Chelly	F	255	4060	1480	
Organ Rock	F	265	5540	1039	
Pennsylv.	F	320	6579	263	
Miss	F	360	6842	197	
Ouray Lms.	F	367	7039	56	
Elbert	F	374	7095	235	
McCracken	F	380	7330	107	
Aneth	F	387	7437	91	
Bright Angel	F	561	7528	32	
Tapeats	F	590	7560	135	
Precambrian	F	640	7695	135	

Ages for the formations in the Hopi well were obtained from the Decade of North American Geology time scale for major events (e.g., end of the Jurassic) and interpolated based on rock thicknesses for most other units. Sensitivity studies show that thermal modeling is relatively insensitive to uncertainties in ages. As more data become available the ages used can be refined. All modeling was done using 10 m.y. time increments and LLNL kinetics.

No temperature data were available when this preliminary modeling study was carried out. However, most simple intracratonic basins have had relatively undisturbed thermal histories with geothermal gradients that remain fairly close to average. Maturity calculations were carried out using unchanging gradients of 25°C/km and 35°C/km. The presence of mid-to-late Tertiary volcanics on the periphery of the basin suggests that geothermal gradients may have been higher over that time span. This possibility has been modeled by increasing the geothermal gradient to 45°C/km over the last 30 m.y. In the absence of paleosurface data, surface temperature was kept constant at 15°C throughout the burial history, though this is somewhat higher than the present value of 13°C (55°F) reported by Druitt (1976).

Table 11–7 summarizes the combinations of burial histories and geothermal gradients used in the preliminary thermal models of the Hopi No. 1 well in the Black Mesa basin.

For a cool temperature regime of 25°C/km and an erosional loss of 7600 ft in the Tertiary, only the deeper parts of the section enter the oil window and achieve maturities corresponding to a vitrinite reflectance in the range 0.5% to 0.7 % (see Fig. 11–7). Only the lower part of the Dakota and older rocks became mature. This is inconsistent with measured surface values for vitrinite reflectance and implies higher geothermal gradients in the past.

Table 11–7 Summary of Combinations of Burial Histories and Geothermal Gradients Used in Modeling the Hopi No.1 Well.

(± : deposition/erosion at unconformity)

25°C/km geothermal gradient

Figure 11–7: L. Cret ± 1000 ft; Tert ± 7600 ft

35°C/km geothermal gradient

Figure 11–8: L. Cret ± 1000 ft; Tert ± 7600 ft

Figure 11–9 : L. Cret ± 1000 ft; Tert ± 5450 ft

Figure 11–11: L. Cret ± 1000 ft; Tert ± 5450 ft; 45°C/km last 30 m.y.

Figure 11–14 : L. Cret ± 1000 ft; Tert ± 5450 ft; 50°C/km last 30 m.y.

Figure 11–16: Increasing Maturity for the Aneth as a Function of Time for the Burial History Shown in Figure 11–14.

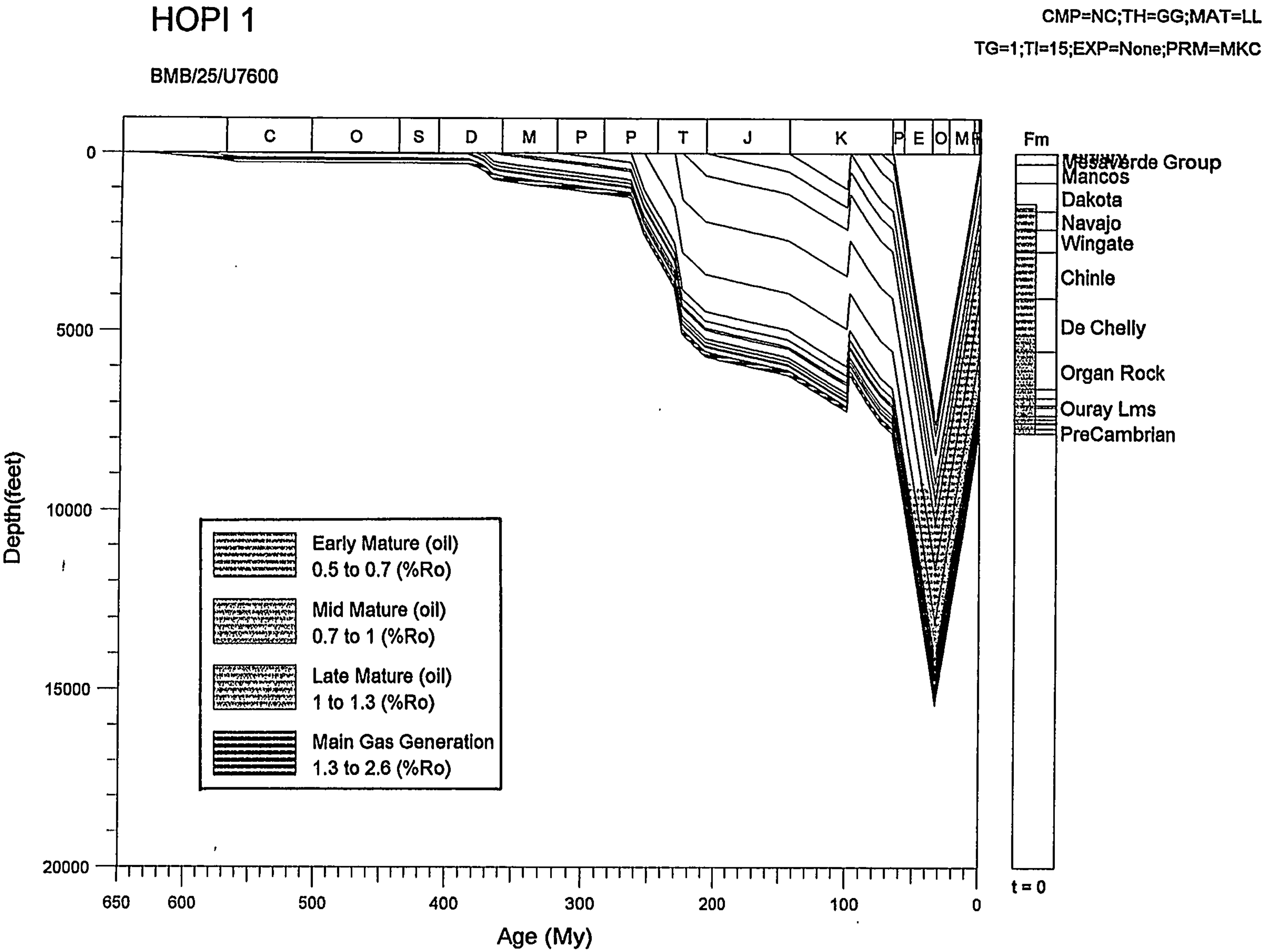


Figure 11–7 Hopi No.1 Burial History and Maturity for 1000 ft Unconformity in the Lower Cretaceous and a 7600 ft Erosional Loss in the Tertiary. 25°C/km Geothermal Gradient.

Increasing the geothermal gradient to 35°C/km leads to earlier generation and higher maturity levels as expected. If the erosional loss is kept at 7600 ft the maturity window extends to the surface (see Fig. 11–8), but when the more realistic value of 5450 ft (see Table 11–5) is used then surface rocks are not mature (see Fig. 11–9), and again the predicted maturity level is less than that observed. Late Tertiary igneous activity probably increased geothermal gradients, and this has been modeling using an initial gradient of 35°C/km that increased to 45°C/km over the last 30 m.y. Selected isotherms are shown in Figure 11–10 and the corresponding burial history plot with maturity windows is given in Figure 11–11. The surface Mesaverde Group is not quite mature, but the calculated vitrinite reflectance values (see Fig. 11–12) agree well with the values of 0.46% obtained for surface coals. The deep burial has moved the lower Organ Rock and older rocks into the gas generating range. Some of these rocks probably have high enough organic contents to be effective source rocks. The fit with measured vitrinite reflectance is not as good when the recent geothermal gradient is raised to 50°C/km (see Figs. 11–13 and 11–14) and calculated R_o values are higher than observed (see Fig. 11–15). Maturity levels are difficult to distinguish for the deeper parts of the burial history shown in Figure 11–14, and so they are presented in a different way in Figure 11–16. This figure gives cumulative maturity (as equivalent vitrinite reflectance) through time, and shows that the Aneth began generating 170 Ma, moved into the main generation window about 60 Ma, and began to generate gas about 30 Ma.

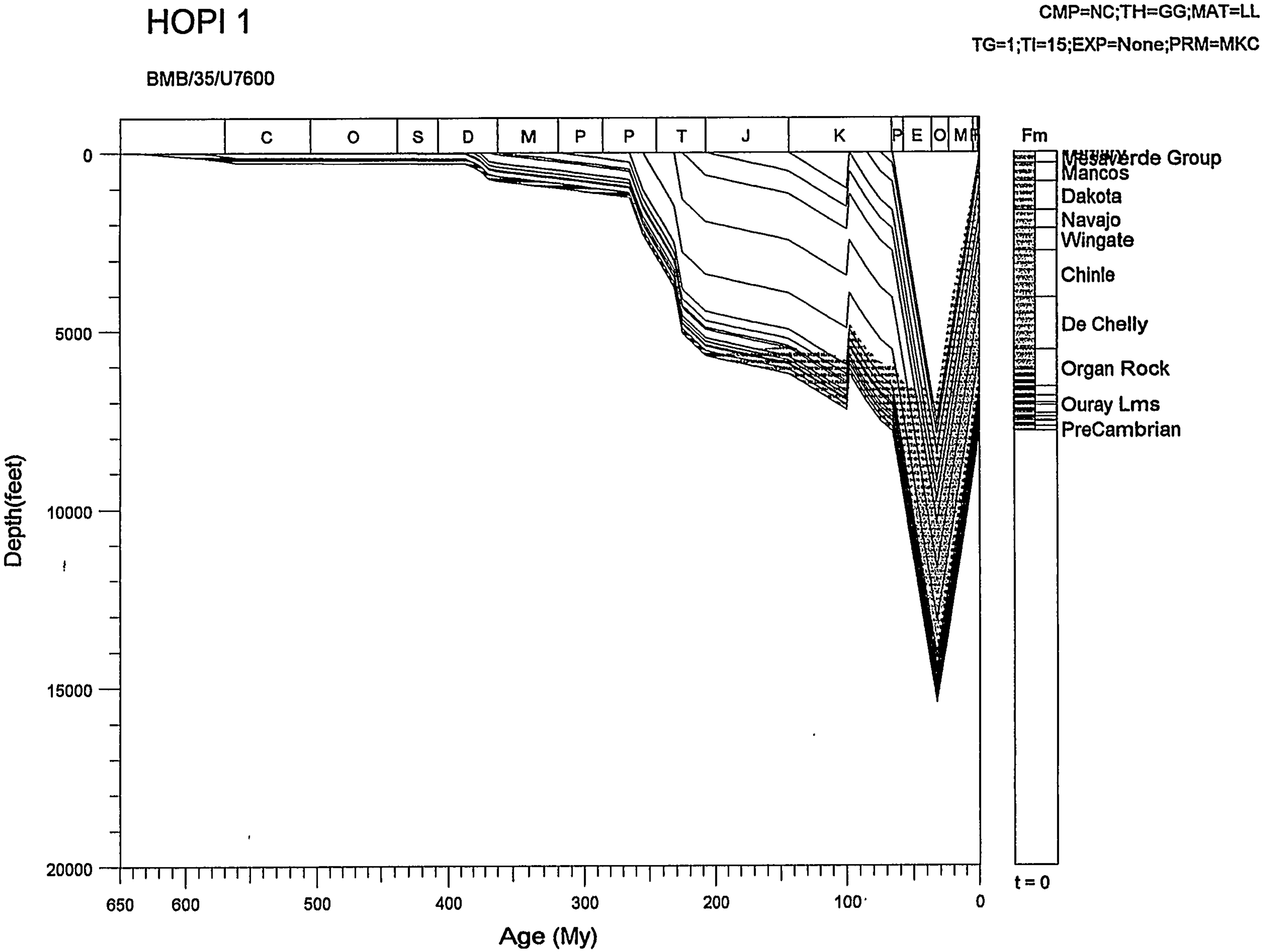


Figure 11–8 Hopi No.1 Burial History and Maturity for 1000 ft Unconformity in the Lower Cretaceous and a 7600 ft Erosional Loss in the Tertiary. 35°C/km Geothermal Gradient.

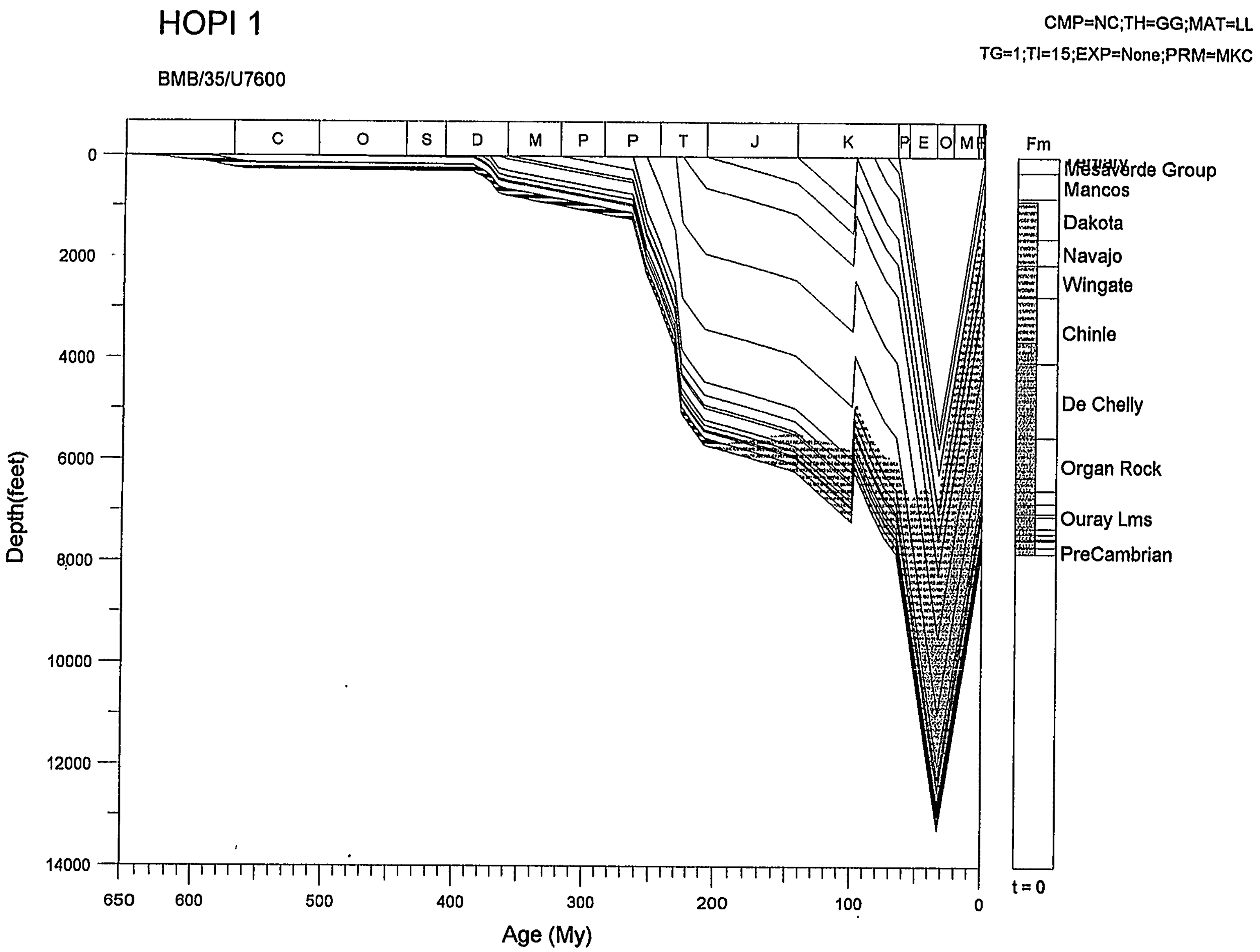


Figure 11–9 Hopi No.1 Burial History and Maturity for 1000 ft Unconformity in the Lower Cretaceous and a 5450 ft Erosional Loss in the Tertiary. 35°C/km Geothermal Gradient.

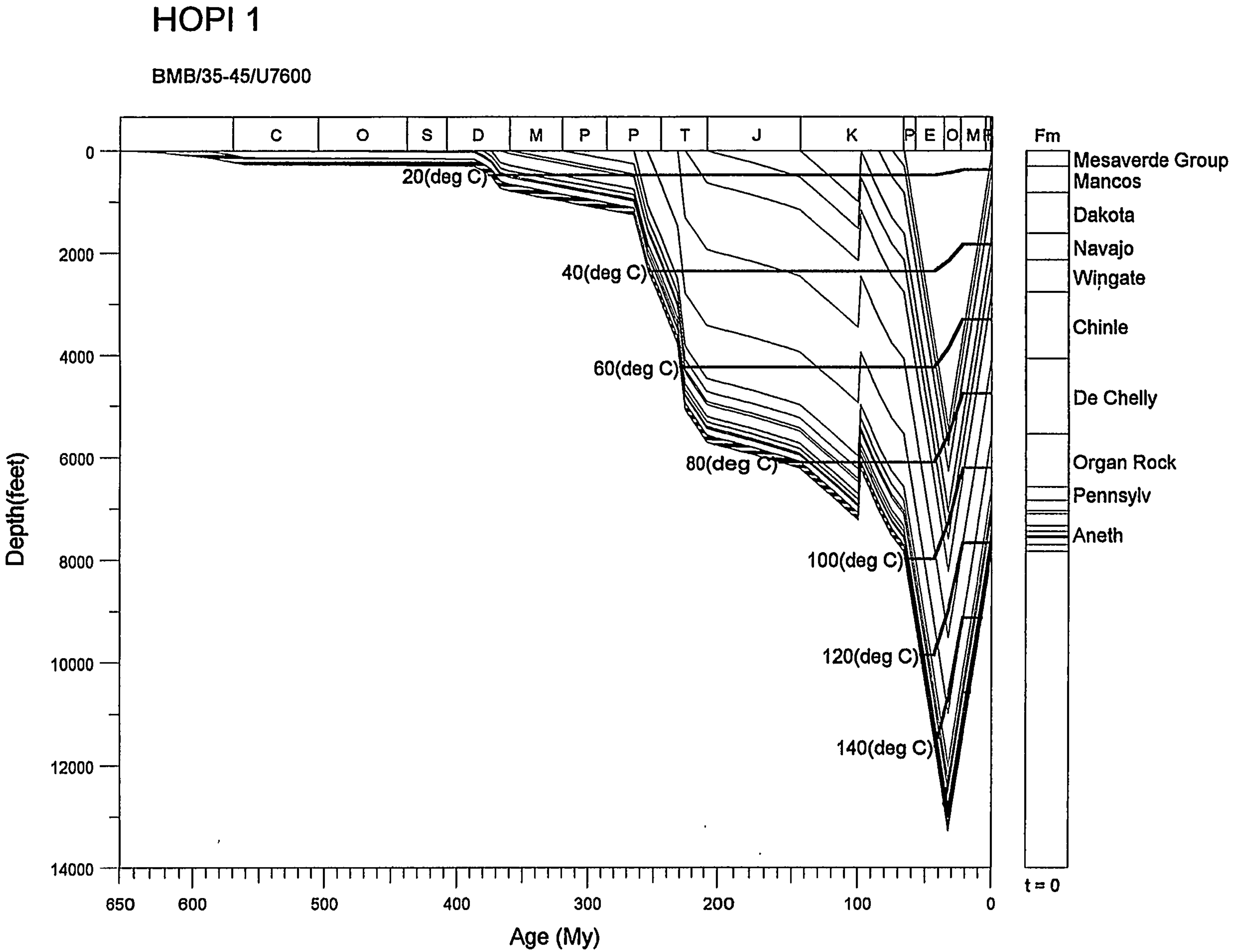


Figure 11–10 Hopi No.1 Burial History Plot with Superimposed Isotherms to Dhow 35°C/km Geothermal Gradient Rising to 45°C/km for the Last 30 m.y.

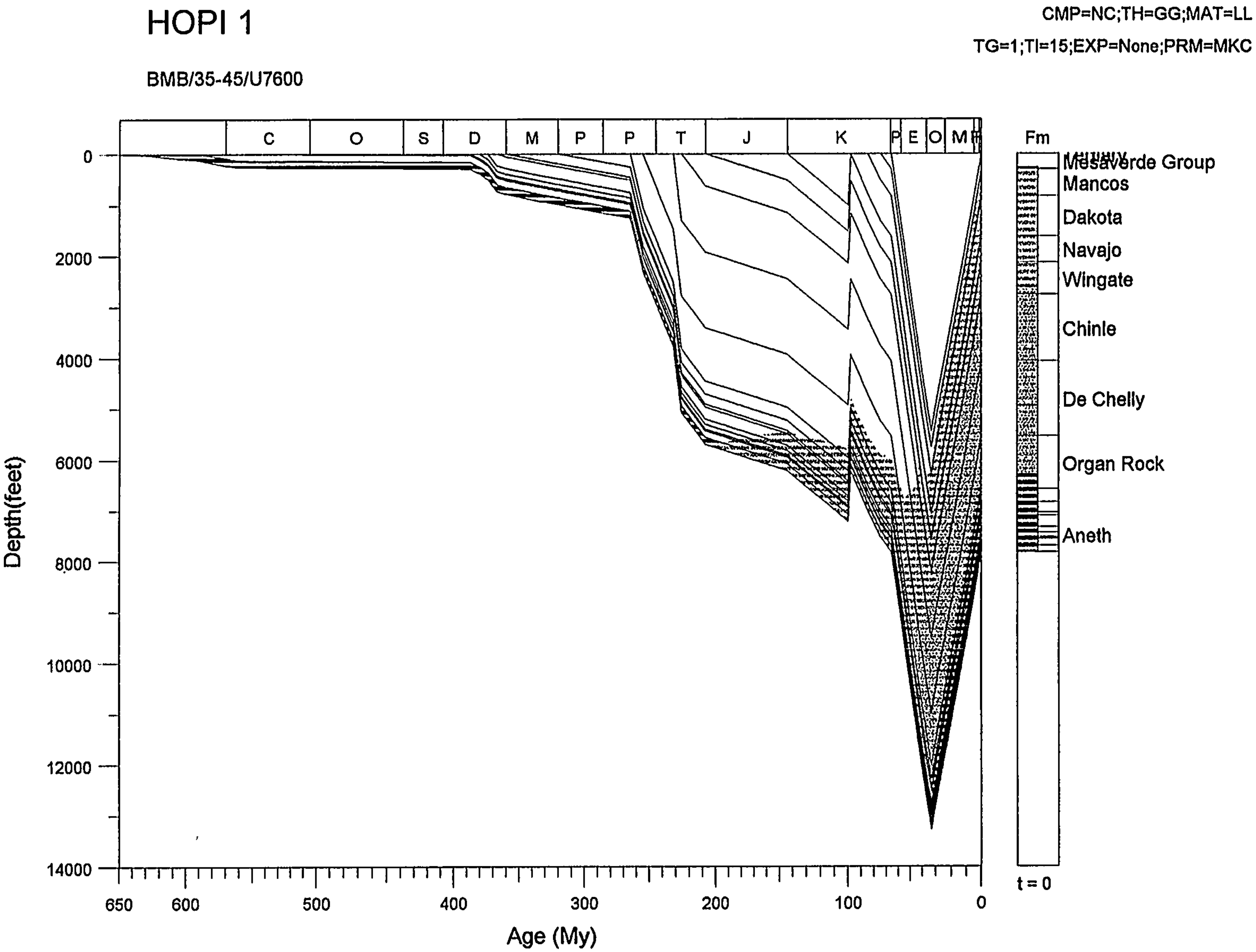


Figure 11–11 Hopi No.1 Burial History and Maturity for 1000 ft Unconformity in the Lower Cretaceous and a 5450 ft Erosional Loss in the Tertiary. 35°C/km Geothermal Gradient rising to 45°C/km for the Last 30 m.y.

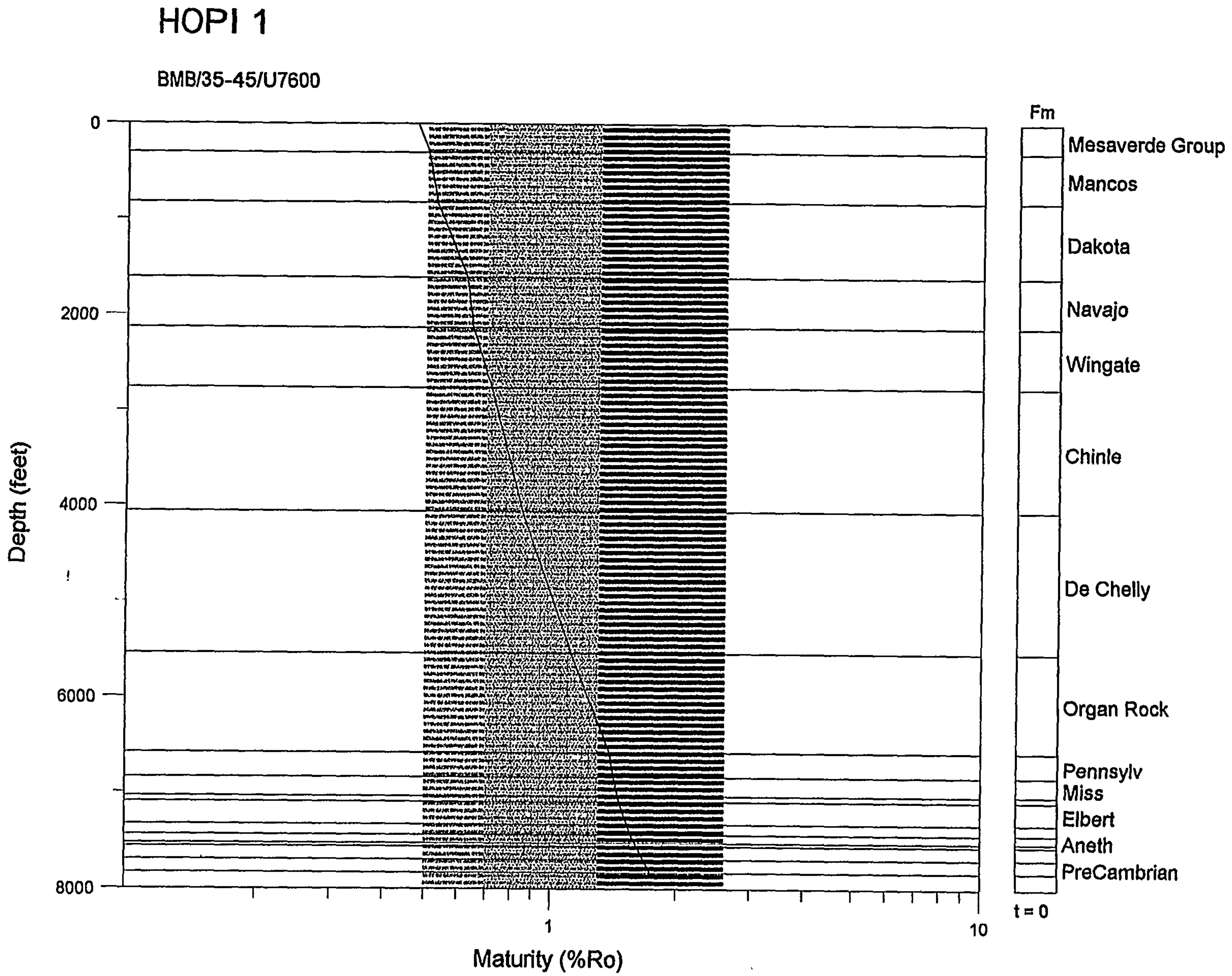


Figure 11–12 Calculated Vitrinite Reflectance as a Function of Depth for the Hopi No. 1 Well Using the Conditions Given in Figure 11–11.

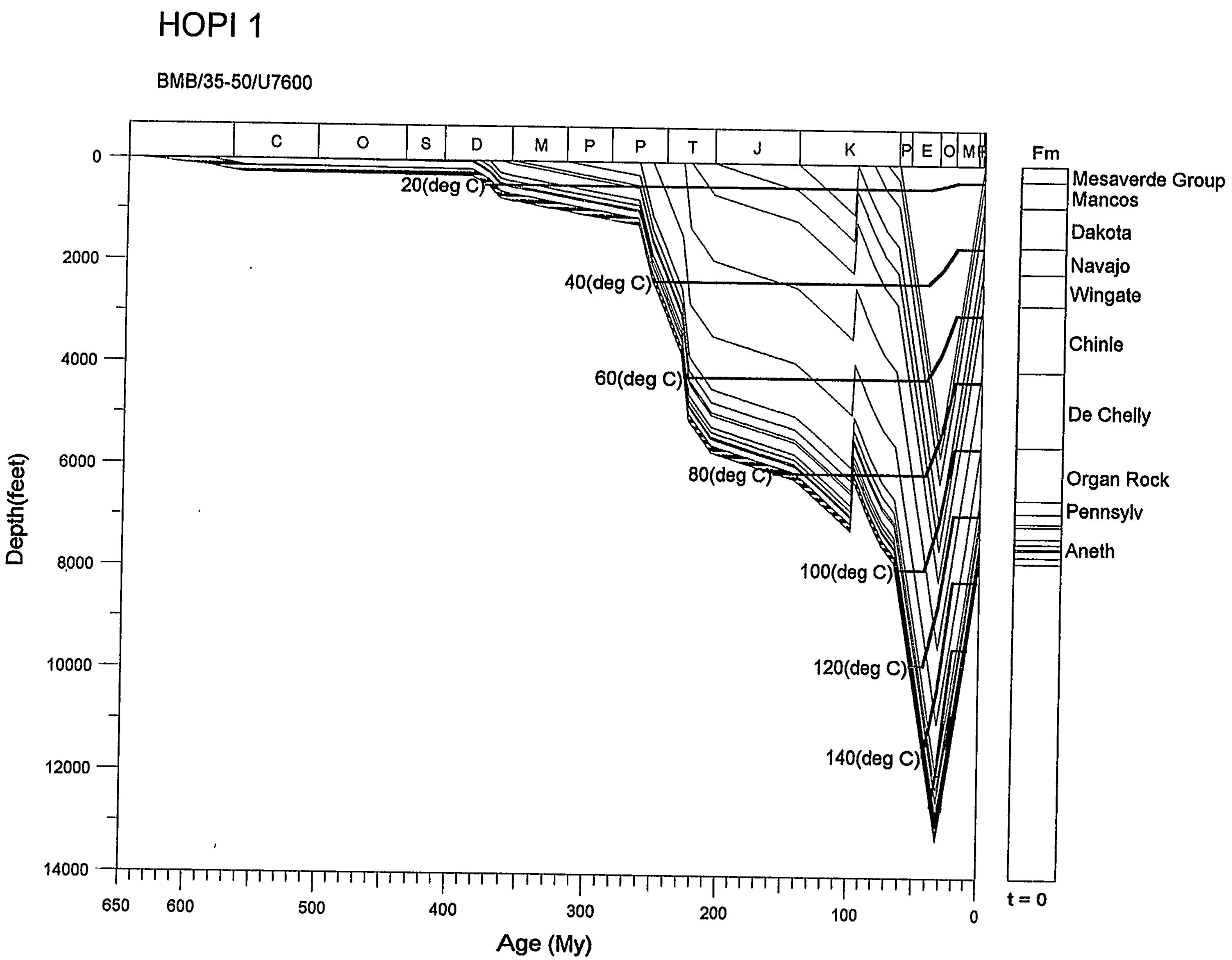


Figure 11–13 Hopi No.1 Burial History Plot with Superimposed Isotherms to Show 35°C/km Geothermal Gradient Rising to 50°C/km for the Last 30 m.y.

