Paleocurrents and depositional environments of the Dakota Group, San Miguel and Mora Counties, New Mexico

Craig R. Bejnar and R. H. Lessard, 1976, pp. 157-163

in:

Vermejo Park, Ewing, R. C.; Kues, B. S.; [eds.], New Mexico Geological Society 27th Annual Fall Field Conference Guidebook, 306 p.

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PALEOCURRENTS AND DEPOSITIONAL ENVIRONMENTS OF THE DAKOTA GROUP SAN MIGUEL AND MORA COUNTIES, NEW MEXICO

CRAIG R. BEJNAR
and
ROBERT H. LESSARD
Earth Science Division
New Mexico Highlands University
Las Vegas, New Mexico 87701

INTRODUCTION

The Dakota Group is a widespread and well known rock stratigraphic unit in the Rocky Mountain region and has gained recognition throughout the area for its reservoir characteristics. The recent discovery of a shallow methane gas field in the Dakota Group near Wagon Mound, New Mexico, has reactivated a commercial interest in this unit as a potential hydrocarbon reservoir in the Las Vegas sub-basin as well as in the Raton basin and adjacent areas. Although many workers have referred to the Dakota Group on the eastern side of the Rocky Mountains, the only detailed stratigraphic studies of the unit are by Jacka and Brand (1972) and Asquith and Gilbert (this Guidebook). This paper supplements these studies with additional information on the geology of the Dakota Group in San Miguel and Mora Counties.

FIELD AREA

The Dakota Group was studied in two overlapping areas in San Miguel and Mora Counties (Fig. 1). The first area is located between Romeroville and La Cueva and extends for 28 miles along the north-south trending Creston Ridge, a prominent hogback in the eastern foothills of the southern Sangre de Cristo mountains. The second area is located between Romeroville and Trujillo (a distance of 32 miles) and is situated along the Canadian Escarpment, the sharply defined southern edge of the Las Vegas Plateau.

The Dakota Group, consisting of three separate units, was examined at 16 localities (Fig. 1). At 13 localities it was measured and described, and at the remaining three localities it underwent a cursory examination. Cross-stratification measurements were made at all 16 localities. A brief description of each locality is given below including its latitude (Lat.) and longitude (Long.), total measured thickness (TT), thickness of the Lower Sandstone Unit (T-LSU), thickness of the Middle Shale Unit (T-MSU), and thickness of the Upper Sandstone Unit (T-USU).

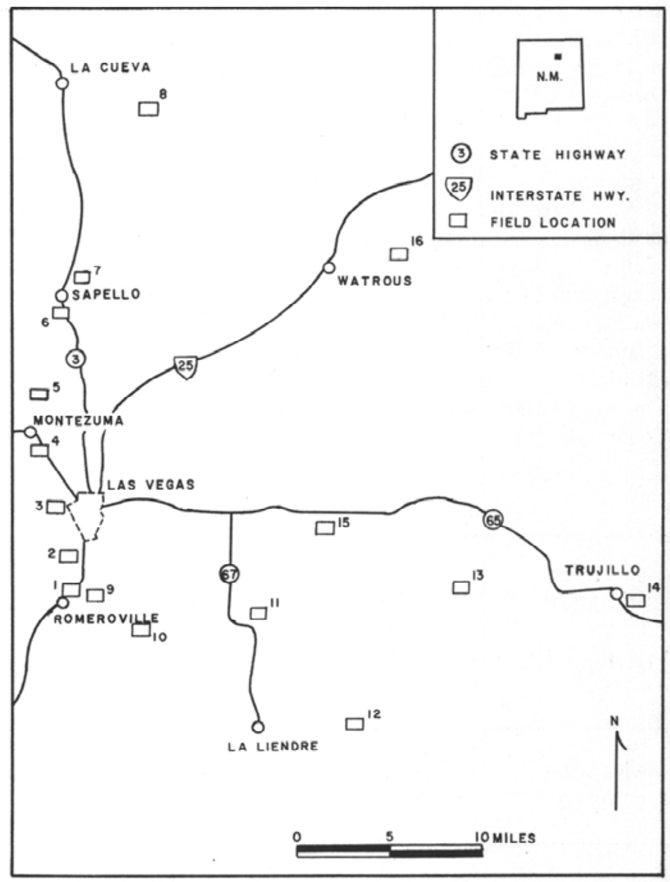

Figure 1. Map showing locations of sections where the Dakota Group was studied.

