DEPOSITIONAL HISTORY OF THE DAKOTA SANDSTONE, SAN JUAN BASIN AREA, NEW MEXICO

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INTRODUCTION

The Dakota Sandstone (Cretaceous) in the San Juan Basin area of northwestern New Mexico and southwestern Colorado (fig. 1) includes rocks which were deposited under diverse marine and non-marine conditions. The purpose of this paper is to show that primary sedimentary structures, bioturbation, fossils, and lithologies in the Dakota provide a basis for recognizing a spectrum of marine and nonmarine environments within this unit and for developing a model to explain the changes in environments in space and during time. Most of the depositional environments and transgressive-regressive cycles illustrated by stratigraphically higher Cretaceous formations in the San Juan Basin are recorded on a smaller scale in the diverse Dakota lithologies. Thus, this study of the Dakota should contribute to a better understanding of other Cretaceous units in the region.

STRATIGRAPHIC NOMENCLATURE

Discussions of the stratigraphic nomenclature of the Dakota Sandstone and the adjacent Mancos Shale of the San Juan Basin region have been summarized by Owen (1966), Dane and others (1971), and Landis and others (1973, this volume). To summarize, the Dakota Sandstone is not subdivided into formal members in the northern part of the San Juan Basin, primarily because in this area the formation is largely nonmarine and contains many lenticular beds of variable lithology. Young (1960) considered the Dakota to have group status in the Colorado Plateau by adding the underlying Cedar Mountain (Burro Canyon) Formation to the formation here termed Dakota Sandstone. In the northern San Juan Basin, Burro Canyon strata are present only locally, so that the Dakota generally has been regarded as a formation in this area. Recognizable Burro Canyon rocks are not knowingly included within the Dakota in this paper, but in some areas the two formations are so similar that they are nearly impossible to differentiate (see Landis and Dane, 1967, p. 2-3).

In the Chama Basin, a northeastern re-entrant of the San Juan Basin, the Dakota may be differentiated readily into lower sandstone, middle shale, and upper sandstone units which could be recognized as formal members (Owen, 1969, p. 79-80). Outcrops of the Dakota in the southern part of the San Juan Basin and further south are composed largely of regularly interstratified marine sandstone and shale beds that are fairly persistent laterally. Previously, in these areas three formal members have been considered part of the Dakota by some authors: the Tres Hermanos Sandstone; the Twowells Sandstone; and the Whitewater Arroyo Shale.

Several different sandstone beds have been called Tres Hermanos by various authors due to confusion about the exact sandstone bed to which Herrick (1900) originally applied the name. Several sandstone beds in other areas have been identified with the Tres Hermanos of the type locality region (Dane, 1959; Owen, 1966). Recently, Dane and others

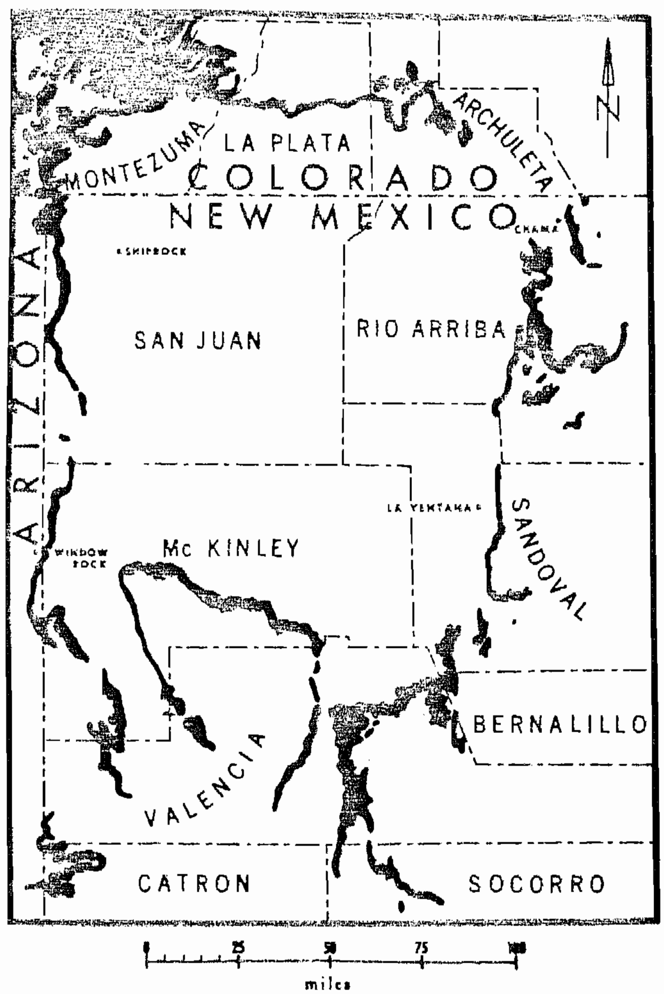

Fig. 1 Outcrop map of Dakota Sandstone in San Juan Basin area. Basin is a Laramide structural feature, not a Cretaceous depositional basin.

(1971, p. 19-20) have pointed out that the type Tres Hermanos is the next sandstone above the one which pertinent publications since Herrick (1900) have generally regarded as the Tres Hermanos in the type region. Therefore, Dane and others (1971) have shown that the true Tres Hermanos Sandstone lies above the Dakota Formation; the Tres Hermanos will not be discussed further in this paper.

The Twowells Sandstone in the southwestern part of the San Juan Basin region, originally described as a member of the Mancos Shale by Pike (1947, p. 36), was recognized by Owen (1966, p. 1026) as a member of the Dakota Sandstone because of its northward merger with the Dakota. Marvin (1967) traced the Twowells eastward and demonstrated that it was the same sandstone then generally regarded (erroneously) as the Tres Hermanos Sandstone of the type region. Dane and others (1971, p. 18), in addition to clearing up confusion about the stratigraphic position of the Tres Hermanos, regarded the Twowells as a tongue of the Dakota Sandstone as did Green and Pierson (1971). Therefore, the Twowells Sandstone is traceable throughout the entire southern part of the San Juan Basin region where it is the uppermost member or tongue of the Dakota Formation. Directly below the Twowells and nearly co-extensive with it is a wedge-shaped body of shale that Owen (1966, p. 1026-1027) named the Whitewater Arroyo Shale Member of the Dakota Sandstone because the Twowells Sandstone separates it from the Mancos Shale throughout very nearly all of its extent in the San Juan Basin area. Alternatively, Dane and others (1971, p. 18) and Green and Pierson (1971) interpreted this unit as the Whitewater Arroyo Shale Tongue of the Mancos Shale because in a small area near La Ventana (fig. 1) and southeast of the Colorado Plateau the Twowells Sandstone is not present to separate the Whitewater Arroyo from the Mancos Shale.

Below the Twowells Sandstone — Whitewater Arroyo Shale pair occur as many as three similar sandstone-shale pairs in much of the southeastern San Juan Basin. These lower pairs had not received formal names prior to the paper of Landis and others (1973, this volume), but some or all of the sandstones and the overlying Twowells Sandstone have been given informal names such as: Lower Tres Hermanos and Upper Tres Hermanos (Lee, 1917, p. 195); Tres Hermanos, 1, 2, and 3 (Hunt, 1936, p. 41-43); 1st, 2d and 3d Tres Hermanos (Young, 1960, p. 178); Tres Hermanos, 1, 2, and 3 (Schlee and Moench, 1963); Mancos a, b, and c (Thaden and others, 1966); and Mancos a, b, c, and d (Thaden and others, 1967). In the latter two cases where Mancos plus a letter designation was used, the sandstone-shale pair was included. All of these sandstone-shale pairs lie below the top of the Twowells Sandstone Member of the Dakota and above the top of the pebbly basal sandstone of the Dakota that rests unconformably on underlying formations. Until recently, many authors had restricted the name Dakota to only this basal sandstone in the southern part of the San Juan Basin. Landis and others (1973, this volume) have now included the strata between the basal unconformity and the top of the Twowells in six formally named rock-stratigraphic units, in stratigraphic order: the Oak Canyon Member; Cubero Sandstone; Clay Mesa Shale; Paguate Sandstone; Whitewater Arroyo Shale; Twowells Sandstone.

AGE-ENVIRONMENTAL RELATIONSHIPS

The Dakota Sandstone is the product of many depositional environments in the San Juan Basin. In general, it grades from lenticular, nonmarine beds of sandstones and carbonaceous shale in the northwestern San Juan Basin near the Four Corners (fig. 1) to regularly interstratified and more laterally persistent marine beds of shale and fine-grained sandstone in the southeastern San Juan Basin near Albuquerque. Correlation within the Dakota using age-diagnostic fossils has not been possible because of the variety of environments and attendant organisms that existed during deposition. Assuming the Dakota to be time-parallel, marine waters must have transgressed over a depositional plain from southeast to northwest during the time the formation was deposited because marine Dakota lies to the southeast and nonmarine to the northwest. If, on the other hand, the Dakota is time-transgressive, nearly any time-space relationship is possible. A complex clastic unit resting on a regional unconformity such as the Dakota could be expected to be time-transgressive to some degree, and fragmentary evidence indicates this to be the case (Haun, 1959; Tyrrell, 1959; Lamb, 1968; Dane and others, 1971). In what direction did the transgression occur? Haun (1959) indicated that the Dakota becomes younger southward across Colorado into the San Juan Basin due to closer vertical proximity to the Greenhorn Limestone and "X bentonite," two approximate time-markers. Tyrrell (1959) suggested that it becomes younger from east to west across the San Juan Basin due to closer approach to oyster zones in the overlying shale. The foraminifera zones in the lowermost Mancos Shale established by Lamb (1968, p. 840) also show the uppermost Dakota coming closer to these zones westward. Dane and others (1971, p. 20-21) interpret the Twowells Sandstone as becoming younger toward the southwest due to closer approach to the *Sciponoceras gracile* ammonite zone. Thickness is not necessarily a criterion of age, so that only extremely cautious interpretation should be made on the basis of stratigraphic thickness below poorly developed zones. Surely rate of deposition and amount of compaction must have varied locally and the lowest occurrence of a particular species at a locality may record only the first appearance of the required environment at the locality rather than the first appearance of that species in time.