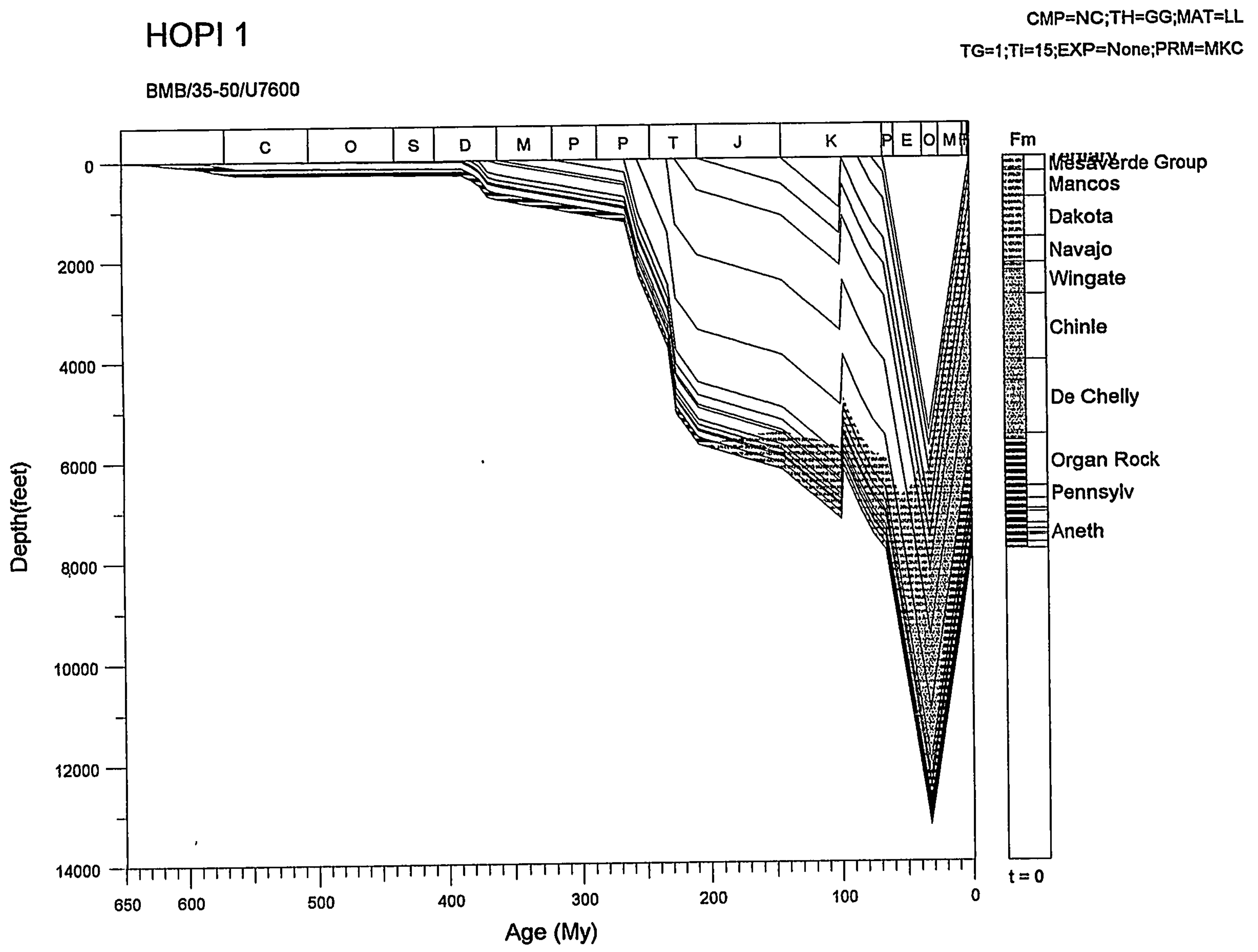


Figure 11–14 Hopi No.1 Burial History and Maturity for 1000 ft Unconformity in the Lower Cretaceous and a 5450 ft Rrosional Loss in the Tertiary. 35^{o}C/km Geothermal Gradient Rising to 50^{o}C/km for the Last 30 m.y.

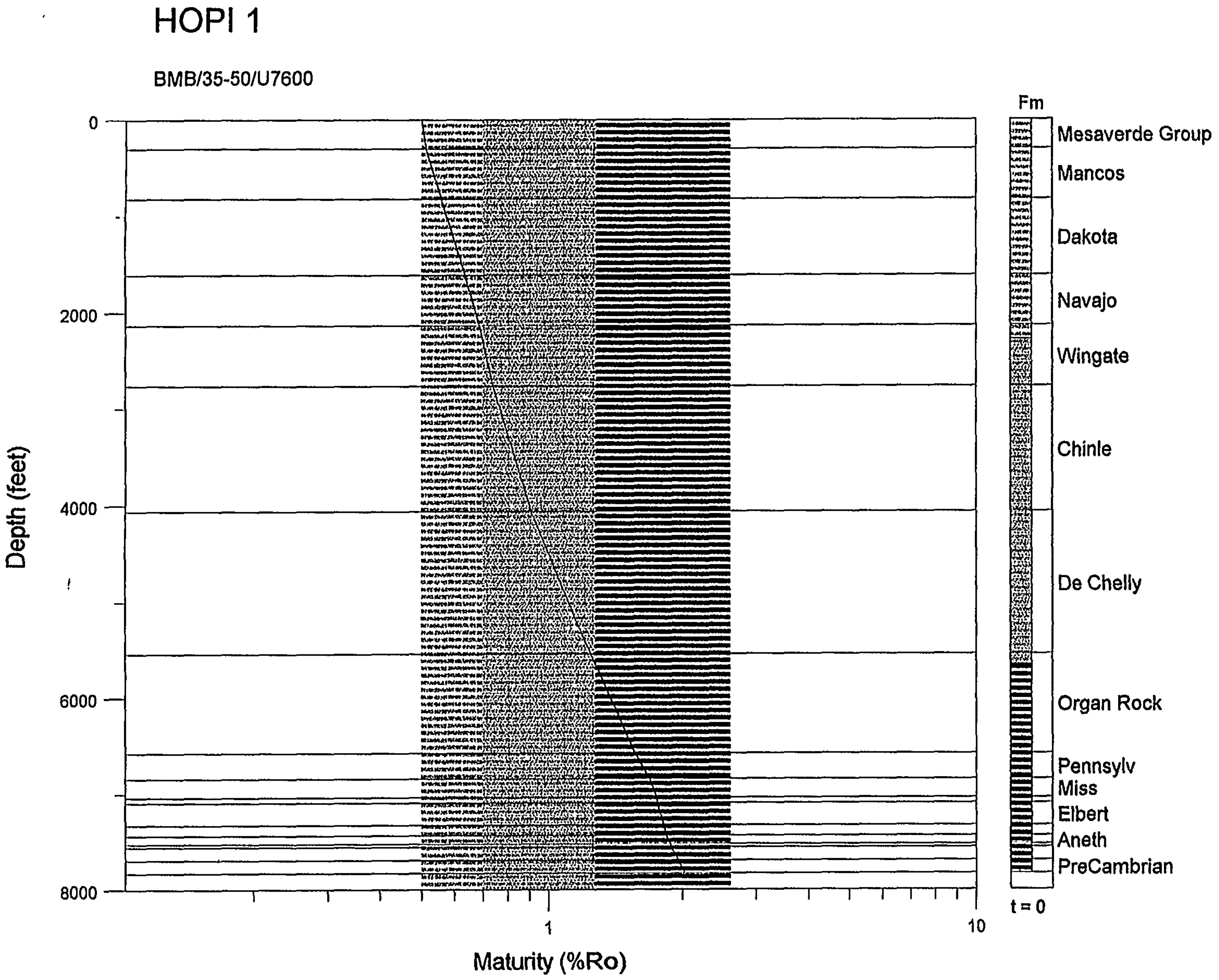


Figure 11–15 Calculated Vitrinite Reflectance as a Function of Depth for the Hopi No. 1 Well Using the Conditions Given in Figure 11–14.

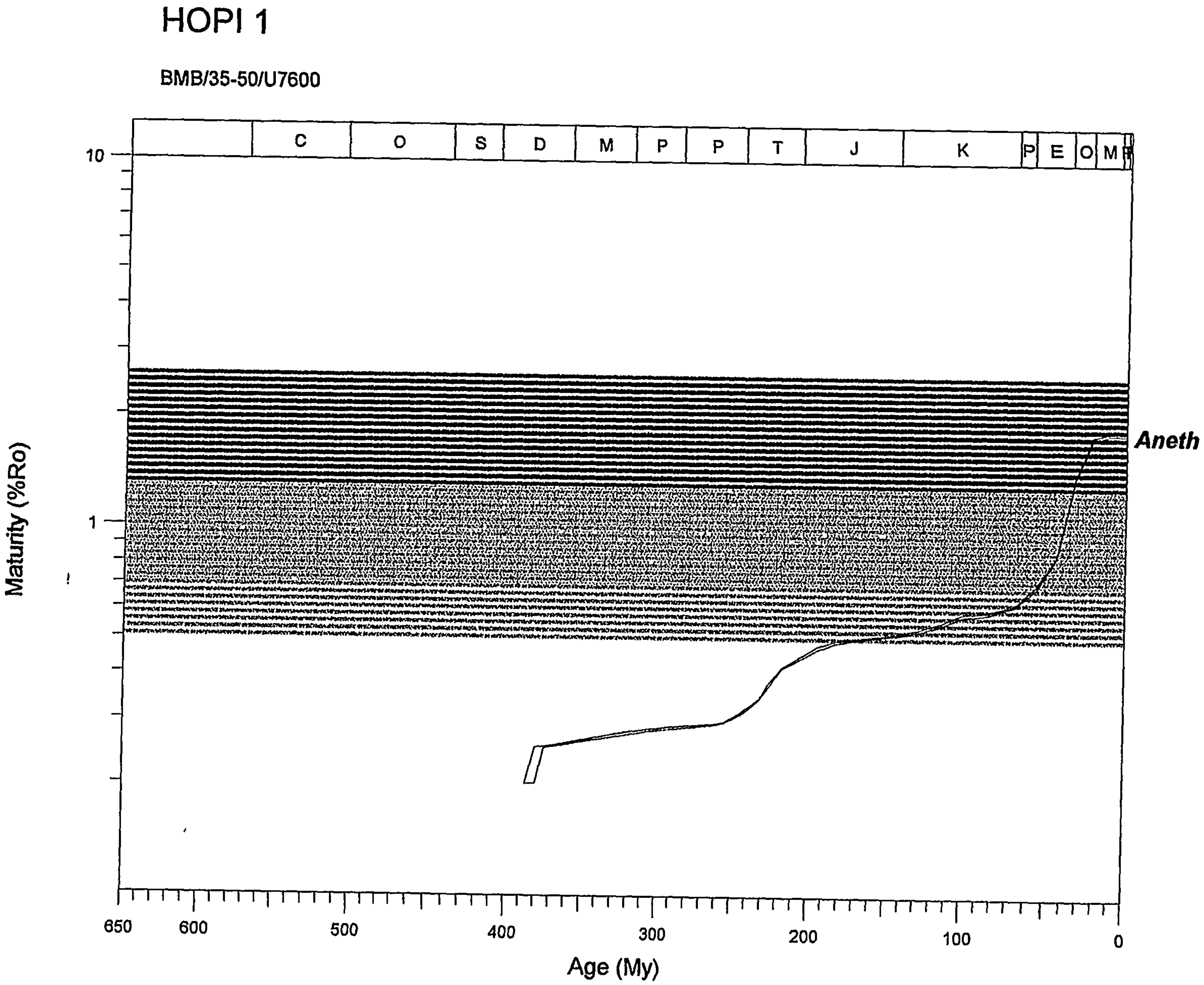


Figure 11–16 Increasing Maturity (R_o) for the Aneth as a Function of Time for the Burial History Shown in Figure 11–14.

11.6 HOPI-9 WELL

The Hopi-9 well was drilled in a part of the Black Mesa basin (see Fig. 11–6) where the surface rocks are part of the Jurassic San Raphael Group and all of the Cretaceous and Tertiary section has been removed by erosion. The well is located in Navajo County, Arizona, Section 9, Township 28N, Range 15E. It was drilled in 1965 by Atlantic Refining Company and reached the Precambrian at a total depth of 6640 ft.

The procedures used for modeling were the same as those described above for the Hopi No. 1 well. Formation tops were taken from electric log data (see Table 11–8) and entered into the BasinMod program. Ages were obtained from the Decade of North American Geology time scale. Vitrinite reflectance data for surface coals was used to constrain erosional loss in the Tertiary (see Table 11–5), but in the absence of data to constrain the paleogeothermal regime a variety of possible thermal histories was modeled. These are summarized in Table 11–9.

At the location of the Hopi-9 well a paleogeothermal gradient of 25°C/km leads to immature surface samples with only the Wingate and deeper formations being in the oil window (see Fig. 11–17). Values can be brought more into line with observations by either increasing the paleogeothermal gradient or by deeper burial in the past. If burial is increased by 2000 ft (to a total of 9600 ft), then the burial history and maturity profile shown in Figure 11–18 are obtained. Alternatively, the paleogeothermal gradient can be increased. A gradient of 35°C/km leads to the burial history shown in Figure 11–19. Surface rocks are just at the onset of generation, but show a considerably earlier onset of petroleum generation in the deeper formations. The expected higher geothermal gradient in the last ~30 m.y. (associated with volcanism) leads to calculated maturities that are too high (see Fig. 11–20). This is indicated more clearly by the vitrinite reflectance/depth profile given in Figure 11–21. Maturities for the whole rock sequence are given in Figure 11–22.

Table 11-8 Input Stratigraphy Data for Modeling the Hopi-9 Well

Formation or Event Name	Type	Begin Age (Ma)	Well Top (feet)	Present Thickness (feet)	Missing Thickness (feet)
Erosion	E	33			-7600
Tertiary	D	66			5600.0
Upper Cret.	D	98			2000.0
Lower Cret.	H	144			
Todilto	F	180	0.0	50.0	
Entrado	F	189	50.0	202.0	
Carmel	F	198	252.0	43.0	
Navajo	F	208	295.0	463.0	
Kayenta	F	218	758.0	332.0	
Wingate	F	226	1090.0	722.0	
Chinle	F	232	1812.0	1041.0	
Shinarump	F	238	2853.0	69.0	
Moenkopi	F	245	2922.0	132.0	
Kaibab	F	250	3054.0	141.0	
Coconino	F	255	3195.0	1517.0	
Supai	F	286	4712.0	830.0	
Pennsylv.	F	312	5542.0	263.0	
Molas	F	320	5805.0	57.0	
Miss.	F	360	5862.0	177.0	
Elbert	F	374	6039.0	209.0	
McCracken	F	380	6248.0	29.0	
Aneth	F	387	6277.0	182.0	
Bright Angel	F	561	6459.0	21.0	
Tapeats	F	590	6480.0	128.0	
Precambrian	F	640	6608.0	1000.0	

Table 11–9 Summary of Combinations of Burial Histories and Geothermal Gradients Used in Modeling the Hopi-9 Well.

(±: deposition/erosion at unconformity)

25°C/km geothermal gradient

Figure 11–17: L. Cret ± 1000 ft; U. Cret +/- 1000 ft; Tert ± 7600 ft

Figure 11–18 : L. Cret ± 1000 ft; U. Cret ± 1000 ft; Tert ± 9600 ft

35°C/km geothermal gradient

Figure 11–19: L. Cret ± 1000 ft; U. Cret ± 1000 ft; Tert ± 5450 ft

Figure 11–20 : L. Cret hiatus; U. Cret ± 1000 ft;Tert ± 5450 ft; 45°C/km last 30 m.y.

Figure 11–21: Calculated vitrinite reflectance with depth for the conditions used in Figure 11–20

Figure 11–16 : Increasing maturity as a function of time for the burial history shown in Figure 11–20.

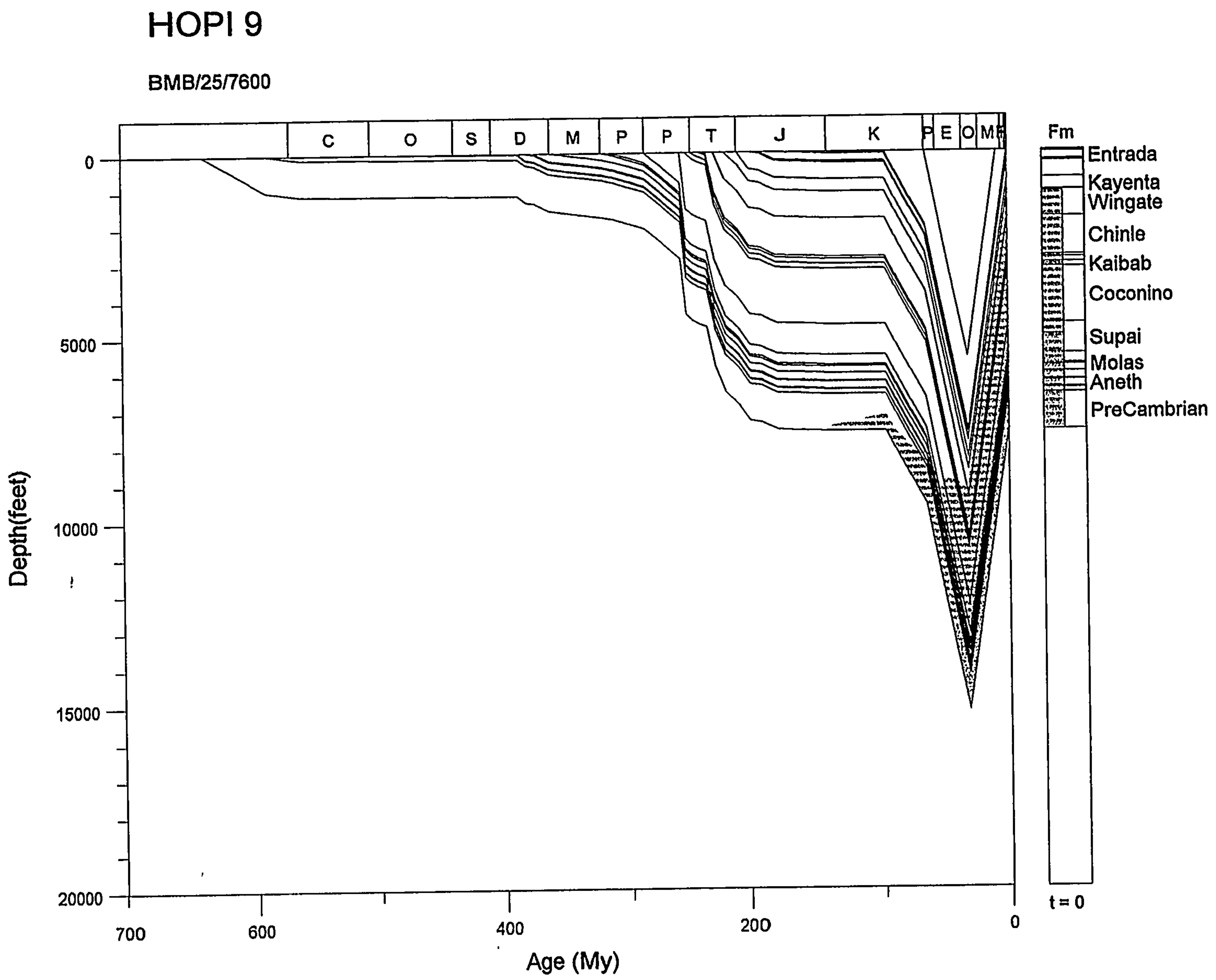


Figure 11–17 Hopi-9 Well. 1000 ft each of the Lower Cretaceous and Upper Cretaceous Deposited and Eroded. 7600 ft of Tertiary Deposited and Eroded. 25°C/km Geothermal Gradient.

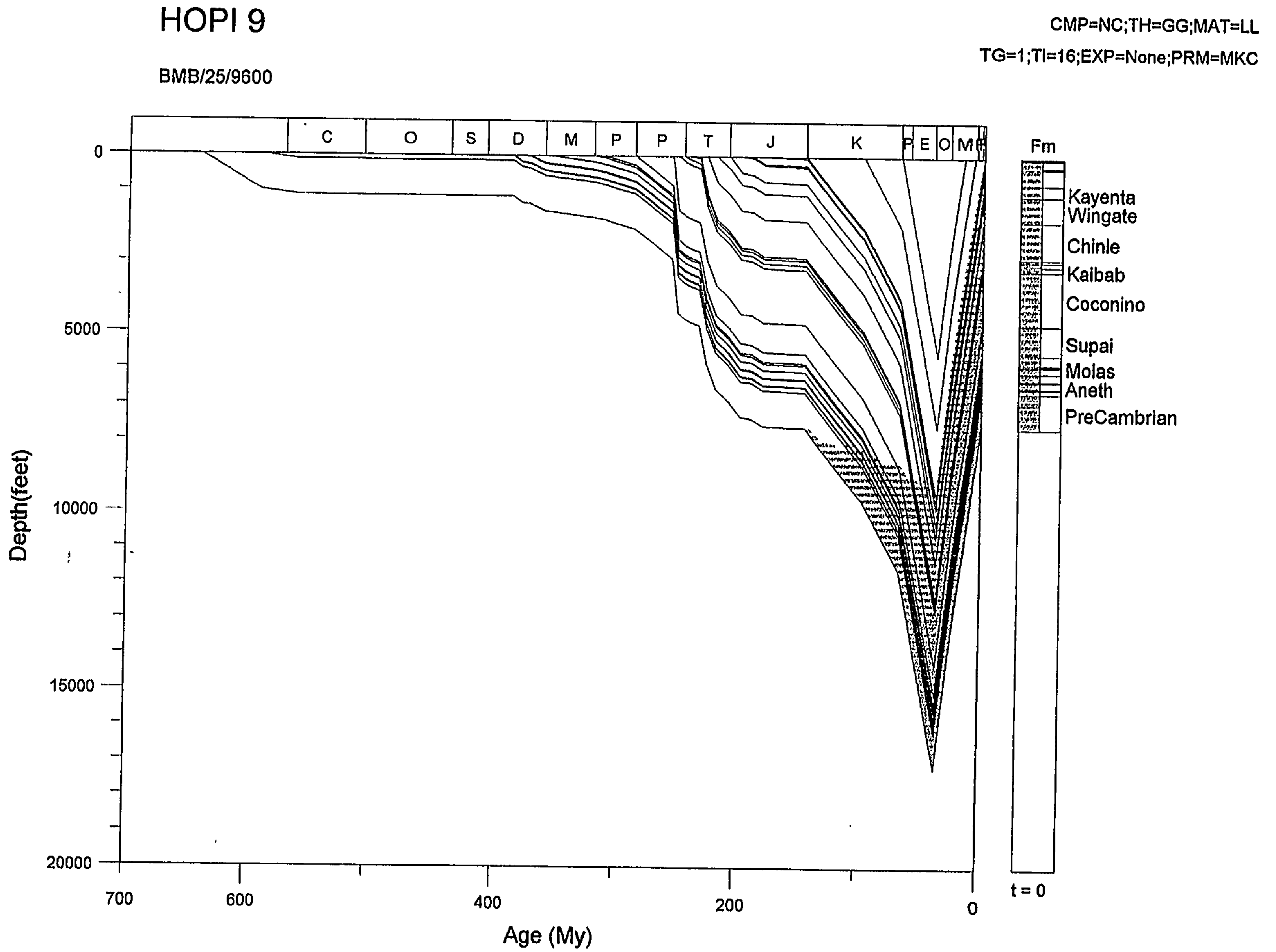


Figure 11–18 Hopi-9 Well. 1000 ft Each of the Lower Cretaceous and Upper Cretaceous Deposited and Eroded. 9600 ft of Tertiary Deposited and Eroded. 25°C/km Geothermal Gradient.

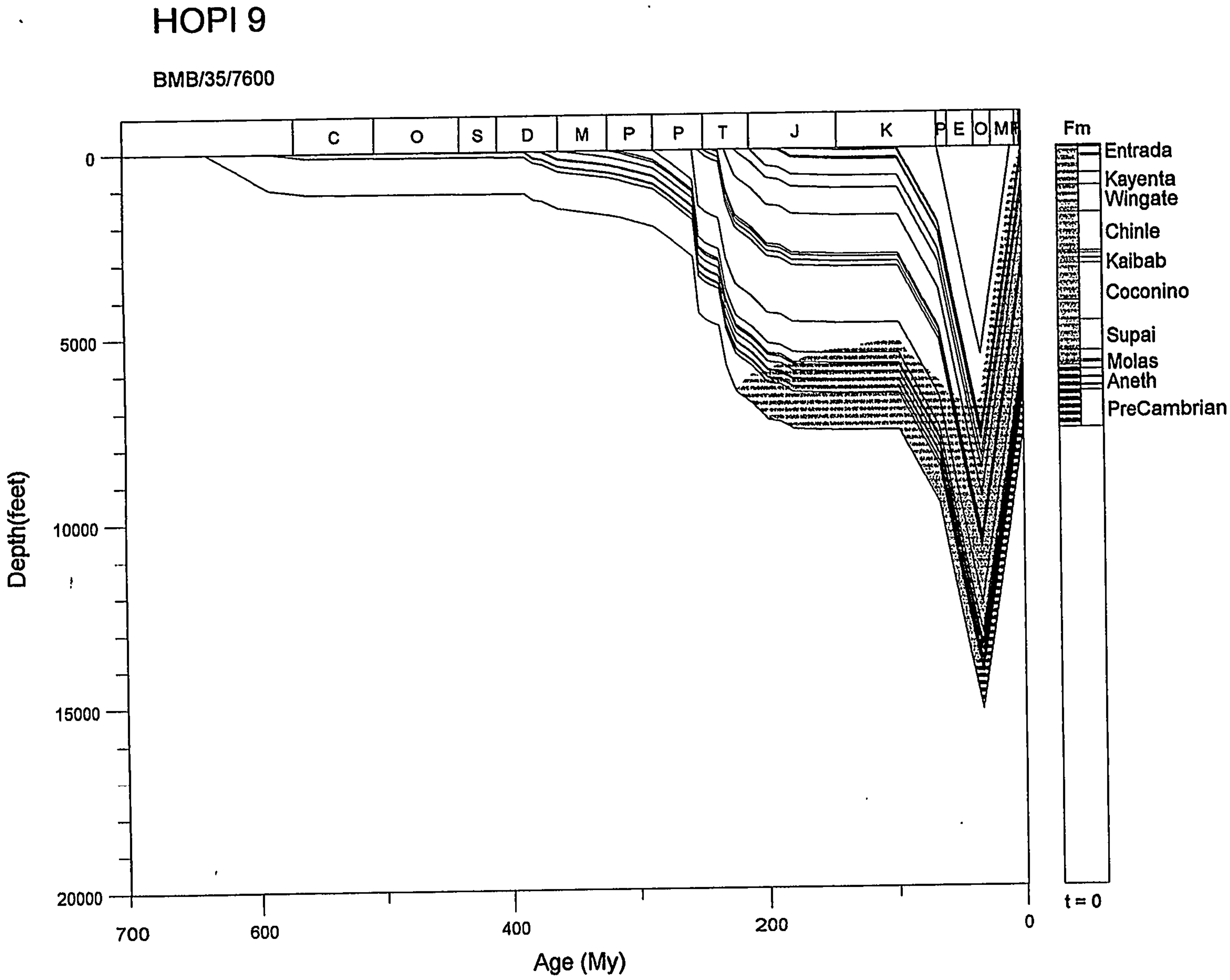


Figure 11–19 Hopi-9 Well. 1000 ft Each of the Lower Cretaceous and Upper Cretaceous Deposited and Eroded. 54500 ft of Tertiary Deposited and Eroded. 35^{o}C/km Geothermal Gradient.

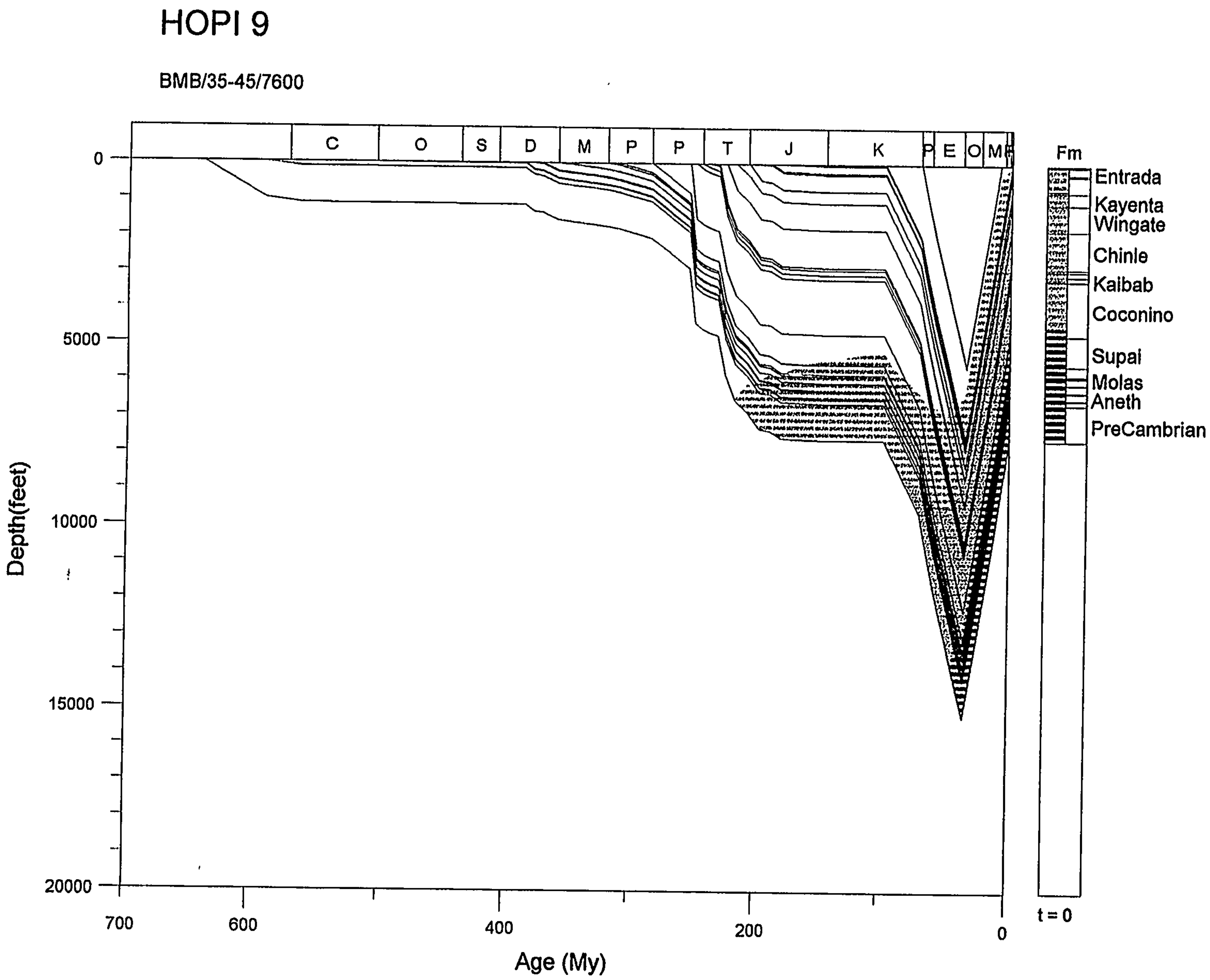


Figure 11–20 Hopi-9 Well. 1000 ft of the Upper Cretaceous Deposited and Eroded. 1500 ft of Tertiary Deposited and Eroded. 35°C/km Geothermal Gradient Rising to 45°C/km Over the Most Recent 30 m.y.