1. Romeroville Gap—Long. 105°15 'A' W; Lat. 35°31 IA' N; TT=105 ft.; T-LSU=79 ft.; T-MSU=14 ft.; T-USU=12 ft.—may not be complete.
2. Kearny Gap—Long. 105°15 W; Lat. 35°33 N; TT=123 ft.; T-LSU=98 ft.; T-MSU=17 ft.; T-USU=8 ft.—may not be complete.
3. Arroyo Hermanos—Long. 105°15' W; Lat. 35°36' N; TT=108 ft.; T-LSU=88 ft.; T-MSU=10 ft.; T-USU=10 ft.
4. Montezuma—Long. 105°16' W; Lat. 35°39' N; TT=121 ft., T-LSU=82 ft.; T-MSU=9 ft.; T-USU=30 ft.
5. Bonita Ranch—Long. 105°16^{1}A' W; Lat. 35°42' N; cursorily examined.
6. Sapello—Long. 105°14/2' W; Lat. 35°46' N; TT=161 ft.; T-LSU=117 ft.; T-MSU=17 ft.; T-USU=27 ft.
7. North of Sapello—Long. 105°16' W; Lat. 35°49' N; TT=117Y2 ft.; T-LSU=931/2 ft.—may not be complete; T-MSU=14 ft.; T-USU=10 ft.
8. Coyote Creek—measured at three different localities in the vicinity of Long. 105°10' W; Lat. 35°55' N, in order to get one complete section; TT=159^1/2 ft.; T-LSU=102 ft.; T-MSU=12^1/2 ft.; T-USU=45 ft.—may not be complete.
9. Box Canyon—Long. 105°12' W; Lat. 35°32' N; TT=99 ft.; T-LSU=89 ft.—may not be complete; T-MSU=6 ft.; T-USU=4 ft.—may not be complete.
10. Pagosa Canyon—Long. 105°10' W; Lat. 35°30' N; TT=89^1/2 ft.; T-LSU=72^1/2 ft.—may not be complete; T-MSU=not present; T-USU=17 ft.—may not be complete.
11. Callon Del Agua—Long. 105°01' W; Lat. 35°39' N; TT=99 ft.; T-LSU=76 ft.; T-MSU=13 ft.; T-USU=10 ft.- may not be complete.
12. Mesa Lauriana—Long. 104°571/2' W, Lat. 35°25' N; TT=1 *55* ft.; T-LSU=118 ft.; T-MSU=not present; T-USU=37 ft.—may not be complete.
13. Conchas Canyon—Long. 104°51' W; Lat. 35°31' N; TT=93 ft., T-LSU=63 ft.—may not be complete, T-MSU=not present; T-USU=30 ft.—may not be complete.

14. Trujillo—Long. 104°41' W; Lat. 35°31' N; TT=53 ft.; T-LSU=36 ft.; T-MSU=5 ft.; T-USU=12 ft.—may not be complete.

15. Unmeasured section east of Las Vegas—Long. 104°59' W; Lat. 35°35' N; cursorily examined.

16. Valmora—Long. 104°55' W; Lat. 35°48Y2' N; cursorily examined.

REGIONAL CONCEPTS OF THE DAKOTA GROUP

In many places in the Western Interior of the United States the basal Cretaceous rock units can be separated into three major divisions (Table 1). Much confusion and a voluminous literature have been generated for over a century by attempts to correlate and name these rocks. The name Dakota Sandstone was first applied to the entire basal Cretaceous sandstone sequence by Meek and Hayden (1861). Since then the term Dakota has been used multifariously by various authors. These problems have been described in other reviews (Long, 1966; Owen, 1966) and will not be treated at length in this paper.

A tripartite division of the Dakota is found in the San Miguel-Mora county area. It consists of a lower conglomeratic sandstone, a middle carbonaceous shale, and an upper sandstone. These three units probably correlate with Colorado units named by Waage (1953, 1955) and McLaughin (1954) (Table 1), who incorporate the lower two units into the Purgatoire Formation. A westward correlation across the southern Rocky Mountains from the Raton Basin into the Chama Basin (Owen, 1969) shows a three part division almost identical to that in the San Miguel-Mora county area (Table 1). The terms proposed by Owen (1969) for these units, the Lower Sandstone Unit, Middle Shale Unit, and Upper Sandstone Unit, have been adopted in this paper. A less definitive correlation of these units has been made with the basal Cretaceous in the Tucumcari basin, located to the southeast of the study area. The Purgatoire Formation has been recognized in this area but its use has been discouraged by Griggs and Reed (1959). In the Colorado Plateau area, the Dakota Group has been divided into two units (Table 1) by Young (1960), the non-carbonaceous Cedar Mountain Formation and the carbonaceous Naturita Formation.