Dane and others (1971) report a study in progress on ammonites and other invertebrate fossils of the Dakota, and the writer has collected two genera of ammonites from the upper part of the Dakota in the southeastern San Juan Basin. However, not enough specimens of index fossils such as ammonites have been reported from the Dakota at widely separated localities to establish accurate correlation which is absolutely essential in evaluating the time-space relationships of the Dakota. Fossils in the Dakota are not really as rare as usually assumed. Many beds, especially in the upper part of the Dakota and in the southeastern portion of the San Juan Basin, contain oysters (in great numbers), other bivalves, gastropods, and a few ammonites. In addition, several types of trace fossils are extremely common in many beds.

Fossils, especially ammonites, that occur in the upper part of the Dakota and the lower part of the Mancos indicate that the upper part of the Dakota was deposited in

Cenomanian (earliest Late Cretaceous) time (Owen, 1969, p. 91; Dane and others, 1971, p. 20-21). The sparsely fossiliferous strata below are of Albian (latest Early Cretaceous) age. The lowest unfossiliferous beds are undated and could be Albian or possibly older.

DAKOTA DEPOSITIONAL MODEL

The Dakota Sandstone is situated between the Upper Jurassic fluvial and lacustrine strata of the Morrison Formation and the Upper Cretaceous neritic strata of the Mancos Shale. Although Haun (1959, p. 2) has pointed out that the Dakota is not regionally unconformable on lower beds throughout the Colorado Plateau — Rocky Mountain area, it does appear to be so in the San Juan Basin area. A low-angle unconformity between Dakota and Upper Triassic and Jurassic formations occurs south of the San Juan Basin proper, and the Dakota rests locally on rocks of Precambrian age east of Chama (fig. 1) (Muehlberger and others, 1960, p. 95; Muehlberger, 1967, p. 23-24). Elsewhere in the San Juan Basin, the contact between the Morrison and Dakota south of La Ventana (fig. 1) by Owen (1963) is erroneous. The contact described is at the base of the uppermost Morrison sandstone bed.

The vertical and horizontal successions of lithologies in the Dakota record changes in depositional environments brought about by an overall transgression of the sea across the San Juan Basin. Lithologies in the Dakota were formed in environments which ranged from fluvial through the various transitional paralic or coastal depositional environments, to offshore neritic. As Walther's Rule (Middleton, 1973) would predict, the result of the changing location of the shoreline can be observed in vertical succession at intermediate points such as the northeastern and southwestern parts of the San Juan Basin or in horizontal arrangement by following the Dakota from the northwestern part of the Basin, where it consists entirely of nonmarine strata, to the southeastern part, where it is composed almost entirely of marine beds. Obviously, such a change is not uniform everywhere, nor was the transgression uniform, as significant, but temporary, regressions occurred during the overall transgression. However, an overall transgressive pattern is detectable. Therefore, in this paper an idealized model based on features actually observed in the Dakota rocks is established (fig. 2) and analogies drawn with some of the wealth of data now available on comparable modern sediments. Regional and local variations from the ideal model are considered also.

Unit 1: Braided-Stream Sandstone

The basal unit of the depositional model for the Dakota is a body of sandstone deposited in a braided-type stream system. This unit consists of sandstone rich in quartz and chert, some of which is pebbly, interbedded with thin lenses of quartz-and-chert-pebble conglomerate and thin lenses of red and green shale (fig. 3) in the lower part and thin lenses of black carbonaceous shale in the upper part. Small chips and larger blocks of shale are widely distributed in the sandstone.

Unit 1 rests on an unconformity which is locally angular (fig. 4). Parts of the unconformity are marked by channels which had depths of several feet in short distances. Generally, the coarsest pebble conglomerate and pebbly sandstone rest on the unconformity. Other fairly large-scale cut-and-fill structures (fig. 5) occur throughout the unit, producing a

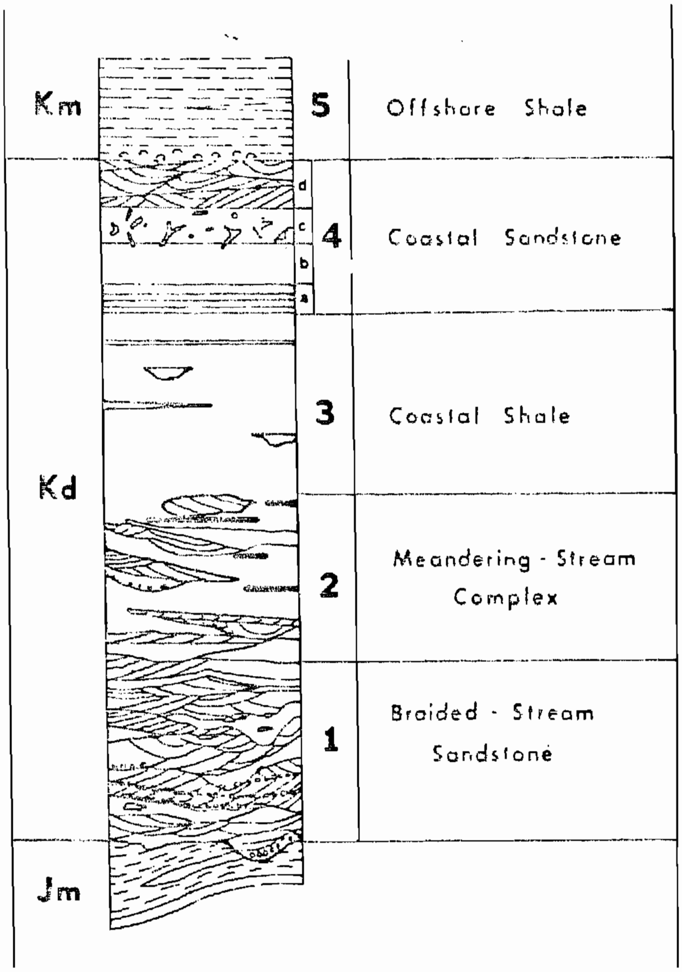

Fig. 2 Idealized vertical depositional model of Dakota Sandstone of San Juan Basin area. Jm = Morrison Formation; Kd = Dakota Sandstone; Km = Mancos Shale. Total thickness is several hundred feet. Unconformity at base of unit 1. Unit 1 is multistory, crossbedded sandstone body with shale lenses. Unit 2 is discrete channel sandstones enclosed in overbank shales with coal beds. Unit 3 is dark carbonaceous shale with marine fossils in upper part. Unit 4 is nearshore sandstone divided into: (a) an interbedded shale-sandstone transition zone, (b) horizontally bedded sandstone, (c) bioturbated sandstone, and (d) crossbedded sandstone. Unit 5 is gray marine shale.

multistory sandstone body with numerous scour surfaces separated by lens-shaped sandstone bodies (fig. 6).

Crossbedding is present in nearly all beds. Most of the larger scale crossbedding displays numerous troughs (fig. 5), while the smaller scale crossbedding tends to be of the planar type (fig. 7). Current ripple marks are relatively rare because most of the sand is too coarse-grained (0.65mm) to have formed ripples.

Numerous fining-upward successions of grain-size and primary sedimentary structures characteristic of fluvial deposits are present in this unit. The grain-size of these successions generally grades upward from pebble to

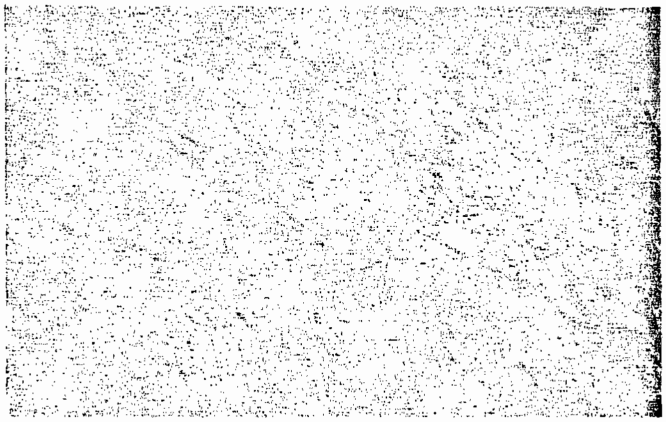

Fig. 3 Red and green shale lens in unit 1 — braided-stream sandstone. Maximum thickness of shale lens (sh) is about 5 feet. Roadcut on U.S. Highway 84 in sec. 11, T.25 N., R.4 E., Rio Arriba County, New Mexico.