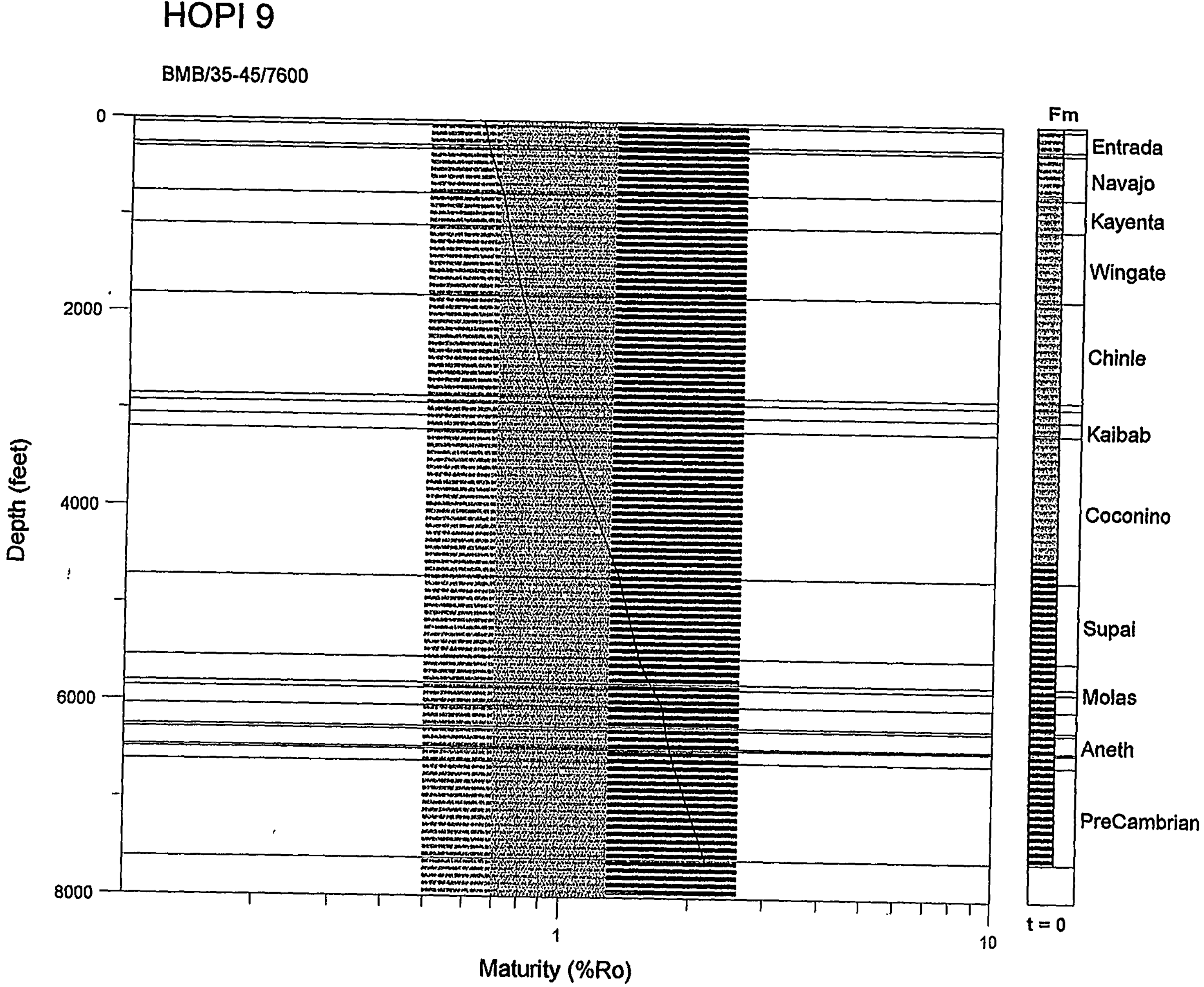


Figure 11–21 Hopi-9 Well. Calculated Vitrinite Reflectance for the Conditions used in Figure 11–20.

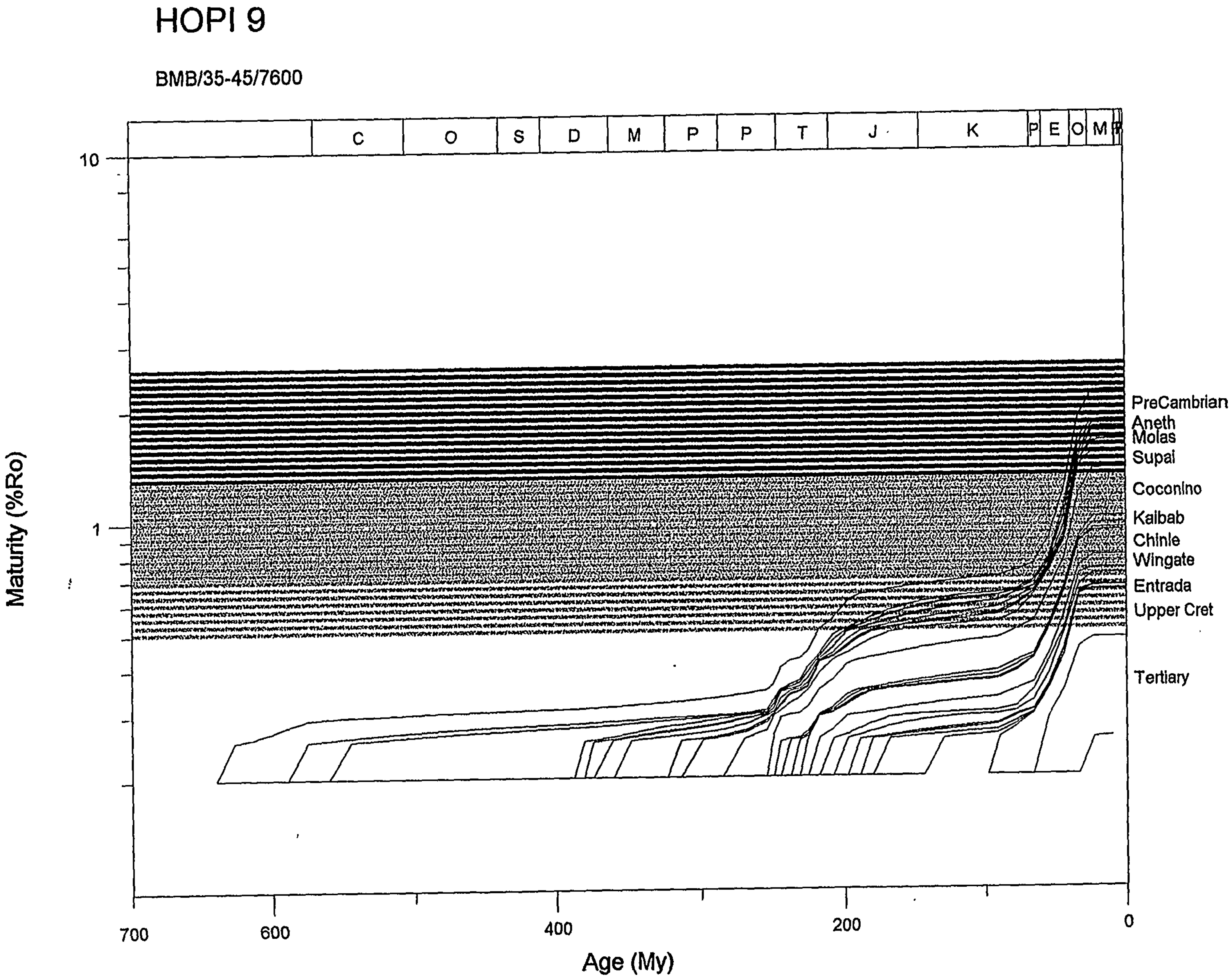


Figure 11–22 Increasing Maturity as a Function of Time for the Burial History Shown in Figure 11–20.

11.7 COLLINS 1X WELL

The Collins 1X was selected as an example of a well drilled on the flanks of the Black Mesa basin (see Fig. 11–6). This well is particularly interesting because hydrocarbon shows were reported in the Precambrian. The well was drilled in 1957–58 by Collins Burial and penetrated the Precambrian at a total depth of 3432 feet. Drilling location was Section 22, Township 34N, Range 8E.

The present surface is the Kaibab (see Fig. 11–10), and comparison with other sections studied suggests that considerable thicknesses of Mesozoic and Tertiary sediments have been lost by erosion. In the absence of suitable data, there is no way of knowing how much rock has been lost, so various thicknesses have been modeled to try and establish the minimum burial required to make the organic-rich Cambrian/Devonian mature. The various combinations used are summarized in Tables 11–10 and 11–11. Combined Mesozoic and Tertiary thicknesses of 4000, 6000, and 8000 ft have been used with the total amount being removed by erosion in the last 30 m.y. or in the last 118 m.y.

Table 11–10 Input Stratigraphy Data for Modeling the Collins-1X Well

Formation or Event Name	Type	Begin Age (Ma)	Well Top (feet)	Present Thickness (feet)	Missing Thickness (feet)
Erosion	E	118			-8000
Meso.-Tert.	D	235			8000
Kaibab	F	245	0	325	
Coconino	F	255	325	880	
Supai	F	303	1205	740	
Redwall	F	360	1945	525	
Muav Lms.	F	533	2470	110	
Tonto	F	548	2580	410	
Bright Angel	F	561	2990	100	
Tapeats	F	590	3090	330	
Granite	F	625	3420	100	

Table 11–11 Summary of Combinations of Burial Histories and Geothermal Gradients Used in Modeling the Collins-1X Well

25°C/km geothermal gradient	
Figure 11–23	Tertiary uplift of 8000 ft
Figure 11–24	Increasing maturity as a function of time for conditions used in Figure 11–23
Figure 11–25	Increasing maturity as a function of time for conditions used in Figure 11–23, but with only 4000 ft of uplift
35°C/km geothermal gradient	
Figure 11–26	Tertiary uplift of 4000 ft
Figure 11–27	Tertiary uplift of 6000 ft
Figure 11–28	Tertiary uplift of 8000 ft
Figure 11–29	Increasing maturity as a function of time for conditions used in Figure 11–26
Figure 11–30	Increasing maturity as a function of time for conditions used in Figure 11–27
Figure 11–31	Increasing maturity as a function of time for conditions used in Figure 11–28
Figure 11–32	Burial history as in Figure 11–28 except that uplift and erosiion started 118 Ma
Figure 11–33	Vitrinite reflectance calculated as a depth profile for the conditions in Figure 11–32
Figure 11–34	Increasing maturity as a function of time for conditions used in Figure 11–33

For a geothermal gradient of 25°C/km even 8000 ft of burial is insufficient to move any of the rocks into the main oil-generating window, and only the deepest are even in the early mature window (see Figs. 11–23, 11–24, and 11–25). At a higher geothermal gradient of 35°C/km maturity increases with the amounts of uplift, as expected, since this implies increased depth of burial. For 6000 ft of uplift, the Muav Limestone and deeper units are currently in the main oil-generating window (though because of the considerable amount of uplift they will no longer be actively generating) (see Figs. 11–26, 11–27, and 11–28). The timing for onset of maturation is summarized for 4000 ft, 6000 ft, and 8000 ft of burial/uplift in Figures 11–29, 11–30, and 11–31.

In addition to uncertainties about depth of burial and amount of uplift the time for the maximum depth of burial is also poorly constrained. The above examples have all assumed uplift occurred in the last 30 m.y. Figure 11–32 is the burial history plot that results when burial and uplift occur at the same rates, so that in this case erosion has occurred over the last 118 m.y. The impact on maturation status is shown in Figures 11–33 and 11–34.

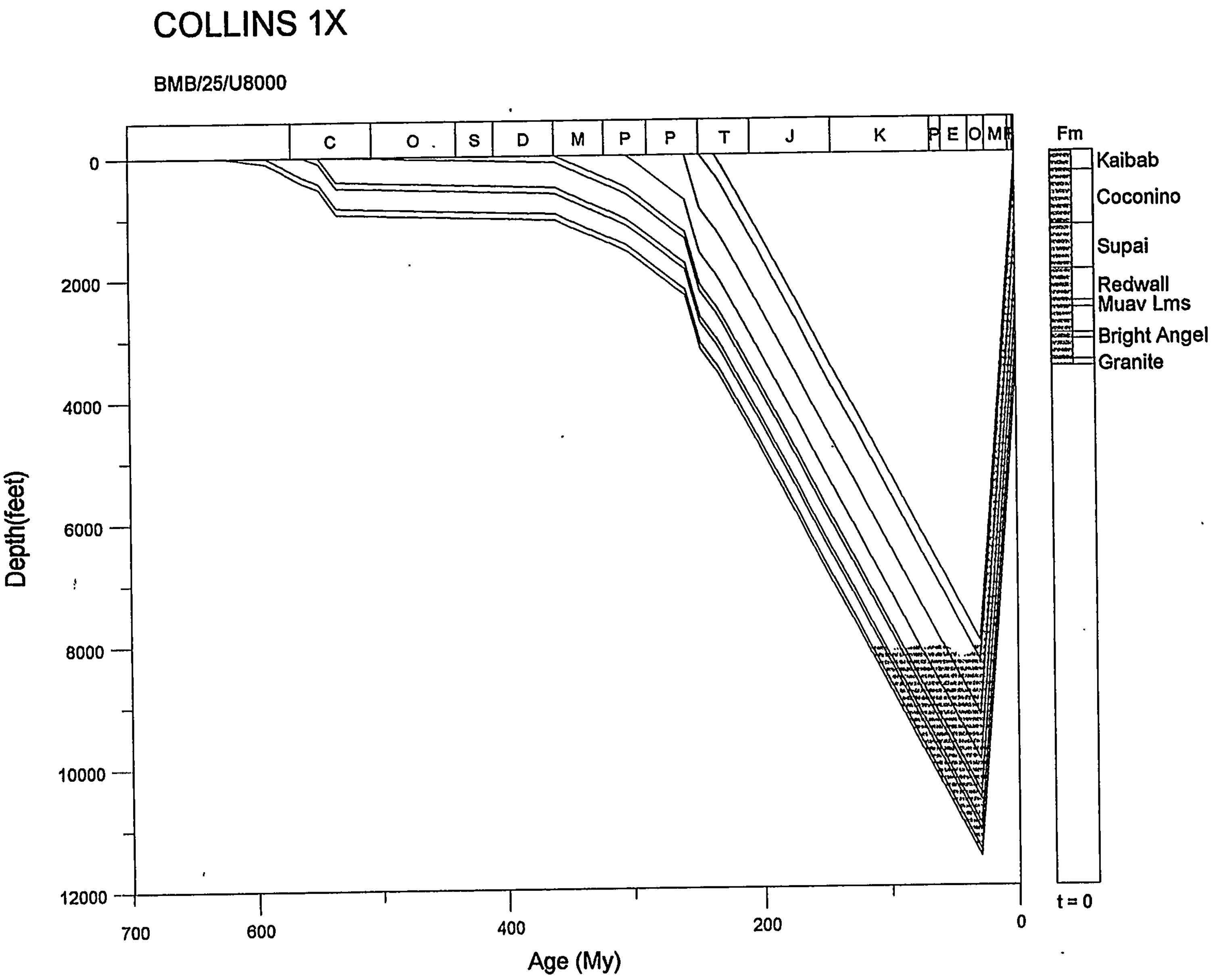


Figure 11–23 Collins 1X Well. 8000 ft of Mesozoic and Tertiary has been Accumulated and Later Removed by Erosion. Geothermal Gradient was 25°C/km.

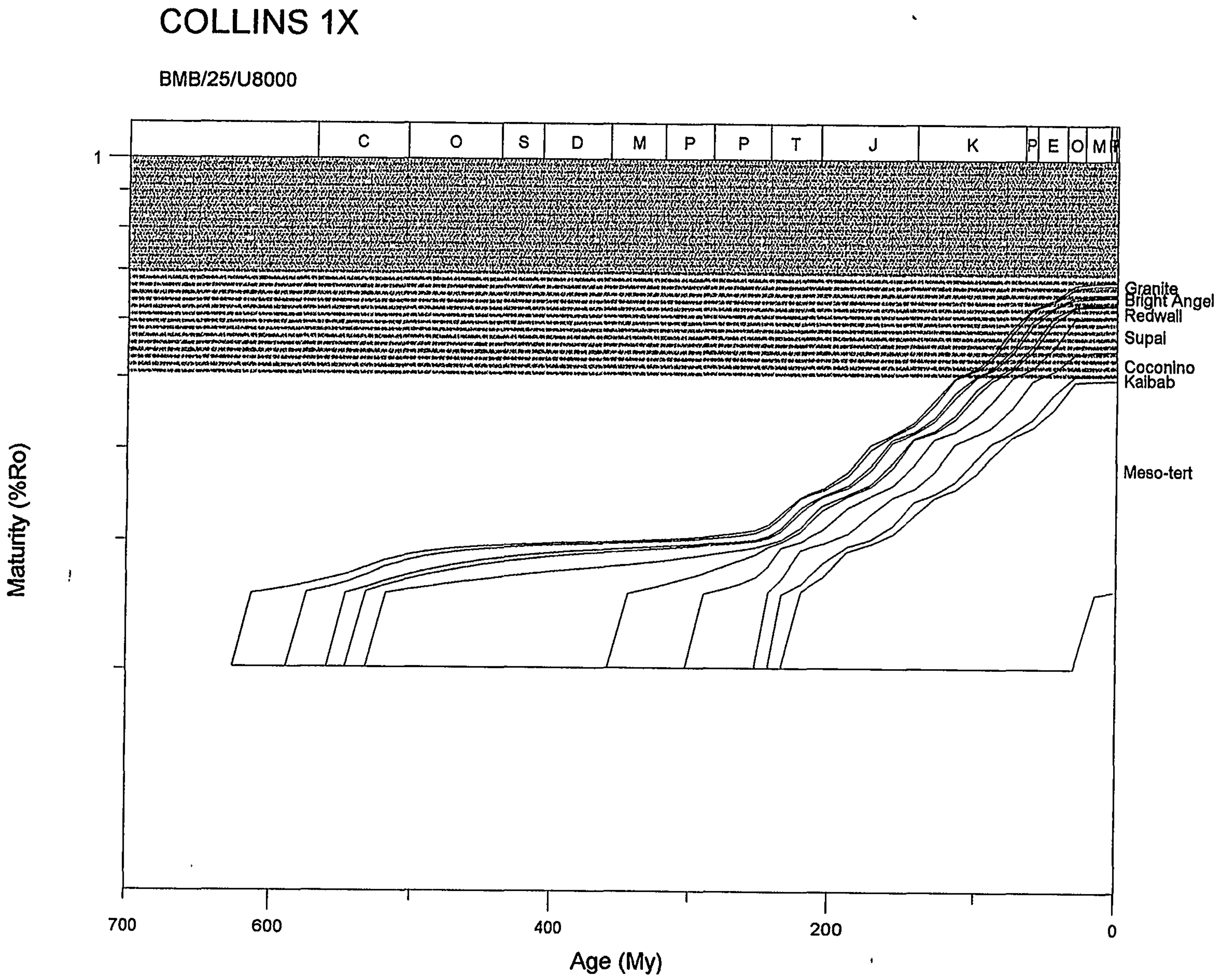


Figure 11–24 Collins 1X Well. Increasing Maturation Through Time with a Burial History that has 8000 ft of Burial and Uplift. Geothermal Gradient was $25^{o}C/km$.

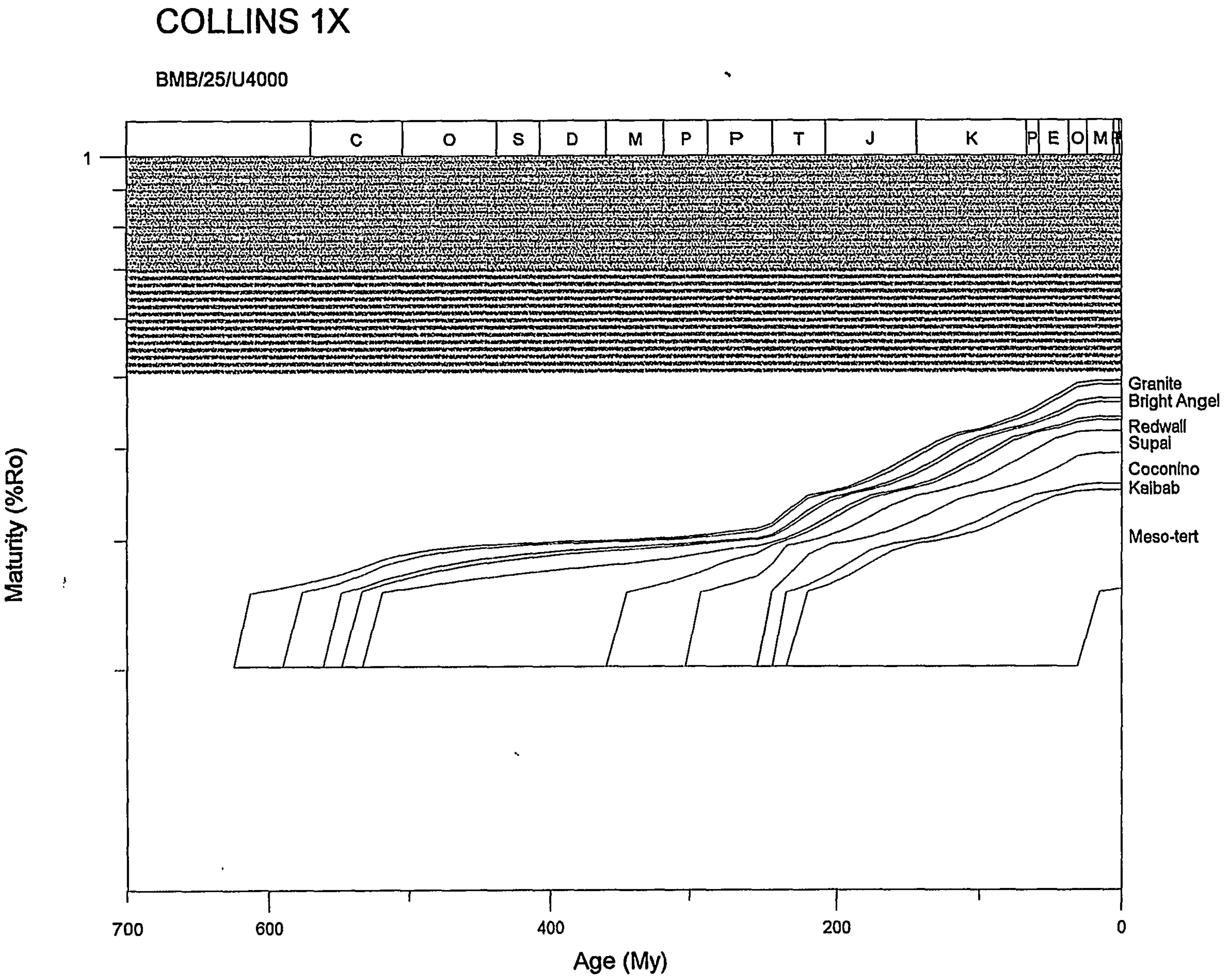


Figure 11–25 Collins 1X Well. Increasing Maturation Through Time with a Burial History that has 4000 ft of Burial and Uplift. Geothermal Gradient was 25°C/km.

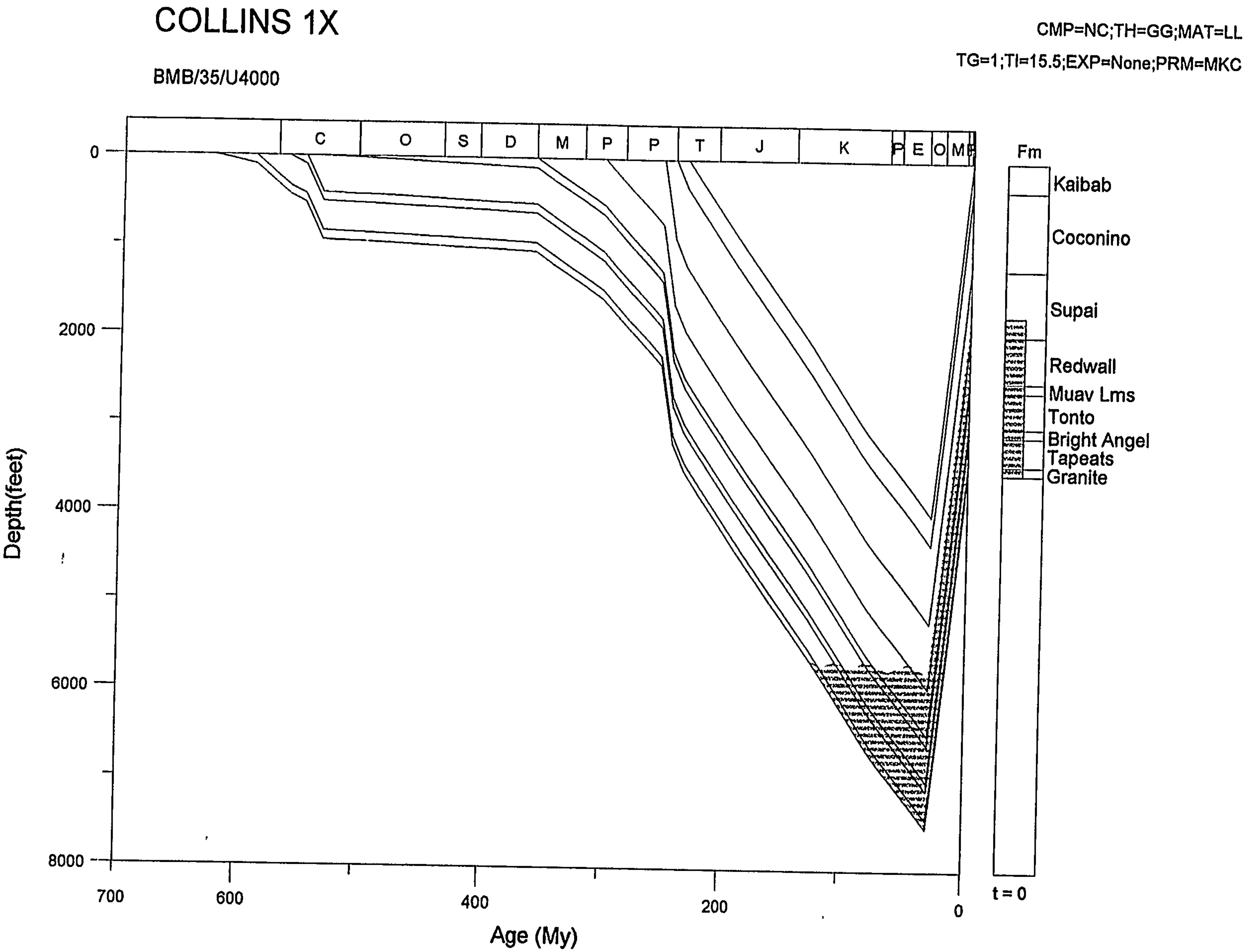


Figure 11–26 Collins 1X Well. 4000 ft of Mesozoic and Tertiary has been Accumulated and Later Removed by Erosion. Geothermal Gradient was 35°C/km.

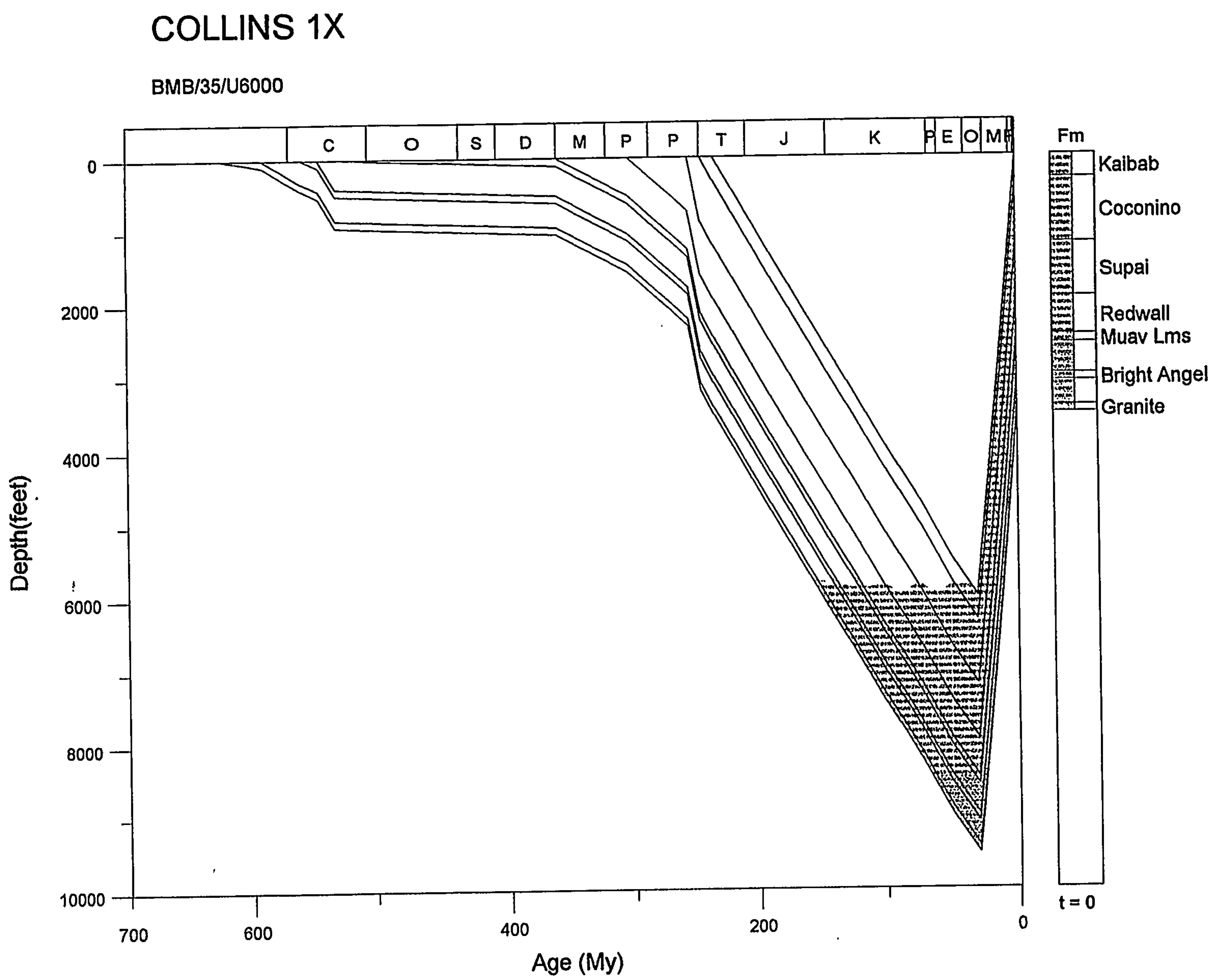


Figure 11–27 Collins 1X Well. 6000 ft of Mesozoic and Tertiary has been Accumulated and Later Removed by Erosion. Geothermal Gradient was $35^oC/km$.

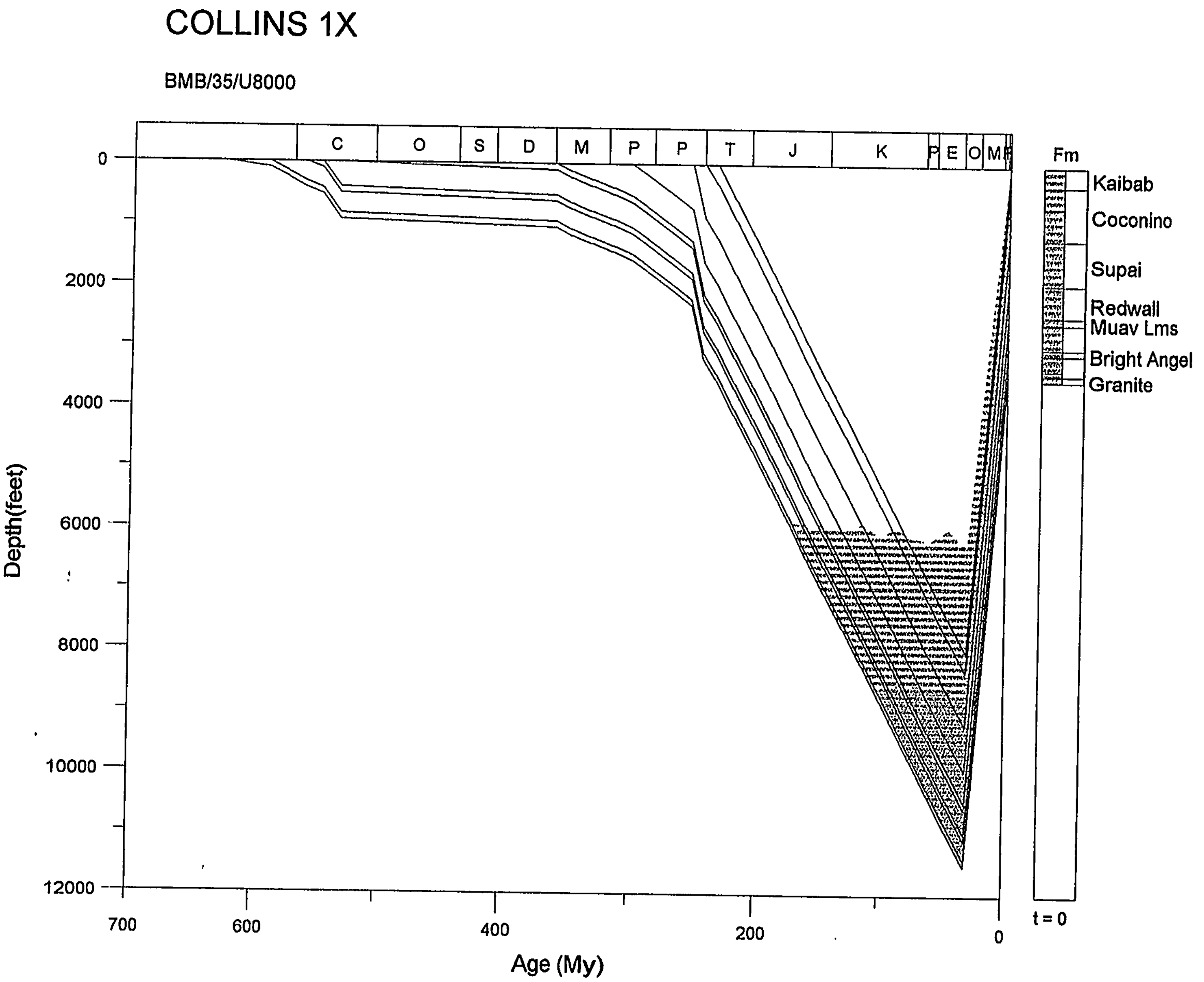


Figure 11–28 Collins 1X Well. 8000 ft of Mesozoic and Tertiary has been Accumulated and Later Removed by Erosion. Geothermal Gradient was 35°C/km.