The divisions of the Dakota Group in the different basins are not necessarily time-stratigraphic equivalents of each other. They are, however, a consequence of the same or similar sedimentary processes operating in different places at different times prior to and during the Cretaceous transgression.

STRATIGRAPHY

Contacts

The Dakota Group overlies the Jurassic Morrison Formation at most of the localities examined in the study area. The contact here appears to be a paraconformity (with some local channeling), whereas in Colorado, the Dakota-Morrison contact varies from disconformable to conformable (Waage, 1955; Haun, 1959). The Graneros Shale overlies the Dakota Group in the study area except where it has been removed by erosion.

Generalized Section

The following generalized descriptive stratigraphic section of the Dakota Group has been constructed from the detailed

Table 1. Nomenclature of basal Cretaceous strata of the Western Interior of the United States

Colorado Plateau Young, 1960		Chama Basin Owen, 1969		This Paper		Southeast Colorado Waage, 1953		Southeast Colorado McLaughin, 1954		Front Range Colorado Waage, 1955		Tucumcari Basin Griggs and Reed, 1959
Mancos Shale		Mancos Shale		Graneros Shale		Graneros Shale		Graneros Shale		Benton Shale		
Dakota Group	Naturita Formation	Dakota Sandstone	upper sandstone unit	Dakota Group	upper sandstone unit	Dakota Sandstone		Dakota Sandstone		Dakota Group	South Platte Formation	Dakota Sandstone
Dakota Group	Naturita Formation	Dakota Sandstone	middle shale unit	Dakota Group	middle shale unit	Purgatoire Formation	Glencairn shale member	Purgatoire Formation	Kiowa shale member	Dakota Group	South Platte Formation	Pajarito Shale
Dakota Group	Cedar Mountain Formation	Dakota Sandstone	lower sandstone unit	Dakota Group	lower sandstone unit	Purgatoire Formation	Lytle sandstone member	Purgatoire Formation	Cheyenne sandstone member	Dakota Group	Lytle Sandstone	Mesa Rica Sandstone Tucumcari Shale
Morrison Formation		Morrison Formation		Morrison Formation		Morrison Formation		Morrison Formation		Morrison Formation		Morrison Formation

stratigraphic descriptions that were made at 13 of the 16 study localities.

Lower Sandstone Unit

The Lower Sandstone Unit ranges in thickness from 63 to 118 ft with a mean of 91 ft (excluding the Trujillo section). This unit comprises about 75 percent of the complete Dakota section. The main rock type is a pale grayish orange to very light gray, conglomeratic to fine-grained, moderate- to well-sorted, silica-cemented, quartz arenite. Limonite cement, along with silica, is locally abundant. This arenite, as well as all the other arenites in the Dakota Group, conform to the following description: In this section the grains are mostly common quartz with straight extinction under crossed nichols. Chert makes up one to five percent of the sand grains in each unit. They include (in decreasing order of abundance) quartz overgrowths in optical continuity with adjacent grains, chert (recrystallized opal?) and opal cementation (minor).

Two distinctive features of the Lower Sandstone Unit are the prevalence of conspicuous medium-scale trough cross-stratification, (described below) and chert-pebble conglomerate lenses. The conglomerate lenses are located mostly in the upper half of the Lower Sandstone Unit comprise as much as 30 percent of the Lower Sandstone Unit locally though the average is less than 10 percent. The quantity of conglomerate varies greatly between closely spaced exposures. Most of the conglomerate lenses are a few feet thick and grade into coarse sandstone, but some discrete conglomerate-filled channels are over 10 ft thick. Other conglomerate zones are persistent across an outcrop and approach sheet-like form. Within many sandstones are layers of chert one or two pebbles thick, probably representing lag concentrates along a channel floor.