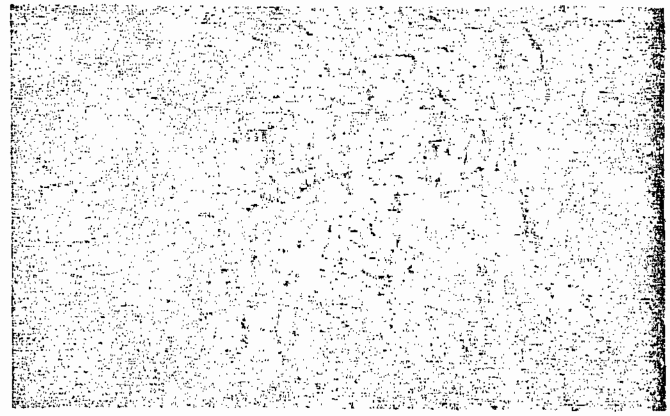

Fig. 4 Unconformable contact with local angularity between Morrison Formation (Jm) and unit 1 of Dakota Sandstone (Kd). Roadcut on U.S. Highway 84 in sec. 11, T.25 N., R.4 E., Rio Arriba County, New Mexico.

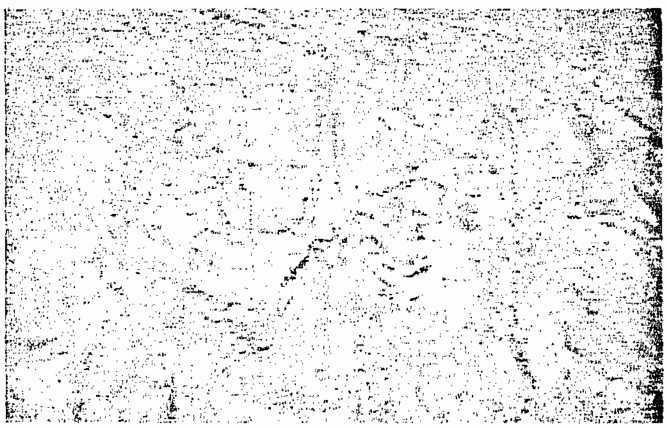

Fig. 5 Large sandstone-filled trough in braided-stream sandstone. Dimension across photograph is approximately 50 feet. Roadcut on U.S. Highway 84 in sec. 11, T.25 N., R.4 E., Rio Arriba County, New Mexico.

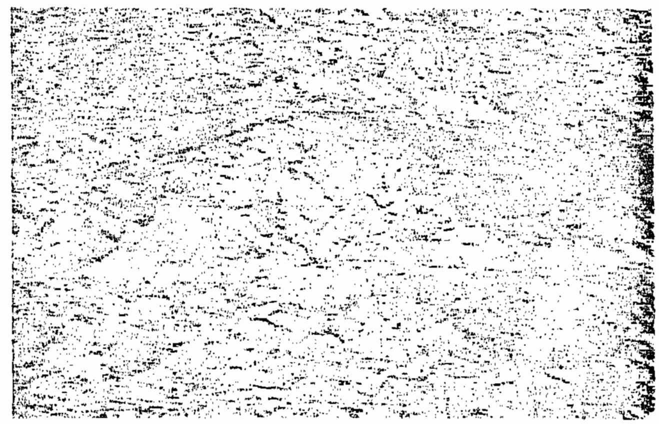

Fig. 6 Wedge-shaped sandstone lens in braided-stream sandstone overlain by onlapping shaly strata. Sandstone lens is approximately 10 feet thick in center. Roadcut on U.S. Highway 84 in sec. 11, T.25 N., R.4 E., Rio Arriba County, New Mexico.

Fig. 7 Planar crossbedding in pebbly sandstone of braided-stream sandstone. Note slight curvature of laminae at base of sets. Maximum thickness of this set is approximately 1.3 feet. Roadcut on U.S. Highway 84 in sec. 2, T.25 N., R.4 E., Rio Arriba County, New Mexico.

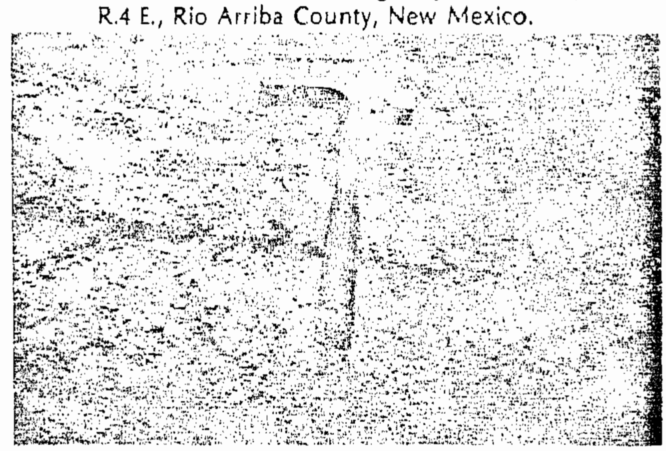

Fig. 8 Graded beds in braided-stream sandstone. Hammer is 0.93 feet long. Roadcut on U.S. Highway 84 in sec. 2, T.25 N., R.4 E., Rio Arriba County, New Mexico.

medium-grained sand (fig. 8). Finer grain sizes are rare. Kukal (1971, p. 87) has described four successive zones of primary sedimentary structures in fining-upward successions: "1. Poor bedding, 2. Megaripple crossbedding (giant trough-bedding grading to planar wedge-shaped bedding), 3. Small ripple crossbedding, 4. Horizontal lamination." Of these, only the lower two generally are present in the braided-stream sandstone. The absence of the upper two may be due to the coarse grain size typical of unit 1 and the lack of well developed point bars in braided-streams. As Kukal also observed (p. 87), "Some of these zones, particularly the upper ones, can be absent."

Grain-size parameters determined by sieve analysis in the braided-stream sandstone show a consistent upward change. Mean grain size in the lower part of the unit ranges from pebble to very coarse sand grades. These conglomerates and pebbly sandstone beds decrease in abundance upward. In the overlying sandstones the mean grain size decreases upward from coarse, through medium to some fine-grained sand near the top. This overall pattern is, of course, complicated by the repeated scour surfaces and associated fining-upward successions. Sorting within unit 1 shows a decrease in standard deviation upward. Many of the pebbly beds are poorly sorted. Sandstones typically are moderately sorted* near the base and better sorted upward. A few beds near the top are very well sorted. Skewness is generally positive (fine-skewed) throughout, but shows a tendency to increase from near symmetrical in the lower part to strongly fine-skewed in the upper part. Kurtosis values are all leptokurtic, with a tendency for leptokurtosis to decrease upward and increase downward. When plotted on the sorting-skewness graph of Friedman (1961, p. 520), nearly all sandstone samples from unit 1 plot in the field for river sands.

Fossils are not present in the lower part of the braided-stream unit but some plant stem and leaf fragments do occur in the upper part in association with the black, carbonaceous shale lenses.

Small amounts of a few stable heavy minerals characterize the braided-stream sandstone. The heavy minerals consist entirely of zircon and tourmaline except for minor amounts of garnet, magnetite, and ilmenite near the base. The zircon shows a gradation from euhedra near the base to angular fragments near the middle to mostly rounded fragments near the top. Clay minerals of the shale lenses are dominantly illite with minor amounts of kaolinite.

The characteristics of the braided-stream sandstone of the Dakota correspond quite closely with modern sediment analogs in braided rivers and such ancient braided-stream deposits as have been described. Descriptions of modern braided-stream sediments are much less common than meandering-stream sediments, and descriptions of ancient braided-stream deposits are quite rare. Doeglas (1962) described the bedding, fabric, and grain-size distribution of several modern braided streams in France, and Williams and Rust (1969) provided more detailed information on similar characteristics of a braided stream in the Yukon. Detailed information on the characteristics of planar crossbedding in a modern braided stream was presented by Smith (1972). Selley (1970, p. 24-36) summarized the characteristics of braided-stream sediments and described an ancient example from rocks of Precambrian age in Scotland.

The pebbly sandstone with a few lenses of shale present in the braided-stream sandstone of the Dakota has essentially the same characteristics of braided-stream deposits described by Doeglas (1962) and Williams and Rust (1969) except that cobbles and coarse pebbles of resistant lithology were not observed in the Dakota.

The arrangement of scour surfaces and larger scale trough and smaller scale planar crossbedding of the Dakota braided-stream unit corresponds quite well with that described from modern braided-stream deposits by Doeglas (1962) and Williams and Rust (1969). The poor sorting, near-symmetrical to mostly fine-skewness, and tendency to leptokurtosis rather than platykurtosis in grain-size parameters of the Dakota also agree almost exactly with the grain-size distribution of modern braided-stream deposits described by Williams and Rust (1969, p. 653). The type and dimensions of planar crossbedding in unit 1 is similar to that described by Smith (1972) in braided-stream sands. The only significant difference between unit 1 sedimentary structures and modern deposits appears to be the relative rarity of ripple marks in the Dakota.

According to Doeglas (1962, p. 169) and Selley (1970, p. 24-25), modern braided streams generally form in areas of steeper gradient and more fluctuating, higher discharge than do meandering-type streams and under climatic conditions which may be semi-arid to arid or periglacial. Such climatic conditions give rise to sparse vegetation and high sediment availability. These streams have access to large amounts of loose sediment, undergo rapid fluctuations in discharge, and have steep gradients, producing fairly coarse, poorly sorted sediments that choke up channels with mid-channel bars. The bars cause braiding to develop because the stream is incapable of maintaining a continuous channel. Braided streams commonly develop on the alluvial apron and extending ribbon-shaped alluvial valleys adjacent to source areas of appreciable relief, although they are not entirely restricted to such areas.