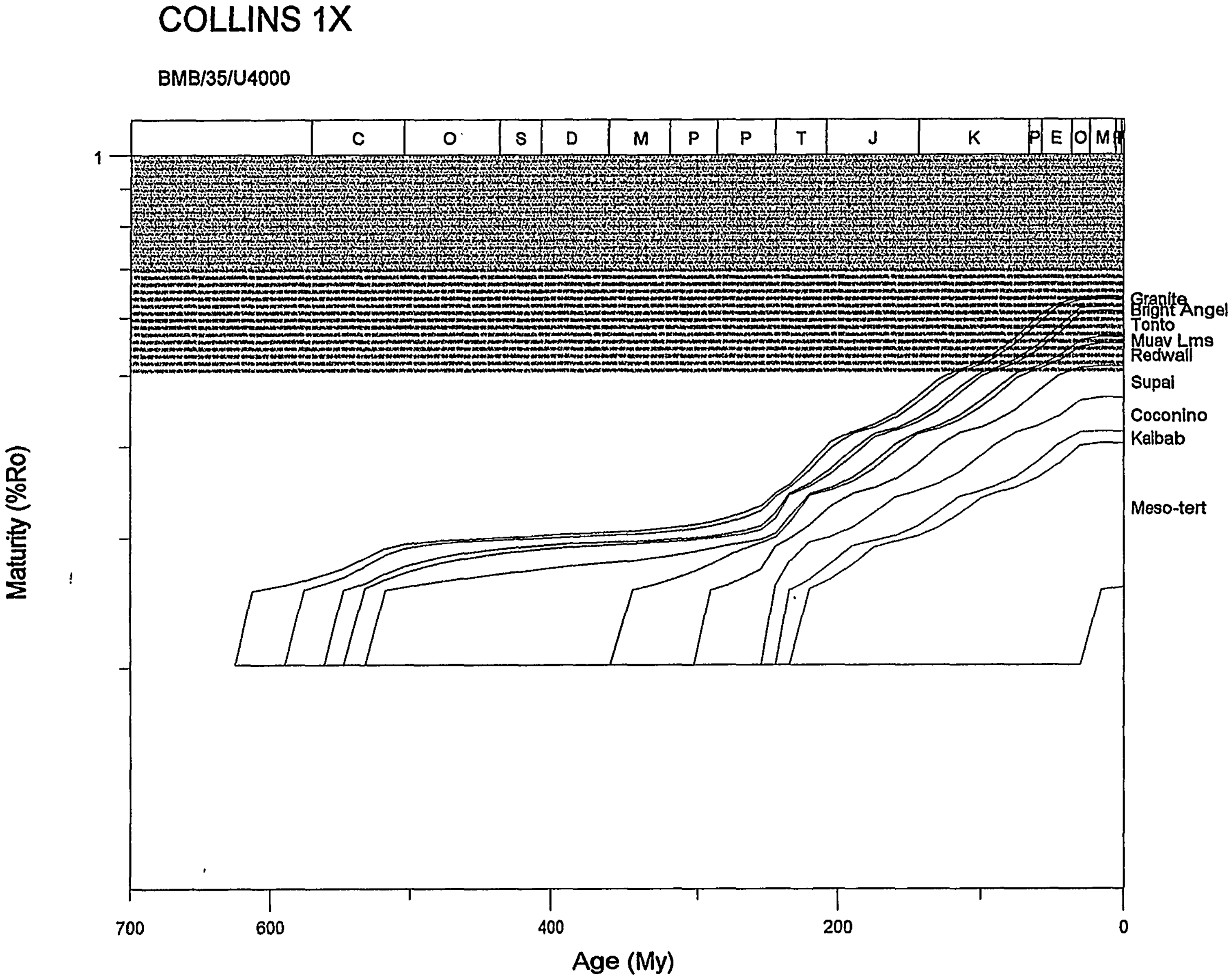


Figure 11–29 Collins 1X Well. Increasing Maturation Through Time with a Burial History that has 4000 ft of Burial and Uplift. Geothermal Gradient was 35^{0}C/km.

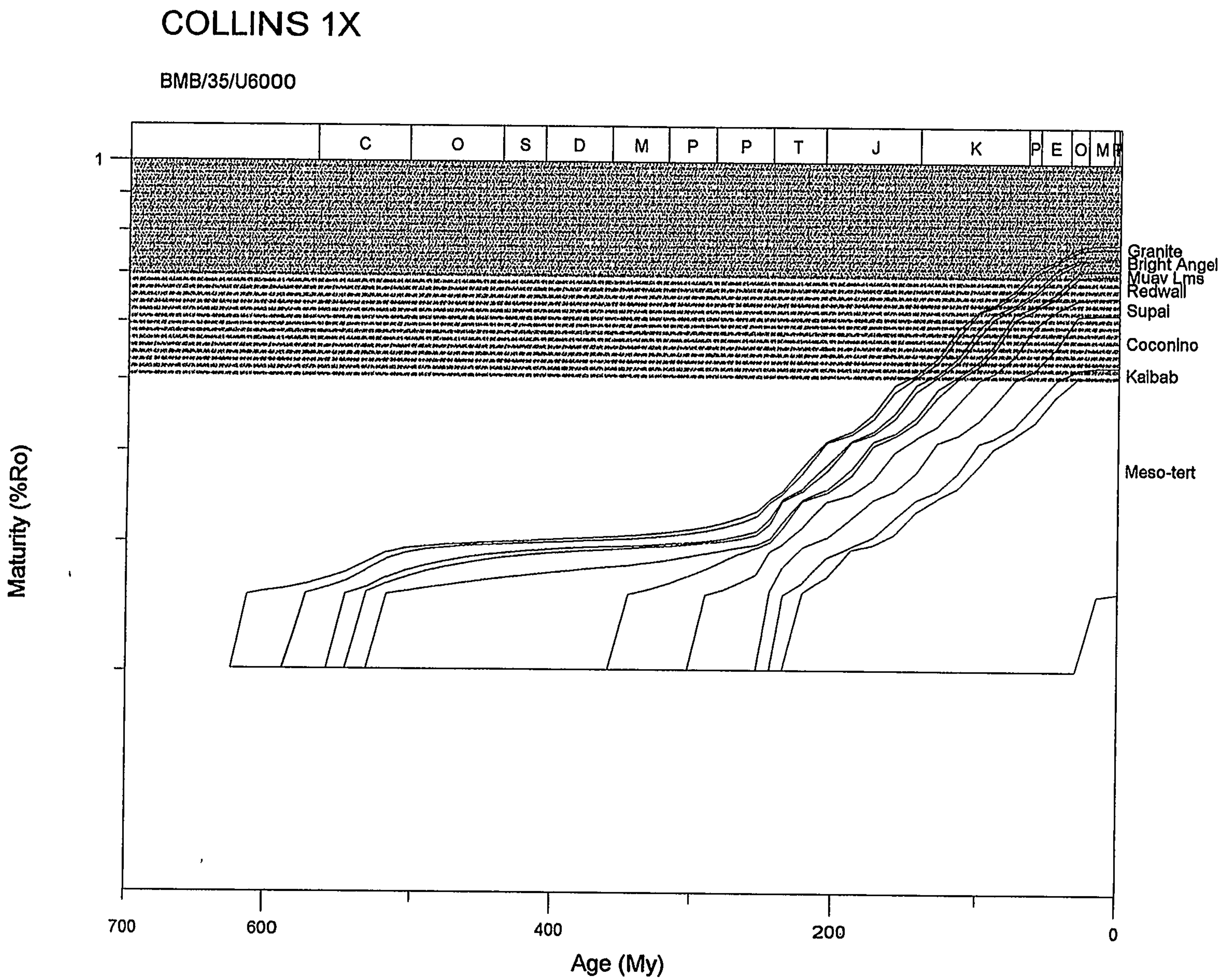


Figure 11–30 **Collins 1X Well. Increasing Maturation Through Time with a Burial History that has 6000 ft of Burial and Uplift. Geothermal Gradient was 35°C/km.**

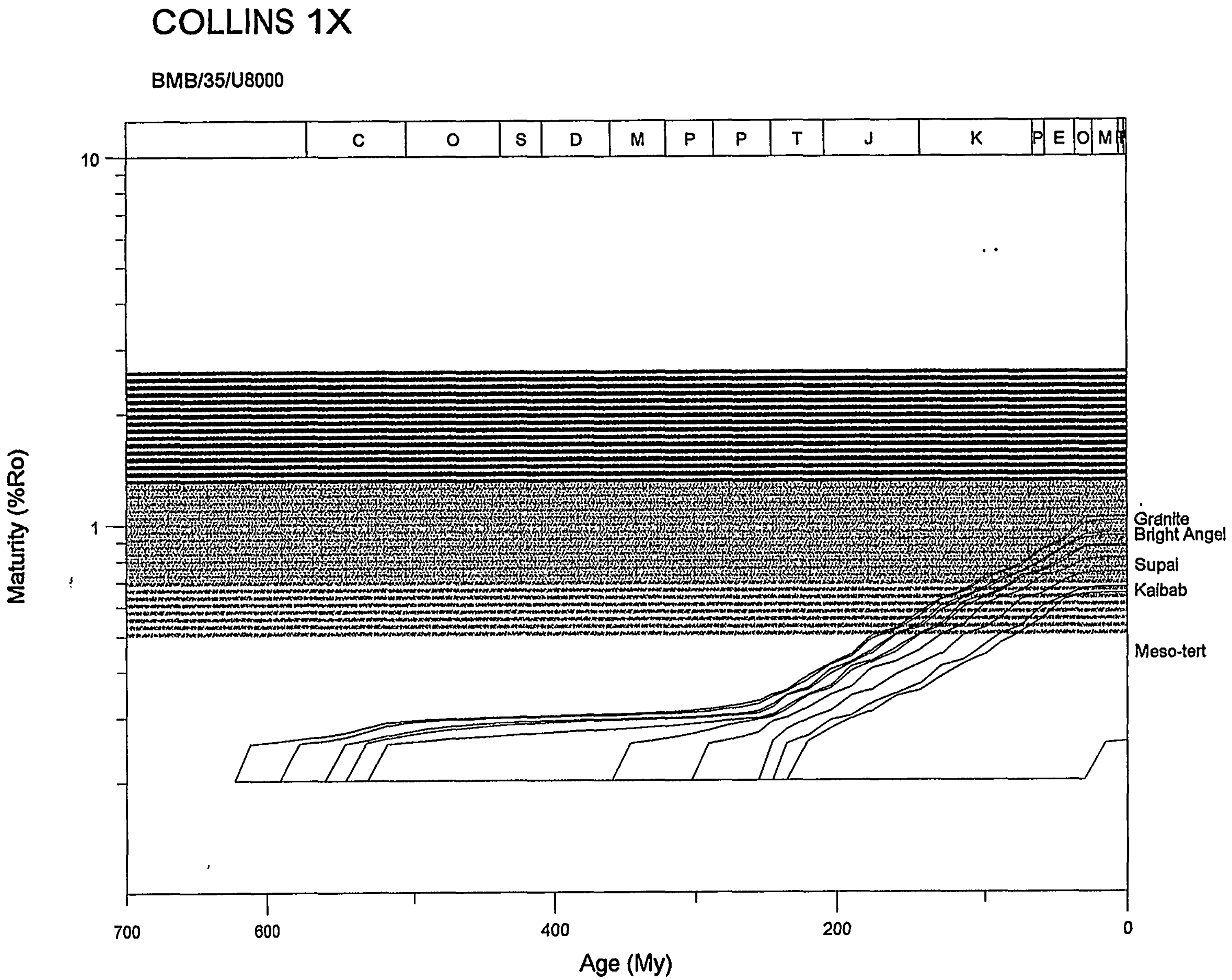


Figure 11–31 Collins 1X Well. Increasing Maturation Through Time with a Burial History that has 8000 ft of Burial and Uplift. Geothermal Gradient was 35°C/km.

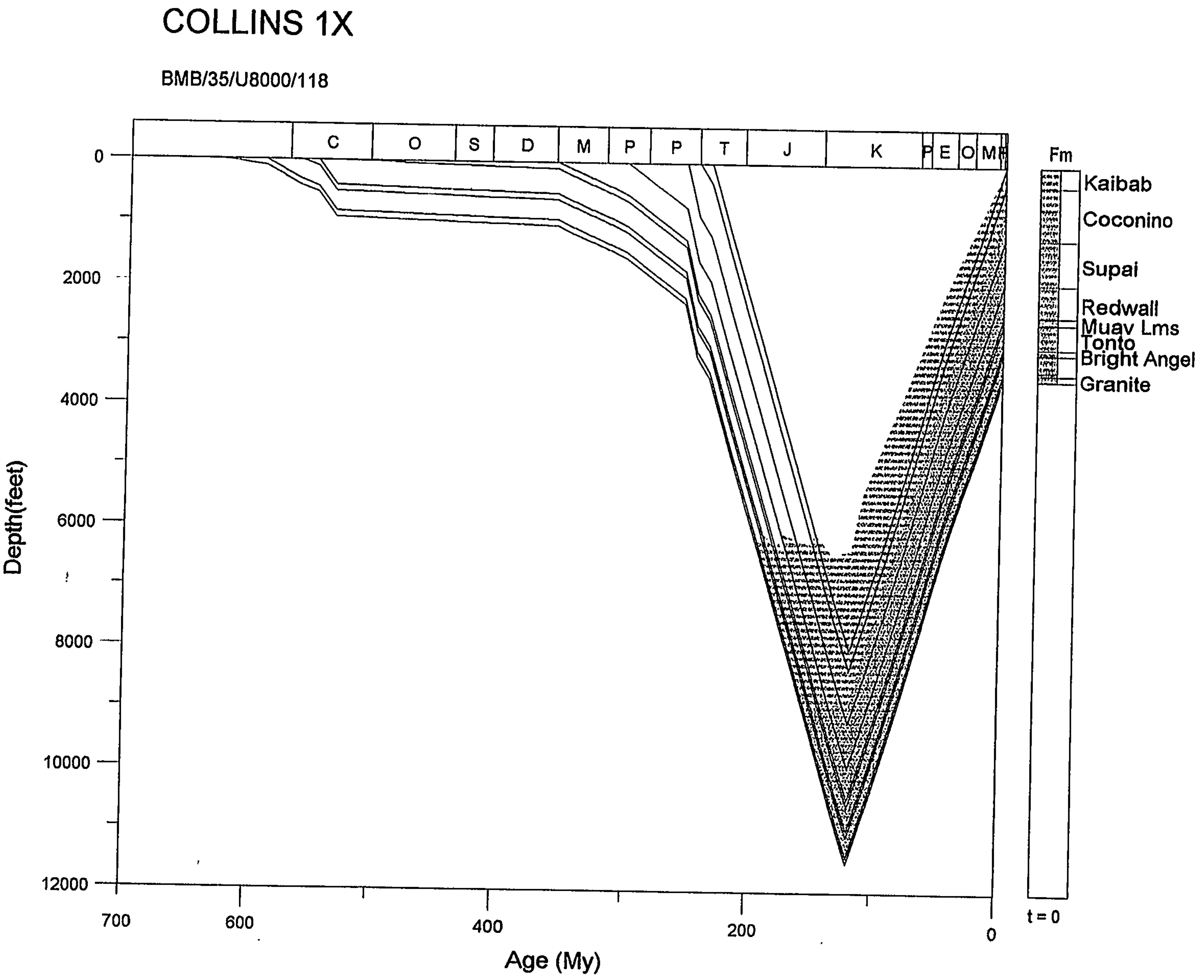


Figure 11–32 Collins 1X Well. 8000 ft of Mesozoic and Tertiary has been Accumulated and Later Removed by Erosion that Started 118 Ma. Geothermal Gradient was 35^{o}C/km

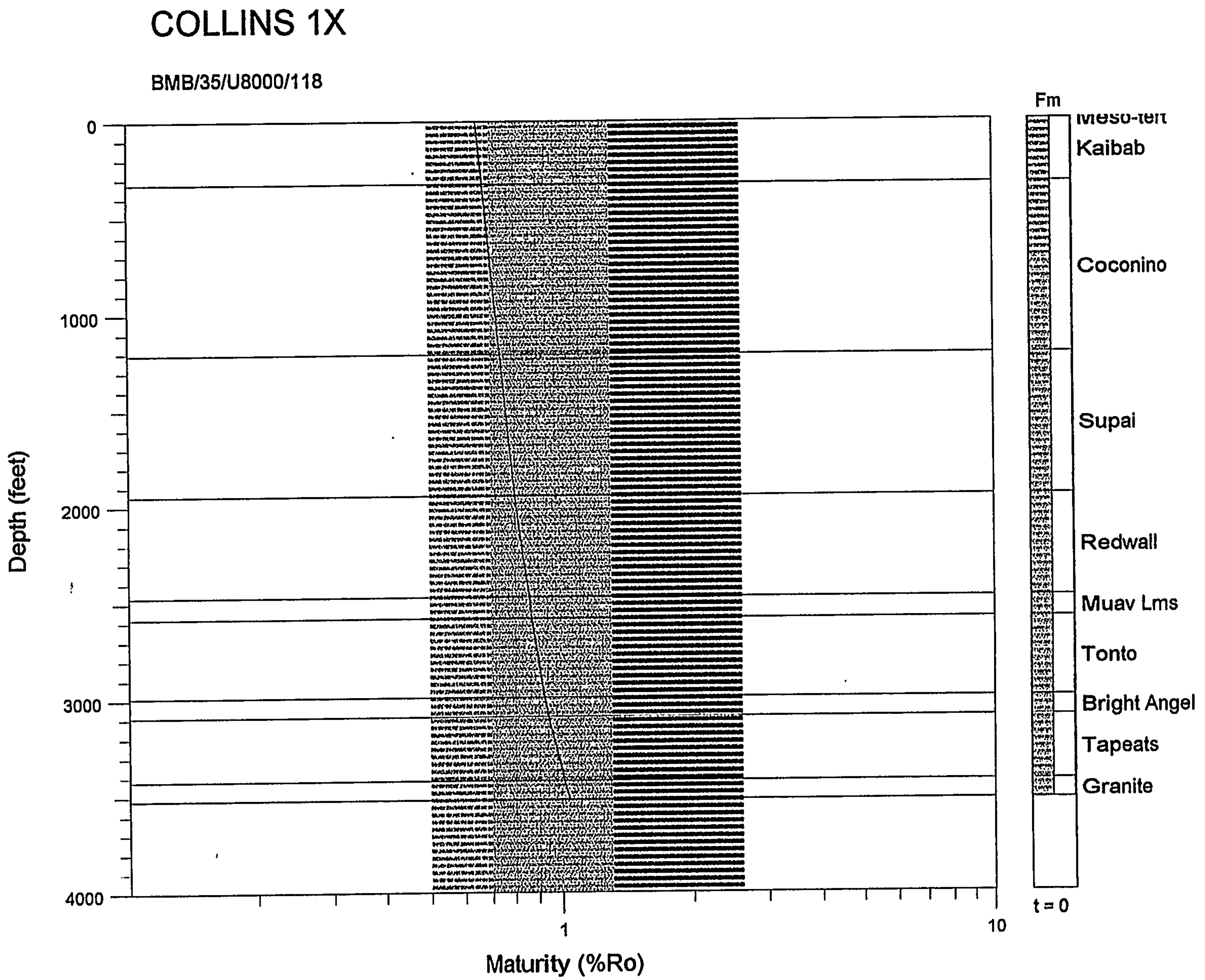


Figure 11–33 Collins 1X Well. Calculated Vitrinite Reflectance Profile Corresponding to the Conditions in Figure 11–32.

COLLINS 1X

BMB/35/U8000/118

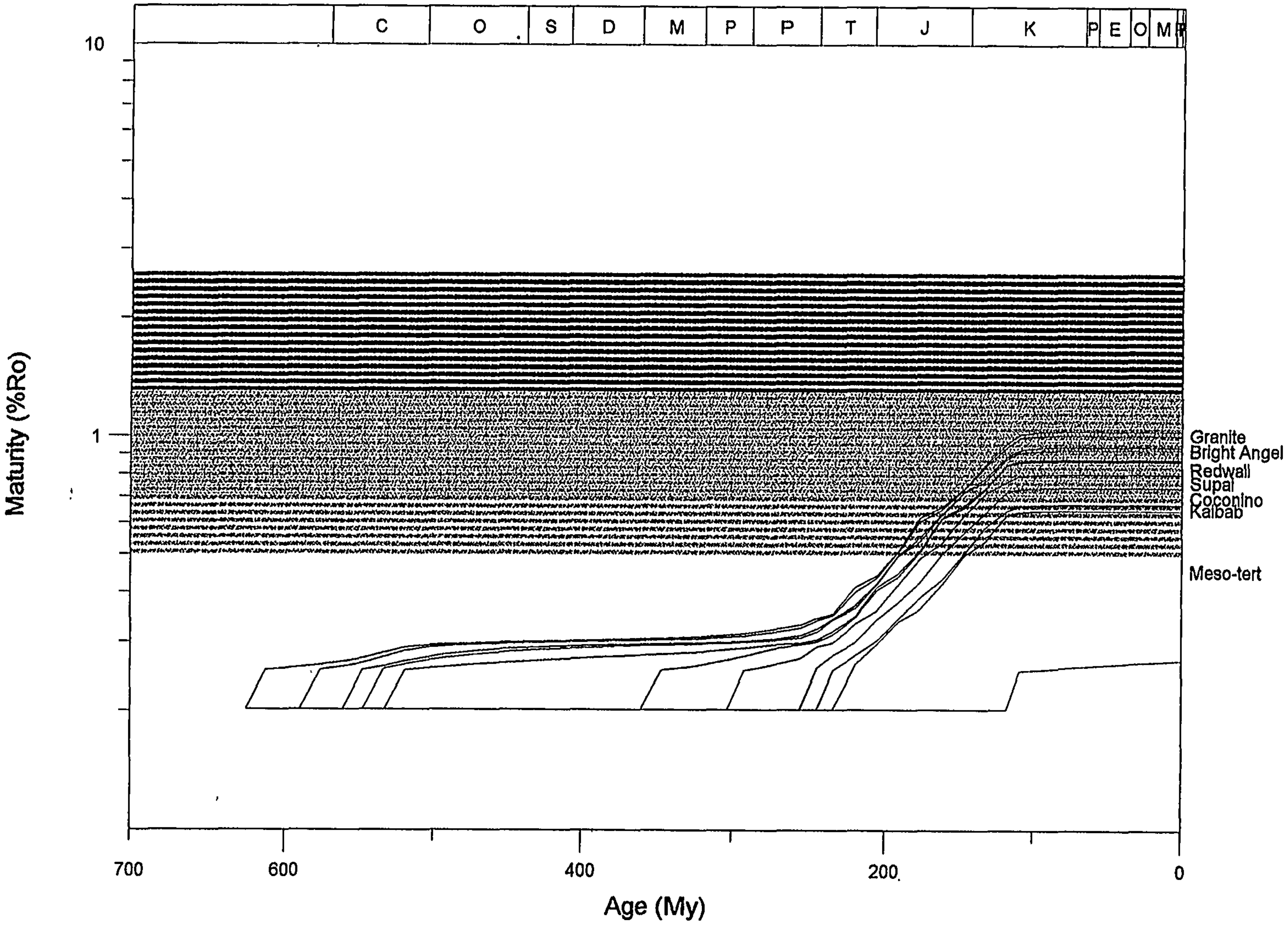


Figure 11–34 **Collins 1X Well. Increasing Maturation Through Time with a Burial History that has 8000 ft of Burial and Uplift when Erosion Starts 118 Ma. Geothermal Gradient was 35°C/km**

12.0 SURFACE GEOCHEMICAL SURVEY METHODS FOR LOCATING HYDROCARBON RESERVES

Geochemical exploration assumes a relationship between surface measurable phenomenon and a hydrocarbon reservoir. For a technique to be successful,

- Oil or gas reservoirs must seep some of their contents to the surface,
- Seeped material, or something associated with it, occurs in sufficient quantity to be measurable,
- Material associated with seeps can be distinguished from nonreservoir related material, and
- Migration of seeped material is sufficiently vertical to be useful in locating the reservoir of origin.

Many surface geochemical techniques have been developed in an attempt to take advantage of perceived surface expressions of a hydrocarbon reservoir. The Black Mesa Region restricts the type of techniques that can be applied.

Survey Locations: Figure 2–3 gives the locations of the primary areas of interest for geochemical study within the Black Mesa Region. The vast majority of these areas are either within the Hopi or Navajo Indian reservations. Details, including the selection criteria, can be found in Reeves and Carroll (1996).

12.1 Special Considerations

Approval of invasive sampling techniques can be difficult and time consuming on Navajo lands. The Hopi Tribe is even more conservative and does not want invasive techniques employed at all. Although "invasive" has not been specifically defined, following discussions with Hopi tribal leaders, invasive techniques have been interpreted to include heavy equipment or drilling. This limits sample collection to the surface sediments. Much of the area is arid and cut by northeast-to-southwest oriented washes, some 4 mi wide, with cliffs 500 ft to 1000 ft high. Furthermore, the large expanse of area to be sampled prohibits the use of time consuming techniques, such as drilling. It is around these restrictions that the surface geochemical program was planned.

12.2 Sample Collection

The geochemistry group evaluated a conventional (manual) soil sampling tube for sampling in the areas selected for evaluation. It is capable of collecting 6-in. long by 3/4-in. diameter core samples. The sampling procedure will need to be conducted twice per hole to obtain the desired 12-in. sampling depth. To facilitate driving the sampling tube, a foot step has been added to the sampling tube shaft. Soil samples are typically collected in plastic tubes or plastic bags. For some types of tests, this storage method is satisfactory, but for sampling adsorbed volatile gases, such storage practices are inadequate because gas can desorb and be lost (gas diffuses through plastic rather easily). Prior to removal, near-surface soil experiences a continuous influx of gas from below and outgassing to the atmosphere at the surface. Once removed from the ground, this steady state process is interrupted and the soil sample will continuously outgas. This gas must be trapped for accurate analytical results and reservoir location. Since a large number of samples need to be collected, the sample containers must be small (no Mason jars) and inexpensive. Also, to prevent loss of desorbed gas during sample transfer at the laboratory, the sample container should be able to be evacuated, heated, cryogenically cooled and accessed without opening directly to the air. A long 1-in. diameter test tube of Pyrex, or of equivalent heat-resistant material, meets these requirements. The test tube is capped with a Neoprene stopper. The sample is accessed through a 1/4-in. hole in the stopper. A glass bead in this 1/4-in. hole serves as a seal until sample processing. At this time, a 1/4-in. diameter stainless tube pushes the glass bead out and the gas can be transferred out for analysis. Plastic tubes with snap caps will be used for methods not involving adsorbed gases.

12.3 Sampling Grid

Two mistakes made in sample collection are not using a sufficiently close sample spacing, and selecting a sample area that is too small. Typically, a 1/10 mi (500 ft) spaced rectangular grid should be used, and the total sampling area needs to be several times the anticipated anomaly size. Real-time analysis may help focus the survey, but since anomalies are based on relative values, sampling over barren areas must be included. To record site locations with sufficient accuracy for future prospecting, the Exploration Group has purchased an optical triangulation rangefinder for accurate sample spacing, and a satellite positioning instrument for site location (accurate to within 15 meters).

12.4 Methods

In order to accommodate the special considerations required of the sampling areas, the following geochemical methods were selected for surface geochemical surveying in the Black Mesa Region. These methods are restricted to those that can be performed on a 12-in. soil plug.

12.4.1 Iodine Survey

Background iodine is often in the 0.5 to 5 ppm range. In the presence of ascending hydrocarbons, the iodine reacts with the hydrocarbon at or very near the surface of the ground and becomes trapped as an organic iodide. Anomalies are identified as a 50% to several fold increase in iodine over the background level. One hypothesis for the near-surface reaction depends on the presence of ultraviolet light to initiate the reaction. Oxygen, probably as a radical, may also be involved. An iodine survey will be an important surface geochemical technique because (1) it responds primarily to nonmethane hydrocarbons, (2) the maximum response is at or near the surface, (3) collected samples are stable, and (4) the presence of other organics does not interfere (Allexan, et al. 1986). If a rapid, real-time analysis scheme could be developed, it would be useful in focusing the field survey. An iodine ion-selective electrode with a portable meter may serve this purpose if the following problems can be satisfactorily addressed:

- Can sulfide ion interference be eliminated?
- Can iodine easily be extracted under field conditions?
- Can a technique be developed that generates only a small volume of waste?
- Can this technique be performed rapidly so that real-time analysis makes sense?

12.4.2 Soil Gas

Due to the shallow sampling depth, there is some question as to whether there will be sufficient adsorbed soil gas. Typically, soil gas is sampled at 3 to 5 feet depth. This will be mostly interstitial gas and will show the most variability with atmospheric pressure, changes in soil moisture, etc. Adsorbed gas should be less susceptible to these problems, but is still subject to removal by oxidation and gas phase partitioning. Low vegetation in the sampling area should reduce background methane of a biogenic origin, as long as one avoids sheep "deposits." The sampling procedure described above will help preserve what soil gas is present.

12.4.3 Metals

Metals, such as vanadium, nickel, copper and manganese, tend to accumulate around the periphery of hydrocarbon seeps due to the reducing environment caused by the rising hydrocarbon. Normal soil processes can also cause these metals to form deposits. To maximize their effectiveness as a hydrocarbon indicator, the amount of organic material and clay content need to be known. Outlying areas barren of hydrocarbons need to be sampled to provide a reference (Tedesco 1995).

12.4.4 Magnetic Susceptibility

As hydrocarbons ascend from a reservoir and create a reducing environment, nonmagnetic forms of iron oxide are converted to magnetite and other forms of magnetic iron oxide which can be detected in the field or the laboratory (Barton 1990). Field measurements provide a better global perspective, but laboratory-derived susceptibility is more readily quantified, free of interferences.

12.4.5 Fluorescence

All crudes contain some aromatic hydrocarbons. The simplest is benzene, C_6H_6, a ring of six carbon atoms with one hydrogen atom attached to each carbon atom. Other aromatic compounds contain two or more six-membered rings fused together. One or more of these hydrogen atoms may be replaced by a hydrocarbon group. These aromatic compounds ascend with the lighter gases, but in reduced amounts. They absorb ultraviolet light (200-350 nm) and re-emit a portion of this energy at a somewhat longer (red-shifted) wavelength. Aromatics are much less volatile and less subject to bacterial attack than the lighter hydrocarbon gases so they persist longer. Man-made aromatics, such as in biocides, can be a source of interference. With the proper spectral stripping or detailed spectral analysis, these interferences can usually be eliminated (Calhoun 1992). In the Black Mesa Region, there is much less chance for this type of interference due to the much reduced use of pesticides, etc.