The conglomerate is dominantly white to gray to black chert with very minor reddish quartzite, white quartz and sandstone fragments that vary in size from 3 in. down to less than 1/4 in. A plot of the maximum pebble size at various localities suggests a fining to the east. The light gray to black chert contains bryozoans and fusulinids indicating a silicified, late Paleozoic carbonate rock source area. Many chert pebbles have dense gray centers surrounded by thick weathered rims of white tripolitic chert. Some are completely weathered.

The conglomerate beds in the Lower Sandstone Unit are generally more weakly cemented than the surrounding sandstones. The cement is usually a variable admixture of a white clay material and silica.

Thin clay-gall conglomerate and discontinuous, light-green claystone layers can be found in the lower portion of the sandstone unit at most sections and are associated with minor amounts of chert. The clay galls, whose average diameter is approximately 1 in., are obscure because they weather rapidly. They form part of a poorly delineated, repeated, vertical sequence consisting of (from top to bottom): 1) trough cross-stratified sandstone, 2) thin, discontinuous, clay-gall conglomerate, 3) an erosional surface. Some of the erosional surfaces show as much as 6 ft of relief. Carbonaceous matter is found in the uppermost portions of the Lower Sandstone Unit near its contact with the black shales of the Middle Shale Unit.

The Lower Sandstone Unit at Trujillo is only 36 ft thick and does not contain any conglomerates. It and the Pajarito Shale are intercalated at their contact for a thickness of 5 ft locally.

Middle Shale Unit

The Middle Shale Unit consists of two intercalated lithologic types including a silty, fine-grained sandstone and a black carbonaceous shale. It characteristically weathers to a covered slope. The Middle Shale Unit is persistent from north to south, and varies from 9 to 17 ft in thickness. The unit is thinner and discontinuous along the west to east traverse. Little or no carbonaceous material is present in the Dakota Group east of Mesa Lauriano.

The shale generally is grayish olive to medium dark gray and weathers to lighter grays. The sandstone typically is light gray to grayish orange and weathers grayish yellow. Both the sandstone and shale contain dark disseminated carbonaceous matter. The sandstones contain abundant wood fragments which have been replaced by limonite or occur as empty molds.

All but 2 ft of the black shales and thin sandstones of the Middle Shale Unit at Coyote Creek have been truncated by a small paleoriver channel, indicating at least a partially fluvial origin for this unit.

Upper Sandstone Unit

The base of the Upper Sandstone Unit was defined as the top of the highest black shale of the Middle Shale Unit. The sandstones above this contact consist of three distinct lithologic types. The most common is a light gray, fine- to medium-grained, well-sorted, silica-cemented, very well indurated quartz arenite that weathers to grayish-orange-pink or pale red. Its distinctive features are vertical trace fossil burrows and/or well-developed, small-scale tabular planar cross-stratification.

The second lithologic type is a mottled very light to dark gray sandstone that develops dark yellow-orange blotches when it weathers. It is clayey, fine- to medium-grained, and moderately to poorly sorted with fine, irregular, dark carbonaceous partings and swirls. An interesting feature of this sandstone is the complete destruction of its bedding by extensive bioturbation, probably accounting for its poor sorting.

The third type of sandstone is characterized by a profusion of carbonized wood fragments (some replaced by limonite and others occurring as wood molds). This type of arenite comprises the entire Upper Sandstone Unit at Coyote Creek, where the unit is a grayish yellow to mottled light and dark gray, clayey, fine to medium grained, well to moderately sorted, and well indurated sandstone. This lithologic type resembles the better sorted sandstones in the Middle Shale Unit.

In general, the sandstone in the Upper Sandstone Unit tends to be finer grained than in the Lower Sandstone Unit but hand specimens from the two units often cannot be distinguished from each other. Stylolitic bedding surfaces are common in the Upper Sandstone Unit. The top of the Upper Sandstone usually forms the top of the exposure and is eroded to some degree, hence only minimum thicknesses can be recorded; however, most of the eroded sections have measured thicknesses similar to the few complete sections.

PRIMARY STRUCTURES

Primary sedimentary structures in the study area include stratification, cross-stratification, ripple marks, soft sediment deformations and burrows. A detailed discussion of the cross-stratification and ripple marks will be presented in this section and one dealing with burrows in the section on paleontology.

Cross-Stratification

Six hundred and seventy three cross-strata dip measurements were made. Unfortunately, three dimensional views of the cross-stratification are scarce, making positive identification of the cross-stratification type difficult. Trough cross-stratification predominates in the Lower Sandstone Unit, whereas tabular-planar cross-stratification predominates in the Upper Sandstone Unit. Cross-stratification is generally absent in the sandstones of the Middle Shale Unit.

