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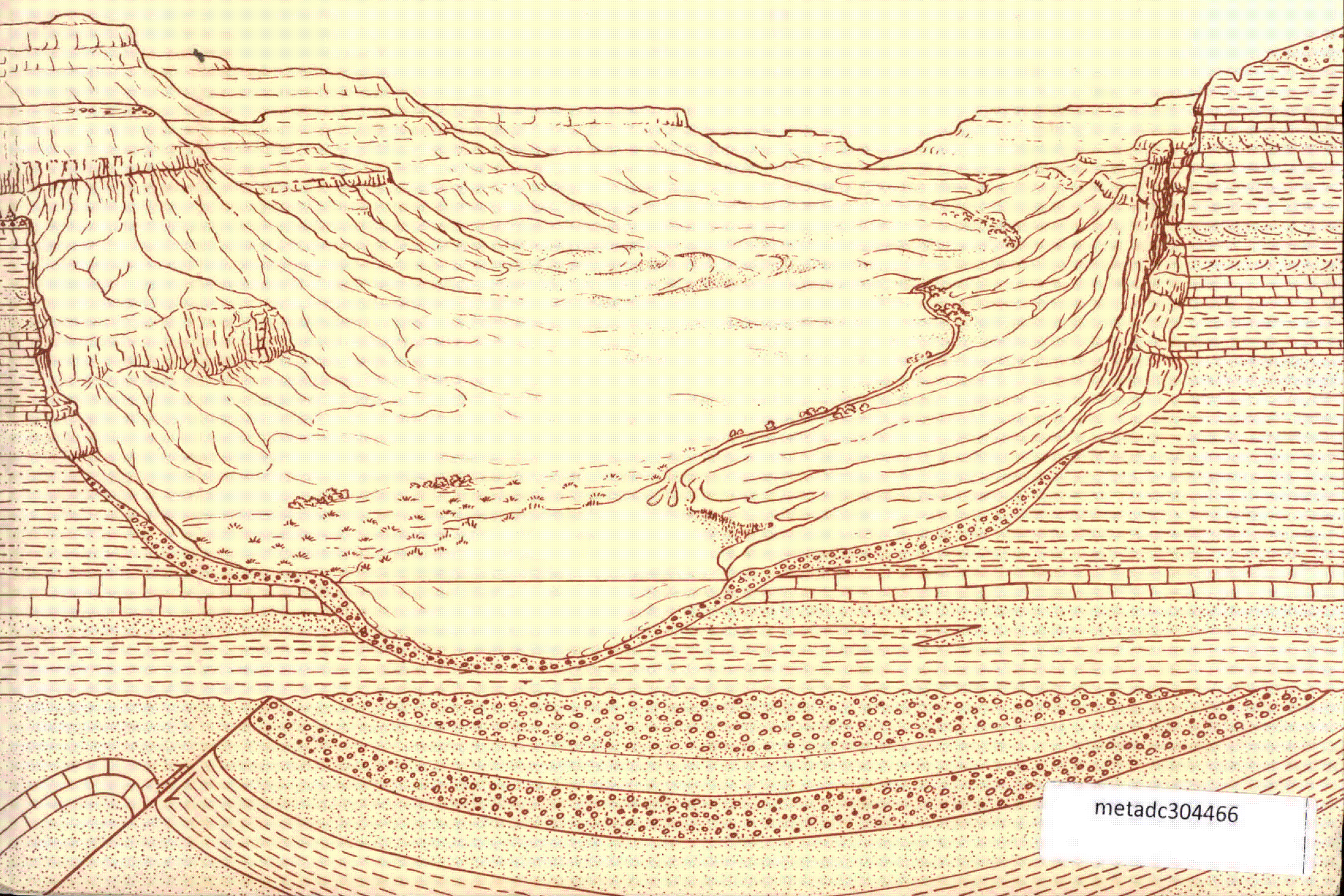

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By WILLIAM M. AUBREY

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By GARY SKIPP and W. M. AUBREY

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EVOLUTION OF SEDIMENTARY BASINS—SAN JUAN BASIN

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(J) New interpretations of the stratigraphy and sedimentology of uppermost Jurassic to lowermost Upper Cretaceous strata in the San Juan basin of northwestern New Mexico, by William M. Aubrey.

(K) X-ray diffraction studies of the <2-µm fraction from the upper part of the Brushy Basin Member of the Upper Jurassic Morrison Formation and the Lower Cretaceous Burro Canyon Formation in the Four Corners area, Colorado, by Gary Skipp and W.M. Aubrey.

Chapter J

New Interpretations of the Stratigraphy and Sedimentology of Uppermost Jurassic to Lowermost Upper Cretaceous Strata in the San Juan Basin of Northwestern New Mexico

By WILLIAM M. AUBREY

A multidisciplinary approach to research studies of sedimentary rocks and their constituents and the evolution of sedimentary basins, both ancient and modern

U.S. GEOLOGICAL SURVEY BULLETIN 1808

EVOLUTION OF SEDIMENTARY BASINS—SAN JUAN BASIN

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New Interpretations of the Stratigraphy and Sedimentology of Uppermost Jurassic to Lowermost Upper Cretaceous Strata in the San Juan Basin of Northwestern New Mexico

By William M. Aubrey

Abstract

Recent studies have led to several new interpretations of the stratigraphy and sedimentology of uppermost Jurassic to lowermost Upper Cretaceous rocks in the San Juan basin of western North America.

The Jackpile Sandstone Member of the Morrison Formation in the eastern part of the basin is tentatively correlated with the Burro Canyon (?) Formation in the Chama basin based on similar lithologic and fluvial characteristics and southerly paleocurrent directions. Both units consist of laterally extensive sandstone sheets and have generally scoured bases, although they probably locally interfinger with underlying lacustrine deposits in the Brushy Basin Member of the Morrison Formation.

In the northwestern part of the San Juan basin, more abundant and laterally extensive lenticular fluvial sandstones upward through the Brushy Basin–Burro Canyon interval suggest that the Brushy Basin saline lake in this part of the basin was gradually overwhelmed and filled by sediments of the Burro Canyon fluvial system. The boundary between the underlying lacustrine deposits of the Brushy Basin Member and the overlying fluvial deposits of the Burro Canyon Formation is arbitrary, and the fluvial sandstones could just as easily be included in the Morrison Formation. In particular, the Karla Kay Conglomerate Member of the Burro Canyon Formation, the stratigraphically lowest of the sandstones of the Burro Canyon in the northwestern part of the basin, has a strong affinity with the Morrison because it pinches out laterally into mudstones that are typical of the Brushy Basin lacustrine deposits and because it contains pebble suites typical of the Morrison. Stratigraphic relationships are not fully resolved; thus, the Karla Kay is not assigned to the Morrison in this report.

Fluvial rocks of the Encinal Canyon Member at the base of the Dakota Sandstone fill paleovalleys incised into underlying formations in the San Juan basin. In the southeastern part of the San Juan basin, the Encinal Canyon is truncated by a transgressive erosion surface at the base of the overlying marine Mancos Shale. To the northwest in the Four Corners area, however, the transgressive erosion surface is absent and fluvial strata of the upper part of the Dakota lie on the Encinal Canyon. Incision and backfilling of the paleovalleys is probably related to sea-level fluctuations in the Western Interior seaway.

Manuscript approved for publication January 28, 1991.

INTRODUCTION

This report summarizes the results of several studies concerning the stratigraphy and sedimentology of uppermost Jurassic to lowermost Upper Cretaceous rocks in the San Juan basin and adjacent areas (fig. 1). The Upper Jurassic to mid-Cretaceous interval, which is generally less than 150 m thick, consists primarily of sandstone and is bounded above and below by fine-grained strata. It is composed of part or all of several formations and represents a variety of alluvial and marginal-marine environments with complex facies relationships. Stratigraphic relationships between formations and facies relationships within formations are poorly understood, partly because facies in adjacent formations are commonly so similar that they are difficult to distinguish and partly because age-diagnostic fossils and isotopic dates with which to establish proper stratigraphic relationships are rare. Although reliable dates are lacking, detailed petrographic and sedimentologic studies presented here advance understanding of the

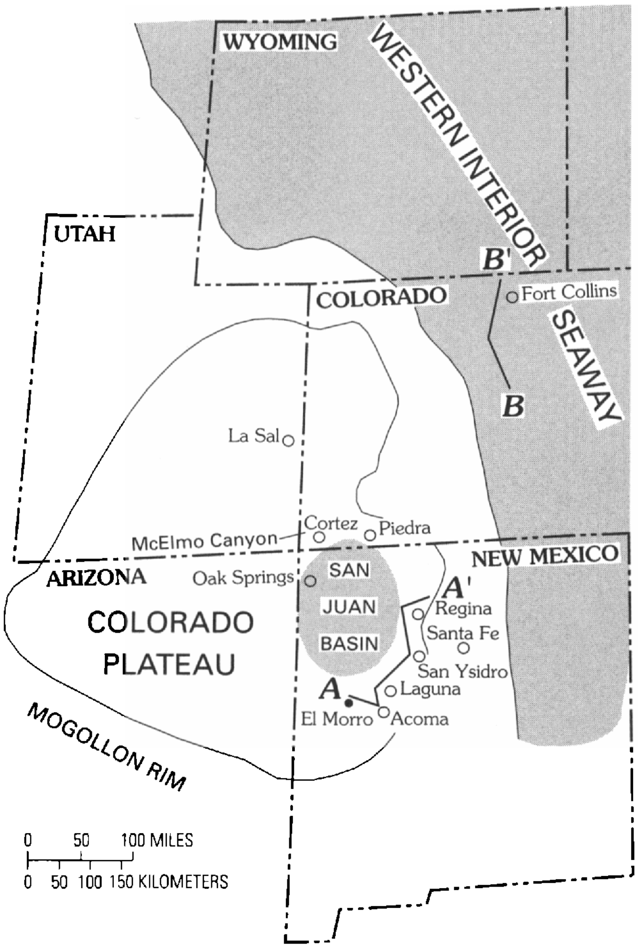


Figure 1. San Juan basin and surrounding areas in southeastern part of the Colorado Plateau (outlined). Screened area shows maximum extent of Western Interior seaway during Skull Creek (late Albian) transgression. Lines of section *A–A'* and *B–B'* (fig. 9) are also shown. Modified from McGookey (1977).

stratigraphy and depositional patterns of these rocks and the sedimentologic processes that occurred during their deposition.

These studies, which were part of the U.S. Geological Survey Evolution of Sedimentary Basins Program, were undertaken because the Upper Jurassic to mid-Cretaceous interval is of considerable economic importance. Uppermost Jurassic rocks in the southeastern part of the basin contain the Jackpile uranium deposit, one of the Nation's largest sedimentary uranium deposits, and mid-Cretaceous rocks in the northern part of the basin contain significant quantities of oil and gas.

PREVIOUS WORK

The predominantly sandstone interval discussed in this report includes the Jackpile Sandstone Member of the Morrison Formation, the Burro Canyon Formation, and the Dakota Sandstone (fig. 2). The interval is underlain by the Brushy Basin Member of the Morrison Formation and overlain by the Mancos Shale. A major regional unconformity occurs at the base of the Dakota Sandstone. The discussion that follows is based primarily on the earlier work of others. In later sections, I discuss stratigraphic and sedimentologic problems and present new interpretations.

Morrison Formation

The Upper Jurassic Morrison Formation in the San Juan basin is subdivided into four members, in ascending order, the Recapture, Westwater Canyon, Brushy Basin, and Jackpile Sandstone Members. The Recapture Member was deposited in eolian, lacustrine, and fluvial environments (Condon and Peterson, 1986) and the Westwater Canyon Member in an alluvial-plain environment (Turner-Peterson and others, 1980; Turner-Peterson, 1986). The Brushy Basin Member was deposited in a lacustrine environment and the Jackpile Sandstone Member in a fluvial environment; these latter two members are discussed in greater detail.

Brushy Basin Member

The Brushy Basin Member of the Morrison Formation, which includes the world's largest and oldest known playa-lake complex, was deposited in a basin that extended 500 km from the southern edge of the present-day San Juan basin to north of the present-day Uncompahgre uplift (fig. 7) and was approximately 300 km wide (Turner-Peterson and others, 1986). The Brushy Basin consists of green, olive, and maroon mudstone interbedded with tuff beds containing abundant ash that came from a magmatic arc several hundred kilometers to the west. Differential alteration of the ash due to salinity and alkalinity variations in the paleolake resulted in concentric zones of authigenic minerals (Bell, 1986; Turner-Peterson and others, 1986). Ash in tuff beds deposited in mudflats around the perimeter of the lake altered to bentonite, whereas ash in succeeding zones progressing toward the center of the lake typically altered to clinoptilolite, analcime, and albite. The bentonite beds generally are white, the clinoptilolite beds brick orange, and the analcime and albite beds dark green, bluish green, or olive. Beds that contain albite, analcime, and clinoptilolite form hard resistant layers because of abundant authigenic silica. Interbedded mudstone in the bentonite and clinoptilolite authigenic mineral facies is generally smectitic, whereas mudstone in the analcime and albite facies is generally illitic (C.E. Turner-Peterson, U.S. Geological Survey, oral commun., 1986). The smectitic beds swell when wet and have a "frothy" weathered appearance; in contrast, the nonsmectitic beds have a fissile or "hackly" weathered character (Ekren and Houser, 1959). In the

System	Series	Four Corners Area		Chama Basin		Southeastern San Juan Basin
Cretaceous (part)	Upper (part)	Mancos Shale		Mancos Shale		Mancos Shale
		Dakota Sandstone	Main body (fluvial)	Dakota Sandstone	Main body (marginal marine)	Intertonguing Mancos Shale and shelf sandstones of the Dakota Sandstone
			Encinal Canyon Member		Encinal Canyon Member	Encinal Canyon Member of the Dakota Sandstone
	Lower	Burro Canyon Formation		Burro Canyon (?) Formation		Jackpile Sandstone Member of the Morrison Formation
? Jurassic (part)	? Upper (part)	Brushy Basin Member of the Morrison Formation		Brushy Basin Member of the Morrison Formation		Brushy Basin Member of the Morrison Formation

Figure 2. Correlation chart of Upper Jurassic to mid-Cretaceous rock units for several locations in San Juan basin. Stratigraphic and age relationships for Burro Canyon Formation, Burro Canyon (?) Formation, and Jackpile Sandstone Member of Morrison Formation are tentative.

southern part of the San Juan basin, fluvial channel sandstones are locally interbedded with lacustrine deposits of the Brushy Basin Member (Bell, 1986). The Brushy Basin averages about 75 m in thickness in the basin (C.E. Turner-Peterson, oral commun., 1989).

Jackpile Sandstone Member

The Jackpile Sandstone Member of the Morrison Formation (Freeman and Hilpert, 1956; Owen and others, 1984) overlies the Brushy Basin Member in the southeastern part of the San Juan basin. The Jackpile is made up of white, kaolinitic, fine- to medium-grained, crossbedded, fluvial sandstone and thin interbeds of pale-green mudstone and siltstone. In the Laguna area, it is as thick as 70 m and occupies a northeasterly trending downwarped zone that is about 16 km wide and at least 50 km long (Granger, 1968). Along the western edge of the Nacimiento uplift (fig. 7), the Jackpile is as thick as 50 m. It is locally absent, however, in the Majors Ranch area between Laguna and the Nacimiento uplift (Santos, 1975). Although the base of the Jackpile Sandstone Member is generally a scoured surface, the Jackpile is thought to locally intertongue with underlying mudstone of the Brushy Basin Member (Beck and others, 1980).