12.4.6 pH

Some researchers have observed a reduction in pH within the reducing environment of a hydrocarbon seep (Tedesco 1995). This is an easy test to perform and should be conducted on the collected soil samples.

12.5 Survey Status

At present, permission to collect samples has not been received from either the Hopi or Navajo Tribes. Without these samples, no further work is possible. The well density in these target areas is very low. No surface geochemical surveys have been located within the study area to offer supplemental data.

13.0 AERIAL RADIOMETRIC (NURE) DATA: A POTENTIAL METHOD FOR THE LOCATION OF HYDROCARBON RESERVOIRS

13.1 The Radiometric Survey

Historically, the presence of a hydrocarbon seep seemed to correlate with a radiometric low (Harnett 1994). The total gamma count was measured in these radiometric surveys. These devices were actually measuring primarily the potassium-40 since its absolute concentration was highest and these detectors were most sensitive to the lower energy gamma rays emitted by potassium-40. Today, the more sophisticated radiometric surveys measure potassium-40, uranium and thorium independently, and are referred to as windowed gamma ray surveys.

A windowed gamma ray survey is base on the principle that naturally-occurring and ubiquitous potassium-40, uranium and thorium concentrations are somehow modified by the presence of near-vertical ascent of microscopic gas bubbles (mostly methane) through a network of interconnected, groundwater-filled joints and bedding planes.

As hydrocarbons migrate towards the surface, they may react with sulfates in the groundwater, or be attack by sulfate-reducing bacteria, to produce hydrogen sulfide and carbon dioxide (or organic acids, R-COOH):

Biochemical degradation:

$$H^+ + SO_4^{-2} + CH_4 \rightarrow H_2O + CO_2$$

Chemical degradation:

$$C_nH_m + SO_4^{-2} \rightarrow CaCO_3 + H_2S + CO_2 \text{ (or R-COOH)}$$

Carbon dioxide or organic acids can then release Potassium-40 and Uranium adsorbed onto shales through ion exchange, or through the direct destruction of shales:

$$CaAl_2Si_6O_{16} + CO_2 \rightarrow CaCO_3 + SiO_2 + Al_2O_3$$

Water soluble Potassium-40 and Uranium can then migrate away from the hydrocarbon site.

Hydrogen sulfide has no effect on Potassium-40, but can precipitate Uranium as UO_2, resulting in Uranium accumulation in the vicinity of the hydrocarbon seep.

$$UO_2^{+2} + S^{-2} \rightarrow UO_2 + SO_4^{-2}$$

As a result, in humid climates and in the presence of hydrocarbons, Uranium in the top few inches of soil may be leached away. In dry climates, it may accumulate. The Potassium-40, however, will decrease under either condition due to leaching. Thorium is unaffected by chemical action or leaching. If hydrocarbons are not present, naturally occurring Potassium-40, Uranium and Thorium seem to be present in a constant ratio. Therefore, normalizing to the Thorium concentration can remove site-to-site variations in Potassium-40 and Uranium.

13.2 What Is the NURE Data?

The NURE (National Uranium Resource Evaluation) radiometric data consists of air reconnaissance measurements of those portions of the gamma ray spectrum corresponding to the radioactive decay of potassium-40, uranium and thorium (or, more correctly, the daughter products of uranium and thorium). Contractors charged with collecting these data also measured residual magnetism and the geologic unit. These data were collected between 1974 and 1981 over most of the lower 48 states, Alaska and parts of Canada in an effort to locate domestic uranium deposits, and has more recently found use in petroleum exploration in Texas (Saunders et al. 1987). Helicopter-mounted gamma-ray spectrometers collected the radiometric data along east-west flight lines spaced nominally three mi apart with north-south tie lines flown at 12 mile intervals. Altitude and air speed were maintained as constant as practical, and corrected to an altitude of 400 ft and a speed of 104 mph. Each data point represents the number of counts recorded over a one second interval and corresponds to approximately 180 feet along the flight path and 400 feet on either side of the flight line. This limits coverage to about 5% of the total area. There are a variety of corrections made to the raw data. Some of the more important ones are:

- Aircraft background radiation (assumed to be constant during flight)
- Atmospheric radon (referred to as atmospheric bismuth in the USGS open file reports)
- Cosmic radiation (estimated by high altitude flights over water)
- High-energy gamma-ray contribution (Compton scattering - corrected by spectral stripping)
- Altitude (adjusted to 400 feet to correct for atmospheric absorption of radiation)
- Conversion from counts/sec to concentration (% for potassium-40, and ppm for uranium and thorium)

The data and a report describing its collection and processing are available on microfiche or CD ROM from the USGS in Denver, Colorado. Digital radiometric data is available in ASCII format on 9-track tape from the EROS Data Center in Sioux Falls, South Dakota at a cost of $80. per 1° x 2° section (Finch 1987, and Hill 1986).

13.3 Identification of Hydrocarbon Anomalies

To identify radiometric anomalies as attributable to hydrocarbon seeps, one must develop a model to "explain" these responses. One of the more successful and publicized models was put forth by Saunders et al. in 1987. One basic assumption is that whatever changes the concentration of one radioisotope similarly modifies the other two, if no hydrocarbon is present. Based on extensive studies of radiometric surveys over oil fields, Saunders developed a relationship between potassium-40, uranium and thorium data to aid in identification of hydrocarbon anomalies. These are based on the observation that potassium-40 decreases over oil fields and uranium usually increases. Thorium is considered to be strongly tied up in local rocks and soil, and is unaffected by ascending hydrocarbons. With these assumptions, Saunders defined an idealized potassium and an idealized uranium as

$$K_i = (K_{av}/Th_{av}) \times Th_s$$

$$U_i = (U_{av}/Th_{av}) \times Th_s$$

where the subscript "s" refers to the measured or sample value, "i" is the idealized value and "av" is the average value over the area of investigation, usually at least five times as great as the anticipated anomaly (usually several square miles). He then calculates the difference between the idealized and measured values;

$$KD = (K_s - K_i)/K_s$$

$$UD = (U_s - U_i)/U_s$$

In the presence of hydrocarbons, KD is observed to decrease and UD usually increases. To capitalize on both of these relationships, Saunders et al. (1993) define a new quantity, called DRAD, given by

$$DRAD = UD - KD, \text{ or}$$

$$DRAD = \frac{U_s/U_{av} - (K_s/K_{av})}{(Th_s/Th_{av})}$$

Hydrocarbon anomalies are characterized by positive values for DRAD and negative values of KD. Due to the noise inherent in radiometric data, it is customarily smoothed, such as by a 7-point moving average.

13.4 NURE Radiometric Data for the Black Mesa Region

The Exploration Group has received the six sections for northeastern Arizona (Marble Canyon, Ship Rock, Flagstaff, Gallup, Holbrook, and St. Johns) covering the Black Mesa Region, and has down-loaded the relevant data for five of the six sections onto 3.5-in. diskettes. Data for the sixth section (Saint Johns) are in a different format and appear to be raw, uncorrected data requiring extensive modification. This may be a challenge considering the age of the data. Each geologic section of the down-loaded data has approximately 100,000 lines, with a line consisting of latitude, longitude, residual magnetism, potassium-40, uranium and thorium concentrations. Figure 13–1 illustrates the raw NURE data in an area not known to have hydrocarbon potential, but exhibiting relatively high concentrations of the radioisotopes. Figure 13–2 is this same data after using a 7-point smoothing routine.

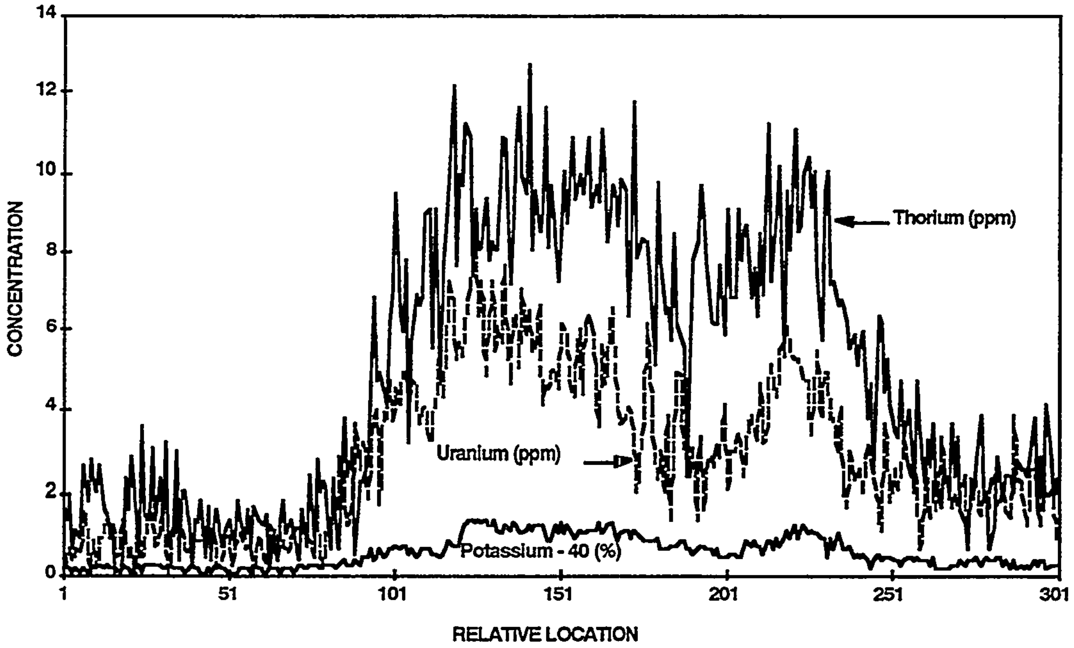


Figure 13–1 Raw NURE Radiometric Data for Potassium-40, Uranium and Thorium near Cameron, Arizona, North of Flagstaff (Distance Along the X-axis Is Approximately 10 mi)

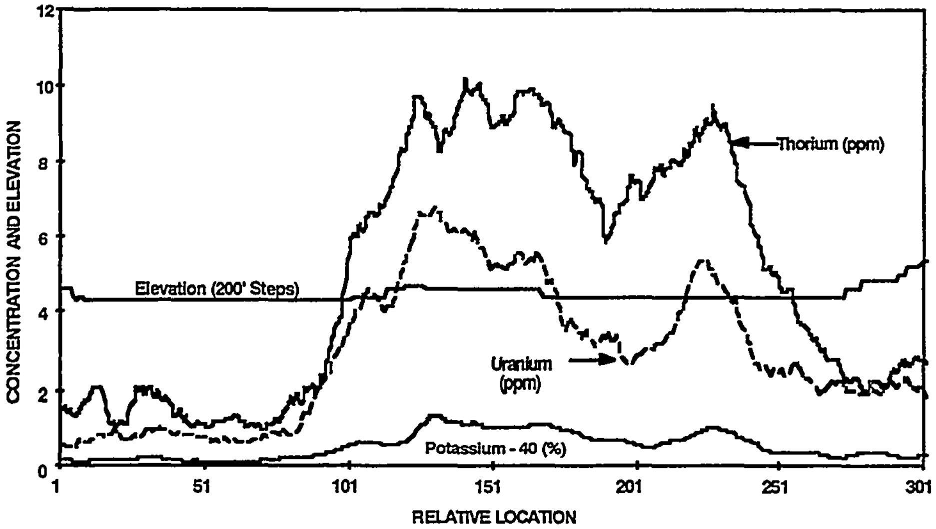


Figure 13–2 Data in Figure 13–1 Subjected to a 7-Point Moving Average Smoothing Routine

This line is taken from the 1° x 2° Flagstaff section, northeast of Cameron, Arizona, and is about 10 mi long, passing over two washes separated by a ridge (400 to 600 feet above the floor of the washes). An approximate vertical profile is included on Figure 13–2 for reference (one step represents 200 feet). Potassium-40, uranium and thorium show marked increases over the central ridge and the east wash. The radiometric high near the center of the east wash may reflect basement faulting suspected to be coincident with many of the area's larger washes. If one looks at the DRAD plot in Figure 13–3, this anomaly almost disappears. There are a number of uranium deposits in the Cameron area and this ridge and wash may be associated with one.

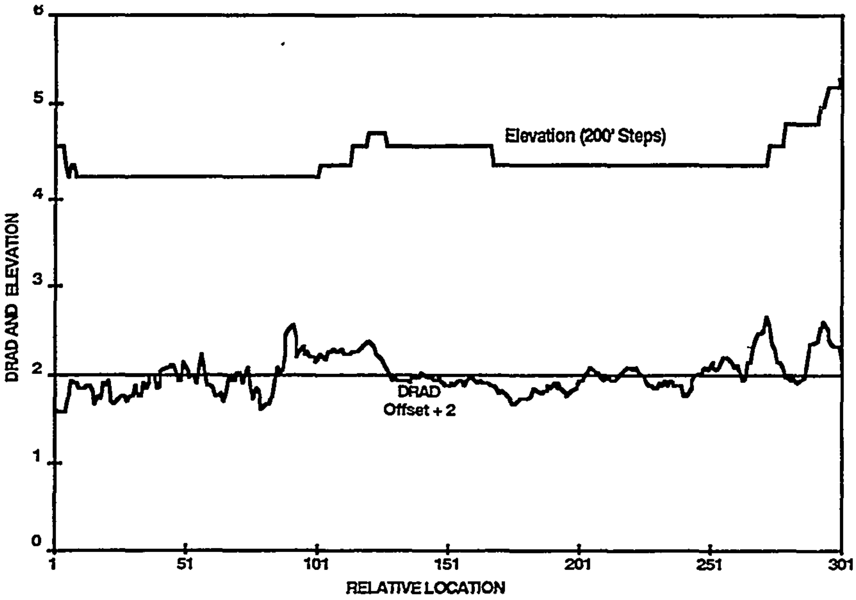


Figure 13–3 DRAD Representation of the NURE Data in Figure 13–2 (Based on Method of Saunders et al. 1987)

Figures 13–4 and 13–5 are a 10 mi long NURE line that passes over the southern edge of an existing oil field in extreme northeastern Arizona. Although outside the Black Mesa target area, it illustrates the behavior of the potassium-40, uranium and thorium data in the vicinity of oil deposits. Figure 13–4 shows the relationship of the flight line and the wells associated with the oil field. Figure 13–5 gives the potassium-40, uranium and thorium response.

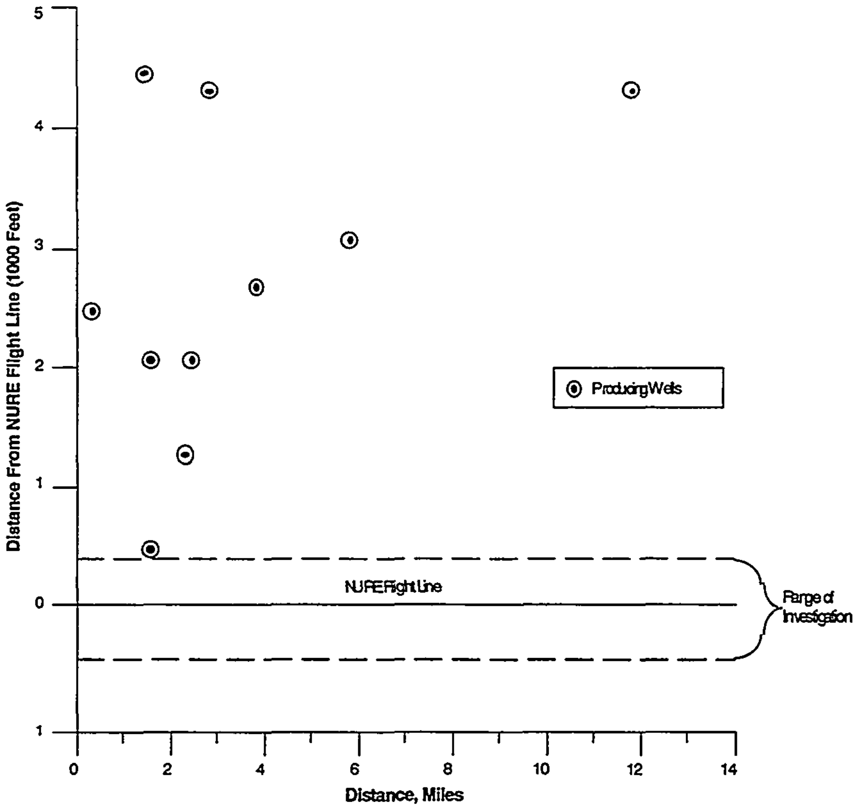


Figure 13–4 **Map View of a NURE Flight Line and Nearby Wells Over an Existing Oil Field in Northeastern Arizona (Horizontal Scale Is in mi but the Vertical Scale Is in Feet)**

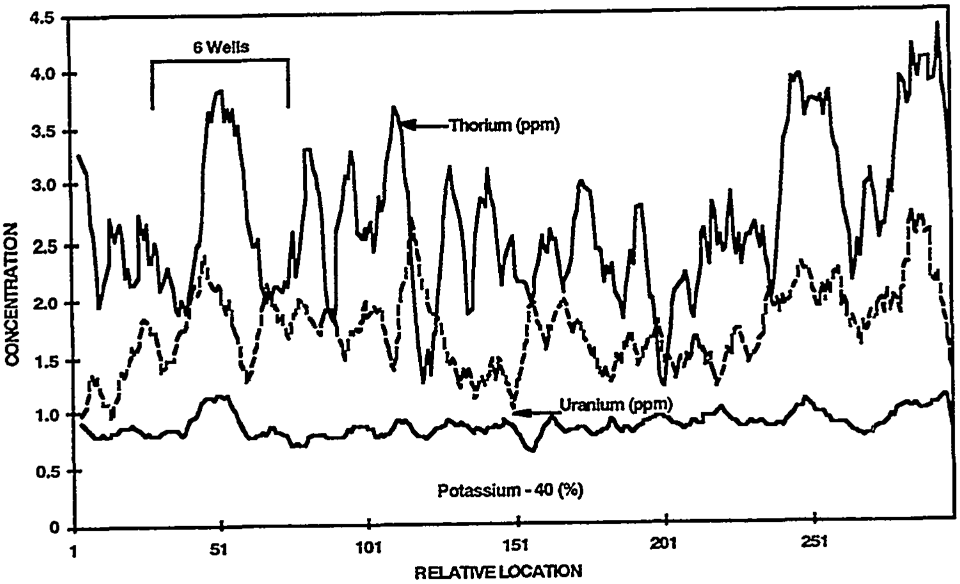


Figure 13–5 **Smoothed NURE Data Passing Just South of an Oil Field in Northeastern Arizona (Distance Along the X-axis Is Approximately 10 mi)**

Unlike the first location described above, the thorium highs generally mirror uranium lows, and potassium-40 tends to follow thorium, but not always. The bracket marks the position of six wells within 1/2 mi of the NURE line and is about 1.2 mi across. There are several areas where the uranium is relatively high, and potassium is low. Figure 13–6 is the plot of this data using DRAD.

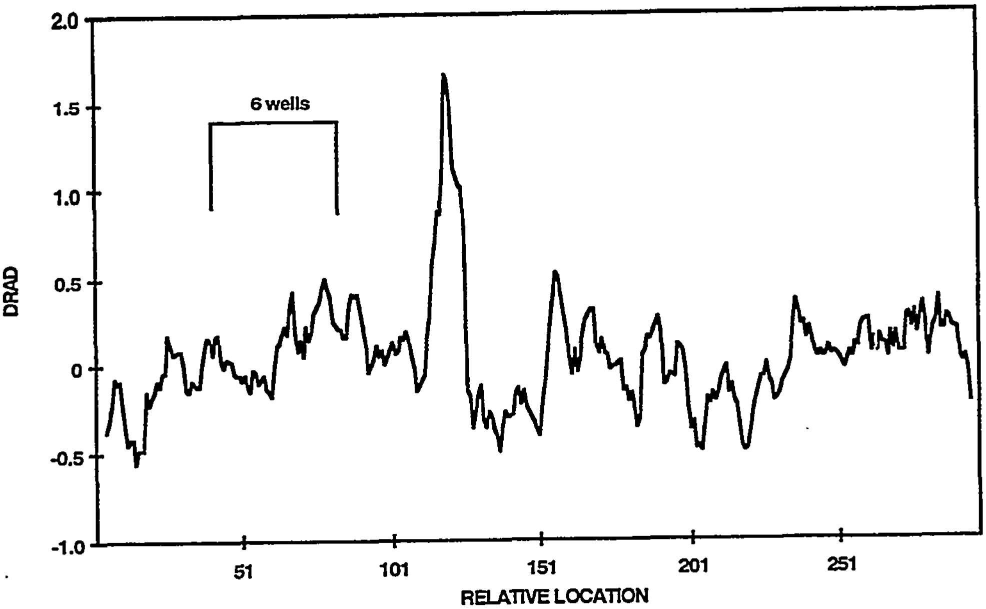


Figure 13–6 **DRAD Representation of the NURE Data in Figure 13–5**

The positive values for DRAD on the right side of the bracket indicate a hydrocarbon potential. Note that this is the approximate location of a nearby well. The spikes at position 120 and 156 are strong indications of hydrocarbon. Figures 13–1 through 13–6 illustrate the NURE data over the Black Mesa region. More work is needed both in areas with oil production and barren areas to develop confidence in DRAD and suggest improvements. Positive excursions of DRAD seem to be more dependent on low values of the thorium concentration, rather than high values of uranium and low values of potassium-40. Furthermore areas with rapid changes in the DRAD (over hundreds of feet, rather than a mile or so) are probably due to natural variations in this region, such as shale outcrops, extreme topographic changes or local water seeps. The current thought is that low values in potassium-40 may be a better indicator of potential hydrocarbon seeps. Once potential targets are identified, these must be confirmed by other methods (such as surface surveys) and a site inspection (drilling into a uranium mine tailing could prove embarrassing and have low hydrocarbon potential).

14.0 HISTORICAL FACTORS AFFECTING HYDROCARBON EXPLORATION IN NORTHEASTERN ARIZONA

Unfortunately, the large amount of drilling along the shallow-basement trend has provided a sizable quantity of data which can easily be misinterpreted. These data have sometimes been taken as being representative of all of northeastern Arizona, suggesting that the entire region is lacking in source bed material with a thin Paleozoic sedimentary section. The few deep wells in the central Black Mesa region (Pierce and Scurlock 1972) have shown that a promising lower and middle Paleozoic section exists just to the north of the densely drilled rail corridor. The general lack of thinness of Cambrian and Devonian beds in most of the wells along the railroad means that petroleum explorationists have extremely limited information on many of the most important formations in the region. The standard well databases for northern Arizona (Pierce and Scurlock 1972; Takahashi and Gautier 1995) do not provide the amount of information oil companies want before they become comfortable with a prospect. Oil companies doing a quick survey, or even a detailed study of the region, have tended to be misled or impeded by the lack of crucial data.

The basement surface rapidly drops 4,000 ft from the highly drilled railroad lands and the area around Holbrook to the region of the Hopi towns to the north, in the central basin–Oraibi trough region (Pierce and Scurlock 1972). This major break in the basement relief is quite ancient. It apparently led to abrupt changes in water depth and environments of deposition between the Defiance-Zuni structural high and the deeper water area to the north. There are many facies changes in the lower Paleozoic section that have not been documented in well cuttings or on outcrop. Prime prospecting targets for the Black Mesa basin include stratigraphic pinch-outs and fracture zones in areas along the basin margin. The subtleties of structure and stratigraphy in the deep basin are almost total unknown. A primary factor that has inhibited development of the Black Mesa region has been a lack of information on key sediments in the deeper portion of the basin.

A second problem has been ready access to the region. Throughout most of its history, drilling in the Four Corners region has been closely tied to lands that were open, in a commercial sense, with simple land titles and easy physical access. For decades, northeastern Arizona was lacking in highways. Route 66 was the only major highway that passed near the Native American lands of the Four Corners. The first two major paved roads that were built across the reservations were not constructed until the 1950s. The railroads have always been interested in adding value to their extensive land holdings by proving up potentially valuable mineral and hydrocarbon resources on their properties. Unfortunately, as discussed above, the railroad in northeastern Arizona passes through an area with little oil potential. In the last few years, with the opening and expansion of commercial coal operations at the northern Black Mesa, additional roads have been opened or improved, and access to the Black Mesa has become relatively easy.

A third significant factor affecting development in northeastern Arizona has been the leasing picture and land titles in the region. Oil drilling in the Four Corners region has traditionally progressed most rapidly on privately owned lands. There was little drilling in the early decades of this century on Native American lands. There were several reasons for this. Firstly, the lands that had been relegated to the Native Americans tended to be remote and hard to reach, under the best of conditions. In cases where industry was interested in drilling on specific Native American lands, there have been numerous impediments, ranging from protected lands in parks or monuments, to legal suits, to development moratoria. The paperwork associated with work on Native American lands has traditionally been much greater than that required for drilling on private tracts.

15.0 CONSIDERATIONS FOR DRILLING ON NATIVE AMERICAN LANDS

Conversations with representatives of the Hopi Nation, the Navajo Nation Minerals Department, and university and industry personnel in Flagstaff provided a number of insights into the history of oil development in Northeastern Arizona and the surrounding area. The first major breakthroughs for oil drilling on Native American lands came in the 1950s. As Table 15–1 (based on data in Schicktanz 1963) demonstrates, there was an explosion of drilling on Navajo lands during that decade.

Table 15–1 Drilling on Navajo Lands, 1950–1960

Year	Number of Wells	Annual Production (bbl)	Annual Royalty
1950	51	133,000	$42,000
1956	54	354,000	Not Available
1960	860	34,273,000	$8,835,000

The great change was brought about through a major leasing program that began in 1957 (Schicktanz 1963). As drilling took place, and royalty checks grew from a few tens of thousands to millions of dollars, the Navajo Nation came to appreciate the value of oil to the tribe. A Navajo Nation oil company has now been organized to encourage additional development. Although there has been a substantial growth in drilling on Navajo lands since mid-century, even in the 1990s few wells have been drilled on the Navajo reservation in northeastern Arizona (Pierce and Scurlock 1972; Takahashi and Gautier 1995). Most of the existing Navajo wells are located in the states surrounding Arizona.

There has been much less activity on the Hopi reservation. Smith and Carpenter (1955) expressed an interesting point of view. They felt, in the 1950s, that the Hopi could realize considerable revenue from oil leasing, if they were willing, but noted that the "tribal religion" prohibited the tribe from offering acreage. Following the highly productive results of the Navajo leasing program of 1957, Washington decided in 1961, despite any concern for religious considerations, to put Hopi lands up for bid. The arrangements for this were not be completed until 1964. Because of the successes on Navajo lands nearby, there was extensive interest in the industry. The bids were so high that they almost totally discouraged smaller, local companies from participation and significantly cooled local interest in the leases. A few major oil companies did submit winning bids, but they held the results confidential for a prolonged period, further dampening potential participation in the region by independent companies.

In 1965, six wells were drilled on the Hopi Reservation and an few additional wells on surrounding lands near the Black Mesa (Pierce and Scurlock 1972; Takahashi and Gautier 1995). These have been the only deep tests in this central structural-basin area to the present day. Several of the wells had promising shows, and drill-stem testing was done (Pierce and Scurlock 1972), but none of the wells were ever completed. With the data from the Hopi wells having been kept tight for an extended period of time, other companies eventually lost interest in the wells.

In 1966, the year following the drilling of the Hopi wells, a large coal mine on the northern portion of the Black Mesa was opened by the Peabody Corporation. The inevitable disruptions of the land around the mine and of local water supplies were very upsetting to the Hopi residents of the mesa. At exactly the same period, long-standing land disputes over reservation boundaries between the Hopi and Navajo flared up again (Barwin 1971). Legal suits were filed between the Hopi and the Navajo, and even between Hopi factions and the Hopi Tribal Council over the right of the tribal council to grant leases and responsibilities for protecting the land, recalling Smith and Carpenter's 1955 references to tribal religion. These legal problems, which moved in and out of court throughout the late 1960s and 1970s, inhibited oil companies from following up on the 1965 programs. Recently, many of these legal questions have been resolved, offering renewed opportunities for cooperation with the two Native American nations in the Black Mesa region.

16.0 DRILLING HISTORY OF NORTHEASTERN ARIZONA

Drilling began relatively late and slowly in the states of the Four Corners in the Southwestern United States. Col. Drake drilled his first discovery well in 1859, at Titusville, Pennsylvania, and drilling rapidly spread to other regions of the country. The first oil discovery well in eastern Colorado was drilled in 1862. However, the first white settlement in southwestern Colorado, Animas City, was not founded until 1873, and the first permanent white entry into the San Juan basin did not occur until 1876. The Four Corners area did not really open up, commercially, until the Denver and Rio Grande Railroad reached Durango, in 1881, and Farmington in 1905. Even today, the white population in northeastern-most Arizona is minimal. The vast majority of the lands in this corner of the state belong to the Hopi or Navajo nations or are part of one of the smaller Reservations in the area. The major exception to Native American land ownership is the railroad corridor through the valley of the Little Colorado River.

Throughout most of its history, the drilling pattern in the Four Corners region has been closely tied to lands that were open, in a commercial sense, with easy access, especially lands that were once owned by, or physically close, to railroad rights-of-way. There are multiple reasons for this. The railroads have always been interested in value-adding to their extensive land holdings, by proving up potentially valuable mineral and hydrocarbon resources on their holdings. In addition, in the rugged landscape of Hopiland and Navajo Country, the railroad rights-of-way are, generally the flattest, most easily accessible terrain.

Ease of access encouraged white settlers to lay claim to these low-lying, flat lands from the earliest days, as they moved west. Once they had taken title to these lands, the new owners, generally were interested in the potential for royalty payments for minerals on their new tracts or ranches. During the conflicts following the Civil War Period, many Native American groups retreated to the more-remote, rugged, hard-to-reach regions of the Southwest. Much of the lands still held by Native Americans have not been tested for hydrocarbons, even in the 1990s, due to general difficulties of access, and, in more recent years, to active opposition to development on the part of the native tribal members. As a result, there have been extensive drilling programs on many of the flat lands in the San Juan basin, and on the Little Colorado plain in northern Arizona, but little drilling in the deepest portions of the Black Mesa basin or in many of the more remote reaches of southwestern Utah.

When an exploration or development-drilling company decides on a potential well location, access and drilling costs play a significant role in deciding between options. A difficult-to-reach site generally will lose out to a site on flater land, unless there is specific data and a special reason for being willing to cope with the greater problems that inevitably will be associated with the rugged site. The earliest drilling in the Four Corners region were some of the exceptions that proved the rule.

16.1 To Drill the Impossible Dream

In southwestern Colorado, very rugged country, but the first region in the Four Corners to be reached by railroad, Archuleta County had some unsuccessful well tests as early as 1905. The first oil field to be discovered in the Four Corners area was found near Mexican Hat, Utah, in a very rough region aptly described by Wengard, in 1960, as "mesas, arroyos, buttes, dry washes, and steep canyons tributary to the master canyon" along the north side of the San Juan River. The landscape there ranges from 3900 to 6200 ft, but oil signs had been reported in the area for many years, and an adventurous prospector by the name of Goodridge was not to be dissuaded by the inconveniences of topography and the lack of roads in the region. The first oil-prospecting lease in southern Utah was granted to Goodridge in 1882, although the severe terrain and poor access prevented any actual drilling in the region until 1907.

The first well at Mexican Hat was spudded during the fall of 1907. The test was completed successfully at a depth of 225 ft on the 4th of March 1908. When the reservoir sand was first encountered, oil reportedly shot 70 ft in the air (Huber 1973). A mini-boom soon followed along the banks of the river. Access to the Mexican Hat area made this work difficult since "heavy equipment" for "deep-well" drill rigs (capable of reaching depths of several hundred feet) had to be brought in over very rough land. Nevertheless, by 1910, there were 10 "deep" rigs on hand, and by 1911, this number had increased to 27 (Wengard 1955). All of this activity was for oil that ultimately ended up being consumed locally, since it proved to be too difficult to cart barrels from the local, steep gorges out to any major population centers or main transportation routes. Ironically, much of the early production was consumed in the drilling of later, less-prolific wells.