Sets of trough cross-stratification range from 0.5 to 10 ft and average about 2 ft in thickness (measured at right angles to the bedding). These fall into the medium-scale cross-stratification of McKee and Weir (1953). The cosets tend to be lenticular. The sets of tabular-planar cross-strata are much thinner, averaging less than half a foot in thickness, and range from small to medium scale.

Cross-strata dip angles average 20° and have a standard deviation of 7.5° in the Lower Sandstone Unit; dip angles in the Upper Sandstone Unit average 21° and have a standard deviation of 6.6°. The average dip angles fall near the lower limit of high-angle cross-stratification (20°) according to McKee and Weir (1953), though Jacob (1973) suggests 15° for this lower limit.

Compass rose diagrams of cross-stratification in both the Lower and Upper Sandstone Units show a distinct unimodal distribution of the cross-stratification in the Lower Sandstone Unit and a bimodal distribution in the Upper Sandstone Unit. The unimodal distribution is towards the east and the bipolar has modes of N. 15° W. and S. 15° E. The unimodality of the Lower Sandstone Unit suggests that its sediments were deposited in a fluvial environment with a regional paleoslope to the east. The bipolarity of the Upper Sandstone Unit suggests that its sediments were deposited in a marine environment whose currents were directed almost at right angles to the paleoslope.

The rose diagrams also indicate a variability of cross-strata orientation. This variability is due to the natural variability in sedimentary processes, such as meandering and longshore currents, and to changes through time in direction and gradient of the paleoslope. One measure of this variability is the standard deviation. The standard deviation of several modern streams ranges from 20° to as much as 83° depending upon gradient and sinuosity (Hamblin, 1958). High-gradient braided streams have the lowest standard deviation; highly sinuous meandering streams have the highest standard deviation (Allen, 1965). Regional variances of cross-strata in modern marine deposits range from 83° to 87° standard deviation, whereas those from fluvial-deltaic deposits range from 71° to 77° standard deviation (Pryor, 1960).

The standard deviation of the cross-stratification dip azimuth directions for the Lower Sandstone Unit is 78° suggesting the Lower Sandstone Unit is fluvial, perhaps of a meandering stream. The standard deviation is high for a fluvial environment. The Upper Sandstone Unit has a standard deviation for the cross-stratification directions of almost 97°, suggesting a marine environment with highly variable current directions.

Ripple Marks

Unfortunately, ripple marks were found *in situ* only at Kearny Gap. They are near the top of the Lower Sandstone Unit and occur on at least five separate cross-strata surfaces which are 1 to 2 in. apart. The bedding planes are structurally tilted 48° eastward, the cross-strata tilt southeastward at 56°, and the ripple crests are oriented almost north-south and plunge about 36°. The ripple crests clearly do not lie parallel to the strike of the cross-stratification even after structural rotation corrections have been made.

The high values of RI (ripple index) and CI (continuity index) associated with these ripples indicate that they have an eolian origin and are not "oscillatory wave ripples which form in the intertidal zone" as suggested by other authors.

Ripple marks found in float of the Upper Sandstone Unit have a different form from those at Kearny Gap. They are symmetrical straight ripples of probable wave origin. These ripple marks have a ripple spacing of 2 in. and a height of about 'A in. for a RI of about 8.

HEAVY MINERALS AND THEIR PROVENANCE

An analysis of the heavy mineral assemblage of the Dakota Group indicates an ultra-stable assemblage of zircon and tourmaline with some rutile, garnet and hornblende. Zircon may be well-rounded or euhedral; the tourmaline is well-rounded.

The idiomorphic zircon is an indicator of a volcanic source (Callender and Folk, 1958). The extreme rounding of the majority of zircon grains and all tourmaline grains suggests that they are second cycle and derived from sedimentary rocks. The underlying Morrison Formation contains similar zircon and tourmaline grains along with a larger suite of metastable heavy minerals (Mankin, 1958). The sediments of the Morrison Formation and the Dakota Group could have come from the same source area and some of the Dakota Group may have reworked Jurassic Morrison Formation.