The limited distribution of unit 1 is also consistent with the interpretation that this unit is a braided-stream complex. It is essentially restricted to the Chama Basin, a northeastern re-enterant of the San Juan Basin, and grades into other types of sandstones to the west and south. Hence, this area was probably nearer to a major source area than was any other part of the basin because maximum formation thickness, maximum coarseness, and maximum proportion of sandstone in the Dakota Formation are all found in the northeastern part of the San Juan Basin. Approximately half of the thickness of the Dakota Sandstone in the Chama Basin consists of the approximately 200 feet of braided-stream sandstone. An excellent and easily accessible example of this unit may be seen in the roadcuts south of Tierra Amarilla along U.S. Highway 84 in sec. 2 and 11, T.25 N., R. 4 E., Rio Arriba County, New Mexico. In addition, Muehlberger and others (1960, p. 95) report several localities in the Brazos Peak area east of Chama (fig. 1) within five miles of the main Dakota outcrop

*Sorting, skewness, and kurtosis terms used in this paper correspond to those of Folk (1968, p. 46-48).

where the Dakota probably rests unconformably on metaquartzites of Precambrian age. The braided-stream sandstone was apparently deposited on a moderately steep, sparsely vegetated alluvial apron adjacent to the metamorphic and sedimentary source area. Large amounts of quartz-rich sediment were derived from the Brazos Uplift of New Mexico and Colorado, east and north of the Chama Basin. The generally south to southeast paleocurrent direction based on limited observations agrees with this paleogeographic picture. The stable heavy-mineral suite, increase in roundness, and decrease in grain size vertically indicate a lowering sedimentary and quartz-rich metamorphic source area. The only area located so far where braided-stream conditions certainly developed was the Chama Basin — apparently due to the right combination of sediment supply, gradient, and low-density vegetation. Local, thinner sandstones in other parts of the San Juan Basin, such as in northwestern Socorro County, show some braided-stream characteristics, but none approach the degree of development, areal distribution, or thickness of the Chama Basin unit. Unit 1 is recognizable throughout nearly all of the Chama Basin where it forms approximately the lower half of the Dakota Formation. In most exposures the braided-stream sandstone grades upward and laterally into a meandering-stream complex of channel sandstones and overbank dark shales which mark the transition between the lower sandstone unit and middle shale unit. This transition reflects decreased gradient, lowered sediment supply, finer grain size, and greater amount of vegetation as shown by the change from the thin green and red shale lenses within most of the braided-stream sandstone to the dark, carbonaceous shales with plant fragments of the meandering-stream complex.

Unit 2: Meandering-stream Complex

Adjacent to the braided-stream sandstone is a complex unit of discrete fluvial channel sandstones enclosed in overbank flood-basin deposits. Lithologically unit 2 consists of mostly dark-gray carbonaceous shale, a few thin coal seams, siltstone, and thin channel sandstones.

The channel sandstones are mostly quartz and chert-rich arenites with local pebbly beds and thin conglomerates near the base, although much less pebbly than the braided-stream sandstone. As calculated from measured section thickness, 53 percent of the meandering-stream complex is sandstone — only 2 percent is conglomerate. The finer grained sandstone, siltstone, and shale beds generally contain obvious finely divided carbonaceous material and less obvious plant fragments.

The meandering-stream complex rests on the undulating surface of the unconformity at the base of the Dakota or gradationally on the braided-stream sandstone where the latter is present. The coarsest grained strata (fig. 9) and preponderance of channel sandstones occur in the lowest part of the complex in most exposures. Many of the channel sandstones are quite distinct with abrupt boundaries (fig. 10). Others form a single sandstone bed composed of overlapping channels (Fig. 11).

The channel sandstones of unit 2 commonly contain fluvial fining-upward successions with the following sedimentary structures in ascending order: (1) a massive to medium-scale crossbedded subunit, (2) a smaller-scale crossbedded subunit with ripple marks or parting lineation (fig. 12), and (3) horizontally laminated silty strata which are not as common as (1) and (2). Both trough and planar varieties of crossbedding are commonly present in the channel sandstones. The crossbedding may be locally distorted or

Fig. 9 Large block of sandstone probably from previously deposited Dakota Sandstone, that was eroded and redeposited in lower part of a Dakota channel sandstone. Block marked by hammer is approximately 2 feet thick and 10 feet long. Underlain by pebble conglomerate and overlain by crossbedded sandstone. In tributary canyon to Red Wash in SE¼, sec. 8, T.30 N., R.20 W., San Juan County, New Mexico.

Fig. 10 Cross-sectional view of discrete Dakota channel sandstone completely enclosed in shale. In transition zone near top of meandering-stream complex. Note impure coal (black) and bentonite (white) beds at base of channel. Maximum exposed thickness of channel sandstone is 20 feet. In bank of Red Wash in sec. 15, T.30 N., R.20 W., San Juan County, New Mexico.

even overturned by soft-sediment deformation (fig. 13). Parting lineation is more common than ripple marks — somewhat unusual for fluvial sandstones.

Grain-size parameters of the channel sandstones show the expected fining-upward pattern in individual channel sandstones and in unit 2 overall. The coarsest strata are almost everywhere at the base of the lowest sandstone in the formation where it rests unconformably on underlying formations. In these cases, the rock generally consists of less than five feet of pebbly sandstone with a mean grain size in the coarse or very coarse sand grade. Most of the channel sandstones are fine-grained, with some medium-grained strata in the fairly abrupt transition between the pebbly beds and the fine beds. Some sandstones in the upper parts of fining-upward successions have a mean grain size in the very fine sand grade. Except for the pebbly strata, the channel sandstones are rather well sorted. The degree of sorting improves with decreasing grain size. For example, fine-grained channel sandstones are about equally divided between moderately well sorted and well sorted while very-fine-grained sandstones are nearly all well sorted. Of twenty-one channel sandstone samples analyzed by sieving, 67 percent are fine-skewed (about ⅓ of these are strongly fine-skewed), 23 percent are near-symmetrical, and only 10 percent are coarse-skewed. The upper part of fining-upward successions and channel sandstone beds generally have the highest positive skewness values. Nearly all samples are leptokurtic but a few are mesokurtic. The mesokurtic values are most common near the top of fining-upward successions and sandstone beds. Except for some of the coarse-skewed samples, all samples plot in the field for river sands on the grain-size parameter graphs of Friedman (1961, p. 520).

A stable suite of heavy minerals is present in the channel sandstones. Zircon is the most abundant heavy mineral in all samples analyzed. Euhedral and angular grains, both of which contain rutile inclusions, are most abundant, but appreciable numbers of subrounded to rounded grains occur in many samples. Several varieties of tourmaline and colorless to pink garnet are the other two abundant heavy minerals. Less abundant heavy minerals not present in all samples include magnetite, ilmenite, hematite, biotite, apatite, and corundum.

The channel sandstones contain few fossils, although most channel sandstones contain moderate amounts of finely divided carbonaceous material probably derived from vegetation. Petrified wood, including some logs several feet in length, and poorly developed trace fossils were observed at several exposures, mostly in beds transitional with the overlying coastal shale and in some overbank deposits.

The overbank sediments of the meandering-stream complex are predominantly shale, including minor amounts of siltstone and sandstone, which makes up 44 percent of the meandering stream complex as calculated from thicknesses in measured sections. However, if precompaction thicknesses were available, the shales would be twice the volume of the channel sandstones. Rather impure coal beds, up to three feet, but normally thinner, compose about 1 percent of the complex based on measured thicknesses.

The overbank deposits generally either grade laterally

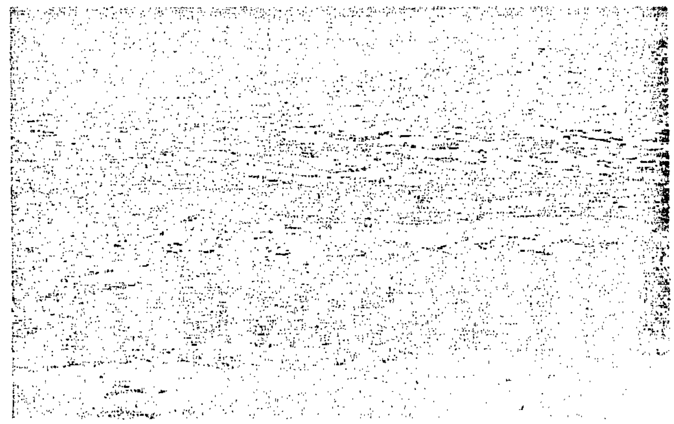

Fig. 11 Composite sandstone bed made up of three separate filled channels (1, 2, and 3). Note thin coal bed in Dakota overbank shales below sandstone. In bank of Red Wash in sec. 15, T.30 N., R.20 W., San Juan County, New Mexico.

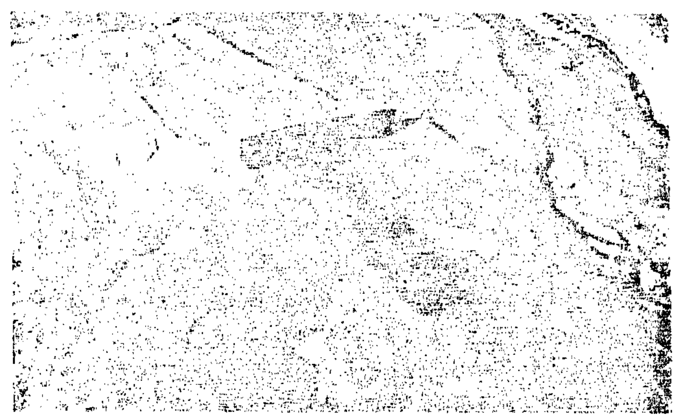

Fig. 12 Parting lineation on bedding plane of Dakota channel sandstone. Hammer head is 0.57 feet long. In tributary canyon to Red Wash in sec. 8, T.30 N., R.20 W., San Juan County, New Mexico.