Burro Canyon Formation

A fluvial sandstone unit that is lithologically similar to the Jackpile (Owen and Siemers, 1977) occupies the same stratigraphic position above the Brushy Basin in the northeastern part of the San Juan basin and the neighboring Chama basin (figs. 2, 4, 7) as the Jackpile in the southeastern part of the San Juan basin. This unit is generally considered, however, to be equivalent to the Burro Canyon Formation in southwestern Colorado (McPeek, 1965; Saucier, 1974; Ridgley, 1977, 1979, 1987). It is tan, kaolinitic, fine to medium grained and locally conglomeratic, and crossbedded and contains interbeds of green and red mudstone and siltstone. The conglomerate is characterized by tan, gray, white, and cream chert and cherty limestone pebbles (Ridgley, 1977); the most common chert pebbles are tan, nonporous, and somewhat earthy looking (Aubrey, 1988a). The Burro Canyon (?) in the Chama basin is from about 15 to 60 m thick (Ridgley, 1983a, b, c). Its basal contact with the underlying Brushy Basin Member is generally sharp and is thought to be unconformable by some workers (Saucier, 1974; Ridgley, 1983a, b, c, 1987).

Mudstone and interbedded lenticular, conglomeratic, fluvial, channel sandstone at or near the top of the Brushy Basin Member near Four Corners have also been included in the Burro Canyon Formation by some workers (Ekren and Houser, 1959, 1965). Mudstone included in the Burro Canyon is generally green, olive or maroon, nonsmectitic, and hackly or fissile weathering (Ekren and Houser, 1959, 1965). The channel sandstone bodies are composed of fine- to coarse-grained sandstone and conglomeratic sandstone and conglomerate that contain pebbles of varicolored chert, quartzite, silicified limestone, and siltstone. The sandstone bodies are more numerous, less coarse, and more laterally extensive in the upper part of the Brushy Basin–Burro Canyon interval than in the lower part. The lowest channel sandstone unit, the Karla Kay Conglomerate Member of the Burro Canyon Formation (Ekren and Houser, 1959, 1965), consists of dendritic shoestring channel deposits that are as much as 600 m wide and 20 m thick (Ekren and Houser, 1959).

The Burro Canyon and Morrison Formations are thought to interfinger in the Four Corners area (Ekren and Houser, 1959, 1965) because the channel sandstone bodies are interbedded with both hackly weathering nonsmectitic mudstone (included in the Burro Canyon Formation) and frothy weathering smectitic mudstone (included in the Brushy Basin Member). The lower contact of the Burro Canyon is placed at the base of the lowest sandstone or at the base of the lowest hackly weathering mudstone (Ekren and Houser, 1959, 1965). Consequently, the thickness of the Burro Canyon in the area is highly variable and can change drastically within a few tens of meters; maximum thickness in the Four Corners area is about 45 m.

Sub-Dakota Unconformity

The sub-Dakota unconformity is a major regional unconformity throughout the southeastern Colorado Plateau (fig. 1). It is slightly angular along the southern margin of the plateau, including the southern and western parts of the San Juan basin where the Dakota Sandstone progressively overlies older Jurassic, Triassic, and Paleozoic rocks to the south. In most of the rest of the plateau, the Dakota disconformably overlies either the upper part of the Morrison Formation (McGookey and others, 1972) or the Burro Canyon Formation (Stokes, 1952; Craig and others, 1955; Carter, 1957; Quigley, 1959; Craig, 1981).

The southern margin of the Colorado Plateau is commonly assumed to have been uplifted and tilted to the north during the Early Cretaceous after deposition of the Upper Jurassic Morrison Formation and before deposition of the Upper Cretaceous Dakota Sandstone (Owen, 1982). Uplift is thought to have been centered in the area south of the Mogollon rim (fig. 7) in central Arizona and southwestern New Mexico. Erosion accompanying uplift is believed to have been responsible for truncation of the Morrison and older rocks to the south.

Dakota Sandstone

The Dakota Sandstone was deposited in response to the westward transgression of the Western Interior sea across the region. Although several minor regressions occurred during deposition, overall the Dakota has a transgressive character.

The formation represents a complex variety of continental, marginal-marine, and marine environments. It is generally thought to be composed of almost entirely continental strata in the northwestern part of the basin and mostly marine strata in the southeastern part (Owen, 1973). Where present, continental strata are overlain by marginal-marine or marine rocks.

The areal distribution of various ammonite species can be used to outline approximate shoreline positions (fig. 3) during deposition of the Dakota in the middle to late Cenomanian (earliest Late Cretaceous) (Cobban and Hook, 1984). During the middle Cenomanian, a large marine bay, the Seboyeta bay (Hook and others, 1980), covered much of northwestern New Mexico including the southeastern part of the San Juan basin. Marine strata in the area of the bay consist of several Dakota shoreface or shelf sandstones (Nummedal and Swift, 1987) that intertongue with the marine Mancos Shale. In ascending order, these sandstones are the Cubero, Paguate, and Twowells Tongues of the Dakota Sandstone (Landis and others, 1973). The Cubero and Paguate, which are middle Cenomanian in age, are restricted to the area of Seboyeta bay; the Paguate Tongue is present over a larger area than the stratigraphically lower Cubero Tongue because of bay expansion during the middle Cenomanian (Hook and others, 1980). As the shoreline transgressed westward, it became straighter and the bay less distinct (fig. 3). The Twowells Tongue, which is late Cenomanian in age, is not restricted to the area of the bay and is present locally in eastern Utah and Arizona and southwestern Colorado, as well as in northwestern New Mexico.

In southeastern Utah and southwesternmost Colorado, the Dakota consists primarily of ribbon-type fluvial sandstone bodies and carbonaceous paludal shale deposited in coastal-plain or deltaic environments (Owen, 1973; Aubrey, 1988b). These rocks, which are probably laterally equivalent to the marine shelf sandstone and marine shale of Seyboyeta bay, were deposited as the westward advance

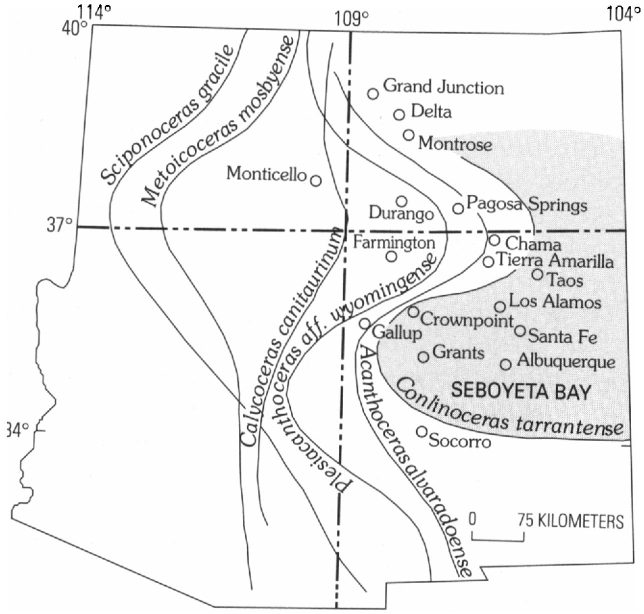


Figure 3. Shoreline positions on west side of Western Interior seaway during deposition of upper part of Dakota Sandstone in middle and late Cenomanian time. Shoreline positions are based on distribution of ammonite fossils in lower part of marine Mancos Shale and interfingering Dakota shelf or shoreface sandstones. Screened area represents ancient Seboyeta bay during early Cenomanian time. Modified from Cobban and Hook (1984).

of the shoreline across the region slowed or paused. The fluvial Dakota, which comprises almost all of the Dakota in the northwestern part of the San Juan basin, is as thick as 45 m. Dakota shelf sandstones and interfingering Mancos shales in the southeastern part of the basin are about 110 m thick. Because the uppermost shelf sandstone, the Twowells Tongue of the Dakota, onlaps fluvial rocks in the northwestern part of the basin, the total stratigraphic rise of the base of marine shale across the basin is about 110 m (Molenaar, 1977).

Mancos Shale

The marine Mancos Shale was deposited on the Dakota as the Western Interior sea transgressed across the region. The Mancos consists of generally gray to dark-gray gypsiferous shale and is as thick as 680 m in the San Juan basin.

STRATIGRAPHIC RELATIONS OF MORRISON AND BURRO CANYON FORMATIONS

East Side of the Basin

The relationship between fluvial rocks of the Burro Canyon (?) Formation in the Chama basin and the Jackpile Sandstone Member of the Morrison Formation southwest of the Chama basin on the western margin of the Nacimiento uplift is problematic. The units occupy the same stratigraphic position between the Brushy Basin Member of the Morrison Formation and the Dakota Sandstone and are lithologically similar fine- to medium-grained fluvial sandstones (Owen and Siemers, 1977). The Jackpile, however, is generally considered to be latest Jurassic in age, and the Burro Canyon (?) must be considered late Early Cretaceous in age (Stokes, 1952; Tschudy and others, 1984) if it correlates with type Burro Canyon in southwestern Colorado (McPeek, 1965; Saucier, 1974; Ridgley, 1977, 1987). This apparent age difference suggests that the Burro Canyon (?) and Jackpile are two separate units somehow separated by a major unconformity, but age-diagnostic fossils have not been reported from either the Burro Canyon (?) or the Jackpile in the San Juan basin region and their relative ages within the Late Jurassic to Early Cretaceous time interval are unknown. An isotopic age of 146±34 m.y. from early diagenetic clays in the Jackpile Sandstone Member (Lee and Brookins, 1978; modified by Ludwig, 1980) indicates only that diagenesis occurred sometime during the Late Jurassic or Early Cretaceous (Ludwig, 1980).

Santos (1975) correlated the Jackpile Sandstone Member in the Laguna area with the sandstone between the Brushy Basin Member and the Dakota Sandstone as far north as Cuba on the east side of the basin. Saucier (1974) extended the Burro Canyon designation for this interval from the Chama basin as far south as La Ventana about 22 km south of Cuba. Saucier (1974) thought that the Burro Canyon along the east side of the San Juan basin could be differentiated from the Jackpile chiefly because the Burro Canyon has a generally sharp erosional basal contact and is locally conglomeratic and the Jackpile has a gradational but locally erosional contact and lacks conglomerate except for a few pebbles locally near its base.

I believe, however, that the Jackpile Sandstone Member and the unit called the Burro Canyon (?) Formation in the eastern San Juan basin region may be the same formation and will henceforth refer to that formation as the Jackpile–Burro Canyon (?) interval in this paper. Detailed measured sections of the Jackpile–Burro Canyon (?) interval south of Cuba (sections 3–8, plate 1) (also see Aubrey, 1988a) provide no evidence for a major break or unconformity between the Jackpile and Burro Canyon (?) as suggested by Saucier (1974). Walking out the interval between sections has revealed the presence of local scour surfaces, typical of fluvial sandstone, but they do not appear to mark a significant break in the record. The interval, therefore, probably represents a single, depositionally continuous fluvial unit. Detailed field descriptions (Aubrey, 1988a) of measured sections (sections 1–12, plate 1) suggest, as do previous studies (Owens and others, 1975; (Owen and Siemers, 1977), that except for differences in the amounts of pebbles the Jackpile and Burro Canyon (?) are lithologically similar fine- to medium-grained quartzose sandstone. No detailed comparative petrographic studies, however, have been made.

The base of the Burro Canyon (?), like the base of most fluvial sandstones, is commonly scoured and thus is generally thought to be an unconformity (Ridgley, 1987). The Burro Canyon (?), however, like the Jackpile locally grades into or interfingers with the underlying Brushy Basin Member and thus may be conformable. Near Dead Mans Peak in the Chama basin (NE¼ sec. 7, T. 25 N., R. 2 E.), a thin sandstone tongue within the green fine-grained facies of the upper part of the Brushy Basin grades laterally into the main body of the Burro Canyon (?). The basal contact in the Dead Mans Peak area generally is a scour surface, but locally is gradational. Sandstone beds in the upper part of the Brushy Basin Member in the Elk Spring section (plate 1) south of Cuba resemble those in the overlying Burro Canyon (?) (of Saucier, 1974), especially in the composition of the pebbles they contain (Aubrey, 1988a). These beds may be a tongue of Burro Canyon (?) that interfingers with the Brushy Basin.

Paleocurrent directions from the Chama basin and the east side of the San Juan basin south of Cuba suggest a northwesterly source area for the Jackpile–Burro Canyon (?) interval. Trough axes measured in this study from individual channel sandstones in the Burro Canyon (?) in the Chama basin trend predominantly to the southeast; those of some channel sandstones, however, trend east or north (fig. 4). Paleocurrent measurements from fluvial beds in the Jackpile south of Cuba generally trend southeasterly (Santos, 1975), although locally near San Ysidro some beds trend northeasterly and the overall trend is to the east (Flesch, 1974). Trough axes measured in this study from the area south of Cuba also indicate a generally southeasterly flow direction for Jackpile paleostreams (fig. 4). Southeasterly paleoflow directions on the east side of the San Juan basin are consistent with southeasterly paleoflow directions measured by Turmelle (1979) in the Burro Canyon on the north side of the basin.

A northern or northwesterly source direction would explain the decrease in the number of conglomerate and conglomeratic sandstone beds between the Burro Canyon (?) of the Chama basin and the Jackpile at the southern part of the Nacimiento uplift (plate 1). The Jackpile may lack conglomeratic beds simply because it represents a more distal part of the Jackpile–Burro Canyon (?) fluvial system.

Northwestern Part of the Basin

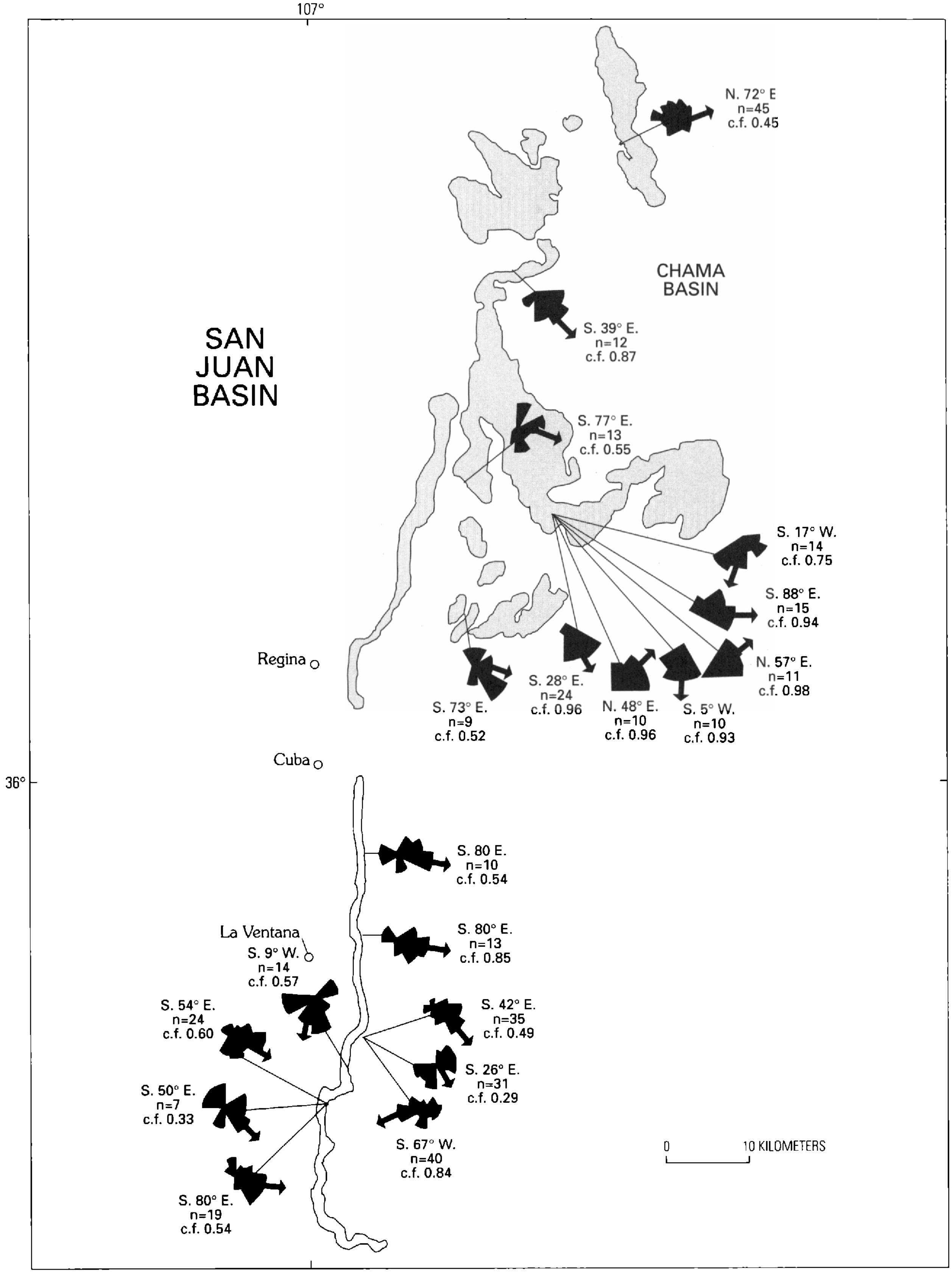
Lenticular sandstones of the Burro Canyon in the northwestern part of the San Juan basin (Ekren and Houser, 1959, 1965) become more abundant and laterally extensive toward the top of the section and were probably deposited by a fluvial system that gradually overwhelmed and finally filled in the Brushy Basin lake. Saline lake conditions still existed when the Karla Kay Conglomerate Member and other stratigraphically low conglomeratic sandstones in the Burro Canyon were deposited. These sandstones are present laterally to mudstone containing bentonite beds, thin green hard beds, and possible clinoptilolite typical of the Brushy Basin lacustrine deposits (compare sections 1 and 1a, which are only about 100 m apart, plate 2).