PALEONTOLOGY

The Dakota Group contains few fossils. The only megabody fossils present are carbonized wood fragments and wood molds in the Middle Shale and Upper Sandstone Units, silicified logs at the base of conglomeratic channels in the Lower Sandstone Unit, sand-filled root casts in the Middle Shale Unit at Coyote Creek and an exterior mold of a coniferous cone in the sandstone of the Middle Shale Unit at Montezuma. A dinosaur footprint was recently found in Dakota float near Ft. Union, N.M. Trace fossils are widespread and locally abundant in the Upper Sandstone Unit. Palynomorphs were extracted from the carbonaceous Middle Shale Unit at two locations. The root casts, trace fossils and palynomorphs will be discussed in some detail due to their paleoenvironmental and paleogeographical significance.

Root Casts

Two 1 ft thick shale beds at the top of the Middle Shale Unit at Coyote Creek contain hundreds of sand-filled, downward-bifurcating, downward-tapering, cylindrical casts. They have been interpreted as either the root casts of small trees or brush. Some of the root casts can be traced with difficulty through a 2 in. sand bed between the two shales.

Trace Fossils

The trace fossils with the widest distribution are vertical burrow casts. The two most abundant are *Skolithos (=Scolithus)* and *Ophiomorpha (=Halymenites).* The *Skolithos* tubes have diameters averaging about 0.1 in. and a length averaging 4 to 8 in.; a tube 12 in. long was found at the Conchas Canyon section. They are straight, never branched, and typically crowded. *Skolithos* tubes are found in the indurated, moderately- to well-sorted, medium- to coarse-grained sandstones of the Upper Sandstone Unit, except for a single questionable occurrence in the Middle Shale Unit at Canon Del Agua.

The *Ophiomorpha* tubes are vertical, unbranched, average .5 to 1 in. in diameter and have wart-like external ornamentation with smooth interiors. They vary in length from 6 to 10 in. and may occur either singly or less commonly, in closely spaced groups. They are believed to have been made by a marine decapod crustacean similar to the recent *Callianassa major.* The modern burrows are abundant in well-sorted, massive-bedded sands in wave-agitated littoral and shallow neritic conditions, especially in the zone between mean sea level and low tide on beaches that face the open ocean (Weimer and Hoyt, 1964). Like *Skolithos, Ophiomorpha* is found in the Upper Sandstone Unit.

Other trace fossils in the Upper Sandstone Unit are U-tubes *(Arenicolites)* and U-in-U tubes *(Rhizocorallium* and *Corophioides).* The unsculptured, pencil-sized U-tubes are separated by about 1.5 in., are commonly about 3 in. long, and were probably made by marine polychaete worms.

U-in-U tubes are U-shaped with spreiten. They tend to be larger than the simple U-tubes, but the spreite are frequently poorly preserved and it is often difficult to distinguish between the two forms.

In contrast to the foregoing trace fossils, which more or less shared the same high-energy sand environment, two additional trace fossils, *Thalassinoides* and *Planolites* (from a relatively quieter environment) are found in the carbonaceous, silty sandstones of the Upper Sandstone Unit. *Thalassinoides* is represented by Y-shaped tubes about 0.5 in. in diameter forming largely horizontal tunnel systems without special surface ornamentation. Commonly *Thalassinoides* is so profuse that it obliterates both bedding and previously formed burrows, and is largely responsible for the bioturbated zones in the Upper Sandstone Unit. *Planolites* burrows are 0.2 to 0.4 in. wide and irregular in course and direction. They are present in the bioturbated beds of the Upper Sandstone Unit and have a single occurrence in the upper part of the Lower Sandstone Unit. Grant and Owen (1974) have also found *Planolites* in the Lower Sandstone Unit in the Chama Basin.

Palynomorphs

Samples of the black to gray carbonaceous shale in the Middle Shale Unit of the Dakota Group were collected from seven localities and examined for palynomorphs. The samples from Romeroville and Coyote Creek were the only ones that contained extractable palynomorphs. The thin green mudstones and clay galls in the Lower Sandstone Unit were also examined but proved to be barren.

The pollen and spores from Romeroville Gap and Coyote Creek show no significant areal or stratigraphic variation. The specimens are exclusively terrestrial and come from ferns, lycopods, conifers, gymnosperms and perhaps primitive angiosperms. They include in order of abundance: *Cicatricosisporites* cf. C. *magnus* and *C. dorogenis,* fern spores of the Schizaeaceae; *Lycopodiacidites* sp., a lycopod spore; *Dictyophyllidites* sp., *Cyathidites minor,* and *Gleicheniidites* sp., all fern spores; unidentified sulcate pollen grains; gymnospermous pollen or primative angiosperm pollen; bisaccate coniferous pollen; *Alisporites* sp., coniferous pollen; fungal spores; and *Schizocystia* cf. *S. laevigata.*

The presence of terrestrial palynomorphs and the absence of hystrichospheres and dinoflagellates would seem to negate the contention that the sediments of the black shales were deposited in a marine lagoonal or paludal environment.