Fig. 13 Overturned planar crossbedding in Dakota channel sandstone. Hammer is 1.0 feet long. In tributary canyon to Red Wash in sec. 8, T.30 N., R.20 W., San Juan County, New Mexico.

into channel sandstones (fig. 14) or have an erosional contact with younger channel deposits (fig. 10). The overbank deposits tend to have a vertical and horizontal succession of three types of shale lithologies, although this succession is quite irregular in its development and must be pieced together from separate exposures. The lowest, and least common, lithology is a gray-green shale similar to shale lenses in the lower part of the braided-stream sandstone. It is commonly associated with the coarser grained, noncarbonaceous channel sandstones. It is succeeded by a silty, dark gray to black carbonaceous shale which locally contains separate thin siltstone beds. The silty, dark shale is the most common. The third type of shale is similar to the second, but is a dark-gray to black, carbonaceous, clayey shale rather than silty. Both of the latter two types of shale are associated with coal beds. The clay mineralogy of all three shale types is similar, with kaolinite the dominant clay mineral but with fairly abundant illite.

Abundant finely divided carbonaceous material, carbonized wood fragments, uncommon plant leaf and stem impressions, petrified wood, and trace fossils are the only fossils observed in the overbank deposits. None of these, however, occur in the gray-green shale. Where the overbank shales grade into coastal shale or sandy strata, indistinct burrows commonly mark the transition zone.

Dakota sediments of the meandering-stream complex are quite comparable to modern analogs and other ancient examples described by many workers (Selley, 1970, p. 22-51; Kukal, 1971, p. 72-109; Visher, 1971, p. 84-97; and Pettijohn and others, 1972, p. 453-466). Modern and ancient meandering-stream deposits are more fully studied than any other deposits. The Dakota meandering-stream complex described herein is similar to the Cretaceous example of Shelton (1967, p. 2446-2447). The channel sandstones have the scoured basal surface, fining-upward succession of grain size and sedimentary structures, carbonaceous matter and plant fossils that characterize stream-channel deposits. The dark, carbonaceous overbank shales and coal lenses are very similar to modern floodplain deposits in humid climates. Natural-levee or bank deposits have proved difficult to identify in the Dakota. However, some thin siltstone and thicker very fine-to-fine-grained flat-bedded sandstone beds adjacent to channels are probably natural-levee deposits. Kukal (1971, p. 106) has calculated that only 6 percent of the volume of several modern alluvial complexes consist of natural-levee (bank) deposits and a comparable value is probably applicable to the Dakota meandering-stream complex. The segregation of channel sandstone from overbank shales, the abundance of the latter, the finer grain size, and the evidence for the presence of abundant vegetative cover serve to differentiate the meandering-stream complex from the braided-stream sandstone.

In contrast to previously described braided-stream environments, meandering-stream complexes form in areas of gentler gradient and lower discharge, but where seasonal discharge is fairly steady and sediment availability is relatively low due to the more subdued topography and extensive vegetation cover produced in characteristic humid climates (Selley, 1970, p. 22). This combination of slower but more

Fig. 14 Partially gradational lateral contact of channel sandstone (right) with overbank shale (left). Sandstone is 10 feet thick at right. Roadcut on U.S. Highway 84 in sec. 2, T.25 N., R.4 E., Rio Arriba County, New Mexico.

consistent flow velocity and the inhibiting effect of dense vegetation on vertical erosion in the source area and lateral erosion of stream banks produce the relatively fine-grained channel sandstones segregated from the silt- and clay-size overbank sediments observed in the Dakota. The extent of such meandering stream complexes over most of the San Juan Basin Dakota is evidence of widespread alluvial-plain deposition that developed between the near-source braided streams and the coastal environments that marked the margin of an advancing sea. As time passed while the sea advanced, the coastal sediments were deposited on the alluvial-plain sediments which previously had been deposited on the braided-stream sediments nearer to the source area.

The meandering-stream complex is the most areally extensive unit in the Dakota of the San Juan Basin. With the exception of some of the southeastern part of the basin, where coastal and marine rocks comprise all of the Dakota, some part of the thickness of the formation in the rest of the basin consists of meandering-stream strata. The best development is in the northwestern part of the basin near the Four Corners where the entire thickness (average approximately 150 feet) of the Dakota is composed of complex channel and overbank units with transitional beds to coastal deposits near the upper contact of the Dakota. An easily accessible and well displayed example of such a development may be seen west of Shiprock along Red Wash and its tributaries upstream from New Mexico Highway 504 in T. 30 N., R. 20 W., San Juan County. As the Dakota is followed eastward, southeastward, or southward from the Four Corners the meandering-stream complex beds occupy progressively lower positions in the Dakota as they are onlapped by Dakota coastal and marine strata.

Widespread alluvial plains existed over nearly all of the San Juan Basin area during deposition of unit 2. As sea level rose and source areas were eroded down, the already low gradients of the meandering-streams decreased further, resulting in deposition of finer grained channel sandstones and more coal beds. Eventually coastal environments developed progressively landward across the former alluvial plains so that the coastal shales and sandstones were deposited above the fluvial sediments.

Unit 3: Coastal Shale

The coastal-shale unit includes the predominantly fine-grained sedimentary rocks that form the transition between fluvial and offshore-marine deposition. Lithologically the unit is predominantly dark, carbonaceous shale. Thin siltstone and lenticular sandstone beds make up a minor part of the unit. Thin bentonite beds occur at a few localities.

Both the lower and upper contacts of the coastal shale are normally gradational with adjacent sandstones. The gradation at the base is most commonly irregular with much intertonguing while the gradation at the top is almost everywhere quite regular with regular interbedding.

Horizontal bedding is the dominant sedimentary structure of the coastal shale. Bedding in the lower part of the unit is commonly poorly or irregularly developed but bedding in the upper part of this unit is much more regular and distinct (fig. 15).

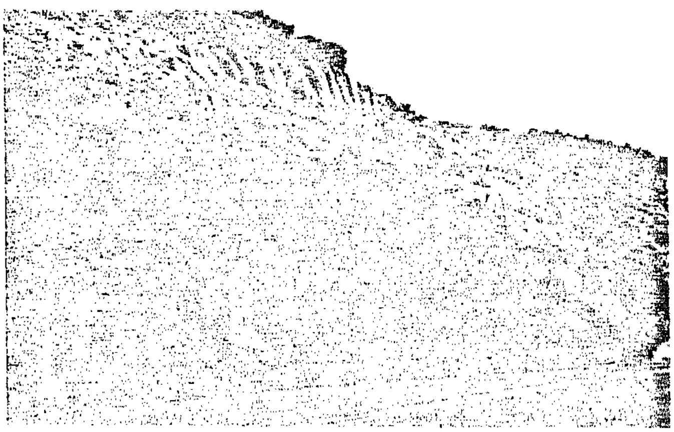

Fig. 15 Coastal shale (unit 3) in Oak Canyon Member. Unit 3 overlies a thin basal sandstone at lower right and is overlain by coastal sandstone unit at upper left. Note increase in distinctness of bedding and lighter color upward. In roadcut approximately 3.5 miles northwest of Acoma Pueblo, Valencia County, New Mexico.

Most of the shale in this unit is silty. Shales in the upper part of unit 3 are generally coarsest and commonly contain distinct siltstone beds and local very fine-to fine-grained sandstones. Some of the sandstones which are channel-like and locally crossbedded may have been tidal-channel fills.

Fossils, although not abundant in unit 3, show the increasing influence of marine conditions during deposition. Some plant fossils occur in lower parts of the unit; small vertical burrows of the *Skolithus*-type commonly appear locally near the middle of the unit and are most obvious in the silty and sandy strata. Larger, branching, variously oriented burrows of the *Thalassinoides*-type occur in the upper part of unit 3. Oysters and other marine and brackish-water mollusks occur locally near the top of the unit.

The coastal shales contain kaolinite and illite, as do the fluvial shales. Some mixed-layer illite-montmorillonite also is present in the coastal shales but not the fluvial shales; this mineral may possibly reflect deposition in saline water.

Modern mud deposits in coastal environments have not been studied in as much detail as coastal sand deposits. Mud deposition occurs in low energy, sheltered locations such as lagoons, tidal flats, marshes, and estuaries where wave and tidal action is impeded by barriers, broad tidal flats, marsh vegetation, or orientation at high angles to the coastline, respectively. Close examination of geometry, adjacent lithologies, trace fossils, and shelly fossils are necessary to differentiate among these coastal environments. Unfortunately, not enough detailed observations have been made on the coastal-shale unit to identify specific subenvironments. Deltaic deposits might be expected to occur in coastal deposits of the Dakota as in some higher Cretaceous formations in the area. However, except for some very thin and local delta-like strata, no deltaic deposits have been identified in the Dakota of the San Juan Basin.

Although less widely distributed than fluvial units within the Dakota, coastal shales are present over much of the San Juan Basin. In the northwest part of the basin they occur in the middle part of the formation. In the latter two areas they form an extensive middle shale unit that has been used by Smith and others (1961, p. 16) to subdivide the Dakota into three units: lower sandstone, middle shale, and upper sandstone. Such a three-fold subdivision is common in much of the Western Interior region of the U.S. Thickness of the coastal shale, where present, ranges from a few feet to 100 feet or more. A well exposed, easily accessible example of the coastal shale unit may be examined in roadcuts on U.S. Highway 84 south of Tierra Amarilla in sec. 2, T.25 N., R.4 E., Rio Arriba County, New Mexico.

