INFORMATION TO USERS

This manuscript has been reproduced from the microfilm master. UMI films the text directly from the original or copy submitted. Thus, some thesis and dissertation copies are in typewriter face, while others may be from any type of computer printer.

The quality of this reproduction is dependent upon the quality of the copy submitted. Broken or indistinct print, colored or poor quality illustrations and photographs, print bleedthrough, substandard margins, and improper alignment can adversely affect reproduction.

In the unlikely event that the author did not send UMI a complete manuscript and there are missing pages, these will be noted. Also, if unauthorized copyright material had to be removed, a note will indicate the deletion.

Oversize materials (e.g., maps, drawings, charts) are reproduced by sectioning the original, beginning at the upper left-hand corner and continuing from left to right in equal sections with small overlaps.

ProQuest Information and Learning
300 North Zeeb Road, Ann Arbor, MI 48106-1346 USA
800-521-0600

UMI®
Studies of Sedimentary Environments in the Cretaceous Dakota Sandstone in Northwestern Colorado

by

Donald Wilson Lane

A THESIS
SUBMITTED TO THE FACULTY
IN PARTIAL FULFILLMENT OF THE
REQUIREMENTS FOR THE DEGREE OF
DOCTOR OF PHILOSOPHY

Houston, Texas
March, 1961
# CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>INTRODUCTION</td>
<td>1</td>
</tr>
<tr>
<td>Purpose of Study</td>
<td>1</td>
</tr>
<tr>
<td>Methods of Study</td>
<td>1</td>
</tr>
<tr>
<td>Criteria</td>
<td>1</td>
</tr>
<tr>
<td>Field Methods</td>
<td>1</td>
</tr>
<tr>
<td>Laboratory Methods</td>
<td>3</td>
</tr>
<tr>
<td>Recent Sediment Studies</td>
<td>4</td>
</tr>
<tr>
<td>Previous Work</td>
<td>4</td>
</tr>
<tr>
<td>GENERAL STRATIGRAPHY</td>
<td>9</td>
</tr>
<tr>
<td>Lithologic Description</td>
<td>9</td>
</tr>
<tr>
<td>Correlation</td>
<td>11</td>
</tr>
<tr>
<td>ENVIRONMENTAL CRITERIA</td>
<td>12</td>
</tr>
<tr>
<td>Fluvial Environment</td>
<td>12</td>
</tr>
<tr>
<td>Tidal Flat Environment</td>
<td>15</td>
</tr>
<tr>
<td>Beach Environment</td>
<td>21</td>
</tr>
<tr>
<td>Lagoon Environment</td>
<td>25</td>
</tr>
<tr>
<td>Marsh Environment</td>
<td>27</td>
</tr>
<tr>
<td>Shallow Sub-Littoral Environment</td>
<td>28</td>
</tr>
<tr>
<td>DAKOTA ENVIRONMENTS</td>
<td>32</td>
</tr>
<tr>
<td>East Rifle Creek Locality</td>
<td>32</td>
</tr>
<tr>
<td>Elk Creek Locality</td>
<td>33</td>
</tr>
<tr>
<td>New Castle Locality</td>
<td>34</td>
</tr>
<tr>
<td>Burns Locality</td>
<td>36</td>
</tr>
<tr>
<td>Derby Mesa</td>
<td>36</td>
</tr>
<tr>
<td>Big Alkali Creek</td>
<td>38</td>
</tr>
<tr>
<td>Toponas Locality</td>
<td>40</td>
</tr>
<tr>
<td>Wolcott Locality</td>
<td>41</td>
</tr>
<tr>
<td>Dillon Locality</td>
<td>43</td>
</tr>
<tr>
<td>Rocky Point Locality</td>
<td>44</td>
</tr>
<tr>
<td>Alameda Parkway Locality</td>
<td>47</td>
</tr>
<tr>
<td>Van Bibber Creek Locality</td>
<td>50</td>
</tr>
<tr>
<td>Plainview Locality</td>
<td>51</td>
</tr>
<tr>
<td>Spring Canyon Dam Locality</td>
<td>52</td>
</tr>
<tr>
<td>CONCLUSIONS</td>
<td>56</td>
</tr>
<tr>
<td>REGIONAL SUMMARY</td>
<td>57</td>
</tr>
<tr>
<td>Regional Summary of Dakota Environments</td>
<td>57</td>
</tr>
<tr>
<td>Comparison with Dakota of Adjacent Areas</td>
<td>58</td>
</tr>
<tr>
<td>Summary of Paleogeography</td>
<td>62</td>
</tr>
<tr>
<td>Cretaceous Seaways</td>
<td>62</td>
</tr>
<tr>
<td>Source Areas</td>
<td>62</td>
</tr>
<tr>
<td>Geographic Location</td>
<td>63</td>
</tr>
<tr>
<td>Climate</td>
<td>63</td>
</tr>
<tr>
<td>Summary of Pre-Benton Cretaceous Geologic History in the Western Interior of the United States</td>
<td>63</td>
</tr>
</tbody>
</table>
CONTENTS