AGE OF DAKOTA GROUP

The overlapping ranges of the pollen and spores from the Middle Shale Unit indicate an upper Lower Cretaceous age (either Aptian or Albian) for the unit. The absence of tricolpate grains, which evolved in the Albian, might lend some support to the Aptian age, but tricolpate grains are also absent at many known Albian localities (Kremp, written communication). The upper Lower Cretaceous age is in agreement with that determined by most workers in this area (McGookey, 1972). The upper part of the Upper Sandstone Unit has been assigned a Cenomanian age on the basis of mega-body fossils found in adjacent areas (Owen, 1969). The exact age of the Lower Sandstone Unit is uncertain due to the lack of fossils in the unit.

PALEOCLIMATE

While no climatic interpretation of the Dakota Group can be advanced with certainty, the authors agree with most workers that the climate was warm and humid (Jacka and Brand, 1972; Willard, 1964; Millison, 1964; Mankin, 1958). Evidence supporting this contention includes: (1) the nearly complete absence of feldspar and climate-sensitive heavy minerals in all the units, (2) thick tripolitic weathering rinds on chert pebbles, (3) abundance of silica-cementation which, according to Mankin (1958) suggests a humid climate, and (4) the presence of temperature sensitive ferns such as Schizaeaceae.

INTERPRETATION OF DEPOSITIONAL ENVIRONMENTS

Lower Sandstone Unit

The coarse- to medium-grained, moderately-sorted, predominately trough cross-stratified sandstones of the Lower Sandstone Unit, which contain some well-developed channel and irregular scour surfaces, are interpreted as having been deposited in a fluvial environment. The unidirectional modality and low variance (79° standard deviation) of the trough cross-stratification support this conclusion. The overall geometry of the unit suggests that its sediments were either deposited by a braided stream or by a low sinuosity meandering stream.

In the Lower Sandstone Unit the lack of either topstratum or floodplain fine-grained sediments indicates a low ratio of suspended to bed load, which is typical of braided and coarse-grained, point-bar deposits (McGown and Garner, 1970). The absence of mud could also be due to extensive sorting and reworking of the sediments under very slow rates of deposition. The discontinuous mudstone layers and clay-gall conglomerates in the lower sandstone unit are more common in braided stream sediments than in more homogeneous point bars (Smith, 1970). On the other hand, the variance in the cross-stratification dip directions within the Lower Sandstone Unit is relatively high for stream deposits, which suggests deposition by a meandering stream system.

Fluvial systems vary within a whole spectrum between braided and highly meandering channel patterns, so that categorizing even modern streams may be difficult. McGowan and Garner (1970) state that an ancient fluvial sequence dominated by foreset cross-strata and trough-fill cross-strata could be either lower point-bar, chute-bar, crossover, or braided-stream deposits." Many authors who have worked on this problem stress the uncertainty in trying to reconstruct the morphologies of paleorivers.

Middle Shale Unit

The Middle Shale Unit consists of fine-grained, carbonaceous sandstones intercalated with black carbonaceous shales. This lithology indicates a relatively quiet, but fluctuating, environment of deposition similar to the floodplains of Recent low-gradient rivers. The channel sandstone in the Middle Shale Unit at Coyote Creek, which is lithologically similar to the fluvial sandstones in the Lower Sandstone Unit, supports a fluvial origin.

Fossils in the Middle Shale Unit are mostly terrestrial plant remains that consist of molds of wood fragments, carbonized films, and palynomorphs of ferns and conifers to be expected in a fluvial environment. The large root casts of Coyote Creek indicate dry land to fairly shallow water.

The shale-sandstone lithofacies of the Middle Shale Unit is persistent along the north-south paleoshoreline strike, but is discontinuous at right angles to it. Facies which parallel coastal shorelines are usually relatively near sea level and close to the coast.