From the point of the local oil industry, it is lucky that the initial drilling took place as early as it did, prior to studies by trained petroleum geologists, because subsequent information and review has shown that the existence of commercially recoverable quantities of oil in this region should be a near impossibility. The Mexican Hat oil field is located along the deepest portion of the axis of the Mexican Hat syncline. The oil was first discovered at a depth of only 225 ft in relatively shallow rocks on a promontory surrounded on three sides by deep gorges of the San Juan River. This is in violation of many of the basic tenets of petroleum geology and engineering:

- Oil is supposed to migrate to and accumulate on anticlines, not in synclines.
- The deep incisions of the river through the geologic section should, theoretically, have allowed most of the Mexican Hat oil to escape to the atmosphere or to have become degraded upon exposure to bacteria. Any petroleum remaining in this environment should be tarry or "dead" oil.
- Recent geologic studies have indicated that a large amount of overburden has been stripped off the area. Because of this erosion and the unloading of the section, any local reservoirs should now be severely underpressured. Oil gushers should not occur in this setting.

- Finally, it is questionable if the Mexican Hat portion of the section is in the oil window in terms of thermal maturity. The thermal maturity of the shallow section is an issue because the oil has been interpreted as being locally-sourced.

The studies that have been done around Mexican Hat reportedly do not show evidence for significant migration from deep or lateral sources into the floor-area of this syncline. For these shallow reservoirs or immediately-adjacent beds to have self-sourced their own oil would have required relatively high temperatures, which are difficult to explain at these depths in this location.

The oil at Mexican Hat may have been trapped in small algal mounds or reefs. It is difficult to document the geology of the early wells in the area since so few records were kept on the initial drilling, and so much information was lost. Many of the early operators may have attempted to apply regional names to algal mound units which were of extremely limited lateral extent.

16.2 An Overview of the Four Corners

Other than the production at Mexican Hat, southern Utah and the surrounding states had no early oil or natural gas strikes. By 1910, there were many wells clustered right around Mexican Hat and to the east, upstream on the San Juan, near other reported oil shows, but most of the more remote stepouts and all of the exploratory holes were reported as dry. The few wells drilled in southwestern Colorado had also been unsuccessful. There was no other significant exploration activity in the Four Corners region during the earliest years of the Twentieth Century.

Operators throughout the four states generally kept a sharp eye out for signs of oil when they were drilling for water, and some wells were drilled to "look for oil," but most of these locations were chosen at sites where the operators were relatively certain that they could be assured of a water well if no oil was found. In the arid country of the Four Corners region, water had a value for most of the settlements and outlying ranches that was at least as high as any possible value that oil might have. Since water and oil do not mix well, it is generally unlikely that an optimal oil location is being picked if the operator also wants a good opportunity to produce potable water from a hole.

Following the first Mexican Hat boom and the scattered dry test wells in Archuleta County, Colorado, the next reported oil test in the Four Corners region was located near Farmington, New Mexico. This well location was near "civilization," on easy- and inexpensive-to-drill land, accessible to the railroad. This test was drilled in 1907, just two years after completion of the railroad track to Farmington. Although the hole was dry, interest continued in the region for oil and gas drilling, and many operators kept their eyes open for signs of hydrocarbons.

The test near Farmington began a pattern that would hold for several decades.

Northwestern New Mexico was considered "open" to development. The country was relatively easily accessible, containing large open areas. In addition, it was served by rail. Whites had taken over most of the flatter, more-accessible low country. The local settlers wanted and were willing to encourage development and industry in the San Juan corner of the state.

Southeastern Utah was a much less attractive target for drilling. The dry holes in the area surrounding Mexican Hat and the extremely rough land discouraged most thoughts of further work in that area. Much of southeastern Utah was so barren that it held little attraction for either Whites or Native Americans. There were few communities in the region to support a drilling industry.

Southwestern Colorado was also "remote," in most senses of the word. Many blocks of land were tied up in Reservations or Federal holdings. These lands required extensive paperwork and often faced bureaucratic roadblocks for any development plans, but that made little difference, since much of the land was physically hard to get to. In many stretches, the railroad through the region followed a series of canyons and gorges, and rugged terrain limited travel or the movement of equipment into many parts of the southwestern-Colorado back country. Where a few test wells had been drilled, on lands boosted by railroad access, there had been no production and little to encourage further investment. Incentives to drill were low in most parts of southwestern Colorado.

Northeastern Arizona was also considered to be rugged and too remote to be of interest to local or outside interests for drilling. Well over 90% of northeastern Arizona, and virtually all of the Black Mesa basin, is still held by the Hopi or Navajo nations or one of the smaller Native American groups. Leasing or permitting in Northeastern Arizona on these tribal lands has always been burdened by a great deal of paperwork and bureaucratic hindrances. In addition, many of the Native American settlements around the Black Mesa region have opposed change or "improvement" of their land. Only one railroad crosses the region, and it lies well to the south of the prime, most-prospective portion of the basin. The topography of the Little Colorado plain favors drilling, but the subsurface geology in this region is not especially favorable to the generation of hydrocarbon reserves.

The primary considerations for drilling throughout the Four Corners region during the early part of the century, and, to a large extent, even today, have been:

- internal access (the ability to move around, locally, within the region),
- outside access (the ease of transportation to the outside world),
- the interest of the local population in development,
- and, lastly, a sound, geologic reason for drilling.

This is the inverse of a normal exploration and development approach. In most oil and gas producing regions, geologic analysis of the subsurface comes first. A geologic reason is determined for drilling, then a company copes with potential surface problems of access and leasing, etc. In the early history of oil drilling in the Southwest, operators decided first what part of the surface they could reasonably get to, then they drilled, often with little understanding of the subsurface. It took several decades of hit and miss drilling before the larger oil and gas accumulations of the region were discovered. The following section traces the pattern of oil strikes and development in the Four Corners region.

16.3 A Boom That Went Bust

A well being drilled in 1911 for water in McKinley County, New Mexico, south of Farmington, instead struck oil at a depth of 350 ft (Matheny 1964). As would so often be the case, this site was not particularly favorable, geologically, but could be reached and settled relatively easily. Promoters quickly showed up, talking about a giant oil play and riches for the land owners. Speculative activities and a mini-drilling boom swept the plains and hills near the initial hole. More than 50 additional wells were quickly drilled in the immediate region of the discovery well. Although there were many shows, and a large number of the wells were completed, many of the completed wells really should have been plugged, considering the oil economics of that time and the transportation problems in this frontier region. The bubble lasted only a short time before it burst, and the promotional activities, overblown promises associated with this boom, and the large number of uneconomical completions left a bad taste in the mouths of many local residents.

The entire oil industry was tarred and left with a very poor reputation in the minds of most of the ranchers around Farmington following the events of 1911. This low repute helped to inhibit any additional exploratory activity around the San Juan basin for several years.

Even with a mini-boom in New Mexico and known production at Mexican Hat, oil activity languished in other portions of the Four Corners. Outside the Mexican Hat area, most of southeastern Utah was still too difficult to reach to be of interest for oil prospecting, as was southwestern Colorado. Northeastern Arizona was still looked upon as "Indian Country." The farmers and ranchers of northwestern New Mexico had a bellyful of drilling promotions and the associated risk. These were practical men, still trying to grab a handhold on the land. The battle for water was constant. The soil was fragile, and not accustomed to supporting continuous large crop cycles or over-sized herds on limited tracts. Raids from renegade Indians, white bandits, and rustlers were ongoing problems. There was little time or money for interest in the Four Corners for "exotic" activities like oil drilling during the first two decades of the twentieth century, when most peoples concerns still involved basic economic survival and protection of self and property.

Although the local ranchers, farmers and herders in the Four Corners had lost most of their interest in oil following the first promotional bust, work on assessments of the region continued in the background. Government agencies had been tasked with evaluating the potential of the entire lands of the United States, and their studies continued concerning the mineral (including oil) resources throughout the western states. In addition, oil companies began to take an interest in the area. A number of reports were written on the geology of the region, increasing understanding of stratigraphy and structure of the Southwest.

It was immediately apparent to the outsiders and large companies that certain areas would afford better targets for exploration than others. Deep basins offered thick accumulations of source rocks and reservoirs, as well as an opportunity for sufficient depth-of-burial to "cook" and mature these beds into the oil window. The initial exploratory drilling in New Mexico, Utah, and Colorado was widely scattered across both shallow and deep portions of the San Juan, Paradox and Kaiparowits basins. In Arizona, however, the deep portions of the Black Mesa basin were not touched by a bit during the first sixty years of this century.

More than 98% of the surface and mineral rights in the Black Mesa region are held by the U.S. Government or Native American tribes. During the first half of the century, Government agencies in Washington followed policies that generally tended to keep these lands closed to prospecting interests. Eventually the Native Americans were given more autonomy and control over their own lands, but this period coincided with a period of Inter-tribal disputes which have led to confused ownership claims in many of the prime portions of the Black Mesa basin. Thus, there has been little incentive to pursue oil or gas exploration or to overcome the various barriers to leasing and drilling in this prime region of northern Arizona.

16.4 The Foundation of a Local Industry

Following the activity lull of the Teen's, drilling would resume in the San Juan area by the start of the next decade. The 1995 USGS National Assessment of the United States Oil and Gas Resources map for 1925 shows more than 40 productive wells in the San Juan basin. Several of these were drilled across the border from New Mexico, in southwestern Colorado. Each new producing well in this easily-accessible region encouraged additional development, although the success ratio, basin wide, was still quite low and would remain so for several more decades. The initial successes in Colorado were long range stepout wells along trend from known production in New Mexico.

Early drilling in Utah and Colorado lacked even the modest results of the San Juan area. Despite the lack of early success, exploration continued over the decades in Utah and southwestern Colorado, and eventually, significant production was discovered in both of these states.

The poor early results in now-productive areas in both Utah and Colorado demonstrates the importance of perseverance in exploration in areas where available data is nonexistent or minimal. To date, there have been only six deep exploratory oil wells drilled on the Hopi lands in the Black Mesa region. A similar number have been drilled near the Hopi Reservation, in the deeper portions of the Oraibi Trough play. This is far fewer than the number necessary to learn about and test an area of this size. By way of comparison, the nearby Kaiparowits basin had 27 dry holes drilled before the first oil discovery was made in 1964 (Kunkel 1961). In the deep portion of the Paradox basin, there were tens of dry holes before the first discovery wells were drilled in the 1950s. Development drilling followed the early discovery wells in each of these states, and the geology of the individual fields has become better known. With better geologic understanding has come improvements in well success ratios. Improved success ratios and good payouts have encouraged successful drilling in many difficult-to-reach areas in Utah and Colorado in the Paradox basin.

Each of these regions today is known to be productive, but production has been discovered only after extensive testing and a very high percentage of dry holes. This type of concerted drilling has never taken place in the prime, deep-basin region of Arizona. The following section outlines the general pattern of drilling around the Four Corners during the Twentieth Century.

16.5 Pre-War Drilling

Despite the low esteem in which oil drilling was held in the Four Corners area after the McKinley County bust, another oil and natural gas exploration phase began in New Mexico during 1920. Oil and gas seeps had been recognized along the Animas River for many years, and, finally, money was raised for a drilling program. A natural gas discovery well was drilled during 1920 south of the town of Aztec, New Mexico, upriver from Farmington. This well and offsets were adequate to supply the town of Aztec with its natural gas needs for many years to come. This well kicked off another drilling round in the region. Additional natural gas wells and oil wells were drilled in San Juan County, in the deeper portions of the San Juan basin.

The first exploratory well in northeastern Arizona was drilled in 1920. It was a relatively shallow hole, going down only to the Permian Supai, and failed to produce any oil. It did encounter water, however, and was completed in the Coconino Sandstone as a water-producing hole. As has been mentioned, prospectors who are hoping to find water as a economic backup do not always select optimal locations for oil discoveries. The earliest significant exploratory activity in northeastern Arizona was also restricted in options, since the primary efforts were made mostly on nonreservation lands, thus eliminating most of the northeastern corner of the state, including all of the deep basin area in the Black Mesa, from consideration.

The first large-scale exploratory programs in northern Arizona were located on the Defiance Uplift and to the south of the Black Mesa region, south of the Hopi and Navajo Reservations, along a general trend following the course of the Little Colorado River and the railroad lands. Most of this river plain lay on, or immediately adjacent to, the ancient Zuni-Defiance High, an area which lacks or had an exceedingly thin lower Paleozoic section. These areas were both poor selections for oil prospecting, in terms of geology, but represented areas where land and lease situations allowed promotions to be sold. These were the places where money for drilling could be raised by smaller, local interests and firms.

By 1920, the first small pools of both oil and natural gas had been discovered in the adjacent, analogous San Juan basin, just across the state line in New Mexico, and the Mexican Hat field to the north in Utah was well known. Nongeologists who were being approached for investment money generally did not recognize that the drilling in New Mexico and Utah was occurring on structures in the deeper portions of the San Juan and Paradox Basins. Comparable deep-basin sites in Arizona were not to be tested for many decades.

In New Mexico, an additional natural gas field was discovered in 1921 and a new oil field was first encountered in 1922. These successes fed on themselves, and exploration spread successfully across the border, to the north, into Colorado in 1924. The area's first oil pipeline was constructed that same year. The open lands of northwestern New Mexico made development relatively easy, and the pipeline system was expanded and several small refineries were constructed in the area by 1926. True science was introduced to the basin with the first geophysical survey in the region, a magnetometer study, that was run in 1926.

The first serious test in the deep portion of the Kaiparowits basin, in south-central Utah, was drilled in 1921 by the Ohio Company. This hole went only to the Mississippian, and was nonproductive. Meanwhile, Arizona activity lagged behind the New Mexico drilling, even though the Little Colorado valley was relatively accessible. A few new wells were drilled on the flat lowlands of the Little Colorado desert landscape during the late 1920s. There was very little additional drilling in the corner of the state until the late 1930s. A second, shallower, test was drilled to the Permian in the Kaiparowits basin during 1930. This test also proved to be dry, but had multiple shows reported in the shallow sands.

During the early years of the 1930s, production began to increase in the San Juan basin, and discovery wells spread widely, including into some of the southern portions of the basin. At the same time, the analogous portion of the Black Mesa region remained untested. The local San Juan pipeline system was extended, with several new lines being constructed in the San Juan region during the 1930s, but a limited local market for natural gas kept a tight lid on the incentives to drill for additional supplies during many of these years. Some of the discoveries from this period included the first local production from unconventional fractured shale reservoirs in the Mancos Shale units (Matheny 1964). Although the local climate in the San Juan region favored development there, while it lagged in surrounding areas, the local industry was still dependent on the market, and the national downturn during the Depression kept drilling incentives low even in a remote area like the Southwest during the 1930s.

During World War Two, military demands spurred the national economy, and demand for natural gas increased in the San Juan area. The number of producing wells increased in the San Juan basin, particularly with the discovery of a major Pennsylvanian natural gas field (Barker Dome) in 1942. This, encouraging additional drilling in New Mexico, but most of the tests in southeastern Utah were still indicating that state had little in the way of hydrocarbon reserves. There was no drilling in the Kaiparowits basin, after 1930, until well after World War II.

In Arizona, several additional tests were added along the railway corridor east of Flagstaff, and an additional test was drilled on the Defiance Uplift. In addition to that test on the Defiance uplift, the first exploratory well on the Coconino Plateau was spudded around the end of the War. This well was located to the west of the Hopi Reservation, in an area where the subsurface was virtually unknown. This well was well to the north of the Railroad lands, and was roughly equidistant from the nearest Arizona control and from wells drilled in adjacent basins in Utah, to the northeast and northwest of the Coconino Plateau.

16.6 Summary of Activity in the Four Corners at the End of World War Two

By 1945, there had been roughly 22 exploratory oil wells drilled in all of northern Arizona. sixteen of these had been located on the Little Colorado plain, south of the Hopi and Navajo Reservations, and six wells had been drilled on the Defiance Uplift, well east of the Hopi Reservation, but nothing had been drilled in the deeper portions of the Black Mesa basin, the region that was structurally similar to the productive area of the San Juan basin . As late as 1945, Utah also looked like it would remain a nonproductive State. On the basis of drilling results through the War years, it appeared that there was very little potential for any significant, economic accumulations of hydrocarbons in southeastern Utah. Virtually all the drilling in Utah had come up dry by 1945, and many operators in the area had become convinced that the region contained no good, economic reservoirs. Today the Paradox basin has been recognized as a significant producing region in the southwest.

The rationale for early drilling on the Defiance Uplift was apparently the concept that hydrocarbons should have migrated updip to structurally high areas in the region. The Uplift qualified as being the structurally highest feature in this portion of the state. This reasoning was accurate, as far as it went, but overlooked the fact that the San Juan reserves were being discovered structurally high, on an anticline, but that this anticline was located in the deeper, central portions of the basin, where the source beds, reservoirs, and caprocks were thickest, not high on the flanks of the basin . The Defiance Uplift was relatively deficient in each of the three key requirements for good hydrocarbon prospects; source rocks, reservoir beds, and traps. The rocks on the Defiance structure were high, but, in most places, were cut off from deeper source rocks by stratigraphic pinchouts, sharp bends and structural barricades along monoclines, or by faulting.

The linear band of drilling south of the Reservations follows the course of the Little Colorado River, the Painted Desert outcrops of the Chinle Formation, and, apparently most importantly, the railroad right-of-way through the desert flats east of Flagstaff. This suggests that these locations were chosen more to test the hydrocarbon potential of the lands which were owned by the railroad, rather than on the basis of sound, detailed geologic analyses and a plan to drill the best possible geologic locations. The Basement is relatively shallow and the sedimentary section is relatively thin across this entire zone. As on the Defiance Uplift, the railroad lands do not have a high potential for sources/reservoirs/traps, but have been extensively drilled.

16.7 Post-War Drilling Activity

In the immediate post-war period, between 1945 to 1950, activity in the deep portions of the San Juan basin expanded further, but drilling remained relatively scarce in the surrounding states. New scientific geophysical-analysis techniques were being introduced to petroleum exploration around this time as wartime discoveries and advances were applied to peacetime uses, including the oil and gas industry. According to Umbach 1952, "many companies and independents completed magnetometer and gravity meter surveys" in the larger Four Corners area during 1945 and 1946. By 1947, seismic field surveys were becoming common. Umbach reports that there were 52 crew-weeks of seismic work completed in the San Juan basin during 1946. This number went up to averages of 250 crew-weeks in both 1947 and 1948.

Exploration activity in the San Juan basin dropped during 1949, as plans for a major pipeline through the region ran into regulatory roadblocks. Production in the San Juan basin had included a large number of natural gas wells, and many of the local "oil" wells actually were capable of producing both oil and gas. With no large-scale, interstate pipeline to act as an outlet, drilling for natural gas was inhibited in an area with little in the way of population or industry, and no significant local demand. Plans had been proposed by El Paso Natural Gas during the late 1940s for a major pipeline across the region, but regulatory approval in Washington was slow in coming, reflecting extensive controversy and local opposition to the pipeline across Native American lands and in this pristine environment.

The lack of an outlet for natural gas also had a dampening effect in the surrounding states. Explorationists in Arizona, Utah, and southwestern Colorado were also prospecting with oil being their primary target, since there was limited markets and uses for natural gas in those areas, as well. While the success in the San Juan was breeding success, the lack of production in Arizona and Utah provided "proof" that there was no oil in commercial quantities to be found in either of these states. With these problems, drilling in Utah in the late 1940s was minimal. The Black Mesa region of Arizona had no test wells drilled in the deeper portions of the basin during this period of time.

Finally, in 1949, a deep, Cambrian test was drilled in the Kaiparowits basin of Utah, To the north of the Black Mesa region. This hole was not productive, but had stains from dead oil in multiple shallow beds. The interest of the California Company was aroused by this time. They had monitored the old tests in the Kaiparowits and had heard of the shows and stains. The company eventually drilled a Cambrian test in the Kaiparowits two years later, in 1951. During a prolonged period of extensive testing in this hole, California swabbed more than 16,000 barrels of oil from the Mississippian section, and had multiple shows in four of the shallower formations. In 1952, the California company completed four additional basin Kaiparowits tests, with shows or "good shows" (Kunkel 1961) in each of these wells.

Exploration would continue without success (in the sense of a producing well) in the Kaiparowits for another decade. Work and access in this area was not particularly easy, but the land was relatively easy to lease and repeated shows kept the interest of companies alive. Multiple wells were drilled in the basin during several of these years. The initial activity was by independents, but by 1957, when most of the holes proved to have significant shows, the majors reappeared on the scene, and eventually took almost complete control of the drilling activity. Most of the larger shows were logged in the shallow units. Although 11 separate units were reported to have had shows in these wells (Kunkel 1961), there were only six formations that consistently had indications of economic reservoir qualities. Interestingly, only one of these, the Mississippian Redwall Limestone, was in the deeper portions of the section. The other five potential reservoir units were Permian or Triassic in age.

It has generally been assumed that the best source beds throughout the Four Corners are in the deepest portions of the section. The shallower units are generally dismissed as important source beds. The oil shows in Utah suggest that there has been substantial migration upward, into shallower units, or that there has been the proper mix of conditions, including sufficient depth of burial, for the sourcing of hydrocarbons in shallower carbonates, shales, and evaporites, some of which were apparently deposited in sabkah-type environments. If the Permian section has provided a source for hydrocarbons in the Kaiparowits basin, it suggests that there may be shallower source units in the Black Mesa region, as well.

In the years immediately after the war, exploration in Arizona continued to be limited to several additional wells along the Railroad right-of-way, south of the Hopi and Navajo reservations. Drilling during the late-1940s included a test east of the town of Holbrook. No exploratory wells were added on the Defiance Uplift during this period. The results of the earlier test on the Coconino Plateau apparently aroused some interest in that area, and three additional wells were added west of the Hopi reservation. Two of these wells were on Babbitt lands. One of the holes was a shallow test, while the other two penetrated the deeper section. All of these holes were outside the limits of the Oraibi Trough.

The El Paso pipeline was eventually approved in Washington by the Federal Power Commission during July 1950. A 24 in. line was constructed, offering an outlet that could carry natural gas to major markets in California. Geophysical crew activity in the Four Corners quickly went up to its best levels ever in the Four Corners, with 276 crew-weeks being worked in 1951 in the San Juan basin, alone. With proven production expanding, the formation of an indigenous infrastructure for a local oil and natural gas industry, and, now, a pipeline outlet, drilling and production exploded in the San Juan basin during the early 1950s.

Prior to the construction of the pipeline, many operators had only been willing to drill in areas which they thought were oil prone, since natural gas did them little good in remote locations. Now, the well activity-level went up significantly, and exploration spread into previously untested areas that were thought to be more gassy than oil-prone. Well completions in the San Juan went from 47, in 1949, when the pipeline was facing severe local opposition, to 267, in 1951, even though the pipeline was not approved until the year was half over, and still had to be built. Production in the San Juan spread to the east, well beyond the previously-known older fields on the main producing structures, and a large number of wells were added, successfully, north of the state line, in Colorado. A large percentage of these new wells were natural gas producers, or combination oil and gas completions.

Once the El Paso pipeline reached the area, companies found they could afford to venture some new tests that would have been far too risky in the previous limited and unsure market. The San Juan basin was not the only region to benefit from the new construction. From this point on, other Four Corners areas, including Utah would be recognized as regions with a viable oil and gas industry. Sinclair drilled a Cambrian test to the north of the Hopi Reservation, on the Navajo Reservation, during 1952. A core was cut from the Cambrian section, but the hole did not reach the basement. This test was in the Shonto area, north of the Black Mesa, proper. Although the location is near the Oraibi Trough, no Aneth beds were reported, and the

McCracken Sandstone was reportedly only 23 ft thick. The thin McCracken section and the lack of any deeper Devonian beds suggests that this spot may have formed a shoal or island along the margin of the Oraibi deep when the thicker shales were being deposited in the trough. Little interest was stirred by the Sinclair drilling, and no offsets have followed this test.

Following the completion of the main El Paso pipeline and some spur lines, the number of wells in Utah increased greatly. With the increase in drilling, a reef play was identified in the southern Paradox basin, stimulating geophysical activity across that region during the early 1950s. Exploratory drilling expanded into several previously untested portions of the Paradox basin, and a number of new producing areas were discovered. Stepouts and extension wells were successful close to the Arizona border. Eventually, drilling extended across the state line, and the first commercial production within the state of Arizona was established. The discovery wells drilled in Utah and northernmost Arizona included both oil and natural gas wells.

16.8 Four Corners Fields in Arizona

Shell reported encouraging shows of oil and natural gas in a Navajo well located in 41N-29E, in 1954. They then completed a discovery well in the adjacent township during December 1954. This well was the first of several in what would be named the East Boundary Butte field. Both oil and natural gas would be produced in this field. A few development wells were added in the late 1950s, but the majority of the East Boundary Butte wells were not drilled until the late 1960s.

El Paso Natural Gas drilled a natural gas discovery well at Bita Peak, in Apache County, Arizona, in 1956. El Paso was not able to get this well on line until 1962, demonstrating the remoteness of the region and the difficulties of operating in the back country. This exemplifies the fact that few small independents were able to operate in the environment of the Four Corners. Smaller independent operators cannot afford to take high risks for a product that they cannot market for many years after discovery.

A number of additional interesting discovery wells were drilled in this extreme northeastern corner of Arizona during the late 1950s or 1960s. The following section discusses several of the more important wells and fields in this region.

The Dry Mesa field was discovered on a small anticline in Apache County during 1959. This structure had only 35 ft of closure at the level of the productive Mississippian units. Production appears to come from highly-fractured Mississippian dolomites. Mineralization in some of these cracks suggests that mineral-rich fluids have reached the region from the Carrizo intrusive complex more than 10 miles to the east. Data on the oil-water contact demonstrates that the system is tilted to the northwest, apparently due to an active hydrodynamic drive through the reservoir rocks in this area. Most of the lower Paleozoic section is missing in this area. The Mississippian section overlies approximately 50 ft of Devonian rocks, which were deposited directly on the Precambrian basement. The deepest test well in the field encountered more than 300 ft of red quartzite in the Precambrian.

The Twin Falls Creek field, discovered in 1957, was drilled by Superior. The second well on the structure was the discovery well. It penetrated the Mississippian and Devonian sections, then went directly into the Precambrian. This is another example of production on a basement high, with very little or no lower Paleozoic section in the area. The Precambrian in this hole was a quartzite, not granite.

In 1960, Texaco made a discovery in the Tohache Wash area, near Teec Nos Pos, Arizona, in a well on the Navajo Reservation. The discovery well had oil in the Devonian Aneth formation, a prime target and potential source unit in the Black Mesa region. The Aneth oil is generally assumed to have been self-sourced in the light-brown to brown Aneth dolomites or interbedded brown or black shales. This well was initially perforated in the Devonian Aneth and produced oil for two years. Later in the decade, in 1968, the well was recompleted, this time in the Mississippian Leadville. The Leadville recompletion yielded helium-rich natural gas. The market for helium was poor in the late 1960s and early 1970s, so the well was abandoned in 1970.

No offset holes were drilled here, and this well was not given "field" status. If and when the helium market improves, the Tohache Wash region is assumed to hold additional potential for that gas, and additional drilling may take place. The section in this well includes a thin Cambrian section below the Devonian beds. The basement in this hole was described as "basic" igneous rock, not as granite. If the helium has a deep source in the basement, as is commonly assumed, it would be interesting to know how it reached the Mississippian section. The gas appeared to be richer in helium in the shallow Mississippian beds than in the deeper Leadville section. The helium worked its way into the Mississippian section without disturbing the Devonian reservoirs and the Aneth oil.

Texaco drilled another Devonian oil discovery in 1963 at Walker Creek, near Mexican Water, Arizona, on the Navajo Reservation, five townships due west of the Tohache Wash well. The production here comes from the McCracken sandstone, the unit that overlies the Aneth dolomites and shale beds. The oil in this well apparently was derived from Aneth source beds. The oil contains a different chemical fingerprint and much less gas than is normally seen in the Four Corners region in shallow reservoir sands. This indicates that the McCracken here has not been charged by migration through some circuitous route from Pennsylvanian or other shallow reservoirs via faulting and fractures.

Three offsets were drilled around the Walker Creek well, to the south and west, in an attempt to extend and increase production. These wells showed that the subsurface here is almost as rugged as the local surface. The discovery well proved to be structurally higher than any of the offsets. The top of the McCracken was 110+ ft to 160+ ft lower in the offset wells than in the discovery well. Much of this relief is quite ancient. The paleogeomorphology appears to have been quite rugged by Devonian time. The Cambrian section thins by almost a factor of ten in a little over eight-tenths of a mile. This may represent differences in deposition and/or post-depositional erosion.

The Dineh-Bi-Keyah field is another geologic oddity that has yielded oil in Arizona. This field was discovered by Kerr-McGee in 1967 (Danie 1978, 1980). The production comes from a Tertiary Syenite sill. This field is high on the Defiance Uplift, an area with minimal source material and, supposedly, with few good traps or seals. The production apparently comes from porosity and fractures in the sill material. The source is speculative, but has been hypothesized as being the adjacent Pennsylvanian units (McKenny and Masters 1968). If there are adequate source rocks in beds as shallow as the Pennsylvanian, it makes much of northeastern Arizona much more prospective.

The production at Dineh-Bi-Keyah was almost missed by Kerr-McGee (Pohlmann 1967a, b). The first well in the field was spudded in January 1965, drilled to TD and cased during February of that year, then put on hold for evaluation, due to weather and access conditions, until summer. Perforations were shot in June 1965, and the target Coconino sandstone, the only unit considered to be potentially productive, was found to contain helium, but in uneconomical quantities. The well was then plugged (McKenny & Masters 1968).

Not everyone at Kerr-McGee was happy with this decision, however. During drilling, shows of oil had been recorded at unexpected depths. Sample analysis showed that these oil signs were in an unusual, unidentified rock. The staff could not agree if the beds which had the show were igneous or metamorphic, but, in either case, any good petroleum geologist knew that they could not be reservoir rocks, despite the misleading shows. The electric and geophysical logs also "proved" that there could be no oil at the depths where the shows had been reported.

A more detailed analysis of the well cuttings by mineralogists still failed to resolve the question of the lithology of the subject rock unit, but confirmed that it could not possibly be a reservoir formation. Nevertheless, some individuals in the geology and engineering departments retained an interest in the reported shows, especially since Kerr-McGee had a very large acreage block surrounding the plugged well. There was a good lease position to be proved up by this well that kept interest in the hole alive.

Two years later, in 1967, Kerr-McGee agreed to reenter the well for additional tests. The hole was reopened, serviced, and perforated at the depths of the old shows (McKenny and Masters, ibed). The results did not come easily, and the hole had to be acidized, then fraced. This led to the first production in the area and the decision to drill an offset well. This second well was also a success, and the Dineh-Bi-Keyah field was born.

Table 16–1 summarizes the drilling for the initial successful oil and gas fields of Arizona.

Table 16–1 Oil and Gas Fields of Arizona

Field Name	Discovery Year	Exploration Methodology	Product	Comments
		Four Corners Area		
Bita Peak	1956	strat test	G	Algal Mound
Black Rock	1971	seismic	G	Algal Mound
Dineh-Bi-Keyah	1967	surface geology	O	Tertiary Sill
Dry Mesa	1959	surface mapping	O	Fractured Mississippian
East Boundary Butte	1954	seismic	O, G	Combo Strat & Struct Traps
Teec Nos Pos Ismay	1963	seismic ?	G, O	Algal Mound
Tohache Wash	1967	seismic	H, O	Includes Devonian Aneth Oil
Toh Atin	1962	seismic	O	Plugged, Area Too Remote
Toh Atin, North	1956	seismic	G	Plugged, Area Too Remote
Twin Falls Creek	1957	seismic	G	Algal Mound
Walker Creek	1963	seismic	O	Production From Devonian
		Holbrook basin		
Navajo Springs	1960	stepout	H	Faulted Anticline
Pinta Dome	1950	surface mapping	H	Faulted Anticline

Product code: G = gas, H = helium, O = oil

As can be seen, the largest number of drilling successes have come in the extreme northeastern corner of the state, along the southwestern margin of the Paradox basin, or, in the case of Dineh-Bi-Keyah, on the crest of the Defiance Uplift. Elsewhere in Arizona, during the 1950s and early 1960s, drilling continued primarily along the railroad right of way, on the lands south of the Reservations. Prior to 1957, the Navajo Nation had granted relatively few oil or gas leases. In 1957, a large lease sale opened up large blocks that had previously not been available for testing. The fields listed in the table above were generally on these Navajo lands. This lease sale marked the beginning of a new era in northeastern Arizona.