During deposition of rocks higher in the section, where sandstones of the Burro Canyon are much more laterally extensive, fluvial conditions probably prevailed. Mudstones interbedded with these stratigraphically higher Burro Canyon sandstones contain thin hard beds almost identical in appearance with altered tuff beds in the Brushy Basin lacustrine deposits but different in composition. The thin beds are composed mostly of silica and do not contain diagenetic zeolites or feldspars that characterize the altered tuff beds in the saline lake deposits. Nonetheless, abundant silica, euhedral zircons (fig. 5), uniform thickness, and wide lateral extent suggest that they may also be altered tuffs. Differences in composition between the Brushy Basin and stratigraphically higher hard layers may reflect changes in pore water chemistry that occurred as fluvial conditions replaced those of the saline alkaline lake.

Ekren and Houser (1959, 1965) thought that all mudstones in the Brushy Basin Member of the Morrison Formation were smectitic and all those in the Burro Canyon Formation nonsmectitic. They used this guide to distinguish between the Burro Canyon and Morrison Formations in the Four Corners area, and they interpreted alternating smectitic and nonsmectitic mudstone beds as interfingering of the two formations.

Recent work, however, indicates that the Brushy Basin Member contains both smectitic and nonsmectitic mudstone (C.E. Turner-Peterson, oral commun., 1986) and that sandstone of the Burro Canyon near Four Corners, especially in the lower part of the section, is interbedded with and lateral to smectitic mudstone. McElmo Canyon, where Ekren and Houser (1959, 1965) did extensive mapping, is between the smectitic clinoptilolite facies to the west and the nonsmectitic analcime facies to the east (C.E. Turner-Peterson, oral commun., 1986). At least in the lower part of the section, where saline alkaline lake conditions existed, alternating smectitic and nonsmectitic beds may be better explained by lateral interfingering of the clinoptilolite and analcime facies within the Brushy Basin than by

Figure 4 (facing page). Paleocurrent directions for Jackpile–Burro Canyon (?) interval on east side of San Juan basin and in neighboring Chama basin. Number of data points (n) and consistency factor (c.f.) are also shown. Rose diagrams represent trough axes from individual channel sandstones. All but three resultant vectors have a south component. Screened areas are undifferentiated Dakota Sandstone and Burro Canyon (?) Formation.


107°
36°
N. 72° E
n=45
c.f. 0.45
CHAMA
BASIN
SAN
JUAN
BASIN
S. 39° E.
n=12
c.f. 0.87
S. 77° E.
n=13
c.f. 0.55
S. 17° W.
n=14
c.f. 0.75
S. 88° E.
n=15
c.f. 0.94
N. 57° E.
n=11
c.f. 0.98
Regina
S. 73° E.
n=9
c.f. 0.52
S. 28° E.
n=24
c.f. 0.96
N. 48° E.
n=10
c.f. 0.96
S. 5° W.
n=10
c.f. 0.93
Cuba
S. 80 E.
n=10
c.f. 0.54
La Ventana
S. 9° W.
n=14
c.f. 0.57
S. 80° E.
n=13
c.f. 0.85
S. 54° E.
n=24
c.f. 0.60
S. 42° E.
n=35
c.f. 0.49
S. 26° E.
n=31
c.f. 0.29
S. 50° E.
n=7
c.f. 0.33
S. 67° W.
n=40
c.f. 0.84
0
10 KILOMETERS
S. 80° E.
n=19
c.f. 0.54

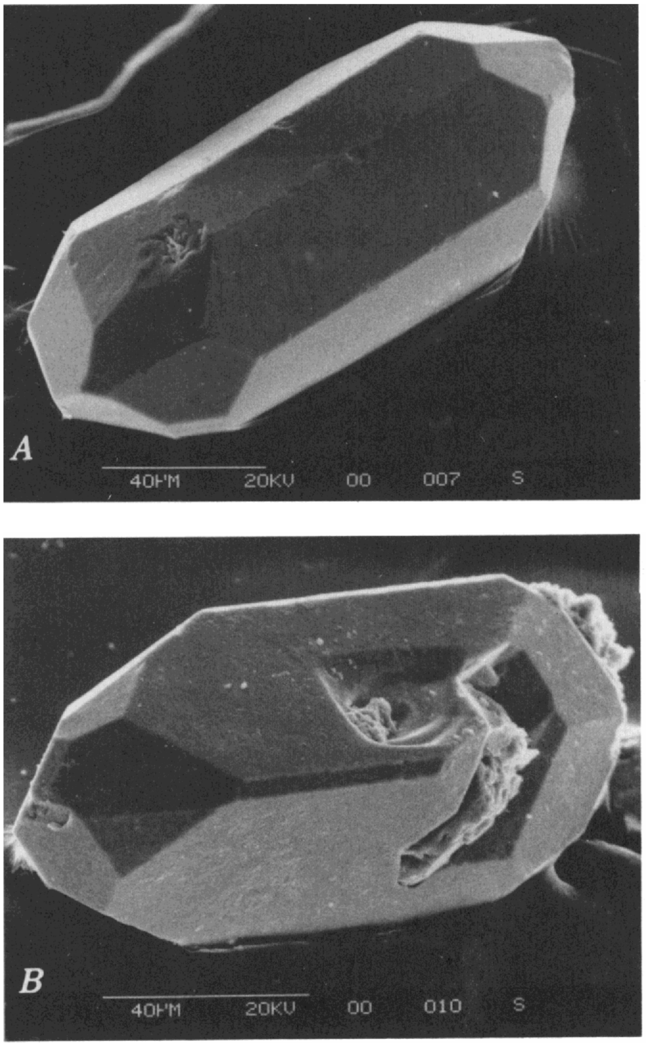


Figure 5. Scanning electron microscope photographs showing euhedral zircons from hard siliceous beds that are interbedded with sandstones of Burro Canyon Formation. *A*, Near Piedra, Colo. *B*, McElmo Canyon, Colo.

interfingering of the Brushy Basin and overlying Burro Canyon.

Palynomorphs from the upper part of the Burro Canyon Formation about 50 km north of McElmo Canyon indicate a late Early Cretaceous age (Tschudy and others, 1984). The Burro Canyon in the McElmo Canyon area grades into the underlying Brushy Basin Member, which is generally considered late Jurassic in age. Conceivably then, the Burro Canyon in McElmo Canyon could represent all of the Early Cretaceous, or about 40 m.y. (Tschudy and others, 1984). Lack of age data from the Brushy Basin Member and from the Burro Canyon in the northwestern part of the basin, however, makes tenuous any finer age designation than sometime in the latest Jurassic–Early Cretaceous interval.

The boundary between the Brushy Basin Member of the Morrison Formation and the Burro Canyon Formation in the northwestern part of the San Juan basin is arbitrary because of the apparent gradational relationship between lacustrine and overlying fluvial strata. The fluvial sandstones in this area could just as easily be included in the Morrison instead of the Burro Canyon. In particular, the lowest of the fluvial sandstones, the Karla Kay Conglomerate Member, has an affinity to the Morrison Formation because it is within fine-grained facies typical of the Brushy Basin lake deposits and because it locally contains brightly colored chert pebbles and granules that are typical of the Morrison Formation (Fred Peterson, U.S. Geological Survey, oral commun., 1989). Stratigraphic relationships are not yet fully resolved, however, and the Karla Kay is not assigned to the Morrison in this report.

Outcrop patterns and trough axes from the Karla Kay in McElmo Canyon indicate easterly, southeasterly, and northeasterly paleoflow directions (fig. 6). These directions are similar to those in the Jackpile–Burro Canyon (?) interval in the Chama basin. Paleoflow directions from the Burro Canyon Formation in southeastern Utah and west-central Colorado, however, are to the northeast (Craig, 1981).

Rocks included in the Burro Canyon Formation in the Four Corners area have a markedly different architectural style than those in the Chama basin. The Burro Canyon in the Four Corners area is composed of lenticular ribbon sandstone encased in mudstone and siltstone, whereas the Burro Canyon (?) in the Chama basin consists of thick sheetlike sandstone deposits that contain a few thin, fine-grained lenses (Ridgley, 1987). Although both units may be conformable with the underlying Brushy Basin Member of the Morrison Formation, their different architectural styles and the lack of age data make stratigraphic relations uncertain.

Karla Kay Conglomerate Member Near Oak Springs

The conglomeratic sandstone that caps the mesa at Oak Springs (fig. 1) on the west side of the San Juan basin is generally and probably incorrectly thought to be part of the Dakota Sandstone. Instead, it probably correlates with the Karla Kay Conglomerate Member of the Burro Canyon Formation in McElmo Canyon. Both units are about 60 m above the base of the Brushy Basin Member and contain distinctive granules and small pebbles of purple, red, and green chert. Both are characterized by abundant petrified wood, chalcedony cement that fills larger than grain size areas, and fine-grained olive-green intraclasts and beds. Quartz overgrowths and carbonaceous plant debris, typical of sandstone in the Dakota, were not found.

Sixteen measurements of trough axes from the conglomeratic sandstone at the top of the mesa at Oak Springs indicate a paleoflow direction of S. 19° E. (consistency factor 0.92), consistent with paleoflow directions in the Karla Kay in McElmo Canyon.

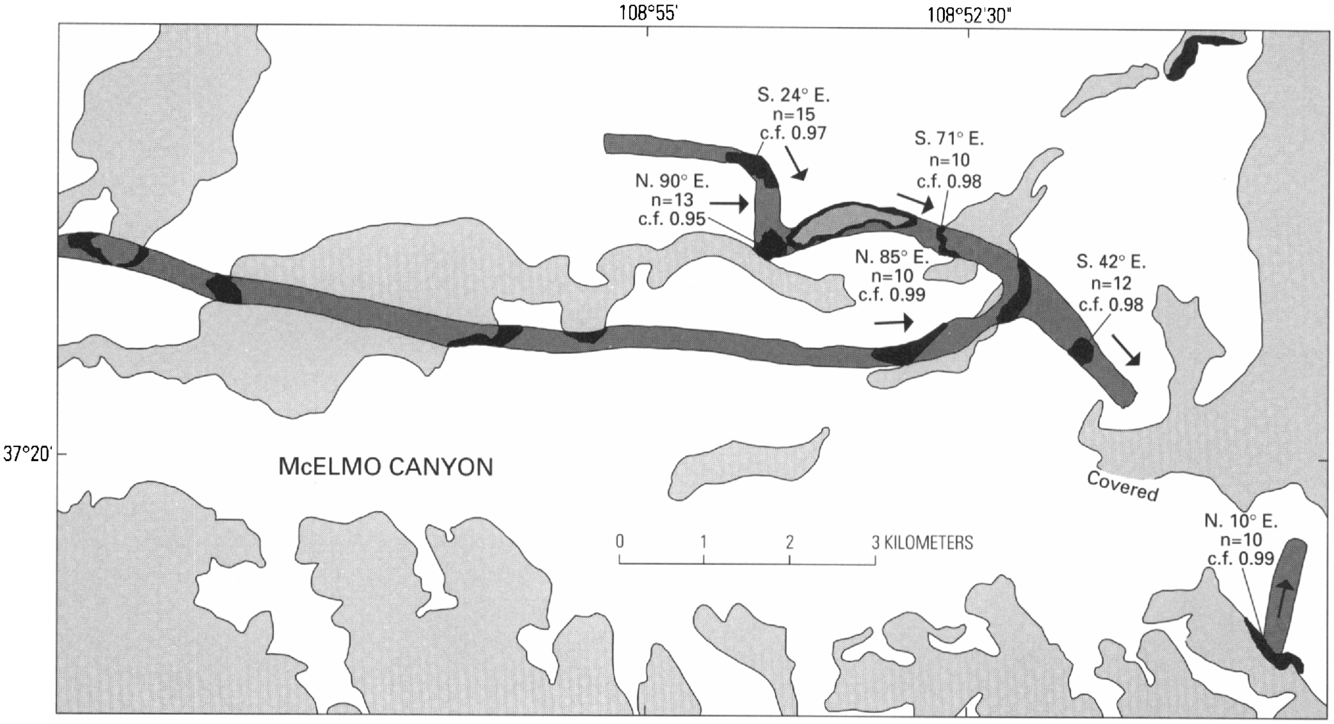


Figure 6. Outcrops of Karla Kay Conglomerate Member of Burro Canyon Formation (shown in black) (Ekren and Houser, 1965) and Karla Kay channels (dark screen) in McElmo Canyon area. Channel fill between outcrops has been undercut, but channel locations are commonly marked by large blocks of Karla Kay lying on underlying less resistant mudstone. Average paleocurrent directions for Karla Kay, including number of data points (n) and consistency factor (c.f.), are shown at several locations. Light screened areas are outcrops of Burro Canyon Formation and Dakota Sandstone (Ekren and Houser, 1965).

DAKOTA SANDSTONE

Timing of Pre-Dakota Erosion

Uplift and erosion responsible for the angular unconformity at the base of the Dakota Sandstone are generally considered to have occurred during the Early Cretaceous. Unconformities in Jurassic sections that onlap positive areas along the southern margin of the Colorado Plateau (Dobrovolny and Summerson, 1946; Silver, 1948; Maxwell, 1976, 1982; Peterson, 1986) indicate, however, that the southern plateau region was tectonically active during the Jurassic. This Jurassic tectonic activity is probably at least partly responsible for the slight angularity of the unconformity at the base of the Dakota in that region. Locally in the area of the Defiance uplift on the west side of the San Juan basin, uplift and erosion occurred during some part of the Early Cretaceous, after deposition of the Morrison Formation and before deposition of the Dakota Sandstone. Stratigraphic sections (fig. 7) on the south and west sides of the basin indicate that Morrison strata were uplifted and tilted to the east and north, away from the southwestern part of the basin (Condon and Peterson, 1986). The Morrison in this area was eroded and subsequently overlain by the Dakota Sandstone.

Incised Paleodrainage Surface

Lowering of base level near the end of the Early Cretaceous caused streams in the southeastern plateau region to incise a drainage surface that is preserved beneath the Dakota Sandstone, both in the north where the basal Dakota unconformity is disconformable and in the south where it is angular. Depth of incision generally ranges from less than a meter to approximately 15 m but is 30 m or more in some places (fig. 8) (Carter, 1957; Maxwell, 1976; Aubrey, 1986a, 1988a, c). Locally, as much as 12–15 m of relief occurs laterally within a few tens of meters. Paleovalleys are from several hundreds of meters to several kilometers wide and of unknown length (Carter, 1957; Maxwell, 1976; Aubrey, 1986a, 1988c) and generally trend northeast (Carter, 1957; Maxwell, 1976) or east.