Unit 3 reveals the progressively greater influence of marine conditions upward, as shown by the increase in marine fossils. The plant fossils in the lower part of the unit indicate deposition in a dominantly nonmarine environment or a near-shore marine environment to which plants from nearby land areas were transported. The change from straight, vertical burrows to more horizontal, branching types upward in the unit may record changes from intertidal to subtidal conditions. The marine fossils in the uppermost part of the unit indicate near-normal salinity.

The coastal sandstone unit is a prominent, laterally persistent, fine to very-fine grained, quartz-rich sandstone which includes a basal subunit of interbedded sandstone and shale which is transitional with the underlying coastal-shale unit. Part of the sandstone is commonly burrowed and many outcrops contain marine fossils. The upper contact is typically abrupt and planar.

In some exposures the coastal-sandstone unit displays a succession of four subunits which can be identified on the basis of differences in sedimentary structures. In ascending order, these are: (1) the basal transition subunit which consists of horizontally bedded shale and sandstone interbeds; (2) horizontally bedded sandstone; (3) prominently burrowed (bioturbated) sandstone; (4) crossbedded sandstone. These subunits are not everywhere present nor in the exact same order everywhere, but the above succession is fairly common. The detailed vertical succession and the lateral extent of each subunit awaits further work.

The interbedded subunit is quite similar, but on a somewhat smaller scale, to the typical basal transition zone characteristic of higher Cretaceous sandstones that are regressive (Sears and others, 1941, p. 103). Of the four subunits this one is by far the most extensive.

The horizontally bedded subunit is present at most outcrops, but may be thin or rather massive appearing so that the bedding is not very obvious. It commonly is the thickest of the four subunits (fig.16).

The bioturbated subunit (fig. 17) is present, at least locally at a large majority of exposures. It may form the entire thickness at a given exposure, the burrowing having destroyed any bedding which existed previously. In other cases the burrowed sandstone may occur only in flattened pods or "nests" a few feet in diameter (fig. 18). The burrows that characterize this unit are of different types, but contrast with the small, vertically oriented burrows characteristic of the coastal shale in that the former are larger, commonly branching, and are less oriented. The *Thalassinoides* type is more common than the *Planolites* type. Siemers (1973, this volume) discusses Dakota trace fossils.

The crossbedded subunit (fig. 19) is the most varied and least extensive of the four. Different types and scales of crossbedding are developed, even at the same locality. Much of the crossbedding is rather small scale but large-scale, steeply dipping crossbedding similar to eolian types is present locally, especially where the sandstone unit is rather thick. Planar crossbedding is more common than trough-type. Some of the exposures contain low-angle planar crossbedding similar to that developed on modern beaches. Detailed study of type and orientation of crossbedding in this subunit is needed. A good example of the development of these four subunits may be seen in the Paguate Sandstone south of Grants on La Ventana Ridge a short distance east of

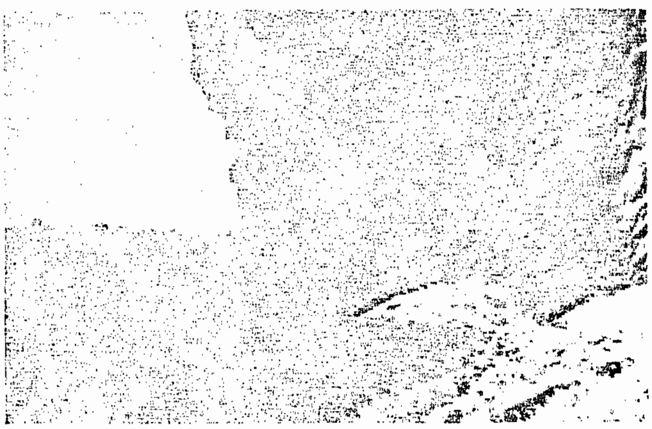

Fig. 16 Horizontally bedded subunit of coastal sandstone. Thickness of sandstone is nearly 90 feet. Sec. 2, T.36 N., R.3 W., Archuleta County, Colorado.

Fig. 17 Bedding-plane exposure of *Thalassanoides*-type burrows near top of Twowells Sandstone. Note large size, branching character, and orientation mainly parallel to bedding. Hammer is 0.93 feet long. Nutria Monocline, sec. 22, T.15 N., R.17 W., McKinley County, New Mexico.

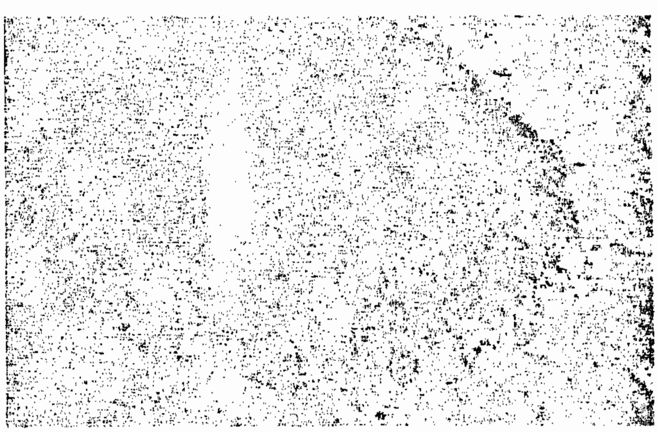

Fig. 18 *Thalassanoides*-type burrows in pod-shaped "nest" on upper surface of coastal sandstone. Diameter is approximately 3.5 feet. Near Ojito Spring in Ojo del Espirtu Santo Grant, Sandoval County, New Mexico.

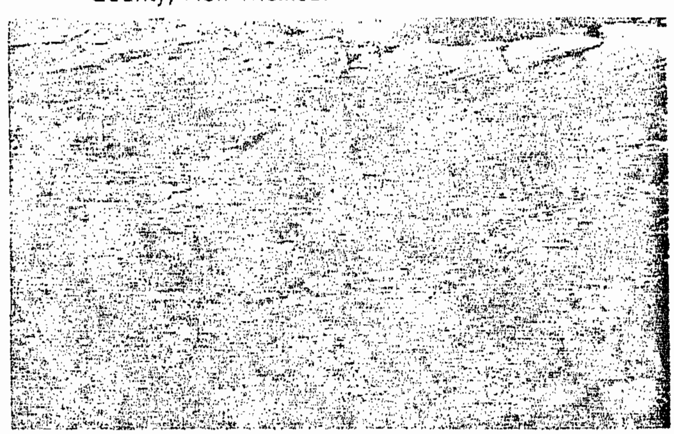

Fig. 19 Large-scale crossbedded subunit overlying horizontally bedded subunit. Near north end of McCarty Mesa in NW¼, sec. 34, T.10 N., R.8 W., Valencia County, New Mexico.

New Mexico Highway 117 near the center of sec. 17, T.9 N., R.9 W., Valencia County, New Mexico.

In spite of the development of several subdivisions based on sedimentary structures, grain-size variations in unit 4 are small, but consistently developed. The mean grain size is restricted to the very fine and fine sand grades, and, in contrast to the fluvial sandstone units, it consistently coarsens upward. Along with the mean grain size increase upwards, the sorting improves upward from moderate to well-sorted. Skewness is fine or very fine at the base, but the value of positive skewness decreases upward. Locally, a few coarse-skewed, well sorted sandstones occur. Kurtosis is generally leptokurtic or very leptokurtic throughout, but with the value decreasing upward.

Bivalves occur in many areas in the coastal-sandstone unit along with the above-mentioned trace fossils. Gastropods are less common and ammonites occur locally. Fossils are most common in the basal interbedded subunit (fig. 20) and decrease in abundance upward, none having been found in the crossbedded subunit.

The most common fossils are species of the oysters *Gryphaea* and *Exogyra*. *Inoceramus* is the most common other bivalve. The ammonite *Turrilites* has been reported (Owen, 1969, p. 91) along with *Buchiceras* by Sharp (1953) and *Metoicoceras* and *"Mantelliceras"* by Dane and others (1971). Sharp (1953) and Dane and others (1971) also listed other bivalves and gastropods from the coastal sandstones.

In contrast to the fluvial sandstone units, the coastal-sandstone unit contains a much greater variety of heavy minerals including some metamorphic types. Zircon and tourmaline, common in all Dakota sandstones, are present in the coastal sandstone as well, along with abundant garnet and spinel and some kyanite in the southern San Juan Basin area, but not the Chama Basin. The coastal sandstone is locally glauconitic and characteristically micaceous, both muscovite and biotite being present, unlike the fluvial sandstones.

Modern coastal sand bodies and the higher Cretaceous regressive sandstones (i.e. Point Lookout Sandstone) share many characteristics with the coastal sandstone of the Dakota. The increase upward in grain size and bed thickness, types of

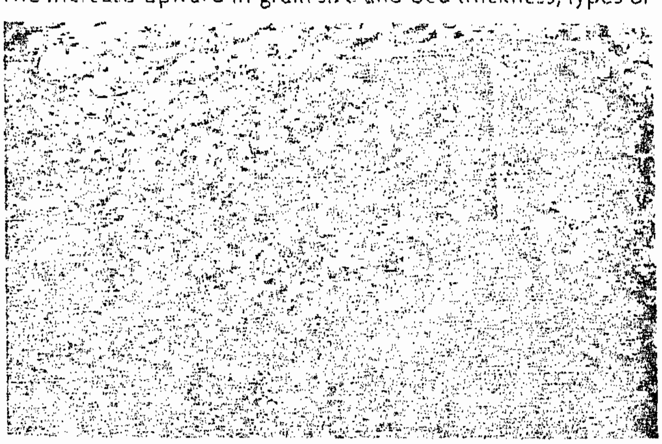

Fig. 20 Oyster coquina bed at top of Twowells Sandstone. Hammer head is 0.57 feet long. Nutria Monocline in sec. 22, T.15 N., R.17 W., McKinley County, New Mexico.

sedimentary structures, trace fossils, low-angle crossbedding, low variability of grain-size parameters, and presence of the marine indicator glauconite as observed in the Dakota coastal-sandstone unit compare closely with the characteristics of coastal sand bodies as summarized by Potter (1967). The four most diagnostic genetic characteristics of a coastal sand barrier, as described by Shelton (1967, p. 2449) from the Cretaceous of Montana, are (1) low-angle inclined bedding in the upper part, (2) mottled (burrowed) structure in the lower part, (3) upward increase in grain size, and (4) gradational lower and lateral contacts. Unit 4 displays all of these same characteristics. A modern analogy with similar characteristics is the prograding Galveston barrier island, Texas, (Bernard and LeBlanc, 1965, p. 158).