Elsewhere in Arizona, most of the drilling continued to be along the railroad right-of-way and on other privately-held lands, south of the Reservations. This drilling eventually led to an interesting discovery. A cable tool rig drilling a test northeast of Holbrook in 1950 encountered a large flow of unusual gas in the shallow Coconino Sandstone. A test showed that the sample included a large helium content. The productive feature was a large faulted anticline, known as the Pinta Dome. At the time, there were no local facilities for dealing with helium production, and no economic demand for the gas in the immediate region, so the well was shut in. There would not be another helium well drilled in the area until 1956.

In 1956, 1957, 1958 and 1960 additional helium wells were added at the dome. None of these wells were actually produced until 1961, by which time there were 14 helium wells in the region. Six of these were put onto production in 1961. The Pinta Dome gas was unusually rich in helium, generally well over 5%, with some zones as high as 8+%. This richness is exceptional for gas straight from the wellhead. The long delay in putting these wells into production was due to fluctuations in the market for helium.

The U.S. Government has often been the only customer for the product, and prices have often been quite low. At the time when Pinta Dome was initially discovered, any helium that was encountered had to be produced and transported to a federal helium plant at Farmington, New Mexico. Because of the richness of the local product and the concentration of wells, Kerr-McGee decided to build its own helium plant near the field. When this plant was completed, production increased substantially. The marketing of helium has always presented problems, mostly associated with unreliable or low prices. Having a local market stabilized activity at Pinta Dome and encouraged additional drilling and development.

Production from the fields northeast of Holbrook would continue until 1977. Starting in 1960, associated fields were drilled at Navajo Springs and East Navajo Springs. While many wells around the Pinto Dome were drilled for helium, an associated activity, prospecting and testing for potash, led to the drilling of many other holes in the surrounding area. At a minimum, Pinta Dome field included 19 wells, and the Navajo Springs/East Navajo Springs had roughly 80 productive wells or dry holes. By 1971, there had been a total of 126 wells drilled in the immediate Holbrook vicinity (Conley 1971).

The origin of the helium-rich reservoirs is a matter of extensive geologic conjecture. The Pinto Dome area is near and to the southeast of the Hopi Buttes diatreme area. It lies along the ancient Defiance-Zuni high, a northwest-southeast positive basement trend that was a persistent highland-island-shoal area throughout most of lower Paleozoic time. It has been assumed that the helium has entered the shallow geologic sedimentary section in association with deep-seated intrusions. Igneous material from depth may carry associated Primordial gasses, including helium, from very great depths toward the surface.

Turner 1968, reported that "Known accumulations of helium and other inert gasses seem to be limited to northwest-trending fold elements." Southwest-northeast-trending structures, on the other hand, seem to predominantly produce "conventional," nonexotic, natural gas. This suggests that the southeast-northwest-trending feature may originate from features at different levels within the subsurface than the large crustal faults that are believed to underlie many of the southwest-northeast features.

The southwest-northeast trend is believed to owe its origin to Precambrian Mazatzal-age (1.7 Ga) through-crust faults associated with an episode of major continent-continent collision and obduction. The current drainage pattern across the deep Black Mesa basin has a strongly developed parallel pattern. This parallel linearity presumably is following reactivated fractures above some of these large ancient faults. These faults and fractures may represent a major route for the charging of shallow reservoirs from deep conventional sources of hydrocarbons. This trend also parallels the reported direction of flow in the regional hydrodynamic regime, and fractured areas may represent areas where the oil front has advanced further into the Black Mesa region from sources to the northeast. If evidence is substantiated for Precambrian hydrocarbons in the Chuar, these southwest-northeast fracture may provide the pathway for migration into the Phanerozoiic sediments.

The origin of the southeast-northwest trends is less certain. The Pinta Dome-Hopi Buttes trend is a major recent geologic trend that lies right along the margin of the much more ancient Defiance-Zuni positive feature which seems to have existed as a high in this area possibly as early as the end of the Precambrian. The feature was definitely a high during much of the early Paleozoic.

The leakage of helium from deep sources and trapping in the shallow section provides a model for the sourcing of shallow reservoirs from Chuar-like source beds in the Precambrian section at depth below northeastern Arizona.

16.9 Drilling Status of Northern Arizona in 1960

By 1960, most of the productive areas in northern Arizona had already been identified. Most areas in the region were grossly under-tested. Most of these areas remain grossly undertested even in 1995. During the 1950s wells had been scattered along the railroad contour and on the Defiance Uplift. This pattern has changed little, even today.

U.S. Geological Survey 1995 drilling history map for northern Arizona shows what appears to be 18 wells, all dry holes, in all of Coconino County in 1960. (The limitations of computer monitor displays makes it difficult to count closely-spaced offset wells on these maps.) Ten of these wells are in the southern portion of the county, near lands that appear to relate more to promotional activities and the testing of railroad lands, rather than solid geologic understanding of the region. Navajo County appears to have had 17 wells, all in the southern rail corridor around Holbrook, by 1960.

Apache County is the only region in the northeastern corner of the state with a widely scattered peppering of wells. Apache County had established production by 1960 in the northernmost reaches of the county and at Pinto Dome. In the broad region surrounding Pinto Dome, well over 20 wells had been drilled along and near the Santa Fe Railroad and El Paso Natural Gas pipeline rights-of-way. Following the Navajo lease sales of 1957, nearly 20 locations had been drilled in the southwestern portion of the Paradox basin, on Reservation lands, just south of the Utah state line, and five or six wells had been drilled on or just west of the central portion of the Defiance Uplift. The one area of Apache County that had not been tested at all was the northwestern portion of the county, in the deeper section of the Oraibi Trough.

Even with all this drilling activity, Apache County was still severely undertested by 1960. The discovery wells in northernmost Apache County generally found oil or gas in small algal mounds or on minor structures, noses, or pimples along regional features. Most of the later discoveries were found using the seismic techniques of the late 1950s or early 1960s. It must be remembered that this region is Navajo Country (in the terrain sense, not the ethnic sense), adjacent to Monument Valley. This is a rough landscape.

Very rough terrain and high relief makes it difficult to do detailed seismic work and identify small features on seismic sections, even with the technology available today. It was much more difficult to achieve quality results with the equipment and technology of the 1950s. Crooked lines, winding around or over buttes and mesa, and across washes and arroyos, some filled with large amounts of alluvium and debris all reduced seismic resolution and the ability to recognize subtle traps in northeastern Arizona. Even with a high density of lines, many small features and possible reservoirs were undoubtedly overlooked in the Four Corners section of Arizona. Outside the Four Corners portion of Apache County, almost no seismic work has been done at all.

Many important areas on and around the Black Mesa have not been adequately crossed with seismic lines. Most of the sites that have been shot were covered using older, out-of-date technology. The region that has not been thoroughly studied seismically includes most of the deepest portion of the Oraibi Trough, the part of the basin with the thickest source units and greatest thermal maturity. The geologic knowledge of Hopiland, the local term for the ancestral lands of the Hopi, Nation on the topographic Black Mesa, that existed by 1960 had caused extensive speculation that the reservation lands could hold substantial hydrocarbon resources. Following the successes of the 1957 Navajo leasing program, pressure increased to begin a leasing program on the Hopi land. These pressures bore fruit in the mid-1960s

16.10 The Hopi Leases

Through the early 1960s, there had never been any drilling on the Hopi lands in the deep portion of the Black Mesa basin . This changed during the early 1960s. Following the success of the Navajo leasing program of 1957, Washington in 1961 made the decision to put Hopi lands up for bid. The arrangements could not be completed until 1964. Due to all the promotional speculation and hype surrounding the petroleum potential of this land, the federal administrators decided that the Mesa must be valuable and set the minimum bid requirements quite high. This almost totally discouraged smaller, local companies from submitting bids, and kept overall interest in the leases low. A few majors did submit winning bids.

In 1965, six wells were drilled on the Hopi Reservation. These have been the only deep tests on this land to the present day. Several of the wells had promising shows, and drill stem testing was done, but none of the wells were ever completed, and much of the data gathered was kept tight for some period of time, until outside companies lost interest. A series of serious land and environmental disputes arose around the Black Mesa region soon after the wells were drilled, creating a climate of uncertainty and potential litigation that was totally discouraging to companies that once might have been interested in pursuing development on Hopi Reservation lands. Tenneco had originally had plans to be a major player in the Black Mesa. They were reportedly planning six or seven wells in the region for 1965. Today, there is not a single Tenneco well on Hopi lands. These types of legal problems persisted in the area throughout the late 1960s and 1970s.

A coal mine was opened by the Peabody Corporation on the northern portion of the topographic Black Mesa in 1966, right after the drilling of the five Hopi wells. Inevitable disruptions of the land around the mine and of local water supplies, and aggravated flare-ups of ongoing disputes between the Hopi and Navajo tribes over reservation boundaries all coincided during this period. A number of legal disputes arose, including suits between the Hopi and the Navajo, and between Hopi conservatives and the Hopi Tribal Council. With all this legal activity, land ownership issues remained in court for several years. All of this uncertainty prevented any of the oil companies from following up on their 1965 programs.

Outside the Hopi lease area, a massive drilling program was launched in the Pinto Dome–Holbrook basin–Right-of-Way area between 1960 and 1965. Well coverage here went from relatively sparse to quite dense, especially along the rail corridor. This drilling included tests not only for oil, natural gas, and helium, but also for potash. In northern Apache county drilling spread out of the Paradox basin onto the Tyende Saddle area, where a large seismic program had been undertaken. This drilling program discovered some additional natural gas and oil, including the westernmost and southernmost production, to that date, in Arizona. Drilling reached the northern end of the Defiance Uplift, scattered locations across the Tyende Saddle, and included four wells north of and two wells northeast of the topographic Black Mesa. Live oil was reported in drill stem testing of these holes near the Black Mesa, but none of the wells there was completed. A scattering of wells was added to the railroad right-of-way area in southern Navajo and Coconino Counties, and a wildcat was drilled in northwestern Coconino County. These wells were all dry.

16.11 Post-Hopi Drilling in Northeastern Arizona

In the period from 1965 to 1970, Peabody Coal drilled six water supply wells on the northern portion of the Black Mesa. These wells provided some additional stratigraphic information on the area, but all were shallow holes. The drawdown of the local water table created by these wells led to disputes and animosity with the Hopi settlements, to the south, as some of the older Hopi wells began to go dry. Although most of the Peabody wells only went down into the Mesozoic, and few records have been made available to the oil and gas databases, the first well is reported to have had at least one show of natural gas in the shallow beds. Peabody did not release much information on the later five wells, and the company was not actively prospecting for hydrocarbons, so it is not known if there were shows in any of these other holes.

Elsewhere in northeastern Arizona, a comparatively large number of wells were drilled across the Tyende Saddle and on the northern end of the Defiance Uplift between 1965 and 1970. Much of this drilling was spurred by the discovery of Dineh-Bi-Keyah in 1967. Dineh-Bi-Keyah, like the pool discovered at Mexican Hat, Utah, during the early years of the century, demonstrated that there are oil pools in seemingly "impossible" geologic locations scattered around the Four Corners. The productive igneous rock at Dineh-Bi-Keyah was repeatedly ignored or rejected as being unworthy of completion testing by geologists and engineers during drilling and subsequent sample analysis and test work on the discovery well. The discovery well there was actually plugged. It was only due to persistence on the part of a few individuals, combined with the existence of a very large acreage block in the area that led to the reopening and further testing of the discovery well.

17.0 CONCLUSIONS

17.1 Inhibiting Factors for Oil and Gas Exploration in the Greater Black Mesa Region

To date, there has been no commercial oil production found in the structural Black Mesa region. However, many shows of oil and gas have been documented. These have ranged from the deepest Paleozoic beds, in the Cambrian, up into the Mesozoic section, in the Jurassic. Shows in multiple zones are common around the Four Corners. Wells typically have shows in as many as three formations in the Paradox/Blanding basin areas, including in northeasternmost Arizona. Many of the Black Mesa wells had far more shows per well, frequently in as many as nine zones, during a brief drilling flurry during the 1960s. There has been no follow through to that 1960s activity, however, due to a series of land disputes that flared up between the Native American nations in the area around the same time as the drilling.

The northern portion of the Black Mesa study area includes the entirety of the Hopi reservation and most of the western portion of the Navajo reservation, as well as National Park, National Monument, National Forest, Bureau of Land Management (BLM), or State of Arizona lands. This is the portion of the study area with the greatest potential for hydrocarbons, but the fewest wells. In the southern portion of the region, a larger proportion of the land is privately held, including extensive railroad tracts along a corridor between Gallup, New Mexico, Holbrook, Arizona, and Flagstaff. Several small drilling programs over several decades have tested locations along the railroad holdings, but little of economic interest has been found. Most of this land is located on an ancient basement high, the Defiance-Zuni positive feature. The best conventional local source beds, in the lower Paleozoic are thin or missing in this region, and the entire section is several thousand feet thinner here than it is to the north.

Development in the deep portion of the Black Mesa basin has been inhibited by conflicting ownership claims to large blocks of reservation land on the lowland plains surrounding the Hopi heartland on the topographic Black Mesa. Portions of the original Hopi reservation have been relegated, over a period of many decades, to the Navajo, as the Navajo population, and sheep herds, have increased and spread from their original homes. Extensive trespass, over-grazing by Navajo sheep on Hopi farm fields and expanded squatting caused this conflict to became especially bitter during the 1960s, inhibiting development in the area. The courts have recently ruled on these claims, removing some of the barriers to work in the area.

17.2 Future Potential for Hydrocarbon Prospecting in the Black Mesa Region

Despite a past history of remoteness (paved roads didn't reach the vast majority of the region until the late 1950s or 1960s), the granting of few federal leases until the late 1950s or early 1960s, and difficulties in getting permission for access to desirable areas, the prospects for the greater Black mesa region appear to be excellent.

The Black Mesa appears to have strong possibilities for source rocks in the dark to black clastics and carbonates of the Oraibi trough, as well as in Mississippian carbonates, and in possible Pennsylvanian biohermal growths. The few wells that have been drilled in the prime target areas along the central Oraibi Trough have encountered thick potential source beds in the Devonian section, as well as in shallower units, along with a large number of shows, many of high quality, in every deep test well. Almost all of the drilling in the deeper portion of the Black Mesa basin was squeezed into a single field season, in 1965. Large amounts of data were gathered, but there was no follow-up drilling to more thoroughly test promising units within the basin . Oil field technology has advanced significantly since the mid-1960s, and carbonates that typically would have been ignored at that time can be treated and become excellent producing units using today's completion methodologies. Studies of the deep structure beneath the basin, and of the gravity and magnetic data, indicate that there is an unusually high potential for the existence and concentration of deep- or ultra-deep-sourced hydrocarbons in this region, due to the nature of the local plate-tectonic history of the region, including massive faults that have cut through the entire crust.

A number of promising areas for further testing have not yet been touched by the drill bit around the Black Mesa. Gravity and magnetic modeling suggest that the deepest, potentially richest portion of the Oraibi trough, with the greatest sedimentary accumulation and best thermal-maturity profiles, may lie to the southeast of the Hopi reservation, in an area that has never been drilled. This region apparently has the thickest source beds and superjacent reservoir units in the Devonian section, although the location of the thickest portion of these beds has not yet been identified with certainty. Mississippian carbonates have good source rock potential, and stretch across the entire area. Pennsylvanian reefs have not been reported around the rim of the Oraibi trough, but this is not unusual, since such units are easy to overlook while drilling, and the prime candidate areas for such reefs have not yet been tested. Bioherm development can be expected in the area, based on the pattern of their development in analog regions around the rim of the Blanding basin, at the nearby Four Corners.

basin -flank areas to the northwest and south of the Oraibi trough have thinner sedimentary sections, over all, but presumably also include numerous updip stratigraphic pinchouts of clastic sequences, as key reservoir units thin to zero along the margins of the structural sag which defines the Oraibi feature. Large quantities of oil are typically located in numerous medium to small sratigraphic traps along such basin margins. A few wells have been drilled on the northwestern side of the trough. These wells had large numbers of encouraging shows, although none of the wells underwent any sophisticated or modern completion testing, and the majority of the wells were barely updip from the basin center. Similar stratigraphic traps should exist to the east of the Black Mesa, west of the Chinle wash, again an untested region. Many wells have been drilled on the Defiance uplift, in an area where the Paleozoic sediments have already pinched out. The zone where key beds are pinching out apparently lies well to the west of the present drilling limit.

In addition to conventional prospects in the deeper portions of the trough, and stratigraphic pinchout traps along the margins of the Oraibi sag, there are good possibilities for the development of highly fractured, secondary-porosity reservoirs on the boundary structure between the deep trough and the Shonto plateau. The uppermost slope and knee area of the Cow Springs monocline, from the northern corner of the topographic Black Mesa and Kayenta, has great potential for fractured reservoirs. Production is known from analog structures in many areas of the world. While drilling on such structures has typically tended to be concentrated on the crest of the closure, the areas of greatest productivity are often lower on the slope, in zones where the fracturing is at a maximum. The remote-sensing study identified this region as an area of interest.

A series of regularly-spaced cracks, grooves and erosional gullies can be seen on the exposed surface of Navajo sandstone outcrops on the hillside running along the northwestern side of Highway 160. These depressions reflect a regular fracture pattern along the knee of the monocline. Similar fractures presumably exist at depth, and can make high quality reservoirs where they are overlain by nonbrittle, relatively-plastic cap rocks, which are necessary to form a seal on fracture-reservoir traps. Fine-grained shales can be plastic enough to form such caps. The Cow Springs monocline could be one of the better targets in the study area. Thick source beds lie to the immediate southeast. Migration routes from the deep basin are short, and straight updip. Evidence of fracturing is obvious along the structure. Drilling targets should be relatively shallow, although sample control is so poor in this area that specific targets cannot be identified at this time.

Leasing regulations, managed originally from Washington, and more recently by the local Native American administrations, have complicated drilling plans in the Black Mesa region in the past. The boundaries between Hopi and Navajo lands have recently been clarified, somewhat simplifying planning for work in the area. The Navajo currently have their own oil company, and have been encouraging drilling by other companies, as well as developing the resources on their own lands themselves. Land administration and ownership can be an important consideration when planning for work in northeastern Arizona.

The Hopi own the land and minerals in the deep, central portions of the Oraibi trough, although the deepest portion of the sag may actually lie just to the southeast of the Hopi reservation in an area that has not yet been drilled. Much of the potential locally sourced Paleozoic hydrocarbons should have developed in the thermally mature rocks beneath the Hopi reservation, as shown by the modeling studies conducted in connection with this project. The presence of deep-sourced hydrocarbons in the Black Mesa area is more speculative, but gravity and magnetic modeling strongly suggest the presence of graben structures and thick wedges of low-density material, suggestive of Chuar sediments, at several locations at and around the Hopi lands. Major sutures faults cutting the crust also pass beneath the reservation. The potential is very high for hydrocarbon generation and accumulation in this central basin area. Some of this resource should be trapped in closures beneath the reservation. Folds are extremely subtle in the central portions of the basin, where dips tend to be 1-3 degrees, but they increase in amplitude toward the Cow Springs monocline. Anticlines are much better developed in the northern and western portions of the reservation.

Large quantities of hydrocarbons may have migrated out of the central basin into updip areas around the basin flanks. Much, but not all, of this land is located on the Navajo reservation. One of the most highly prospective areas along the edge of the basin is the fracture zone along the knee of the Cow Springs monocline area. This target area in narrow, and well-defined, making it a relatively easy to define target for drilling. Exploration would be relatively simple here, and comparatively inexpensive. A tiny portion of the Cow Springs target zone passes through the northwest corner of the Hopi reservation. The rest is on Navajo reservation lands.

The southern and eastern margins of the deep basin are characterized by gentle slopes, rather than the abrupt flexing and fracturing found along the Cow Springs structure. Traps here would lie in subtle stratigraphic pinchouts that should be identifiable with high-resolution, 3-D seismic surveys. Hydrocarbons could be locally generated or may have accumulated through migration from thicker units in the central basin . The potentially productive stratigraphic units along the southern side of the trough could reach well up onto the flanks of the Defiance-Zuni uplift, near the Hopi buttes. This prospective area includes large stretches of the Navajo lands, plus nonreservation lands, south of the Hopi and Navajo blocks. Prospective areas on the eastern side of the Oraibi trough lie in a broad band with almost no deep drilling, on the western side of the Chinle Valley. Targets here are also stratigraphic pinchouts, plus possible fault and fracture zones at the western edge of the Defiance uplift. The development of prospects in either of these zones will require the survey of very large areas, although payouts could be high. Several promising areas were seen in this area. Sophisticated seismic work is the logical next step for work in the area. These targets are largely on Navajo lands, although production could extend far into the basin and may reach Hopi acreage.

18.0 REFERENCES

Aiken, Carlos L. V., and J. S. Sumner, 1972. *A Study of Regional Geophysical Data in the Holbrook Area, Arizona.* Arizona Geological Survey Publication OG-23.

Aizawa, J., 1990. Paleotemperatures from Fluid Inclusions and Coal Rank of Carbonaceous Material of the Tertiary Formations in Northwest Kyusku, Japan. *Journal of Mineralogy, Petrology, and Economic Geology,* Vol. 85, p. 145–154.

Allexan, S., J. Fausnaugh, C. Goudge, and S. Tedesco, 1986. The Use of Iodine In Geochemical Exploration for Hydrocarbons, *Association of Petroleum Geochemical Exploration,* Vol. 2, December 1986, p. 71–93.

Ander, M. E., and S. P. Huestis, 1982, Mafic Intrusion Beneath the Zuni-Bandera Volcanic Field. *GSA Bulletin,* Vol. 93, p. 1142–1150.

Anderson, J. L., 1989. Proterozoic Anorogenic Granites of the Southwestern United States. In J. P. Jenney and S. J. Reynolds, eds., *Geologic Evolution of Arizona,* Arizona Geological Society Digest 17, p. 211–238.

Arizona Development Board, 1961. Oil, Gas and Helium in Arizona, Its Occurrence and Potential. *Arizona Oil and Gas Conservation Commission,* Phoenix, Arizona, p. 22–68.

Arizona Geological Survey, 1995. *Oil, Gas, and Helium Production Report, Production through September 1995,* published November 11, 1996, 5 p.

Baars, D., 1983. The Colorado Plateau. *A Geologic History.* University of New Mexico Press, Albuquerque, 279 p.

Barker, Colin E. and R. H. Goldstein, 1990. Fluid-Inclusion Technique for Determining Maximum Temperature in Calcite and Its Comparison to the Vitrinite Reflectance Geothermometer. *Geology,* Vol. 18, p. 1003–1006.

Barker, Colin E. and M. J. Pawlewicz, 1986. The Correlation of Vitrinite Reflectance with Maximum Temperature in Humic Organic Matter. In *Paleogeothermics,* Lecture Notes in Earth Sciences, Vol. 5 (eds. G. Buntebarth and L. Stegena), Springer-Verlag, p. 79–93.

Barnes, C. W., R. L. Eastwood, and Stanley Beus, 1974. Geologic Resume and Field Guide, North-Central Arizona. In T. N. V. Karlstrom, G. A. Swann, and R. L. Eastwood eds., *Geology of Northern Arizona, with Notes on Archaeology and Paleoclimate, Part 1, Regional*

Studies. Geological Society of America, Rocky Mountain Section Meeting, Flagstaff, Arizona, April 27–30, p. 423–441.

Barnes, C. W., 1974. Interference and Gravity Tectonics in the Gray Mountain Area. In T. N. V. Karlstrom, G. A. Swann, and R. L. Eastwood eds., *Geology of Northern Arizona, with Notes on Archaeology and Paleoclimate, Part 1, Regional Studies.* Geological Society of America, Rocky Mountain Section Meeting, Flagstaff, Arizona, April 27–30, p. 442–453.

Barnes, C. W., 1987. Geology of the Gray Mountain Area, Arizona, *Geological Society of America Centennial Field Guide—Rocky Mountain Section*, 1987, p. 379–384.

Barton, R. H., 1990. Relationship of Surface Magnetic Susceptibility Variations to Hydrocarbon and Subsurface Structure, *Association of Petroleum Geochemical Exploration Bulletin* 6, December 1990, p. 1–11.

Barwin, J. R., R. W. King, and C. A. Hassenfratz, 1971. Future Oil and Gas Potential of Northeast Arizona. In *Future Petroleum Provinces of the United States; Their Geology and Potential,* AAPG Memoir 15, Vol. 1, p. 449–469.

Berger, Z., 1994. *Satellite Hydrocarbon Exploration, Interpretation and Integration Techniques.* Springer-Verlag, Berlin, 319 p.

Beus, S. S., 1989. Devonian and Mississippian Geology of Arizona. In J. P. Jenney and S. J. Reynolds, eds., *Geologic Evolution of Arizona,* Arizona Geological Society Digest 17, p. 287–311.

Blakey, R. C., 1989. Triassic and Jurassic Geology of the Southern Colorado Plateau. In J. P. Jenney and S. J. Reynolds, eds., *Geologic Evolution of Arizona,* Arizona Geological Society Digest 17, p. 369–396.

Blakey, R. C., and R. Knepp, 1989. Pennsylvanian and Permian Geology of Arizona. In J. P. Jenney and S. J. Reynolds, eds., *Geologic Evolution of Arizona,* Arizona Geological Society Digest 17, p. 313–347.

Borden, J. L., 1952. Paradox Member of the Hermosa Formation, *Geological Symposium of the Four Corners Region (October 1952).* Four Corners Geological Society, p. 27–35.

Brown, S. C. 1954. Arizona, a Frontier Area (abs.), *Oil & Gas Journal,* 81, April 19, 1954, p. 208

Brown, S. C.; 1956. Petroleum and Natural Gas Potentialities of the Navajo-Hopi Reservation—Arizona and Utah. University of Arizona Press, *Mineral Resources* Vol. 1: p. 64–72.

Brown, S. C., and R. E. Lauth,. 1957. Oil and Gas Potentialities of Northern Arizona. Four Corners Geological Society Guidebook, *Geology of Southwestern San Juan Basin,* Four Corners Geological Society, Second Field Conf., 1957: p. 77–84.

Brown, S. C., and R. E.. Lauth, 1958. Oil and Gas Potentialities of Northern Arizona. In Roger Y. Anderson and J. W, Harshbarger, eds., New Mexico Geologic Society, Ninth Field Conference, October 16, 17, and 18, 1958, *Guidebook of the Black Mesa Basin,* Prepared in Cooperation with the Arizona Geological Society, p. 153–160.

Brown, S. C. and R. E. Lauth, 1960. Northern Arizona Has Good Oil, Gas Prospects. *World Oil,* September 1960, p. 98–106.

Brown, S. C., and R. E. Lauth, 1961. Northeastern Arizona—Its Oil, Gas and Helium Prospects. In, *Oil, Gas and Helium in Arizona, Its Occurrence and Potential,* Arizona Development Board, Arizona Oil and Gas Conservation Commission, Phoenix, Arizona, p. 7–21.

Byington, R. M., 1957. Exploration Highlights in the Four Corners, Area, *Geology of the Southwestern San Juan Basin, New Mexico,* Four Corners Geological Society Second Field Conference Guidebook, 1957, p. 34–35.

Cabeen, T. W., 1958. Land Tenure in Northeastern Arizona, In Roger Y. Anderson and J. W, Harshbarger, eds., New Mexico Geologic Society, Ninth Field Conference, October 16, 17, and 18, 1958, *Guidebook of the Black Mesa Basin,* prepared in Cooperation with the Arizona Geological Society, p. 197–198.

Calhoun, G. G., 1992. Surface Fluorescence Methods Can Identify Potential Oil Pay Zones in Permian Basin, *Oil & Gas Journal,* September 28, 1992, Vol. 90, p. 96 –100.

Chidsey, T. C., M. L. Allison, and J. G. Palacas, 1990, Potential for Precambrian Source Rock in Utah (abs.). In *AAPG Bulletin,* American Association of Petroleum Geologists Rocky Mountain Section Meeting (Denver, Colorado. Sept. 16–19, 1990), Vol. 74 (August 1990), No. 8, p. 1319.

Conley, J. N., 1971. *Index of Samples of Drill-Bit Cuttings and/or Cores of Wells Drilled in Arizona,* Unnumbered Publ., Ariz. Oil And Gas Conservation Commission, June 1971, 71 p.

Conley, J. N., 1974. *Review of the Development of Oil and Gas Resources of Northern Arizona,* Arizona Oil and Gas Conservation Commission, Special Publication 1, 10 p.

Conley, J. N., 1975. Surface Occurrence of Petroleum-Impregnated Rocks in the Colorado Plateau Province. In *Explanatory Text and Well-Data Tabulation to Accompany Well Location*

Map Nine, Colorado Plateau Province, Arizona Oil and Gas Conservation Commission, ii + 45 p., 2 tables, 4 figures.

Danie, T. C., 1978. Dineh-Bi-Keyah. In *Oil and Gas Fields of the Four Corners Area,* Four Corners Geological Society, Durango, Colorado, Vol. 1, p. 73–76.

Danie, T. C., 1980 Dineh-Bi-Keyah Field, Apache County, Arizona (abs.). In AAPG-SEPM-EMD Annual Convention, Denver, Colorado, June 8–11, 1980.

Davis, G. H. 1975. *Tectonic Analysis of Folds in the Colorado Plateau of Arizona.* University of Arizona, OALS Bulletin 9.

Desborough, G. A., F. G. Poole, T. A. Daws, and R. Scarborough, 1984. Hydrocarbon Source Rock Evaluation of the Middle Proterozoic Apache Group, Gila County, Arizona. In J. Woodward, F. F. Meissner, and J. L. Clayton, eds., *Hydrocarbon Source Rocks of the Greater Rocky Mountain Region,* p. 51–55.

Dickas, A. B., and M. G. Mudrey, Jr., 1991. Precambrian Hydrocarbon Potential of the Western Great Lakes (abs.). In *GSA Abstracts with Programs,* Geologic Society Of America, Annual GSA Meeting, San Diego, California, October 21–24, 1991, Vol. 23, No. 5, p A57.

Dickas, A. B., and M. G. Mudrey, Jr., 1992a. The Lake Superior Oronto Group, A Middle Proterozoic Exploration Model for the Late Proterozoic Chuar Group of the Grand Canyon (abs.). In *AAPG Bulletin,* American Association of Petroleum Geologists SW Section Meeting, Midland, Texas. April 21–24, 1992, Vol. 76 (April 1992), No. 4, p. 574.

Dickas, A. B., and M. G. Mudrey, Jr., 1992b. Precambrian Hydrocarbon Potential of the Western Great Lakes (abs.). In *GSA Abstracts with Programs,* Geologic Society Of America, North-Central Section Meeting, Iowa City, Iowa. April 30–May 1, 1992, Vol. 24, No. 4, p. 12.

Druitt, C. E., 1976. *Mean Annual Temperature Map, State of Arizona.* Arizona Geological Survey, Publication GT-2.

Dwights Energydata CD-ROM, 1994, 1995, 1996. Dwights Energydata, Inc., Denver, Colorado.

Elston, D. P., 1979. *Late Precambrian Sixtymile Formation and Orogeny at the Top of the Grand Canyon Supergroup, Northern Arizona,* USGS Professional Paper 1092, 20 p.

Elston, D. P., 1986. Magnetostratigraphy of Late Proterozoic Chuar Group and Sixtymile Formation, Grand Canyon Supergroup, Northern Arizona. Correlation with Other

Proterozoic Strata of North American (abs.), Geological Society of America, Abstracts With Programs 1986 (Rocky Mountain Section), Vol. 18, No. 5., p. 353.

Elston, D. P., 1989a. Grand Canyon Supergroup, Northern Arizona. Stratigraphic Summary and Preliminary Paleomagnetic Correlations with Parts of Other North American Proterozoic Successions. In Jenny, J. P., and S. J. Reynolds, *Geologic Evolution of Arizona*. Tucson, Arizona Geological Society Digest 17, p. 259–272.