In the San Juan basin the deepest known valley is about 30 m deep and is on the east side of the basin near Regina (plate 1). In the southern part of the basin the deepest known valleys are about 20 m deep (fig. 8) and in the northern part about 15 m deep.

Basal Dakota streams degraded into bedrock along the southern margin of the basin. Clasts of the Middle to Upper Jurassic Zuni Sandstone of Maxwell (1976) are

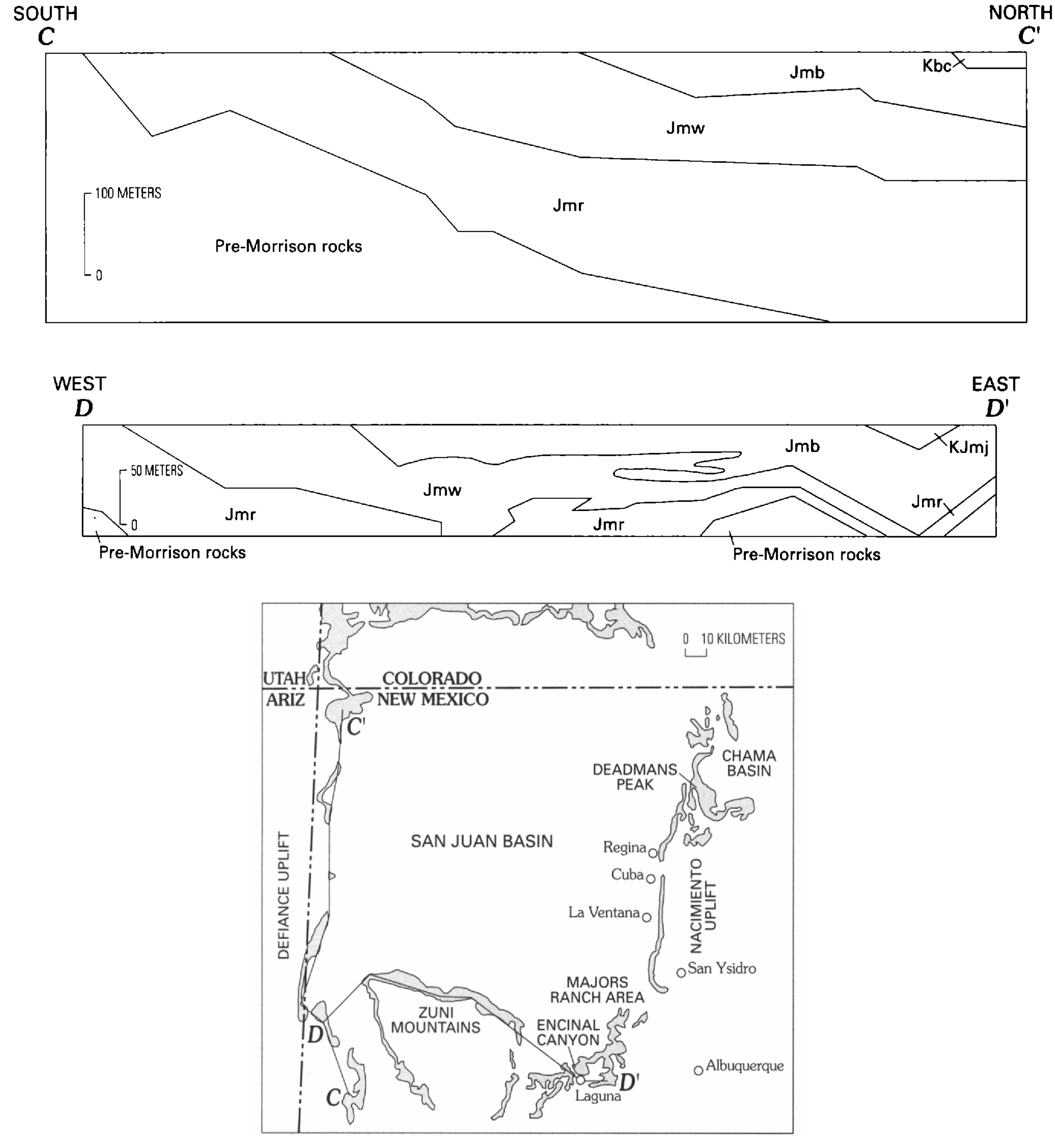


Figure 7. Stratigraphic sections showing tilt of members of Morrison Formation to north and east away from southwestern corner of San Juan basin. Jmr, Recapture Member of Morrison Formation; Jmw, Westwater Member of Morrison Formation; Jmb, Brushy Basin Member of Morrison Formation; KJmj, Jackpile Sandstone Member of Morrison Formation; Kbc, Burro Canyon Formation. Modified from Condon and Peterson (1986). Screened areas on index map are outcrops of Dakota Sandstone.

present in the basal conglomerate of the Dakota at El Morro (fig. 1). Valleys at the base of the Dakota have been cut into Triassic rocks south of Acoma (Maxwell, 1976, 1982).

Alluvial-plain deposits of the Burro Canyon Formation in the northern part of the San Juan basin, eastern Utah, and western Colorado probably were at least partly indurated at the time of incision. Resistant sandstone cobbles and boulders in the basal part of the Dakota Sandstone in eastern Utah and western Colorado probably were derived from the underlying Burro Canyon Formation (Carter, 1957). Clasts of Burro Canyon in the basal Dakota do not necessarily imply, however, that much time passed

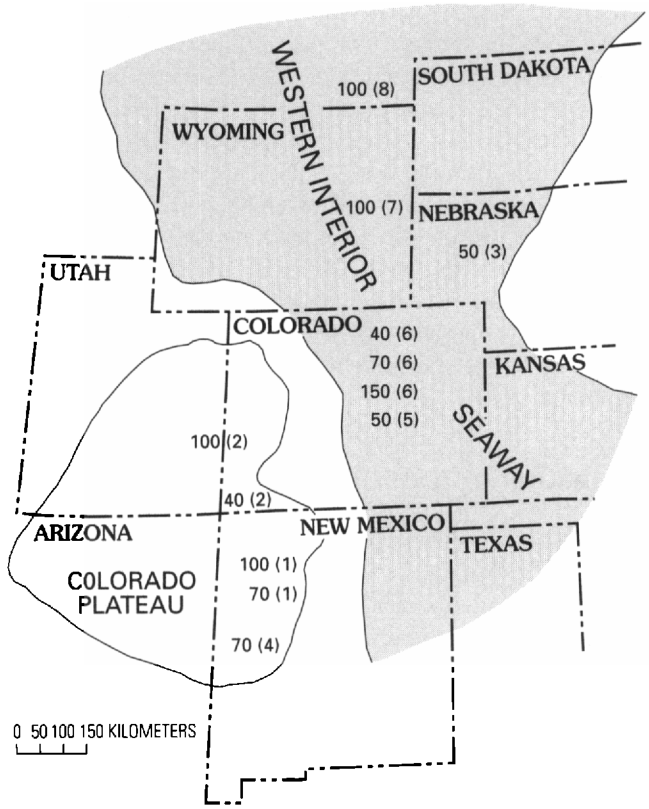


Figure 8. Maximum known depths of incision (in meters) at base of Encinal Canyon Member of Dakota Sandstone (Colorado Plateau) or Horsetooth Member of Muddy Sandstone (Western Interior seaway). Number in parentheses indicates source of data: (1) This study; (2) Carter (1957); (3) Harms (1966); (4) Maxwell (1976); (5) Waage (1953); (6) Weimer (1983); (7) Weimer and others (1982); (8) R.J. Weimer (Colorado School of Mines, oral commun., 1987). Relationship between location of present-day Colorado Plateau and late Albian Western Interior seaway at peak of Skull Creek transgression is also shown (modified from McGookey and others, 1972). Convergence of Colorado Plateau with continental interior during Laramide orogeny probably caused crustal shortening (Hamilton, 1981), which reduced original distance between the plateau and the seaway.

between deposition of the Burro Canyon and Dakota. Abundant minus-cement or primary porosity filled with authigenic chalcedony in a clast from the Cortez area indicates that induration could have occurred early in the history of the rock.

Valley Fill

The incised valleys at the base of the Dakota are filled with strata of the Encinal Canyon Member (plate 1), a recently recognized unit at the base of the Dakota Sandstone in the southeastern part of the San Juan basin (Aubrey, 1986a, b, 1988c, 1989). The Encinal Canyon (fig. 9) consists primarily of gray or brown, quartzose, fine- to medium-grained, locally carbonaceous, crossbedded sandstone that is commonly conglomeratic, especially at its base. It typically is trough crossbedded, but some tabular-planar crossbeds and, more rarely, horizontal or low-angle laminations are present at most locations. Massive to horizontally stratified conglomeratic beds and crudely stratified sandstone beds also are present locally.

Abundant white chalky chert is a distinctive characteristic of the Encinal Canyon Member in the southeastern part of the basin (Aubrey, 1986a). The chert has uneven or rough fracture surfaces and generally is finely porous, pulverulent, and dull or earthy. The chert clasts are subangular to angular and generally range in size from very coarse sand to large pebbles. The brilliant white color and angularity give the chalky chert a unique appearance, especially on freshly broken surfaces. This type of chert is less common in other parts of the basin.

The angular, irregular shape of the chert fragments suggests short-distance transport in the high-energy fluvial environment in which they were deposited, but no source for the chalky chert is apparent in underlying strata.

An absence of lateral accretion surfaces, abandoned channel-fill deposits, and fine-grained overbank deposits suggests that the Encinal Canyon Member was deposited by braided streams. In the eastern part of the basin, however,

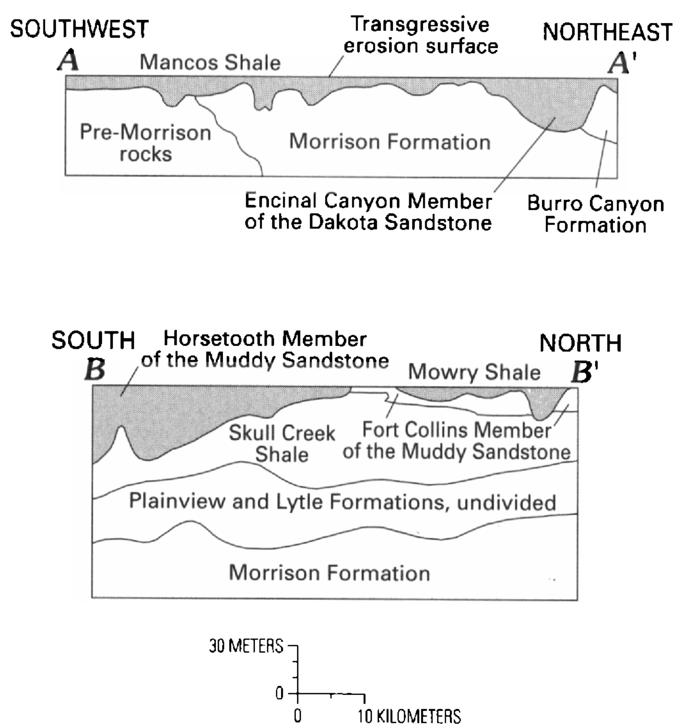


Figure 9. Stratigraphic sections showing incised valleys in southeastern part of San Juan basin and central Colorado. Lines of section shown in figure 1. *A–A'*, Valleys at base of Encinal Canyon Member of Dakota Sandstone incised into continental rocks of Morrison and Burro Canyon Formations in southeastern San Juan basin. Modified from Aubrey (1989). *B–B'*, Valleys at base of Horsetooth Member of Muddy Sandstone incised into marine and marginal-marine rocks of Skull Creek Shale and Fort Collins Member of Muddy Sandstone in central Colorado. Modified from Weimer (1983).

the upper part of the Encinal Canyon contains paralic and marginal-marine rocks that are transitional between underlying fluvial valley-fill deposits and the overlying marine Mancos Shale (Aubrey, 1989). Rip-up clasts of carbonaceous shale at the base of a channelized sandstone in the upper part of the Encinal Canyon near Regina contain dinoflagellates (D.J. Nichols and F.H. Wingate, U.S. Geological Survey, written commun., 1988) that indicate a near-shore environment. Thin coal beds in the Encinal Canyon near San Ysidro (Aubrey, 1988a) were probably deposited in coastal swamps or lagoons.

Many beds of the Encinal Canyon in the southeastern part of the San Juan basin previously were included in the underlying Burro Canyon (?) Formation or Jackpile Sandstone Member of the Morrison Formation, and some workers concluded that there are little or no continental deposits in the Dakota Sandstone in the area (Owen, 1973). Confusion of Encinal Canyon with beds of the Burro Canyon and Jackpile probably resulted because all three units are fluvial and lithologically similar and occupy about the same stratigraphic position. The Encinal Canyon is distinguished from the Burro Canyon and the Jackpile in that it fills the paleovalleys, contains locally abundant carbonaceous debris, and has a different color. Sandstones of the Burro Canyon and Jackpile are generally white or buff (very light brown), whereas those of the Encinal Canyon are generally medium gray or medium brown. Mudstones of the Burro Canyon and Jackpile are green, red, or purple, whereas those of the Encinal Canyon are generally medium gray.

Quartzose, fine- to medium-grained, locally conglomeratic, crossbedded fluvial sandstone has been identified in scoured valleys at the base of the Dakota Sandstone in other areas in eastern Utah and west-central Colorado (Carter, 1957) and southwestern Colorado (Ekren and Houser, 1965; Aubrey, 1988b). These rocks are correlated with the Encinal Canyon Member because of similar lithology and stratigraphic position (Aubrey, 1989).

Age of Valley Incision

Basal Dakota valleys were incised during the late Albian (latest Early Cretaceous). The Burro Canyon Formation, the youngest dated unit beneath the paleodrainage surface in the southeastern part of the Colorado Plateau region, has yielded age-diagnostic palynomorphs near its type locality in southwestern Colorado from near the top of the formation that suggest an Aptian to early Albian age (Tschudy and others, 1984). Palynomorphs recovered from the upper part of the Cedar Mountain Formation, a partial equivalent of the Burro Canyon Formation farther west in the west-central part of the Colorado Plateau, are as young as late Albian; uppermost undated beds in the Burro Canyon Formation may also be late Albian (Tschudy and others, 1984). Palynomorph suites typified by *Nyssapollenites albertensis* Singh collected from basal sandstones of the Dakota in the southeastern part of the San Juan basin, eastern Utah, and western Colorado (Tschudy in Peterson and Kirk, 1977; Tschudy, and others, 1984) indicate that the valley fill is earliest Cenomanian (earliest Late Cretaceous) in age (R.H. Tschudy, U.S. Geological Survey, oral commun., 1986). A palynomorph assemblage from the Encinal Canyon Member on the east side of the San Juan basin near Regina includes the guide forms *N. albertensis* and small angiospermous obligate tetrads, which taken together in the absence of triporate pollen are evidence of an early Cenomanian age (D.J. Nichols and F.H. Wingate, written commun., 1988).

Formation of Incised Valleys

During the later part of the Early Cretaceous, the southeastern Colorado Plateau was about 250 km west of the Western Interior sea in central Colorado (fig. 8). The incised paleodrainage surface preserved at the base of the Dakota Sandstone in the plateau region probably formed in response to a fall in the level of the sea during the late Albian.

A paleodrainage surface similar to the sub-Dakota surface is present within the Dakota Group of central Colorado. The upper part of the Lower Cretaceous Dakota Group in central Colorado consists of the Skull Creek Shale and the overlying Muddy Sandstone (fig. 9). The Skull Creek is composed of marine mudstone and siltstone deposited in the Western Interior sea. The Muddy Sandstone consists of two members, an upper, the Horsetooth Member, and a lower, the Fort Collins Member (Weimer, 1983). The marginal-marine Fort Collins Member grades into the underlying Skull Creek Shale. The generally fluvial Horsetooth Member fills paleovalleys incised into the underlying Fort Collins Member and the Skull Creek Shale (Weimer, 1983). The maximum preserved depth of the valleys is about 45 m (fig. 8).