The coastal-sandstone unit is present south of the San Juan Basin and over approximately the southern half of the San Juan Basin itself as well as throughout the Chama Basin in New Mexico. It extends into Colorado at least as far as northernmost Archuleta County and locally as far west as eastern Montezuma County (fig. 1). In the southern San Juan Basin and to the south, up to four vertical repetitions of unit 4 occur. On the southwest flank of the San Juan Basin and in the Chama Basin only one coastal sandstone bed occurs — the Twowells Sandstone in the southwest and the upper sandstone of the Dakota in the Chama Basin. As many as four coastal sandstone units occur in the southern part of the region, and each sandstone is generally about 25 to 30 feet thick, although local thicknesses to 80 feet were observed. In the Chama Basin the unit is commonly about 100 feet thick.

Sediments of several different coastal environments are present in the coastal sandstone. The interbedded basal subunit and horizontally bedded subunit probably were deposited in the offshore transition zone between offshore marine mud and shoreface sand. The burrowed beds are probably mainly the product of intertidal and shallow subtidal deposition although some shallow sand beds could have been burrowed much later than their initial deposition. The crossbedded strata could have been formed in the surf zone (as described by Clifton and others, 1971), or on a barrier island, or mainland beaches (Dickinson and others, 1972, p. 212), or possibly even in coastal dunes. The high-angle crossbedding is more characteristic of dunes, the low angle of beaches. The coastal sandstone indicates temporary regressions in the overall Dakota transgression inasmuch as it marks a return to more shoreward environments in the upper three sandstones of the southern region. Such a regression need not have been caused by a drop in sea level or a rise in land level. It could have been caused by increased amounts of sediment being delivered to the coast due to uplift in the source area, climatic change, or drainage changes.

Unit 5: Offshore Shale

The offshore-shale unit is a gray, silty, locally calcareous, thinly laminated shale that is similar to typical Mancos Shale. Secondary gypsum crystals are common locally in the shale. Marine fossils are present in most places and are quite abundant locally. Kaolinite and illite are present over all of the San Juan Basin area in unit 5 and generally in the shale just above the Dakota, but in the Chama Basin area mixed-layer illite-montmorillonite occurs as well and montmorillonite is

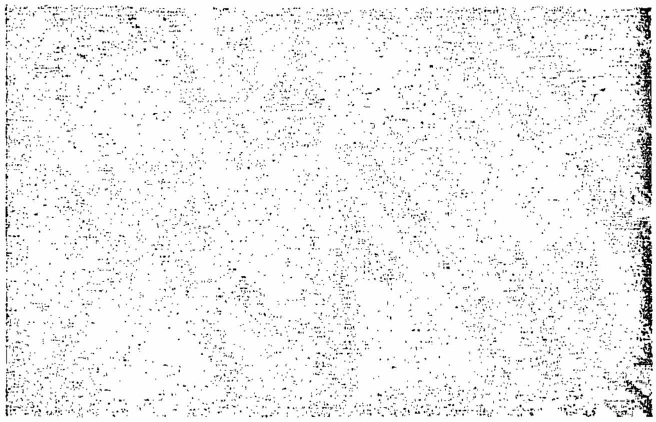

Fig. 21 Rippled upper surface of Twowells Sandstone. Hammer head is 0.57 feet long. Approximately 1 mile east of Window Rock, Arizona.

Fig. 22 Thin, low-angle, small-scale crossbedded, sandy, fossiliferous limestone of offshore-shale unit. Scale in centimeters and inches. Oak Canyon Member. Along paved road approximately 3.5 miles northwest of Acoma Pueblo, Valencia County, New Mexico.

present in the southern San Juan Basin region. Some thin bentonite beds of montmorillonite occur near the Dakota-Mancos contact.

The contact between the offshore shale and the underlying coastal sandstone is rather flat and non-transitional in most places. Thin (less than one foot) sandstone beds may occur in the lower few tens of feet of the shale. The top of the underlying coastal sandstone is a rippled surface (fig. 21) in many places. In other places a concentration of oyster shells marks the contact.

A thin bed of limestone or limestone concretions occur typically within unit 5, commonly in the central part of the shale. These limestones are dark-brown on a weathered surface, very thinly laminated, and contain gastropods and bivalves, the latter mostly in small, broken fragments. Some of the limestone beds have some low-angle cross-laminations (fig. 22). An accessible exposure of unit 5 including the limestone may be seen in the Oak Canyon Member south of Paguate on New Mexico Highway 279 in sec. 4, T.10 N., R.5 W., Valencia County.

The fauna of the offshore shale is of a normal marine type. Megafossils include bivalves, gastropods and ammonites. Lamb (1968) has reported numerous foraminifera, largely planktonic, from this shale.

Less is known about the lithology of modern offshore muds than offshore modern sands. However, faunas of modern offshore muds have received quite a lot of study and are more diagnostic of their environment than is lithology. In the case of the offshore shale unit the presence of ammonites and planktonic foraminifera are indicative of offshore deposition. The environment of the offshore shale corresponds to the shallow mid-shelf clay belt of Kaufman (1969) in his Western Interior Cretaceous marine cycles. Kaufman (1969, p. 227) estimates the water depth for this lithology to have been from 100 to 200 feet. This would place the area below normally effective wave base and allow suspended muds derived from the land to be deposited along with planktonic organisms.

The offshore shale is present nearly everywhere in the San Juan Basin area. In the southern part of the area the lithology is repeated vertically to form wedge-shaped bodies between the cyclic coastal sandstones. In this area, each shale unit averages around 40 feet in thickness. Throughout the basin, unit 5 marks the transgression of normal marine waters that overlapped the Dakota sandstone mass with the marine shales of the Mancos. The transgression produced some erosion and reworking of sediment along the lower contact of the offshore shale with the coastal sandstone.

CYCLIC SEDIMENTATION

The cyclic nature of Cretaceous sedimentation in the Western Interior region has been known for many years. The general transgressive and regressive cycles of Cretaceous rocks in the San Juan Basin were described at an early date by Sears and others (1941) and Pike (1947). Later, Sabins (1964) recognized symmetrical and asymmetrical cycles. Weimer and Haun (1960) and Kaufman (1969) outlined the regional cyclicity of Cretaceous units over large areas of the Western Interior. Hattin (1962 and 1964) described in detail a marine cyclothem in Dakota through Carlile rocks in Kansas. However, cyclothems have not been recognized previously in the San Juan Basin Dakota prior to this report.

In the southern San Juan Basin and in exposures further south to near the edge of the Colorado Plateau, the upper three units of the depositional model (fig. 2) may be repeated in four regular cyclic successions due to four short-period cyclic regressions of the shoreline during the long-period transgression (fig. 23). The regressive deposits of the cyclothems are much more commonly preserved than the transgressive deposits. Most Dakota cyclothems are similar to the assymmetrical cycle of Sabins (1964, p. 293-294) except for the absence of continental strata. The succession consists largely of alternating offshore shale and coastal sandstone units, the coastal shale in most cases having been eroded during exposure or transgression or perhaps not deposited in many areas.