Elston, D. P., 1989b. Middle and Late Proterozoic Grand Canyon Supergroup, Arizona. In *Geology of the Grand Canyon, Northern Arizona* (With Colorado River Guides); Lees Ferry to Pierce Ferry, Arizona; Field Trips for the 28th International Geologic Congress; D. P. Elston, G. H. Billingsley, R. A. Young, and Penelope M. Hanshaw, eds., American Geophysical Union, Washington, DC, p. 94–105.

Elston, D. P., 1993. Middle and Early-Late Proterozoic Grand Canyon Supergroup, Northern Arizona. In *Precambrian: Conterminous U.S.*, The Geology of North America, Volume C-2, J. C. Reed, Jr., Marion E. Bickford, R. S. Houston, P. K. Link, D. W. Rankin, P. K. Sims, and W. Randall Van Schmus, eds., Geologic Society of America. p. 463–595.

Elston, D. P., and C. S. Gromme, 1974a. Precambrian Polar Wandering from Unkar Group and Nankoweap Formation, Eastern Grand Canyon, Arizona; *Geologic Society of America, Abstracts with Programs*, Vol. 6, p. 440–441.

Elston, D. P., and C. S. Gromme, 1974b. Precambrian Polar Wandering from Unkar Group and Nankoweap Formation, Eastern Grand Canyon, Arizona. In *Geology of Northern Arizona, with Notes on Archaeology and Paleoclimate, Part I, Regional Studies;* T. N. V. Karlstrom, G. A. Swann, and R. L. Eastwood, eds., Geologic Society of America, Rocky Mountain Section Meeting, Flagstaff, Arizona, April 27–30, 1974, p. 97–117.

Elston, D. P., and E. H. McKee, 1982. Age and Correlation of the Late Proterozoic Grand Canyon Disturbance, Northern Arizona. *Geological Society of America Bulletin*, Vol. 93 (August), p. 681–699.

Elston, D. P., and G. R. Scott, 1973. Paleomagnetism of Some Precambrian Basalt Flows and Red Beds, Eastern Grand Canyon, Arizona. *Earth and Planetary Science Letters*, Vol. 18, p. 253–265.

Elston, D. P., and G. R. Scott, 1976. Unconformity at the Cardenas-Nankoweap Contact (Precambrian), Grand Canyon Supergroup, Northern Arizona, *Geologic Society of America Bulletin*, Vol. 87 (December), p. 1763–1772.

Elston, D. P., and S. L. Bressler, 1977. Paleomagnetic Poles and Polarity Zonation from Cambrian and Devonian Strata of Arizona, *Earth and Planetary Science Letters*, Vol. 36. p. 423–433.

Elston, W. E., 1960. Structural Development and Paleozoic Stratigraphy of Black Mesa Basin, Northeastern Arizona, and Surrounding Areas. *AAPG Bulletin*, Vol. 44, p. 21–36.

Fellows, L. D., 1994. Carbon Dioxide and (or) Helium Discovery Near St. Johns?, *Arizona Geology*, Vol. 24, No. 3, p. 1.

Finch, W. I. and R. B. McCammon, 1987. *Uranium Resource Assessment By the Geological Survey, Methodology and Plan to Update the National Resource Base*, USGS Circular 994.

Ford, T. D., 1990. Grand Canyon Supergroup: Nankoweap Formation, Chuar Group, and Sixtymile Formation. In *Grand Canyon Geology*, Oxford University Press, New York, p. 49–70.

Ford, T. D., and W. J. Breed, 1969. Preliminary Geologic Report of the Chuar Group, Grand Canyon, Arizona, With an Appendix on the Palynology of the Chuar Shales by C. Downie. In *Geology and Natural History of the Grand Canyon Region*, Four Corners Geological Society Guidebook, Fifth Field Conference, Powell Centenary River Expedition, p. 114–121.

Ford, T. D., and W. J. Breed, 1972a. The Chuar Group of the Proterozoic, Grand Canyon, Arizona. In *24th International Geologic Congress Session Proceedings*, Montreal, Canada, Sec. 1, Precambrian Geology, p. 3–10.

Ford, T. D., and W. J. Breed, 1972b. The Problematical Precambrian Fossil Chuaria. In *24th International Geological Congress Session Proceedings*, Montreal, Canada, Sec. 1, Precambrian Geology, p. 11–18.

Ford, T. D., and W. J. Breed, 1973a. Late Precambrian Chuar Group, Grand Canyon, Arizona, *Geologic Society of America Bulletin*, Vol. 84 (April), p. 1243–1260.

Ford, T. D., and W. J. Breed, 1973b. The Problematical Precambrian Fossil Chuaria, *Palaeontology*, Vol. 16, Pt. 3, August 1973, p. 535–550.

Ford, T. D., and W. J. Breed, 1974a. The Late Precambrian Chuar Group of the Eastern Grand Canyon. In *Geology of Northern Arizona, with Notes on Archaeology and Paleoclimate, Part I, Regional Studies;* T. N. V. Karlstrom, G. A. Swann, and R. L. Eastwood, eds., Geologic Society of America, Rocky Mountain Section Meeting, Flagstaff, Arizona, April 27–30, 1974, p. 54–64.

Ford, T. D., and W. J. Breed, 1974b. The Younger Precambrian Rocks of the Grand Canyon. In *Geology of the Grand Canyon, Museum of Northern Arizona,* p. 21–33.

Ford, T. D., and W. J. Breed, 1974c. The Younger Precambrian Fossils of the Grand Canyon. In *Geology of the Grand Canyon, Museum of Northern Arizona,* p. 34–40.

Ford, T. D., and W. J. Breed, 1975 (c1977). Chuaria Circularis Walcott and other Precambrian Fossils from the Grand Canyon. In Jurij Anexandrovich Orlov Memorial Volume, Singh, S. N. and S. K. Singh, eds., Journal of the Paleontologic Society of India (IND) 20, p. 170–177.

FY 1995 Annual Technical Progress Report NIPER/BDM-0193, issued October 1995, p. 237–271.

Gottesfeld, A. S., 1972. Paleoecology of the Lower Part of the Chinle Formation in the Petrified Forest. In C. S. Breed and W. J. Breed, eds., *Investigations in the Triassic Chinle Formation,* Museum of Northern Arizona Bulletin 47, p. 59–73.

Gregory, H. E., 1909. The San Juan Oil Field, San Juan County, Utah, *USGS Bulletin* 431, p. 11–25.

Gregory, H. E., 1917. *Geology of the Navajo Country—A Reconnaissance of Parts of Arizona, New Mexico, and Utah,* USGS Professional Paper 93, 161 p.

Gregory, H. E., 1938. *The San Juan Country—A Geographic and Geologic Reconnaissance of Southeastern Utah,* USGS Professional Paper 188, p. 123.

Gregory, H. E., and R. C. Moore, 1930. *The Kaiparowits Region, a Geographic and Geologic Reconnaissance of Parts of Utah and Arizona.* USGS Professional Paper 164, 161 p.

Gutman, S. I., and G. A. Heckmann, 1977. *An Integration of Landsat and Geophysical Data in Northeastern Arizona.* USGS, Report No. 599, Report of Work Performed Under USGS Contract No. 94599 for United States Geological Survey.

Hereford, R., 1977. Deposition of the Tapeats Sandstone (Cambrian) in Central Arizona, *Geological Society of America Bulletin,* Vol. 88, p. 199–211.

Heylmun, E. B., 1990. Arizona's Coconino Plateau Seeks Wildcats, *Oil & Gas Journal,* May 23, 1990, p. 110–112.

Hill, P. L., 1986. *Lists and Location Maps of Aeromagnetic and Aeroradiometric Publications from the Department of Energy NURE Program,* USGS Open File Report 86-525-G.

Hinds, N. E. A., 1933, 1935a, 1936, 1938a. Researches on Algonkian Formations of Grand Canyon National Park. In *Carnegie Institute of Washington Year Book 32*, p. 325–328, 34, p. 326–329, 35, p. 331–333, and *Geologic Society of America Bulletin,* Vol. 49, No. 12, Part 2, p. 1885–1886, December 1, 1938.

Hinds, N. E. A., 1935b. Ep-Archean and Ep-Algonkian Intervals in Western North America, Carnegie Institute of Washington Publication 463, preprint, August 20, 1935, p. 1–52 (abs.). In *Geologic Society of America Proceedings for 1934,* June, 1935, p. 319–320.

Hinds, N. E. A., 1938b. An Algonkian Jellyfish from the Grand Canyon of the Colorado, *Science* n. s., Vol. 88, No. 2278, p. 186–187, August 26, 1938.

Hite, R. J., D. E. Anders, and T. G. Ging, 1984. In J. Woodward, F. F. Meissner, and J. L. Clayton, eds., *Organic-Rich Source Rocks of Pennsylvanian Age in the Paradox Basin of Utah and Colorado: Hydrocarbon Source Rocks of the Greater Rocky Mountain Region,* p. 255–274.

Hodgson, R. A. 1965. Genetic and Geometric Relations Between Structures in Basement and Overlying Sedimentary Rocks, with Examples from Colorado Plateau and Wyoming, *AAPG Bulletin,* Vol. 49, No. 7 p. 935–949.

Holm, D. A. 1938. *Report on the Oil Possibilities of Arizona,* Arizona State Land Department, Phoenix, Arizona.

Hubbert, M. King, 1948. *Geophysics,* 13, p. 215–225.

Huber, G. C., 1973. Mexican Hat Oil Field. In *The Geology of the Canyons of the San Juan River, A River Runners Guide,* Seventh Field Conference, Durango, Colorado, Four Corners Geologic Society, p. 51–54.

Hulen, J. B. F. Goff, J. R. Ross, L. C. Bortz, and R. Bereskin, 1994. Geology and Geothermal Origin of Grant Canyon and Bacon Flat Oil Fields, Railroad Valley, Nevada, *AAPG Bulletin,* Vol. 78., No. 4, p. 596–623.

Huntoon, P. W., 1981. Grand Canyon Monoclines: Vertical Uplift or Horizontal Compression?, University of Wyoming, *Contributions to Geology,* 19 (2): p. 127–134.

Jarvie, D. M., 1995. *Geochemical Analysis of the 1-Alpine Federal Well,* Arizona Geological Survey Contributed Report CR-95-A, 47 p.

Jenkins, R. D., and G. R. Keller, 1989. Interpretation of Basement Structures and Geophysical Anomalies in the Southeastern Colorado Plateau. In *Southeastern Colorado Plateau,* New Mexico Geological Society 40th Field Conference Guidebook, p. 135–142.

Johnsson, M. J., D. G. Howell, and K. J. Bird, 1993. Thermal Maturity Patterns in Alaska: Implications for Tectonic Evolution and Hydrocarbon Potential. *AAPG Bulletin,* Vol. 77, p. 1874–1903.

Karlstrom, K. E. and S. A. Bowring, 1993. Proterozoic Organic History of Arizona. In *Precambrian: Conterminous U.S.,* The Geology of North America, Volume C-2, J. C. Reed, Jr., Marion E. Bickford, R. S. Houston, P. K. Link, D. W. Rankin, P. K. Sims, and W. Randall Van Schmus, eds., Geologic Society of America. p. 188–211.

Karlstrom, K. E., 1989. Early Recumbent Folding During Proterozoic Orogeny in Central Arizona. In Grambling, J. A., and B. J. Tewksbury, *Proterozoic Geology of the Southern Rocky Mountains; Boulder, Colorado,* Geological Society of America, Special Paper 235, p. 155–171.

Karlstrom, K. E. and S. A. Bowring, 1991. Styles and Timing of Early Proterozoic Deformation in Arizona: Constraints on Tectonic Models; in K. E. Karlstrom, ed., Proterozoic Geology and Ore Deposits of Arizona, *Arizona Geological Society Digest* 19, p. 1–10.

Karlstrom, K. E., S. A. Bowring, and C. M. Conway, 1987. Tectonic Significance of an Early Proterozoic Two-Province Boundary in Central Arizona. *Geological Society of America Bulletin,* Vol. 99, p. 529–538.

Kashfi, M. S., 1983. Upper Devonian Source and Reservoir Rocks in the Black Mesa Basin, Northeastern Arizona, *Oil & Gas Journal,* Vol. 81, No. 50, December 12, 1983, p. 151–159.

Kunkel, R. P., 1961. *Oil and Gas Fields of Utah,* Intermountain Association of Petroleum Geologists, Mexican Hat Field.

Lepley, L. K., 1977. *Landsat Lineament Map of Arizona with Emphasis on Quaternary Fractures.* University of Arizona, Bureau of Geology and Mineral Technology Open-File Report 77-2.

Lillis, P. G., J. G. Palacas, and A. Warden, 1995. A Precambrian-Cambrian Oil Play in Southern Utah (abs.). In *AAPG Bulletin,* American Association of Petroleum Geologists Rocky Mountain Section Meeting, Reno, Nevada, July 16–19, 1995, Vol. 79 (June 1995), No. 6, p. 921.

Lucchitta, I. 1978. *Basement Control of Structural Features Near the Boundaries of the Colorado Plateau in Arizona.* Basement Tectonic Contribution 46, 3rd International Conference on Basement Tectonics, Durango, Colorado.

Matheny, M. L., 1964. A History of the Petroleum Industry in the Four Corners Area, *Durango-Silverton Guidebook,* Four Corners Geologic Society, Durango, Colorado, p. 39–53.

Matheny, M. L., 1978. A History of the Petroleum Industry in the Four Corners Area. In *Oil and Gas Fields of the Four Corners Area,* Four Corners Geologic Society, p. 17–41.

Matheny, M. L., and R. A. Ulrich, 1983. A History of the Petroleum Industry in the Four Corners Area. In *Oil and Gas Fields of the Four Corners Area,* Four Corners Geologic Society, p. 804–831.

Maxson, J. H., 1961. Geologic History of the Bright Angel Quadrangle, Grand Canyon Natural History Association, scale 1:24,000 (third edition, revised, 1968).

McCaslin, J. C., 1979. There's Still More Oil in Paradox. *Oil & Gas Journal,* Vol. 77, No. 42 (Oct. 15), p. 193.

McCaslin, J. C., 1980. Arizona's Strat Trap Potential Eyed. *Oil & Gas Journal,* Vol. 78, No. 11 (March 17), p. 205.

McKee, E. D. and C. E. Resser, 1945. *Cambrian History of the Grand Canyon Region,* Carnegie Institution of Washington, Publication 563, 232 p.

McKenny, J. W., and J. A. Masters, 1968. Dineh-Bi-Keyah Field, Apache County, Arizona, *AAPG Bulletin,* 52, No. 10, October 1968, p. 2045–2057.

Meissner, F. F., J. Woodward, and J. L. Clayton, 1984. Stratigraphic Relationships and Distribution of Source Rocks in the Greater Rocky Mountain Region. In J. Woodward, F. F. Meissner, and J. L. Clayton, eds., *Hydrocarbon Source Rocks of the Greater Rocky Mountain Region,* p. 1–34. (Includes an extensive bibliography of source rocks indexed by stratigraphic unit.)

Middleton, L. T., 1989. Cambrian and Ordovician Depositional Systems in Arizona. In J. P. Jenney and S. J. Reynolds, eds., *Geologic Evolution of Arizona,* Arizona Geological Society Digest 17, p. 273–286.

Moore, R. T., E. D. Wilson, and R. T. O'Haire, 1960. Geologic Map of Coconino County, Arizona, Arizona Bureau of Mines, University of Arizona, Tucson, 1:375,000 scale.

Nations, D. and E. Stump, 1981. *Geology of Arizona,* Kendall/Hunt Publishing, Dubuque, Iowa, 221 p.

Nations, J. D., D. J. Brennan, and R. A. Ybarra, 1989. Oil and Gas in Arizona. In J.P. Jenney and S.J. Reynolds, eds., *Geologic Evolution of Arizona,* Arizona Geological Society Digest 17, p. 795–815.

Nations, J. D., 1989. Cretacous History of Northeastern and East-Central Arizona. In J.P. Jenney and S.J. Reynolds, eds., *Geologic Evolution of Arizona,* Arizona Geological Society Digest 17, p. 435–446.

Neff, A. W. and S. C. Brown, 1958. Ordovician-Mississippian Rocks of the Paradox Basin in, *Guidebook to the Geology of the Paradox Basin,* Intermountain Association of Petroleum Geologists Ninth Annual Field Conference, p. 102–108.

Nettleton, L. L., 1973. *Elementary Gravity and Magnetics for Geologists and Seismologists,* Monograph Series No. 1, published by the Society of Exploration Geophysicists, Tulsa, Oklahoma.

Noble, L. F., 1914. The Shinumo Quadrangle, Grand Canyon District, Arizona, *USGS Bulletin* 549, 100 p.

Palacas, J. G., 1992. Source-Rock Potential of Precambrian Rocks in Selected Basins of the U.S. In T. S. Dyman, ed., *Geologic Controls and Resource Potential of Natural Gas in Deep Sedimentary Basins in the United States,* US Geological Survey Open File Report, USGS, Reston, Virginia, p. 161–172.

Palacas, J. G., 1993. *Geologic Studies of Deep Natural-Gas Resources in the United States,* USGS Professional Paper, Vol. 1570, USGS, Reston, Virginia, p. 171–204.

Palacas, J. G. and M. W. Reynolds, 1989. Preliminary Petroleum Source Rock Assessment of Upper Proterozoic Chuar Group, Grand Canyon, Arizona (abs.), *America Association of Petroleum Geologists Bulletin,* Annual AAPG-SEPM-EMD-DPA Convention, San Antonio, Texas, April 23–26, 1989, Vol. 73:3 (March 1989), p. 397.

Pawlewicz, M. J., and J. G. Palacas, 1992. Petrography and Rock-Eval Studies of Organic Matter in Precambrian Rocks, U.S.A. and U.S.S.R.. In *USGS Research on Energy Resources 1992; Program and Abstracts,* Eighth Annual V. E. McKelvey Forum on Mineral and Energy Resources, Houston, Texas, February 17–20, 1992, L. M. H. Carter, ed., USGS Circular, p. 58–59.

Peirce, H. W., S. B. Keith, and J. C. Wilt, 1970. *Coal, Oil, Natural Gas, Helium, and Uranium in Arizona,* Arizona Bureau of Mines Bulletin 182, vi + 289 p.; 19 plates.

Peirce, H. W. and J. R. Scurlock, 1972. *Arizona Well Information,* Arizona Bureau of Mines (currently the Arizona Geological Survey), Tucson, Arizona.

Peirce, H. W., 1976. Elements of Paleozoic Tectonics in Arizona. In J. C. Wilt and J. P. Jenney, eds., *Tectonic Digest,* Arizona Geological Society Digest 10, p. 37–57.

Person, M. and G. Garven, 1992. Hydrologic Constraints on Petroleum Generation within Continental Rift Basins: Theory and Application to the Rhine Graben, *AAPG Bulletin* Vol. 76, No. 4 (April 1992), p.468–488.

Picard, M. D., with selections by Boyd R. Brown, A. J. Loleit, and J. W. Parker, 1960. Geology of Pennsylvanian Gas in the Four Corners Region, *AAPG Bulletin* 44, No. 9 (Sept. 1960), p. 1541–1569.

Pohlmann, H. F., 1967a. *The Navajo Indian Nation and Dineh-Bi-Keyah,* 18th Annual New Mexico Geologic Society Field Conference Guidebook, p. 63–69.

Pohlmann, H. F., 1967b. Dineh-Bi-Keyah Lifts Navajo Spirits. *Oil & Gas Journal,* Oct. 9th., 1967, Vol. 65, No. 41, p. 205–206, 208, 210–211.

Pye, W. D. 1967. Arizona: A New Exploration Frontier. *Oil & Gas Journal,* May 8, 1967.

Quarterly Technical Progress Report NIPER/BDM-0110, September 1–December 31, 1994, issued January 1995, p. 91–111.

Quarterly Technical Progress Report NIPER/BDM-0134, January 1–March 31, 1995, issued April 1995, p. 137–160.

Quarterly Technical Progress Report NIPER/BDM-0154, April 1 – June 30, 1995, issued July 1995, p. 140–159.

Quarterly Technical Progress Report NIPER/BDM-0205, October 1 – December 31, 1995, issued January 1996, p. 106–115.

Rauzi, S. L. 1990. Distribution of Proterozoic Hydrocarbon Source Rock in Northern Arizona and Southern Utah, Arizona Geological Survey O&GCC Special Publication 6, 1990, 19 p.

Rauzi, S. L., 1989. Precambrian Structure and Subcrop Map, Northern Arizona and Southern Utah, scale 1:500,000, AGS and Arizona O&GCC.

Rauzi, S. L., 1994a. Geothermal Test Hints at Oil Potential in Eastern Arizona Volcanic Field, *Oil & Gas Journal,* January 3, 1994, p. 52–54.

Rauzi, S. L., 1994b. *Implications of Live Oil Shows in Eastern Arizona Geothermal Test,* Open-File Report 94-1, Arizona Geological Survey, Tucson, Arizona, 16 p. ± 12 maps.

Reches, Ze'ev, 1978. Development of Monoclines, Part I, Structure of the Palisades Creek Branch of the East Kaibab Monocline, Grand Canyon, Arizona. In V. Matthews, ed., *Laramide Folding Associated With Basement Block Faulting In The Western United States,* Geological Society Of America Memoir 151, p. 235–272.

Reches, Ze'ev, and A. M. Johnson, 1978. Development of Monoclines, Part II, Theoretical Analysis of Monclines. In V. Matthews, ed., *Laramide Folding Associated with Basement Block Faulting in the Western United States,* Geological Society Of America Memoir 151, p. 273–311.

Reeves, T. K. and H. B. Carroll, 1994a. Geologic Analysis of Priority Basins for Exploration and Drilling, NIPER/BDM-0062, Issued September 1994.

Reeves, T. K. and H. B. Carroll, 1994b. Selection and Prioritization of Basins for Study in the Exploration and Drilling Program, NIPER/BDM-0061, Issued September 1994

Reeves, T. K., M. Szpakiewicz, B. Sharma, G. L. Guo, and H. B. Carroll, *Integrated Results of Geological, Geophysical, and Remote Sensing Interpretation of Basin Evolution, Lithostratigraphy, and Present Structure within the Greater Black Mesa Region, Northeastern Arizona,* NIPER/BDM-184, Issued September 1995.

Reynolds, M. W. and D. P. Elston, 1986. Stratigraphy and Sedimentation of Part of the Proterozoic Chuar Group, Grand Canyon, Arizona (abs.), *GSA Abstracts with Programs,* Vol. 18:5, p.405.

Reynolds, M. W. and J. G. Palacas, 1988. Potential Petroleum Source Rocks in the Late Proterozoic Chuar Group, Grand Canyon, Arizona, *The Outcrop,* Vol. 37, No. 9, p. 5.

Reynolds, M. W., J. G. Palacas, and D. P. Elston, 1988. Potential Petroleum Source Rocks in the Late Proterozoic Chuar Group (Precambrian) in Grand Canyon, Arizona (abs.). In Carter, L. M. H., ed., *USGS Research on Energy Resources, 1988,* Program and Abstracts, USGS Fourth Annual V. E. McKelvey Forum on Mineral and Energy Resources, Denver, Colorado, February 29–March 2, 1988. USGS Circular 1025, p. 49–50.

Reynolds, M. W., J. G. Palacas, and D. P. Elston, 1989. Potential Petroleum Source Rocks in the Late Proterozoic Chuar Group, Grand Canyon, Arizona. In *Geology of the Grand Canyon, Northern Arizona* (With Colorado River Guides); Lees Ferry to Pierce Ferry, Arizona; Field Trips for the 28th International Geologic Congress; D. P. Elston, G. H. Billingsley, R. A. Young, and Penelope M. Hanshaw, eds., American Geophysical Union, Washington, DC, p. 117–118.

Saunders, D. F., K. R. Burson, J. F. Branch and C. K. Thompson, 1993. Relation of Thorium-Normalized Surface and Aerial Radiometric Data to Subsurface Petroleum Accumulations, *Geophysics,* Vol. 58, October, p. 1417–1427.

Saunders, D. F., S. A. Terry and C. K. Thompson, 1987. Test of National Uranium Resource Evaluation Gamma-Ray Spectral Data in Petroleum Reconnaissance, *Geophysics,* Vol. 52, November, p. 1547–1556.

Schicktanz, W. S., 1963. Navajo Land And Leasing in Utah and Northeastern Arizona, Four Corners Geological Society, A Symposium, *Shelf Carbonates of the Paradox Basin,* Fourth Field Conference, June 12–16, 1963, p. 1–2.

Schneider, R. C., B. Tohill, and J. R. Taylor, 1971. Petroleum Potential of the Paradox Basin . In I. H. Cram, ed., *Future Petroleum Provinces of the United States—Their Geology and Potential,* AAPG Memoir 15; 1, p. 470–488.

Science and Technology Week, 1994. Coal Mine Versus Native Americans for Water. Science and Technology Week [Cable News Network (CNN)] Transcript 251, December 31.

Shoemaker, E. M., R. L. Squires, and M. J. Abrams, 1978. *Bright Angel and Mesa Butte Fault Systems of Northern Arizona,* Geological Society of America Memoir 152, p. 341–367.

Smith, J. D. and W. H. Carpenter, 1955. *Land and Leasing in the Four Corners Area.* Geological Society Guidebook, First Field Conference 1955, p. 20–24.

Summons, R. E., S. C. Brassell, G. Eglinton, E. Evans, R. J. Horodyski, N. Robinson, and D. M. Ward, 1988. Distinctive Hydrocarbon Biomarkers from Fossiliferous Sediment of the Late Proterozoic Walcott Member, Chuar Group, Grand Canyon, Arizona. *Geochimica et Cosmochimica Acta,* Vol. 52, p. 2625–2637.

Sumner, J. S., 1985. Crustal Geology of Arizona as Interpreted from Magnetic, Gravity and Geologic Data. In W. J. Hinze, ed., *The Utility of Regional Gravity and Magnetic Anomaly Maps,* Tulsa, Society of Exploration Geophysics, 1985, p. 164–180.

Szpakiewicz, M., T. K. Reeves, and L. Volk, 1994. *Report from Field Trip to Northeastern Arizona,* prepared for DOE by BDM/NIPER, October 28, 1994.

Takahashi, K. and D. L. Gautier, 1995. USGS 1995 National Assessment of Oil and Gas Resources of the United States. USGS Digital Data Series DDS-30 CD-ROM.

Talwani, M. and J. R. Heirtzler, 1964. *Computers in the Mineral Industries. Part 1—Computation of Magnetic Anomalies Caused by Two-Dimensional Structures of Arbitrary Shape,* Stanford University Publications in the Geologic Sciences, Vol. 9, No. 1, p. 464–479.

Talwani, M., J. L. Worzel, and M. Landisman, 1959. Rapid Gravity Computations for Two-Dimensional Bodies with Application to the Mendocino Submarine Fracture Zone. *Journal of Geophysics Research,* Vol. 64, p. 49–59.

Tedesco, S. A., 1995. *Surface Geochemistry in Petroleum Exploration,* Chapman & Hall, New York, p. 113.

Teichert, C., 1965. *Devonian Rocks and Paleogeography of Central Arizona,* USGS Professional Paper 464, 181 p.

Turner, D. S. 1968. *Natural Gas in Black Mesa Basin, Northeastern Arizona.* American Association of Petroleum Geologists Memoir 9. Vol. 2, p. 3357–1370.

Umbach, P. H., 1952. Exploration and Development in the San Juan, Paradox, and Black Mesa Basins, *Geological Symposium of the Four Corners Region* (October 1952). Four Corners Geological Society, p. 22–26.

Van Gundy, C. E., 1934. Some Observations of the Unkar Group of the Grand Canyon Algonkian, *Grand Canyon Nature Notes,* Vol. 9, p. 338–349.

Van Gundy, C. E., 1937. Nankoweap Group of the Grand Canyon Algonkian (abs.), *Geologic Society of America Proceedings for 1936,* p. 304.

Van Gundy, C. E., 1946. Faulting in the East Part of the Grand Canyon of Arizona. *AAPG Bulletin,* Vol. 30, p. 1899–1909.

Van Gundy, C. E., 1951. Nankoweap Group of the Grand Canyon Algonkian of Arizona. *GSA Bulletin,* No. 62, p. 953–959.

Walcott, C. D., 1883. Pre-Carboniferous Strata in the Grand Canyon of the Colorado, Arizona. *American Journal of Science,* Third Series, Vol. 26, p. 437–442.

Walcott, C. D., 1886a. Classification of the Cambrian System of North America, *American Journal of Science,* Volume XXXII, No. 3, p. 138–157.

Walcott, C. D., 1886b. Second Contribution to the Studies on the Cambrian Faunas of North America, *USGS Bulletin,* No. 30, p. 369.

Walcott, C. D., 1890. Study of a Line of Displacement in the Grand Canyon of the Colorado in Northern Arizona. *GSA Bulletin*, Vol. 1, p. 49–64.

Walcott, C. D., 1894. *Pre-Cambrian Igneous Rocks of the Unkar Terrane, Grand Canyon of the Colorado, Arizona,* with Notes on the Petrographic Character of the Lavas by J. P. Iddings. US GS Annual Report 14, part 2, p. 497–524.

Walcott, C. D., 1895. Algonkian Rocks of the Grand Canyon of the Colorado. Journal of Geology, Vol. 3, p. 312–330.

Walcott, C. D., 1899. Pre-Cambrian Fossiliferous Formations. *GSA Bulletin,* Vol. 10, p. 199–244.

Walcott, C. D., 1914. Pre-Cambrian Algonkian Algal Flora, *Smithsonian Misc. Collections,* Vol. 64, p. 77–156.

Wardlaw, B. R. and Anita G. Harris, 1984. Conodont-Based Thermal Maturation of Paleozoic Rocks in Arizona, *AAPG Bulletin,* Vol. 68, No. 9 (September), p.1101–1106.

Waters, Frank, 1977. *Book of the Hopi,* Penguin Books, New York.

Wengerd, S. A., 1951. Reef Limestones of the Hermosa Formation, San Juan Canyon, Utah, *AAPG Bulletin,* Vol. 35, p. 1039–1051.

Wengerd, S. A., 1955. *Geology of the Mexican Hat Oil Field, San Juan County, Utah,* Four Corners Geologic Society Guidebook, First Field Conference 1955, p. 150–163.

Wengerd, S. A. and J. W. Strickland, 1954. Pennsylvanian Stratigraphy of the Paradox Salt Basin, Four Corners Region, Colorado and Utah, *AAPG Bulletin,* Vol. 38, p. 2157–2199.

Wenrich, K. J., W. L. Chenoweth, W. I. Finch, and R. B. Scarborough, 1989. Uranium in Arizona. In J. P. Jenney and S. J. Reynolds, eds., *Geologic Evolution of Arizona,* Arizona Geological Society Digest 17, p. 759–794.

Werme, D. R., 1981. *Precambrian Geology of the Defiance Uplift, Arizona,* M.S. Thesis, Northern Arizona University, Flagstaff, Arizona.

Willet, S. D. and D. S. Chapman, 1987. Temperatures, Fluid Flow, and the Thermal History of the Uinta Basin. In B. Doligez, ed., *Migration of Hydrocarbons in Sedimentary Basins.* Paris, Editions Technip, p. 553–551.

Wilson, E. D., R. T. Moore, and R. T. O'Haire, 1960. Geologic Map of Navajo and Apache Counties, Arizona, Arizona Bureau of Mines, University of Arizona, Tucson, 1:375,000 scale.

Winston, D., 1990. Evidence for Intracratonic, Fluvial, and Lacustrine Settings of Middle to Late Proterozoic Basins of the Western U.S.A. In Gower, C. F., T. Rivers, and B. Ryan, eds., *Mid-Proterozoic Laurentia-Baltica.* Geological Association of Canada, Special Paper 38, p. 535–564.

Woodruff, E. G., 1912. Geology of the San Juan Oil Field, Utah, *USGS Bulletin 471*, p. 76–104.

Wrucke, C. T., 1989. The Middle Proterozoic Apache Group, Troy Quartzite, and Associated Diabase of Arizona. In J. P. Jenney and S. J. Reynolds, eds., *Geologic Evolution of Arizona,* Arizona Geological Society Digest 17, p. 239–258.