Two important pieces of evidence indicate that the paleodrainage surface at the base of the Horsetooth Member formed either by epeirogenic uplift of the interior basin (resulting in relative lowering of sea level) or by an eustatic lowering of sea level (Weimer, 1983). (1) Root zones at or near the base of the valley-fill sequences in the same stratigraphic position as the marine and marginal-marine rocks that form the sides of the valleys indicate that the valleys were subaerially exposed. Emergence of the marine rocks could have occurred only if the land rose or the sea fell (Weimer, 1983). (2) Incision at the top of the Skull Creek Shale occurred over wide areas of the seaway basin (fig. 8) (Weimer, 1983).

Radiometric dates from the Horsetooth Member of the Muddy Sandstone of approximately 96 to 98 Ma (Weimer, 1983) indicate that emergence and incision in the central Colorado basin coincided with the 97-Ma,

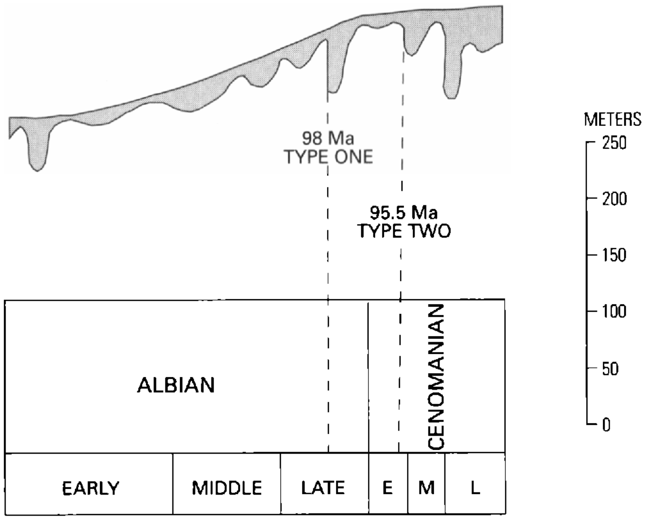


Figure 10. Third-order sea-level fluctuations (screen) during Albian (latest Early Cretaceous) and Cenomanian (earliest Late Cretaceous) time. The 98-Ma type-one sea-level fall is probably responsible for incised paleodrainage surface at base of Dakota Sandstone on Colorado Plateau. Type-one sea-level falls are faster than subsidence at shelf edge and are associated with stream incision. Type-two falls, such as at end of early Cenomanian, are slower than subsidence and are not associated with incised drainage surfaces. Modified from Haq and others (1987).

third-order sea-level fall documented by Vail and others (1977). Recently revised eustatic curves indicate that a sea-level fall occurred at approximately 98 (fig. 10) rather than 97 Ma, during the middle late Albian (Haq and others, 1987). Macrofossils and microfossils (Scott, 1970; Gustason and Kauffman, 1985) support a late Albian age for the upper part of the Dakota Group in central Colorado, an age compatible with the timing of this sea-level fall. To date, only one age-diagnostic macrofossil has been reported from the Muddy Sandstone: *Eopachydiscus* cf. *E. marcianus* (Shumard) (W.A. Cobban, U.S. Geological Survey, oral commun., 1987), found by Reeside (1923) near Fort Collins, Colorado. Young (1986) placed the *E. marcianus* zone in the middle of the late Albian. A middle late Albian age for both the Muddy Sandstone and the sea-level fall indicates that the incised surface at the base of the Horsetooth Member of the Muddy Sandstone resulted from an eustatic fall in sea level.

Potassium-argon dates from biotite in a bentonite bed at the base of the Newcastle Sandstone (correlative with the Muddy Sandstone) in eastern Wyoming are 99.7±1.2, 98.5±1.2, and 100.0±1.2 Ma (Obradovich, 1982). The approximate 98-Ma date for the sea-level fall is compatible with these ages.

Haq and others (1987) estimated the magnitude of the late Albian sea-level fall to be about 165 ft (50 m). Such a size is consistent with the 150 ft (45 m) of incision that occurred in central Colorado.

Incised valleys beneath the Horsetooth Member (near the edge of the seaway) and the Encinal Canyon Member (well inland from the seaway) are probably part of the same drainage surface. Correlation of the paleodrainage surfaces is based upon two important criteria: similar ages of formations above and below the surface and similar depths of incision.

The paleovalleys in both central Colorado and the Colorado Plateau were cut into rocks of latest Early Cretaceous age. In central Colorado, the paleodrainage surface is incised into either the Fort Collins Member of the Muddy Sandstone or the Skull Creek Shale, both of which are late Albian in age. The youngest dated sub-Dakota unit in the southeastern plateau region is the Burro Canyon Formation, which is probably Aptian to early Albian in age, although it could be as young as late Albian (Tschudy and others, 1984).

Valley fill in central Colorado is older than it is on the plateau; the Horsetooth Member of the Muddy Sandstone is probably late Albian in age, whereas the Encinal Canyon Member is earliest Cenomanian. The age difference, however, is slight. Almost identical earliest Cenomanian palynomorph suites, typified by *Nyssapollenites albertensis* and small angiospermous obligate tetrads, are present in the beds of both the Mowry Shale that directly overlie the Muddy Sandstone in central Colorado and the Encinal Canyon Member in the plateau region (R.H. Tschudy, oral commun., 1985; D.J. Nichols and F.H. Wingate, written commun., 1988). Foraminifera indicate a latest Albian to earliest Cenomanian age for the the uppermost, transitional marine part of the Horsetooth Member of the Muddy Sandstone in central Colorado (Gustason and Kauffman, 1985) and a latest Albian to early Cenomanian (Gustason and Kauffman, 1985) or early Cenomanian age (Eicher, 1965) for overlying beds of the Mowry Shale. Upper beds of the valley fill in central Colorado are, therefore, about the same age or slightly older than the valley fill in the plateau region. Such an upstream decrease in age would be expected if the valley fill was deposited in response to the landward transgression of the sea (such that aggradation began near the shoreline and progressed inland up the paleovalleys). Thus, the Horsetooth and Encinal Canyon Members are probably a single, diachronous, alluvial aggradational unit.

The apparent maximum depth of incision is about 45 m at the base of the Horsetooth Member in central Colorado and about 30 m at the base of the Encinal Canyon Member in inland areas (plate 1). Such an upstream decrease in incision depth would be expected if a fall in sea level caused the incision. Encinal Canyon paleovalleys occur at least 320 km inland from the western shoreline of the seaway (fig. 8).

The drainage surface at the base of the Horsetooth and Encinal Canyon Members is probably part of a type-one sequence boundary that formed during the middle late

Albian type-one sea-level fall (fig. 10). Type-one sea-level falls occur faster than subsidence at the shoreline on passive continental margins and are associated with stream incision (Haq and others, 1987). During the subsequent rise in sea level, the drainage surface was preserved by backfilling of the valleys with alluvial deposits.

Transgressive Erosion Surface

In the southeastern part of the San Juan basin, a transgressive erosion surface truncates both the top of the valley fill (the Encinal Canyon Member) and the underlying formations that form the ridges between sub-Dakota paleovalleys (plate 1). This erosion surface is overlain by shale of the marine Mancos Shale, which is interbedded with shoreface or shelf sandstones included in the Dakota Sandstone. Locally, thin lag deposits of reworked material from the Encinal Canyon Member and other underlying rock units lie directly on this surface.

The transgressive surface apparently is only in the southeastern part of the San Juan basin and vicinity, an area that coincides with the eastern part of Seyboyeta bay. In southeastern Utah and the southwesternmost part of Colorado, continental deposits included in the Dakota overlie the Encinal Canyon and the transgressive erosion surface is not present (Aubrey, 1988b).

The transgressive erosion surface, which juxtaposes readily differentiated continental and marine strata, is more easily recognized than the more subtle fluvial sandstone on fluvial sandstone contact at the base of the Encinal Canyon Member (plate 1). The base of the Encinal Canyon, however, is a major regional unconformity that occurs throughout the southeastern Colorado Plateau region, whereas the transgressive erosion surface is of only local extent.

Fluvial Sandstone and Shale in the Four Corners Area

Lenticular, stacked-channel sandstones and fine-grained overbank strata of continental affinity overlie the Encinal Canyon Member in the Four Corners area. The channel sandstones are fine to medium grained and commonly trough crossbedded. The fine-grained overbank deposits consist of gray to dark-gray carbonaceous mudstone and coal. Coal beds are lenticular and from a few centimeters to about a meter thick (Ekren and Houser, 1965).

These strata were deposited in alluvial or deltaic environments. They probably are equivalent to the lowermost Mancos shales and interbedded Dakota shoreface or shelf sandstones in the Seyboyeta bay. The Dakota Sandstone in the Four Corners area is overlain by the Mancos Shale.

SUMMARY AND CONCLUSIONS

Detailed sedimentologic studies have increased understanding of the stratigraphy and sedimentology of uppermost Jurassic to lowermost Upper Cretaceous rocks in the San Juan basin and adjacent areas. The Burro Canyon (?) Formation in the Chama basin in the northeastern part of the study area is tentatively correlated with the Jackpile Sandstone Member of the Morrison Formation on the west side of Nacimiento uplift in the southeastern part of the basin. Both of these fluvial sandstone units generally have erosional bases, but they may locally interfinger with the underlying lacustrine deposits in the Brushy Basin Member of the Morrison Formation. Southeasterly to easterly paleocurrent directions predominate in both formations. The Burro Canyon (?), in the more proximal part of the proposed fluvial system, is locally conglomeratic, whereas the Jackpile, in the more distal part, contains few pebbles.

Southeasterly and easterly paleocurrent directions in the Burro Canyon (?)–Jackpile interval on the east side of the San Juan basin suggest a northwestern or western provenance. Streams in the northern part of the basin may also have flowed from the northwest (Turmelle, 1979). Regional studies, however, document northeast paleocurrent directions in the Burro Canyon in southeastern Utah and southwestern Colorado (Craig, 1982) that indicate a southwest source. If streams flowed northeast from a southerly source, as the regional studies suggest, a structural paleohigh northeast of the San Juan basin may have locally diverted paleoflow toward the southeast in the northern and eastern parts of the basin (Turmelle, 1979).

Lenticular sandstones of the Burro Canyon in the northwestern part of the basin were probably deposited by a fluvial system that gradually overwhelmed and finally filled in the Brushy Basin lake. Stratigraphically lower sandstones of the Burro Canyon are present laterally to Brushy Basin lacustrine mudstones. Higher in the section, where sandstones of the Burro Canyon are much more laterally extensive, fluvial conditions probably prevailed. The conglomerate that caps the mesas near Oak Springs is lithologically similar to and probably correlates with the Karla Kay Conglomerate Member of the Burro Canyon, the stratigraphically lowest sandstone of the Burro Canyon in the Four Corners area.

The boundary between the Brushy Basin and Burro Canyon in the northwestern part of the basin is arbitrary because of the apparent gradation between lacustrine and overlying fluvial strata. Fluvial sandstones included in the Burro Canyon in the northwestern part of the basin could just as easily be included in the Morrison. In particular, the Karla Kay, which is the stratigraphically lowest of the sandstones, has a strong affinity to the Morrison because it pinches out laterally into mudstone typical of the Brushy Basin lacustrine deposits and because it contains pebble suites typical of the Morrison.

Fluvial rocks of the lowermost Upper Cretaceous Encinal Canyon Member at the base of the Dakota Sandstone fill paleovalleys incised into underlying formations. In the northern part of the basin, the Encinal Canyon disconformably overlies fluvial rocks of the upper Lower Cretaceous Burro Canyon Formation. Along the southern margin of the basin, the Encinal Canyon overlies progressively older Mesozoic and Paleozoic formations toward the south. The Encinal Canyon correlates with the Horsetooth Member of the Muddy Sandstone of central Colorado; paleovalleys at the base of the Horsetooth are incised into the marine Skull Creek Shale.

In the latter part of the Early Cretaceous, an epicontinental sea about 240 km east of the San Juan basin was base level for streams in the plateau region. Near the end of the Early Cretaceous, sea level fell, base level was lowered, and streams incised valleys into alluvial deposits of the Burro Canyon Formation and into older formations. The resulting incised paleodrainage surface was preserved as the sub-Dakota unconformity when the succeeding sea-level rise, in earliest Late Cretaceous time, caused Dakota streams to aggrade and backfill the paleovalleys with alluvial sediments of the Encinal Canyon Member.

A transgressive erosion surface in the southeastern part of the San Juan basin truncates both the top of the valley fill (the Encinal Canyon Member) and the underlying formations that form the ridges between sub-Dakota paleovalleys. This erosion surface was formed when the shoreline of the Western Interior seaway advanced across the region, and it is overlain by the marine Mancos Shale. In southeastern Utah and the southwesternmost part of Colorado, continental deposits included in the Dakota Sandstone overlie the Encinal Canyon and the transgressive erosion surface is not present.

Eustatic effects on the deposition of ancient coastal and marine rocks are well known, but eustasy also can affect depositional patterns and processes well inland from the sea. Incised valleys at the base of the Dakota Sandstone at least 320 km inland from the sea indicate that a eustatic lowering of sea level can result in erosion far inland from the sea and play an important role in the formation of unconformities in continental strata.

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Chapter K

X-Ray Diffraction Studies of the <2-μm Fraction from the Upper Part of the Brushy Basin Member of the Upper Jurassic Morrison Formation and the Lower Cretaceous Burro Canyon Formation in the Four Corners Area, Colorado

By GARY SKIPP and W.M. AUBREY

A multidisciplinary approach to research studies of sedimentary rocks and their constituents and the evolution of sedimentary basins, both ancient and modern

U.S. GEOLOGICAL SURVEY BULLETIN 1808

EVOLUTION OF SEDIMENTARY BASINS—SAN JUAN BASIN

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X-ray Diffraction Studies of the <2-µm Fraction from the Upper Part of the Brushy Basin Member of the Upper Jurassic Morrison Formation and the Lower Cretaceous Burro Canyon Formation in the Four Corners Area, Colorado

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Abstract

Studies of the < 2-µm size fraction in samples from fine-grained rocks in the upper part of the Brushy Basin Member of the Upper Jurassic Morrison Formation and the Lower Cretaceous Burro Canyon Formation in the Four Corners area of Colorado indicate significant differences in clay mineralogy between the formations. Clay minerals in the Brushy Basin Member are principally smectitic mixed-layer illite/smectite, whereas clay minerals in the Burro Canyon Formation are predominantly composed of about equal amounts of illitic mixed-layer illite/smectite and kaolinite. Smectitic clays in the Brushy Basin Member formed during diagenesis from the alteration of tuffaceous material incorporated into the bottom sediments of a large, saline alkaline lake. Illitic clays and kaolinite in the Burro Canyon Formation are probably detrital material that was transported to the area by streams. Alternatively, kaolinite may have formed authigenically as part of a weathering profile beneath the major regional unconformity at the top of the Burro Canyon Formation. More work is needed to determine the origin of the kaolinite and its relation to the unconformity.

INTRODUCTION

Weathering characteristics indicate a significant difference in the clay mineralogy of fine-grained facies across the boundary between lacustrine rocks of the Upper Jurassic Brushy Basin Member of the Morrison Formation and fluvial rocks of the Lower Cretaceous Burro Canyon Formation in the Four Corners area of Colorado (Ekren and Houser, 1959, 1965). Weathered mudstones in the Brushy Basin Member have a "frothy" or "popcorn" appearance indicative of abundant smectitic clay. Mudstones in the Burro Canyon Formation, however, lack the popcorn appearance but have a "fissile" or "hackly" character indicative of a lack of smectitic clay. This difference in weathering is persistent elsewhere in the Colorado Plateau in southeastern and east-central Utah (Ekren and Houser, 1959, 1965).

In this study we used X-ray diffraction techniques to determine the occurrence and distribution of clay minerals in the upper part of the Brushy Basin Member and in the Burro Canyon Formation in the Four Corners area (fig. 1). The mineralogy of clays in fine-grained continental rocks is controlled by a variety of factors, including the nature of the source material, climatic conditions, depositional environments, and diagenesis (Potter and others, 1980; Birkeland, 1984). Therefore, knowledge of the mineralogy of the clays in the Brushy Basin Member and the Burro Canyon Formation can be used in reconstructing the depositional and diagenetic history of uppermost Jurassic and Lower Cretaceous rocks in the area.