Upper Sandstone Unit

The presence of diagnostic trace fossils, such as *Ophiomorpha,* place the depositional environment of this unit in the wave-agitated littoral or shallow neritic zones along a beach. These sands commonly have small-scale, tabular-planar cross-stratification which shows 180° reversals in current direction. Such bipolarity is commonly indicative of marine conditions. The modes of the bipolar distribution of current directions are almost at right angles to the paleoslope; hence, they parallel the paleoshoreline. The very high variance of the cross-stratification directions (97° standard deviation) is also indicative of a marine environment. The ripple marks associated with the Upper Sandstone Unit are symmetrical ripples typical of the wave-agitated littoral environment.

The bioturbated sediments in the poorly-sorted carbonaceous sandstones in the Upper Sandstone Unit appear to have been either deposited below wave base or protected from the sorting of wave action by a bar or barrier island.

The origin of the thin-bedded sandstones which contain abundant carbonized wood fragments and wood molds is uncertain. These sands may have been deposited in a marine environment and their terrestrial fossil component carried to the depositional area by currents.

PALEOTECTONIC SETTING

Both this study and regional studies of the petrology and heavy mineral suites of the Dakota Group indicate that the primary source area was dominated by mature sandstones and cherty carbonate rocks (Mankin, 1958; MacKenzie and Pool, 1962; Long, 1966). The only known highlands in the Western Interior of the United States during the Early Cretaceous were the Siever orogenic belt in western Utah and the Mogollon and Burro uplift in southern New Mexico and Arizona (McGookey, 1972). This regional paleogeographic setting may be complicated by remnants of small uplifts in southern Colorado, where the Dakota Group rests nonconformably on Precambrian rocks (Owen, 1969).

The erosion of the Mogollon Highlands in eastern Arizona and the Burro Uplift in southwestern New Mexico caused great quantities of coarse clastics to be shed over southern Arizona, southern New Mexico and northern Mexico during part of the Jurassic and Early Cretaceous time (Kottlowski and Foster, 1962). This area does not appear to be the source of Dakota Group sediments in the study area. Paleocurrent analysis indicates that these sediments came from the west rather than the southwest.

The Siever orogenic belt, some 500 miles to the west, is the probable source of the basal Cretaceous clastics in northern New Mexico. Sediments of Eocambrian through Jurassic age, including a thick Paleozoic carbonate section, were eroded from the Siever orogenic belt during Late Jurassic through Cretaceous time (Armstrong, 1968).

The rapid decrease in pebble size in the Lower Sandstone Unit from west to east does not necessarily require a nearby source. Rivers will transport 3 in. or larger pebbles for long distances, until they are no longer competent to do so, at which point the size will rapidly decrease. Pebble size distributions in southeastern Colorado (Long, 1966) show the same relationships as in northcentral New Mexico.

DEPOSITIONAL HISTORY

The units within the Dakota Group in the study area record a conformable succession of three major environments including a piedmont plain, coastal plain, and a littoral-beach-lagoon-marine complex. These have been recognized by authors in other areas (Kauffman and others, 1969; Owen, 1969; Jacka and Brand, 1972).

The initial deposition of the Dakota Group began on essentially horizontal Jurassic rocks by braided and/or meandering rivers which flowed easterly from their source in the Siever uplift in western Utah. The rivers may have turned southward on the eastern edge of the study area toward the encroaching embayment of the Cretaceous sea to the southeast (Reeside, 1957). In any event, they worked over the sediments sufficiently to sort out the muds so that moderately sorted sands could be deposited. After approximately half the sediments of the sandstone in the Lower Sandstone Unit had been deposited, a marked change in stream regime brought an influx of fossiliferous chert gravel. A pulse of rapid tectonic uplift to the west or northwest could account for this change in regime.

As the source area was worn down and sea level rose, the Cretaceous rivers in the study area became meandering types which deposited fine-grained, carbonaceous sands and muds over extensive flood plains. This was a period of relative quiescence in a swampy coastal plain covered by ferns, conifers, and primitive angiosperms.

Sea level continued to rise and the waters of the surf zone reworked the terrestrial sands. The well-sorted sands of the beach face (and shallow bars) were moved by longshore currents and inhabited by a number of organisms whose only remains are burrows. The carbonaceous sands, which escaped extensive sorting by waves, were churned by other burrowing organisms in search of food. As the shoreline moved westward, the entire area in northcentral New Mexico was submerged below wave base and the sandy marine shales of the Graneros Shale were deposited.

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