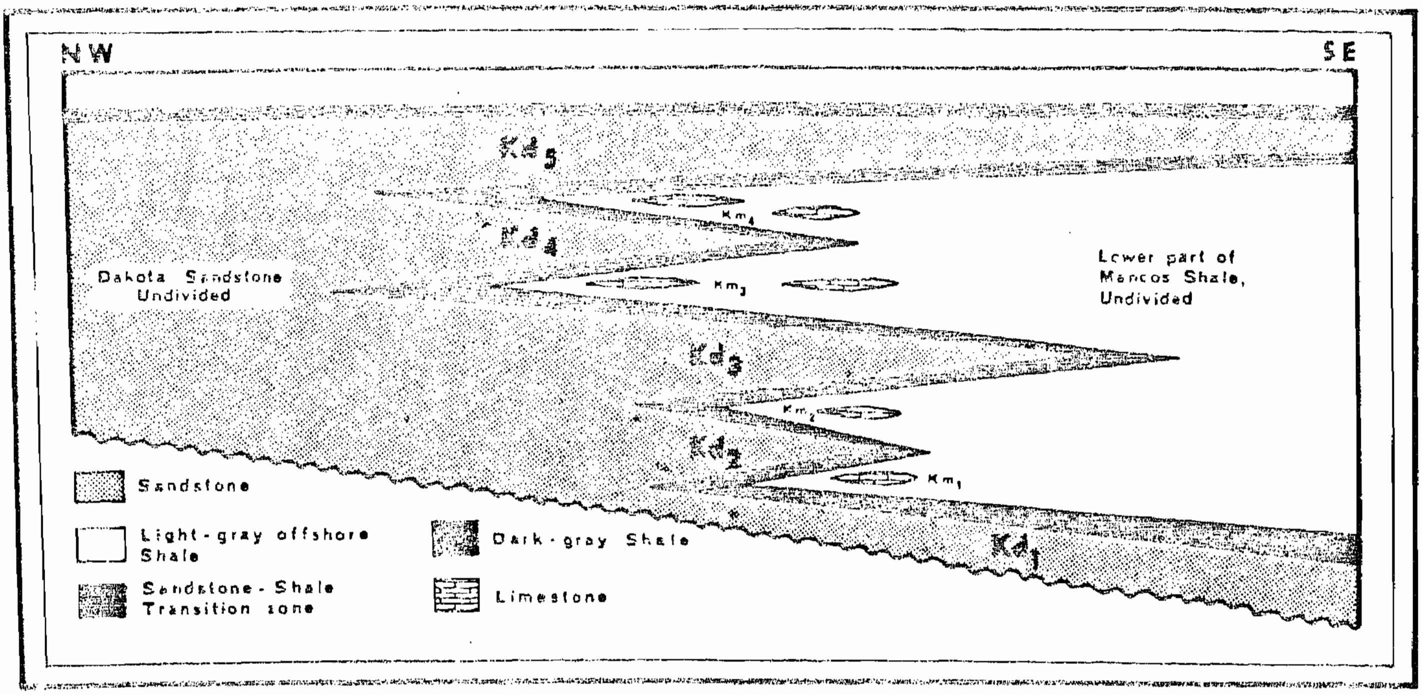

Fig. 23 Schematic cross-section of Dakota-Mancos cyclic units in southern San Juan Basin region. Regressive coastal sandstones wedge-out to south and east; transgressive offshore marine shales wedge-out to west and north. Sandstone-shale transition zone present nearly everywhere; dark-gray shale commonly absent in many places except lower part of Km_1. Kd_5 = Twowells Sandstone; Km_4 = Whitewater Arroyo Shale; Kd_4 = Paguate Sandstone of Landis and others (1973, this volume); Km_3 = Cubero Sandstone of Landis and others (1973, this volume); units below Kd_3 = Oak Canyon Member of Landis and others (1973, this volume).

The vertical succession, from top to base, in a completely developed Dakota cyclothem is:

0.

8. Crossbedded sandstone
7. Bioturbated sandstone
6. Horizontally-bedded sandstone
5. Sandstone-shale interbedded transition zone
4. Light-gray shale
3. Sandy limestone or limestone concretions
2. Light-gray shale
1. Dark-gray shale
0. Basal sandstone

8.

The most commonly developed, persistent phases are 2 and 4 (commonly combined due to the absence of 3), 5, 6, and 7. The least commonly developed is phase 3; phase 0 and 1 are commonly either poorly developed or absent except in the lowest cyclothem. A sharp contact almost everywhere separates phase 8 from the adjacent overlying phase, selected as the cyclothem boundary. Local erosion or nondeposition along this contact may explain the fairly common absence of phases 8, 0, and 1. Phase 3 marks the maximum transgression; phases 0 through 2 are transgressive; 4 through 8 comprise the regressive hemicycle.

The Greenhorn Cyclothem of Kansas (Hattin, 1962, p. 124) is broadly similar to the Dakota cyclothem described here in general lithologic succession and in that the regressive phases are better developed. However, the Kansas Greenhorn Cyclothem strata formed in a lower energy, more central location within the Cretaceous seaway where appreciable thicknesses of persistent limestone beds were formed in the Greenhorn Limestone. Only thin and discontinuous sandy limestones formed in the higher energy, more shoreward location in the San Juan Basin area. This is reflected also in that the average thickness of the Dakota cyclothems is about one-third sandstone while the Greenhorn Cyclothem appears to contain only about one-tenth sandstone.

The periodic regressions that produced the Dakota cyclothems were apparently confined to the southern San Juan Basin area and do not correlate with and were not in phase with cyclic deposition in Kansas. Four Dakota cyclothems formed during approximately Late Albian and Cenomanian time, while the single Greenhorn Cyclothem took approximately all of Cenomanian and Turonian time to form, a much longer period. Thickness of each Dakota cyclothem averages around 60 feet while the Greenhorn Cyclothem is generally 250 feet thick or more.

Unlike many cyclothems, those of the Dakota do not persist laterally for great distances; their extent is measured in tens of miles rather than hundreds. They are, of course, more persistent parallel to depositional strike than normal to it. In particular, the seaward wedge-outs of the cliff-forming sandstones (phases 5-8) eastward and southward into a mass of offshore marine shale is obvious (fig. 23). The wedge-out of the Paguate Sandstone may be seen, for example, southeast of McCartys on the west side of Canipa Mesa in sec. 14, T.9 N., R.8 W., Valencia County. Due to more transitional wedgeouts of the shales into the mass of coastal sandstone (fig. 23) and poorer exposures, the landward wedgeouts are uncommonly observable. However, O'Sullivan and Beaumont (1957) mapped the wedge-out of a shale in the Oak Canyon Member between Coolidge and Mariana Lake in sec. 7, T.15 N., R.14 W., McKinley County. More detailed work on the exact vertical succession at many localities and the lateral extent of each phase is needed. However, some general data on lateral extent is available.

The Twowells Sandstone — Whitewater Arroyo Shale pair, the uppermost in the San Juan Basin Dakota, is the most widespread and well known (fig. 23). The Twowells extends at least as far northwest as the Window Rock area (fig. 1), as far southwest as northwestern Catron County (fig. 1), (Dane and others, 1971, p. 19), as far northeast certainly as the La Ventana area (fig. 1) (Dane and others, 1971, p. 19), and as far southeast as the southeasternmost part of the Colorado Plateau in northwestern Socorro County (fig. 1). This region is approximately 130 miles in diameter. The areal extent of the underlying Whitewater Arroyo Shale is more difficult to determine. Its western boundaries are the same as that of the Twowells, but as the Paguate and lower sandstones wedge-out eastward the Whitewater Arroyo Shale merges with the similar lower shale units into an undifferentiated mass of shale (fig. 23). Such a merged situation exists in the southeast part of the area. The lower three sandstone-shale pairs below are not as extensive as the Twowells and Whitewater Arroyo. The Cubero Sandstone — upper Oak Canyon Shale pair apparently is the next most extensive (fig. 23), the Paguate Sandstone — Clay Mesa Shale pair next in extent (fig. 23), and the sandstone — shale pair in the lower Oak Canyon Member the least extensive (fig. 23).

The age relationships, wedge-out lines, and shoreline trends of the units within the Dakota cyclothems need to be studied further. Marine waters may have entered the San Juan Basin area first in the southeast during Albian time and spread westward and northwestward. The nonmarine parts of the Dakota to the northwest are of uncertain age, but may be Albian as well.

Four significant regressions occurred during the overall transgression during Albian and Cenomanian time, producing the cyclothems described here. Each of the sandstones in the cyclothem is slightly coarser grained and better sorted than the nearest one below. Shoreline trends and marine wedge-outs of the sub-surface regressive sandstone units in the San Juan Basin trend north northwest (see Brock and Gray, 1973, this volume). However, these trends, based on preliminary data, appear to change to north northeast in outcrops south of the San Juan Basin. Such a marine invasion from the southeast is at odds with long-standing opinions of those who have traced Cretaceous rocks from Colorado into New Mexico and have concluded that marine transgression came from the north or northeast into the San Juan Basin with the Dakota becoming younger southward (see: Haun, 1959, p. 1; Weimer and Haun, 1960, p. 178; Haun and Kent, 1965, p. 1791). However, although this may be true for Colorado, the nearness of the Gulf seaway in southern New Mexico or an approach of the Interior seaway, before merger with the Gulf, through northeast and central New Mexico may have brought marine waters into the San Juan Basin area from the southeast before the southward transgressing Interior sea from Colorado reached the northern San Juan Basin. Dakota faunas, however, show more Interior than Gulf affinities. Only additional stratigraphic and paleontologic research will provide answers to these problems.

SUMMARY AND CONCLUSIONS

The Dakota Sandstone in the area of the San Juan Basin includes strata which extend from a basal unconformity to as high as the top of the Twowells Sandstone. Lenticular nonmarine beds of sandstone and carbonaceous shale in the northwest give way to more laterally persistent marine beds of shale and sandstone to the southeast. Although the Dakota was deposited in response to a regional marine transgression, the direction of its assumed time transgression is not entirely clear.

An idealized depositional model for Dakota sedimentation based on observed primary sedimentary structures, grain-size parameters, bioturbation, and fossils consists of the following vertical succession, from the bottom up, or lateral array of major units: (1) braided-stream sandstone; (2) meandering-stream complex; (3) coastal shale; (4) coastal sandstone; (5) offshore shale. Due to regional and local variations in depositional conditions and post-depositional erosion, all five major depositional units of the model are not commonly present at a single locality. The braided-stream sandstone is best developed in the Chama Basin, a northeastern re-enterant of the San Juan Basin, while meandering-stream complexes are widespread, but best displayed in the northwestern San Juan Basin. The coastal-shale unit is also present in the Chama Basin and generally in eastern parts of the San Juan Basin. Coastal-sandstone and offshore-shale units are repeated vertically in the four prominent sandstone-shale pairs of the southern San Juan Basin. The Twowells Sandstone — Whitewater Arroyo Shale pair and three lower pairs form four cyclothems developed in the marine-dominated environment during four brief regressive phases of the overall transgression.

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