In the study area, clays in the Brushy Basin Member are composed of smectitic mixed-layer illite/smectite formed during early diagenesis of slightly reworked airborne tuffaceous material in bottom sediments along the periphery of a large saline, alkaline lake (Turner-Peterson and others, 1986; Fishman and others, 1987; Turner-Peterson, 1987; Owen and others, 1989; Turner-Peterson and Fishman, 1991). In contrast, work presented here

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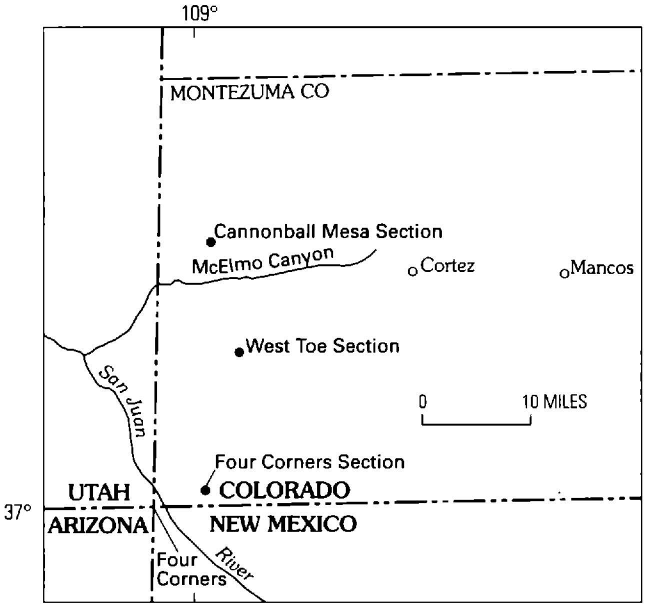


Figure 1. Location of Four Corners area, western United States, and measured sections (solid circles) in study.

shows that mudstones of the Burro Canyon Formation contain about equal amounts of illitic mixed-layer illite/smectite and kaolinite. The illitic mixed-layer illite/smectite is probably detrital material washed into the area by Burro Canyon streams. Kaolinite in the Burro Canyon also may be detrital, a result of erosion in more proximal parts of the drainage basin; or it may have formed as part of a weathering profile beneath the incised paleodrainage surface (the sub-Dakota unconformity) that formed at the top of the Burro Canyon at the end of the Early Cretaceous.

GEOLOGIC SETTING

The Brushy Basin Member of the Morrison Formation is about 150–330 ft thick in the Four Corners area (Ekren and Houser, 1959, 1965; Turner-Peterson, 1987) and consists of tuffaceous mudstone interbedded with thick intervals of tuff containing abundant altered volcanic ash (Turner-Peterson and others, 1986). The Brushy Basin in this area was deposited on the western side of a large saline, alkaline lake, Lake T'oo'dichi' (Turner-Peterson, 1987), that covered most of the eastern part of the Colorado Plateau. Ash in the lake deposits originated in a volcanic arc region southwest of the Colorado Plateau region and was carried to the lake basin by prevailing northwesterly winds (Turner-Peterson, 1987).

Evaporation, which caused drastic fluctuations in the level of the lake, and alteration of ash resulted in a hydrogeochemical gradient in surface waters and pore waters in underlying lake sediments (Turner-Peterson, 1987; Turner-Peterson and Fishman, 1991). During high stands, ash in bottom sediments was exposed to relatively fresh water. During low lake levels, however, pore waters in sediment in the central part of the lake increased in salinity and alkalinity. Ash in tuff beds around the perimeter of the lake, which was only exposed to relatively fresh water, altered to smectitic clays, and a smectite diagenetic mineral zone formed along the perimeter of the lake (Turner-Peterson, 1987). The hydrogeochemical gradient, however, caused ash in tuff beds in succeeding zones toward the center of the lake to alter in part to clinoptilolite, analcime, and albite, respectively (Turner-Peterson, 1987). Four concentric diagenetic mineral zones, therefore, comprise the Brushy Basin lake sediments; the smectite zone is the outermost and the albite zone is in the center. Tuff beds in the clinoptilolite, analcime, and albite zones contain abundant authigenic silica and form hard resistant layers. Clay minerals in mudstone and tuff beds in the outer smectite and clinoptilolite zones generally are composed of smectitic mixed-layer illite/smectite; those in the innermost albite zone consist of illitic mixed-layer illite/smectite (Turner-Peterson and Fishman, 1991). Clay minerals in the intervening analcime zone are highly variable and consist of both smectitic and illitic mixed-layer illite/smectite (Turner-Peterson and Fishman, 1991). These differences in clay mineralogy probably reflect geochemical differences in the pore waters of the bottom sediments (Turner-Peterson, 1987; Turner-Peterson and Fishman, 1991).

The Burro Canyon Formation in the Four Corners area is composed of fluvial, ribbonlike lenses of conglomerate and conglomeratic sandstone and interbedded hackly weathering nonsmectitic mudstone (Ekren and Houser, 1965). The Burro Canyon is 30–200 ft thick in the area (Ekren and Houser, 1965). Compensatory thickening of the Burro Canyon in relation to thinning of the Brushy Basin suggests that the two formations interfinger. The base of the Burro Canyon is placed at the base of the lowest conglomerate or conglomeratic sandstone lens or, where these are absent, at the base of the hackly weathering mudstone (Ekren and Houser, 1959). Conglomerate and conglomeratic sandstone lenses in the upper part of the formation are generally more numerous and cover larger areas than those in the lower part (Ekren and Houser, 1965).

The transition from lacustrine to alluvial deposition in the study area was probably gradual (Aubrey, this volume). Mudstone at the same level as the stratigraphically lowest of the Burro Canyon channel sandstones locally contains smectitic and clinoptilolite-bearing tuffs typical of the Brushy Basin lacustrine deposits. Mudstone higher in the section, where fluvial sandstones are more laterally extensive, contains thin siliceous resistant beds similar in appearance to altered tuff beds in the Brushy Basin lacustrine deposits but without characteristic authigenic clinoptilolite, analcime, or feldspar. Differences in composition between thin resistant beds in the upper and lower parts of the section may reflect changes in pore water chemistry that occurred as fluvial conditions replaced those of the saline, alkaline lake (Aubrey, this volume).

The fluvial deposits of the Burro Canyon Formation are separated from the overlying Upper Cretaceous Dakota Sandstone by a major regional unconformity in the southeastern Colorado Plateau region. An incised paleodrainage surface is preserved at the unconformity (Aubrey, 1986). Paleovalleys generally are about 40–50 ft deep in the Four Corners area (Ekren and Houser, 1959; Aubrey, 1988) but are locally 100 ft deep or more elsewhere in the Colorado Plateau (Carter, 1957; Aubrey, 1989). A eustatic sea-level fall in the Western Interior seaway, which was west of the Colorado Plateau at the end of the Early Cretaceous, resulted in stream rejuvenation and valley incision that formed the unconformity (Aubrey, 1989). The valleys were backfilled during the subsequent sea-level rise when the Western Interior sea transgressed across the plateau region at the beginning of the Late Cretaceous.

Valley fill consists of the fluvial sandstone and conglomeratic sandstone of the basal Encinal Canyon Member of the Upper Cretaceous Dakota Sandstone (Aubrey, 1986). The Encinal Canyon contains abundant carbonaceous debris and thin dark-gray carbonaceous shale. In contrast, carbonaceous material in the Burro Canyon Formation is extremely rare, and mudstones are olive green or maroon.

METHODS

Fifty-six samples were collected in the Brushy Basin-Burro Canyon interval from detailed measured sections (Aubrey, 1988) at three localities in the Four Corners area (fig. 1). Samples were crushed to granule-gravel size (3.3 mm; Wentworth, 1922) or less in a jaw crusher, and 50–100 g of sample was placed in 600-mL beakers to which 400 mL of distilled water was added. The beakers were covered and allowed to stand overnight. Each sample was ultrasonically agitated for 2–5 minutes the next day. If salts in the water caused flocculation, the sample was placed in a 250-mL centrifuge bottle and centrifuged at 5,000 rpm for 1 hour. The water was then carefully decanted without disturbing the clay at the bottom of the bottle. This process was repeated until salts were removed and the clay fraction remained suspended. Suspended silt and clay were placed in centrifuge bottles and spun at 750 rpm for 3 minutes 30 seconds (Jackson, 1979). The suspended <2-μm clay fraction was decanted into separate beakers and suctioned onto 0.45-mm-pore filters. Clays were then transferred to glass slides and allowed to dry at room temperature (25 °C). This method of producing oriented clay mounts is discussed in Drever (1973) and Pollastro (1982).

Three slides of each clay separation were prepared and dried at room temperature. One of the slides was subsequently heated at 550 °C for 1 hour, and another was placed overnight in a closed desiccator over an ethylene glycol bath in an oven at 50 °C. All three slides were X-rayed using CuKθ radiation on a Philips type 150–100–21 goniometer from 2° to 50° 2θ at a scan speed of 2° 2θ per minute.

Clay minerals identified include mixed-layer illite/smectite, kaolinite, chlorite, smectite, and illite. The percent smectite in the mixed-layer illite/smectite was determined using methods described in Reynolds (1980) and Srodon (1980, 1981, 1984). The positions of illite/smectite peaks found between 5.7 and 4.9 angstroms (15.50°–18.03° 2θ), 3.4 and 3.3 angstroms (25.98°–26.77° 2θ) and 2.1 and 2.0 angstroms (42.06°–44.17° 2θ) were noted and plotted on graphs in Srodon (1980, p. 406–407) to determine the percent smectite in illite/smectite clays from samples that contained only a small amount of quartz. If quartz was abundant, then illite/smectite peaks between 2.8 and 2.7 angstroms (31.55°–32.72° 2θ) and 5.7 and 5.4 angstroms (15.50°–16.36° 2θ) were plotted on curves from Srodon (1981, p. 300) to determine percent expandable layers. In some samples, however, peak positions plotted outside these curves. It was then necessary to use illite/smectite peak positions between 5.6 and 5.0 angstroms (15.78°–17.67° 2θ) and 10.1 and 8.5 angstroms (8.75°–10.40° 2θ) and tables from Reynolds (1980, p. 290) to determine the approximate percent smectite. Percent expandable layers in samples that contain a low percent smectite (high percent illite) were identified using a plot in Srodon (1984, p. 340). This plot required the use of the 4.4–3.4 angstrom (20.08°–25.98° 2θ) and 5.4–4.9 angstrom (16.36°–18.03° 2θ) peaks.

Smectite is a general term referring to those minerals that expand to approximately 17 angstroms (5.21° 2θ) upon glycolation and collapse to approximately 10 angstroms (8.84° 2θ) upon heating. Chlorite and kaolinite share most peak positions, and it is difficult to distinguish between them. Both are indicated by peaks from glycolated samples at 7.2–7.1 angstroms (12.27°–12.45° 2θ) and 3.6–3.5 angstroms (24.54°–25.24° 2θ). Upon heating these peaks disappear, and if chlorite is present a peak at 14 angstroms (6.32° 2θ) increases in intensity.

Other minerals present were identified by peak position. All minerals were ranked as trace, present, or abundant based on relative peak intensity (tables 1–3).

RESULTS

Distribution of Clays

Our goal was to determine differences in the clay mineralogy between mudstones in the Brushy Basin Member of the Morrison Formation and the Burro Canyon

Table 1. X-ray diffraction analysis of <2-µm fraction of mudstone and siltstone samples from the Brushy Basin Member of the Morrison Formation and the Burro Canyon Formation in the Cannonball Mesa section
[Location of section shown in fig. 1]

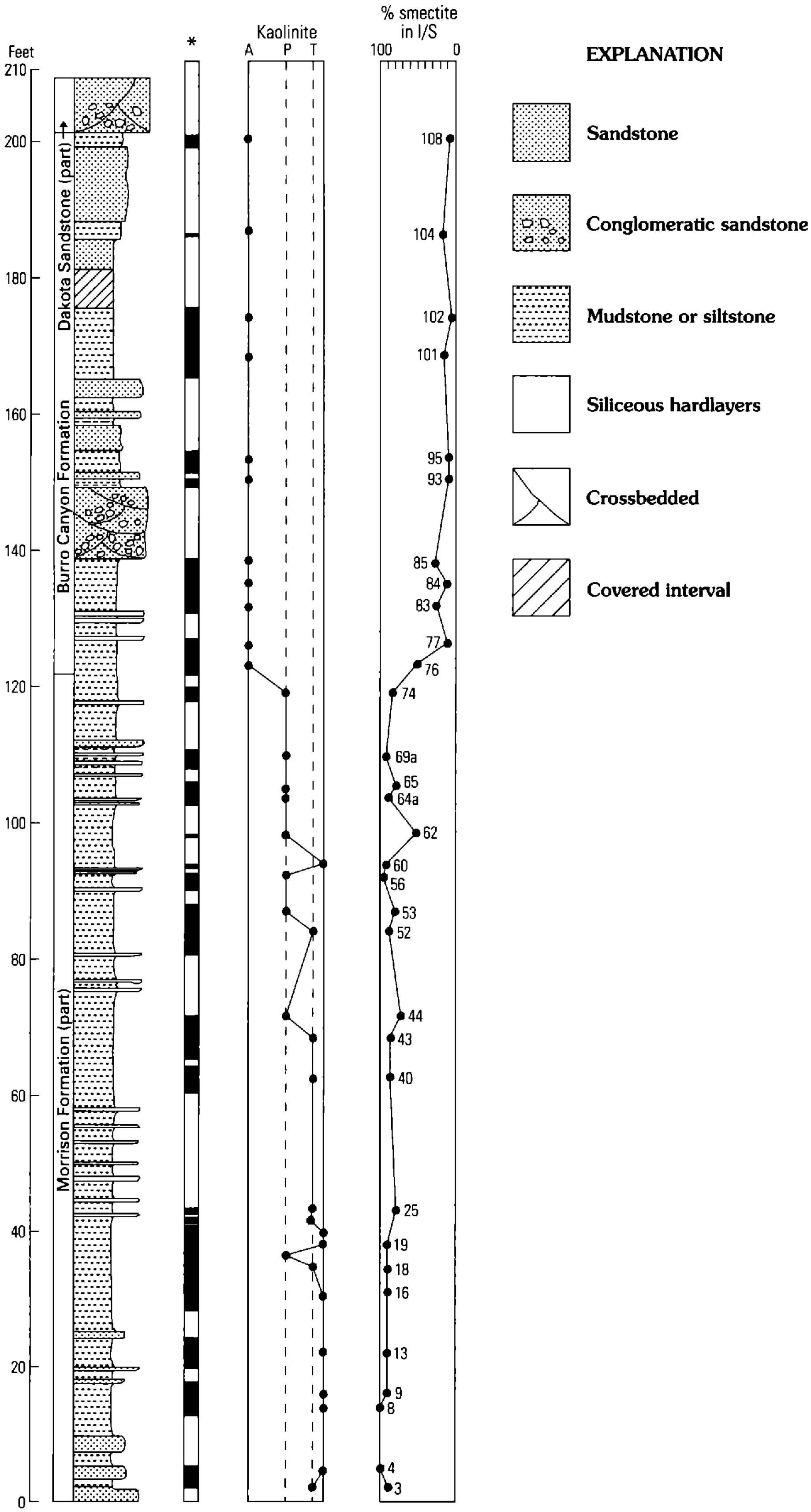
Sample No.	Approximate elevation above base of section (in feet)	Lithology	Percent smectite in I/S	Kaolinite	Other minerals
		Brushy Basin Member of the Morrison Formation			
CBM–3	3	Siltstone	80–100	Trace	Quartz (present).
CBM–4	4.5	Siltstone and sandstone	100	None	Chlorite, quartz, barite (present).
CBM–8	14	Siltstone	100	None	Quartz (trace).
CBM–9	16	Siltstone	90–100	None	Quartz (present).
CBM–13	22	Siltstone	90–100	None	Quartz (trace).
CBM–16	30	Siltstone	90–100	None	Quartz (trace).
CBM–18	34	Mudstone	90–100	Trace	Quartz (trace).
CBM–19	36	Siltstone	90–100	Present	Quartz (abundant).
CBM–20	37	Mudstone	90–100	None	Quartz (present).
CBM–21	39	Mudstone	90–100	None	Quartz (present)
CBM–23	41	Mudstone	90–100	Trace	Quartz (present).
CBM–25	42	Mudstone	70–80	Trace	Quartz (trace).
CBM–40	61.5	Mudstone	80–100	Trace	Quartz (trace).
CBM–43	67	Mudstone	80–90	Trace	Quartz (present).
CBM–44	70	Mudstone	70	Present	Quartz (present).
CBM–52	82	Mudstone	90	Trace	Quartz (present).
CBM–53	85	Mudstone	80	Present	Quartz (present).
CBM–56	90	Mudstone	100	Present	Quartz (abundant); illite (present)
CBM–60	91.5	Mudstone	90–100	None	Quartz (trace).
CBM–62	96	Mudstone	40–50	Present	None.
CBM–64a	101	Mudstone	80–90	Present	Quartz (abundant).
CBM–65	103	Mudstone	70–80	Present	Quartz (present).
CBM–69a	107	Mudstone	90–100	Present	Quartz (abundant).
CBM–74	116	Mudstone	80	Present	Quartz (present).
		Burro Canyon Formation			
CBM–76	119.5	Mudstone	40–50	Abundant	Quartz (trace).
CBM–77	123	Mudstone	5	Abundant	Quartz (present).
CBM–83	128.5	Mudstone	20	Abundant	Quartz (present).
CBM–84	132	Siltstone	5–10	Abundant	Quartz (trace).
CBM–85	136	Siltstone	20–30	Abundant	None.
CBM–93	147	Siltstone	1–10	Abundant	Quartz (present).
CBM–95	150	Siltstone	1–5	Abundant	Quartz (present).
CBM–101	165	Siltstone	15–20	Abundant	Quartz (present).
CBM–102	170	Siltstone	1–5	Abundant	Quartz (abundant).
CBM–104	183	Siltstone	10–20	Abundant	Quartz (present).
CBM–108	195.5	Mudstone	1–10	Abundant	Quartz (present).

Table 2. X-ray diffraction analysis of <2-µm fraction of mudstone, siltstone, and sandstone samples from the Brushy Basin Member of the Morrison Formation and the Burro Canyon Formation in the Four Corners section
[Location of section shown in fig. 1]

Sample No.	Approximate elevation above base of section (in feet)	Lithology	Percent smectite in I/S	Kaolinite	Other minerals
		Brushy Basin Member of Morrison Formation			
FC1–17	11	Siltstone	90–100	None	Quartz (present).
FC1–22	18.5	Siltstone	90–100	Trace	Quartz (trace).
FC1–28?	24.5	Mudstone	100	Present	Quartz, illite (present).
FC1–32	26.5	Mudstone	90–100	Trace	Quartz (abundant).
FC1–34	27.5	Shale	50–60	Trace	Quartz (present).
FC1–35	29.5	Siltstone	90–100	Trace	Quartz (trace).
FC1–38	40	Mudstone	90–100	Trace	None.
FC1–42	47.5	Siltstone	90–100	Trace	None.
FC1–46a	63	Siltstone	90–100	Trace	Quartz (trace).
FC1–46b	64	Siltstone	90–100	Trace	Quartz (trace).
		Burro Canyon Formation			
FC1–52	89	Siltstone	0	Present	Illite (abundant).
FC1–60	94.5	Siltstone	30–40	Abundant	Quartz (present).
FC1–72	106	Mudstone	100	Abundant	Quartz (abundant), illite (present).
FC1–75	110	Sandstone	10–20	Abundant	Quartz (abundant).
FC1–76	112	Siltsone	50		Abundant Quartz (abundant)
FC1–77	115	Mudstone	0–10	Abundant	Quartz (trace).

Table 3. X-ray diffraction analysis of <2-µm fraction of mudstone and siltstone samples from the Burro Canyon Formation in the West Toe section
[Location of section shown in fig. 1]

Sample No.	Approximate elevation above base of section (in feet)	Lithology	Percent smectite in I/S	Kaolinite	Other minerals
WT–1	1.5	Mudstone	30	Present	None.
WT–9	6.75	Mudstone	30	Present	Quartz (trace).
WT–13	9	Mudstone	30	Present	Quartz (present).
WT–18	11.5	Mudstone	25	Trace	None.
WT–24	17	Siltstone	30	Abundant	Quartz (present).


Feet
210
200
180
160
140
120
100
80
60
40
20
0
Dakota Sandstone (part)
Burro Canyon Formation
Morrison Formation (part)
*
Kaolinite
A P T
% smectite
in I/S
100 0
108
104
102
101
95
93
85
84
83
77
76
74
69a
65
64a
62
60
56
53
52
44
43
40
25
19
18
16
13
9
8
4
3
EXPLANATION
Sandstone
Conglomeratic sandstone
Mudstone or siltstone
Siliceous hardlayers
Crossbedded
Covered interval

Formation in the Four Corners area. Clays in the upper part of the Brushy Basin Member generally consist of smectitic mixed-layer illite/smectite (figs. 2–6, tables 1–3). In contrast, clays from the Burro Canyon consist predominantly of approximately equal amounts of illitic mixed-layer illite/smectite and kaolinite based on relative peak intensities (figs. 2, 3, 7, tables 1, 2).

Only the upper part of the Burro Canyon Formation was studied. Maximum thickness of the Burro Canyon is about 80 ft (fig. 2) at the sample localities, but the Burro Canyon is as thick as 200 ft elsewhere in the study area. The hackly appearance of the mudstone, characteristic of the entire Burro Canyon, suggests that samples from the upper part of the Burro Canyon studied here may be representative of the whole formation.

DISCUSSION

The predominance of smectitic clays in the upper part of the Brushy Basin Member is determined in part by the location of the study area on the western margin of ancient Lake T'oo'dichi'. Airborne tuffaceous material that was deposited in the lake in this area altered in relatively fresh pore waters to smectitic mixed-layer illite/smectite (Turner-Peterson and others, 1986; Turner-Peterson, 1987).

The change from smectitic clays in the Brushy Basin Member to illitic clays and kaolinite in the Burro Canyon is abrupt (figs. 2, 3, tables 1, 2), and a diagenetic origin for illitic mixed-layer illite/smectite clays in the Burro Canyon can be ruled out. The Gulf Coast model for illitization of smectite by progressive burial and accompanying increases in temperature (Perry and Hower, 1970) cannot be applied to the Burro Canyon because underlying, more deeply buried mudstones of the Brushy Basin contain abundant smectitic clay but almost no illitic clay. The Burro Canyon was deposited in a high-energy fluvial environment in which fresh water was probably abundant, and it is unlikely that illitic clays in the Burro Canyon formed in a highly saline, alkaline low-temperature environment similar to the environment that converted smectite to illite in the central part of Lake T'oo'dichi'. Therefore, illitic clays in the Burro Canyon are probably detrital in origin.

In the study area, which is on the margin of ancient Lake T'oo'dichi', the illitic mudstone of the Burro Canyon Formation is easily distinguished from the smectitic mudstone of the Brushy Basin Member; however, elsewhere, in the central part of ancient lake T'oo'dichi' where tuffaceous material has altered to illitic mixed-layer illite/smectite, mudstone of the Brushy Basin Member is illitic, not smectitic (Turner-Peterson and others, 1986; Turner-Peterson, 1987). This mudstone has the same hackly appearance as the illitic mudstone in the Burro Canyon and is difficult to distinguish.

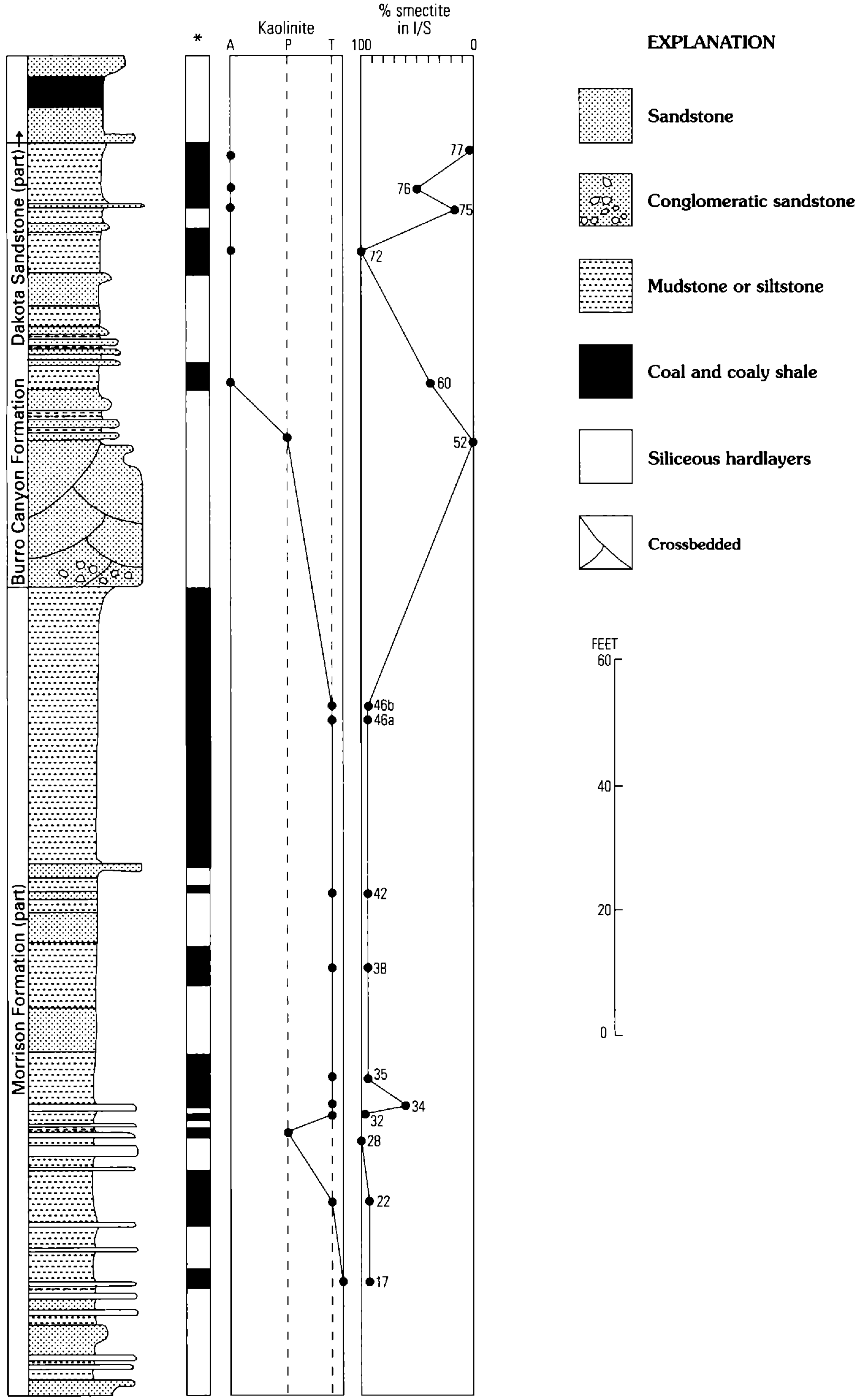
The basal part of the Burro Canyon Formation intertongues with the top part of the Brushy Basin Member (Ekren and Houser, 1959, 1965), and illitic clays in the Burro Canyon may indicate the gradual cessation of volcanic activity in the region. Alternatively, airborne tuffaceous material was the primary source of sediment in the Brushy Basin lake, but detrital illitic mixed-layer illite/smectite transported by fluvial processes was predominant over airborne material during Burro Canyon deposition.

The coincidence between the shift from smectitic clays to illitic clays and the presence of abundant kaolinite (figs. 2, 3, tables 1, 2) suggests that the kaolinite is also detrital. Detrital kaolinite could have been derived from erosion of soil zones, weathering profiles, or older formations exposed in more proximal parts of the Burro Canyon drainage basin.

In situ formation of kaolinite by pedogenic processes requires a humid climate that probably did not exist in the study area during deposition of the Burro Canyon Formation. Nonsmectitic beds in the lower part of the Burro Canyon are juxtaposed with smectitic beds that formed under arid conditions in the Brushy Basin saline, alkaline lake. Formation of kaolinite in soil zones in the Burro Canyon therefore is unlikely.

Lowering of the water table during valley incision at the end of the Early Cretaceous could have resulted in leaching that formed a kaolinitic weathering profile in the Burro Canyon Formation and uppermost part of the Brushy Basin Member. Kaolinitic clay beds (Leopold, 1943) and kaolinitic sandstone (Adams and others, 1978) commonly are present beneath the sub-Dakota unconformity elsewhere on the Colorado Plateau. The close association between kaolinite and illite, however, does not support an authigenic origin for the kaolinite. More data is needed to determine the extent of kaolinite in the Burro Canyon and its relation to the unconformity in the Four Corners area.

Figure 2 (facing page). Measured section showing lithology, percent smectite in mixed-layer illite /smectite, and abundance of kaolinite in fine-grained beds in Cannonball Mesa section (location shown in fig. 1). Column headed by asterisk (*) indicates part of section represented by sample. Abundance of kaolinite subjectively ranked as trace (T), present (P), and abundant (A). Amounts of "abundant" kaolinite and illitic mixed-layer illite/smectite in upper part of section are about equal based on relative peak intensities. Numbers correspond to unit numbers in measured sections (see Cannonball Mesa I section in Aubrey, 1988).


Dakota Sandstone (part)
Burro Canyon Formation
Morrison Formation (part)
*
Kaolinite
A
P
T
% smectite
in I/S
100
0
77
76
75
72
60
52
46b
46a
42
38
35
34
32
28
22
17
EXPLANATION
Sandstone
Conglomeratic sandstone
Mudstone or siltstone
Coal and coaly shale
Siliceous hardlayers
Crossbedded
FEET
60
40
20
0

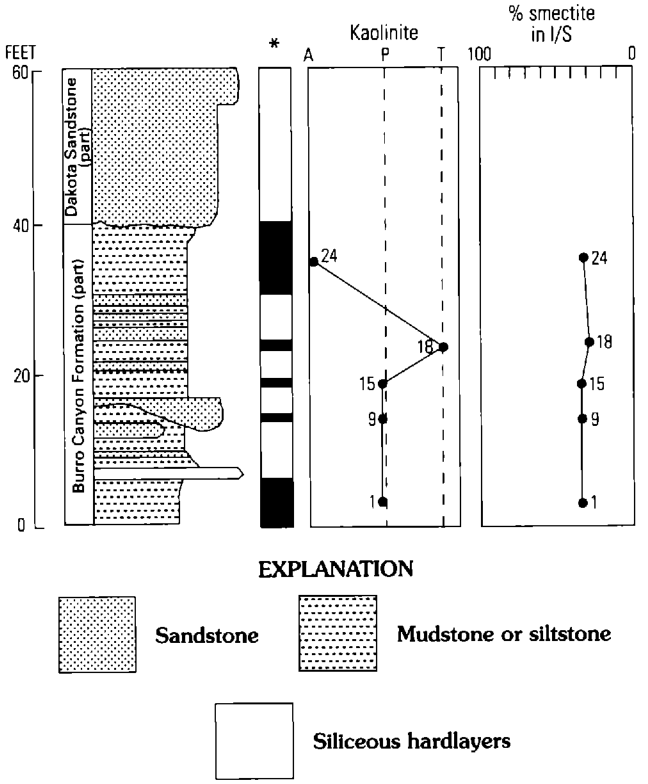


Figure 4. Measured section showing lithology, percent smectite in mixed-layer illite/smectite, and abundance of kaolinite in fine-grained beds in West Toe section (location shown in fig. 1). Column headed by asterisk (*) indicates part of section represented by sample. Abundance of kaolinite subjectively ranked as trace (T), present (P), and abundant (A). Numbers correspond to unit numbers in measured sections (see West Toe section in Aubrey, 1988).

Figure 3 (facing page). Measured section showing lithology, percent smectite in mixed-layer illite/smectite, and abundance of kaolinite in fine-grained beds in Four Corners section (location shown in fig. 1). Column headed by asterisk (*) indicates part of section represented by sample. Abundance of kaolinite subjectively ranked as trace (T), present (P), and abundant (A). Amounts of "abundant" kaolinite and illitic mixed-layer illite/smectite in upper part of section are about equal based on relative peak intensities. Numbers correspond to unit numbers in measured sections (see Four Corners I section in Aubrey, 1988).

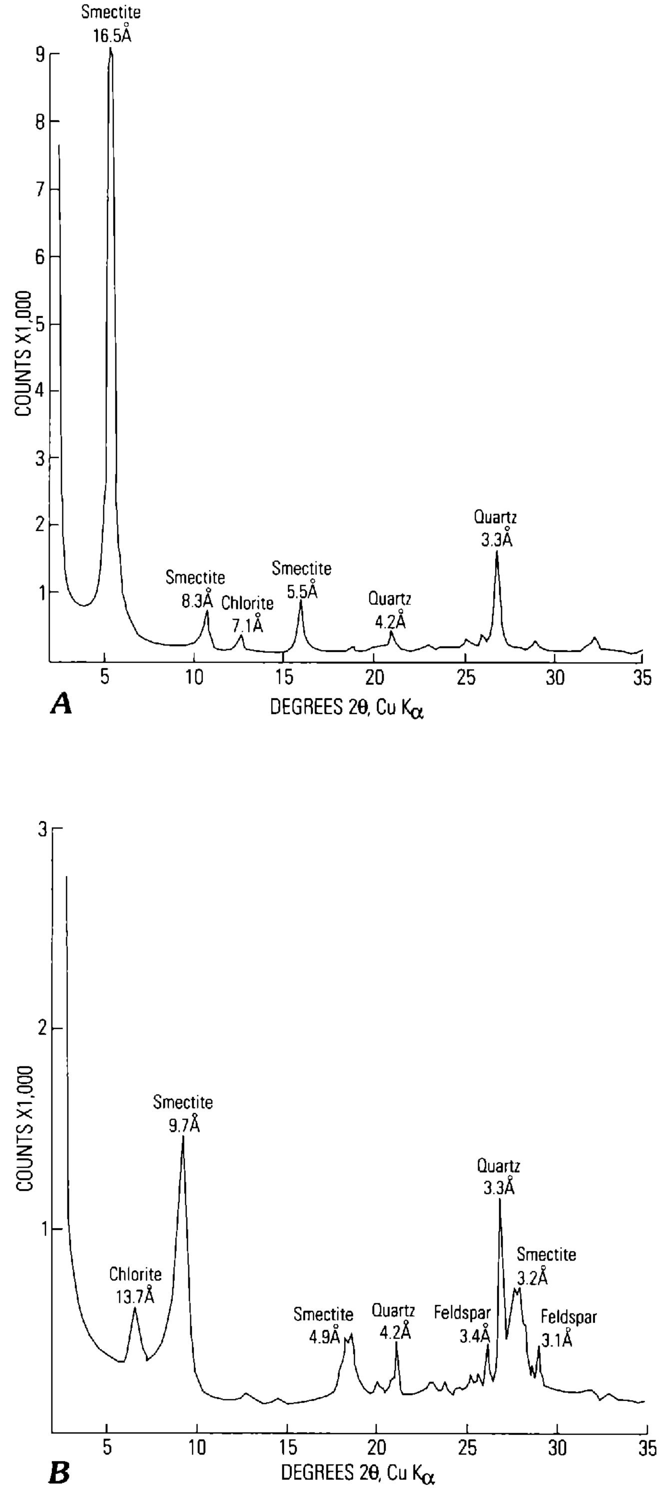


Figure 5. X-ray diffractograms of mudstone from Brushy Basin Member of Morrison Formation containing abundant smectite. Unit 4, Cannonball Mesa section. *A*, Glycol. *B*, Heated at 550 °C.

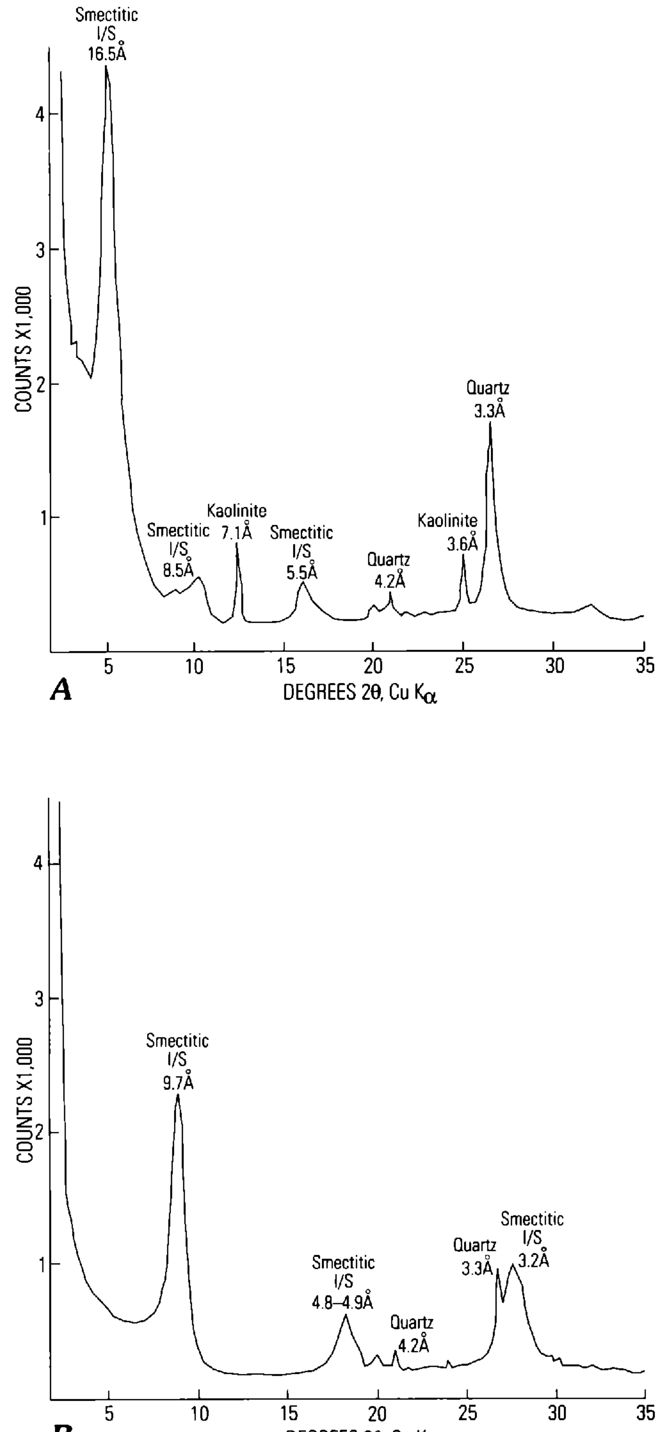


Figure 6. X-ray diffractograms of mudstone from Brushy Basin Member of Morrison Formation in which kaolinite is "present" (see fig. 2 for explanation). Also contains smectitic mixed-layer illite/smectite. Unit 74, Cannonball Mesa section. *A*, Glycol. *B*, Heated at 550 °C.

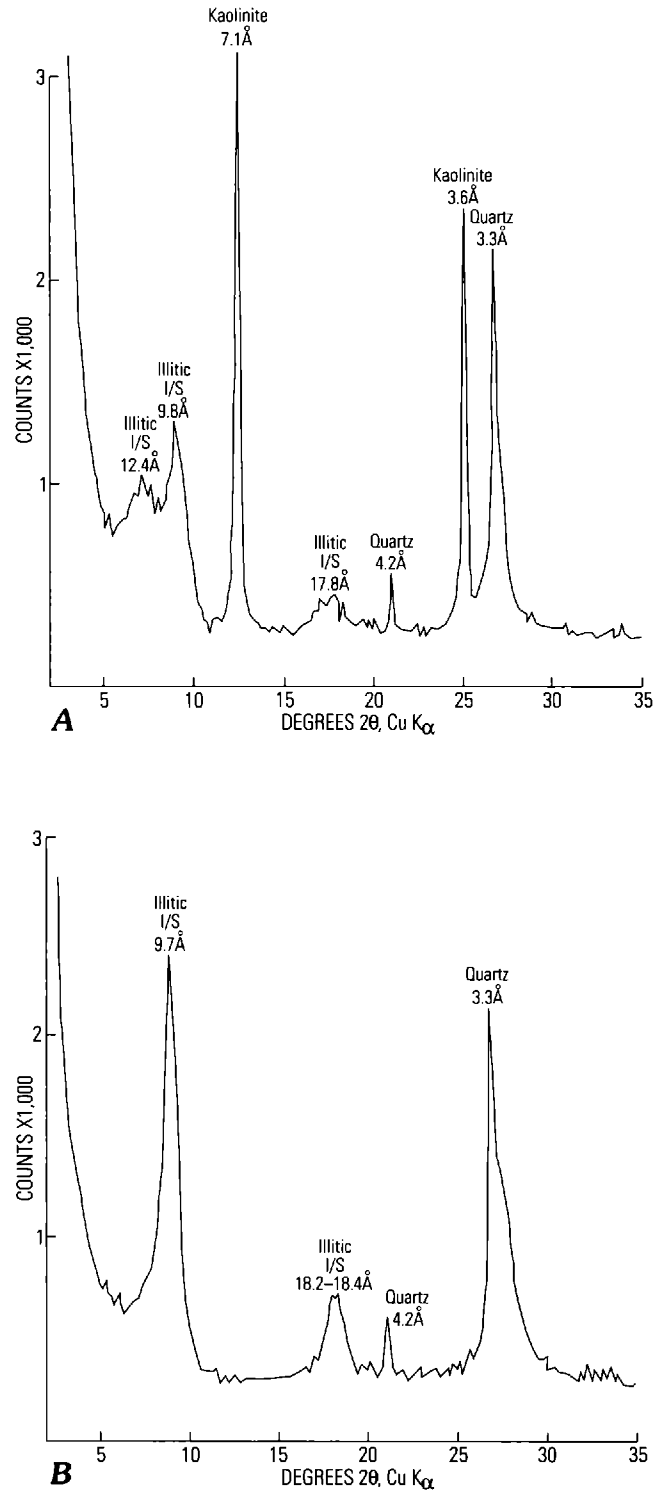


Figure 7. X-ray diffractograms of mudstone from Burro Canyon Formation containing illitic mixed-layer illite/smectite and abundant kaolinite. Unit 101, Cannonball Mesa section. *A*, Glycol. *B*, Heated at 550 °C.

CONCLUSIONS

Clay minerals in the upper part of the Brushy Basin Member of the Morrison Formation in the study area are primarily smectitic mixed-layer illite/smectite, whereas clay minerals in the Burro Canyon Formation comprise about equal amounts of illitic mixed-layer illite/smectite and kaolinite. Smectitic clays in the Brushy Basin formed during early diagenesis of slightly reworked airborne tuffaceous material in the bottom sediments along the periphery of a large saline, alkaline lake. In contrast, illitic clays in the Burro Canyon are probably detrital material washed into the study area by Burro Canyon streams. Kaolinite in the Burro Canyon also may be detrital, or it may have formed authigenically as part of a weathering profile beneath the sub-Dakota unconformity.

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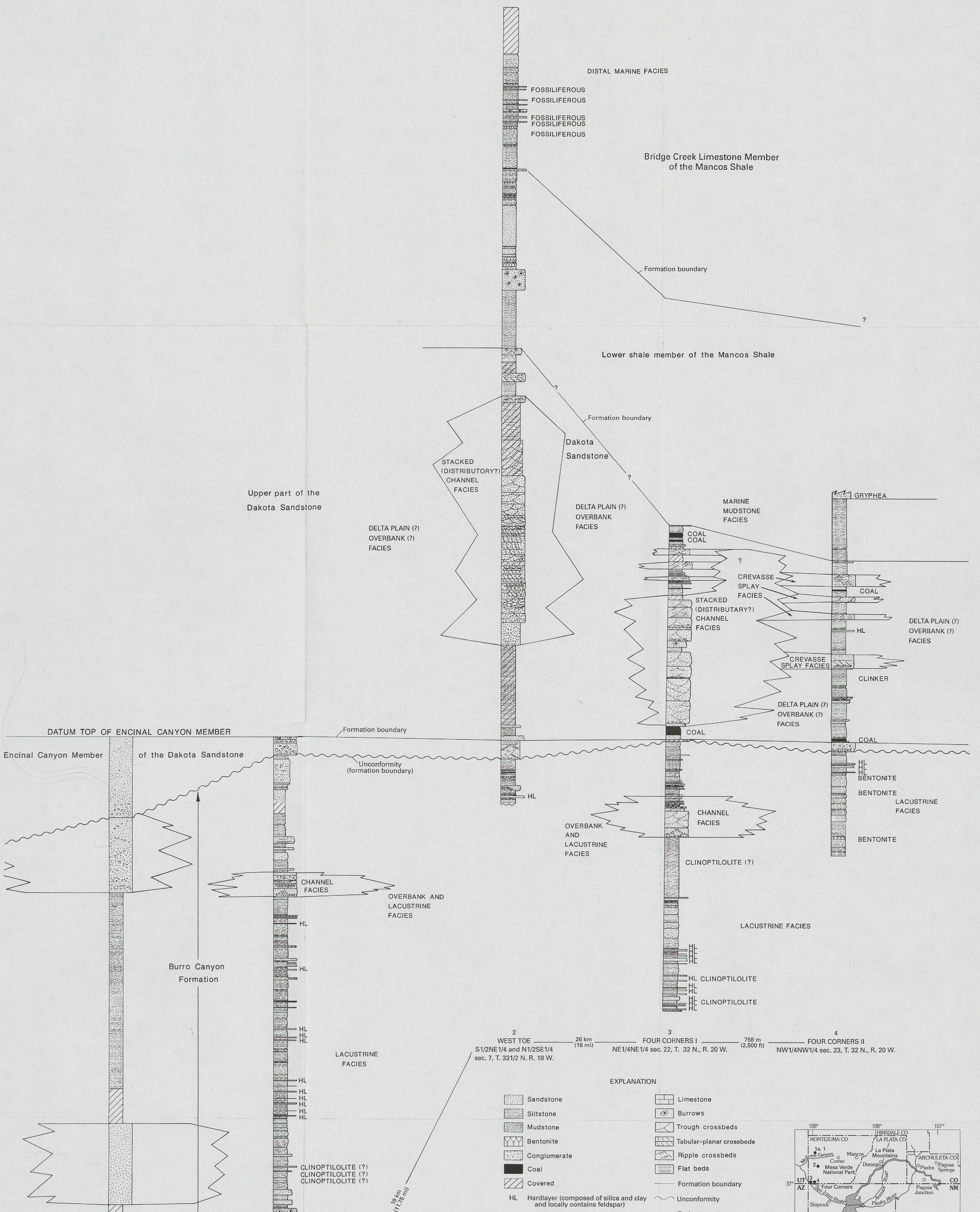
MEASURED SECTIONS SHOWING CORRELATIONS OF UPPERMOST JURASSIC TO MID–CRETACEOUS STRATA, SOUTHEASTERN SIDE OF SAN JUAN BASIN, NORTHWESTERN NEW MEXICO

By
William M. Aubrey
1992



MEASURED SECTIONS SHOWING CORRELATIONS AND FACIES RELATIONSHIPS OF UPPERMOST JURASSIC TO MID–CRETACEOUS STRATA, NORTH SIDE OF SAN JUAN BASIN, SOUTHWESTERN COLORADO

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