APPENDIX ................................................................. 66
REFERENCES ............................................................. 75
LIST OF FIGURES AND TABLES

Figure 1. Index Map of Study Area..................................................... 1
Figure 2. Typical Acetate Peels and Thin Sections of Dakota Rocks..... 9
Figure 3. Lithologic Equivalency Chart............................................. 11
Figure 4. Cross-bedding, San Bernard River point bar deposits........... 13
Figure 5. San Bernard River, Texas.................................................... 13
Figure 6. Bedding surface Features, San Bernard River, Texas............ 14
Figure 7. Flood on the Cheyenne River, Southern Black Hills
           South Dakota........................................................................... 14
Figure 8. Beach and tidal flat ripple marks........................................ 16
Figure 9. Primary structures at the Burns locality............................ 36
Figure 10. Primary structures at the Wolcott locality......................... 42
Figure 11. Primary structures at the Rocky Point locality.................... 46
Figure 12. Primary structures at the Alameda Parkway locality............ 47
Figure 13. Primary structures at the Plainview locality....................... 51
Figure 14. Primary structures at the Spring Canyon Dam locality........... 53
Figure 15. Dakota Sections............................................................... 54
Figure 16. Cretaceous Seaways......................................................... 62

Table 1. Summary of Environmental Characteristics............................ 31
Table 2. Summary of Features in Dakota deposits................................. 55
ACKNOWLEDGEMENTS

Thanks are expressed to Dr. John J. W. Rogers, who advised the writer in this investigation. Rice University and the Society of the Sigma Xi extended financial assistance for the field studies. Messrs. John H. Eaker, Paul C. Ragland, and Robert W. Deininger aided the writer in his study of the Recent sediments of the San Bernard River. Mr. Edwin V. Post of the U. S. Geological Survey gave of his time on several occasions while the writer was in Denver, Colorado.
INTRODUCTION

Purpose of Study

The Cretaceous Dakota Sandstone is a land-derived, relatively unfossiliferous lithogenetic unit which occurs over a large part of the western interior of the United States and Canada. Its thickness over most of this area does not exceed 600 feet. In many places it disconformably overlies a former land surface comprised of a variety of formations and rock types, from Precambrian granites to Late Jurassic mudstones. Above the Dakota, and conformable with it, is a marine black shale whose name and age vary from place to place. Thus the Dakota records the passage of an ancient shoreline over a large part of the western interior of the North American continent, the last large-scale invasion of the craton by marine waters.

The purpose of this study is the reconstruction of sedimentary environments and determination of geologic history from deposits of the Dakota Sandstone in northwestern Colorado. Close study should reveal the presence of several continental, marginal, and marine deposits within the unit.

Methods of Study

Criteria: Sedimentary environments have been interpreted mainly from primary structures, such as stratification and bedding surface features, and from lithology, color, organic content, and shape and size of units. An attempt was made, where possible, to compare features observed in the Dakota with features in Recent sediments.

Field Methods: At each field locality, a section was measured and described, with emphasis on description of primary structures. For future study, color slides were taken of many features. Approximately
List of localities
1. East Rifle Creek
2. Elk Creek
3. New Castle
4. Derby Mesa
5. Big Alkali Creek
6. Toponos
7. Wolcott
8. Dillon
9. Rocky Point
10. Morrison
11. Alameda Parkway
12. Van Bibber Creek
13. Plainview
14. Spring Canyon Dam
110 samples were collected, mostly sandstones and siltstones. Because the Dakota 1) has few reliable zone fossils, 2) does not intertongue noticeably with sub- and superjacent formations, and 3) exhibits rapid lateral facies changes, time relationships between it and other formations and within the Dakota itself are very difficult to establish. Physical relationships in such a formation may be determined by accurate, large-scale mapping. In the present study, an attempt has been made to trace depositional environments, because it is felt that this reflects more accurately the original extent and character of the conditions accompanying the formation of the Dakota. Careful examination may reveal, for instance, the presence of more than one environment within a single sand body.

Determinations of paleoslopes and current directions have not been a part of this investigation. The main purpose is the identification of sedimentary environments, but this does not presuppose a knowledge of the current directions. Though the two are definitely related, they are not inseparable. Depositional environments are an integral part of paleogeography, but not vice-versa. For this reason, no special studies were made of directional properties such as cross-stratification, ripple mark orientation, or changes in textural parameters. There are also practical considerations involved in omitting cross-stratification studies. For instance, one should not indiscriminately measure cross-stratification directions. Proper interpretation of such measurements depends largely on correct identification of the environments in which the cross-strata are found. Cross-strata in fluvial environments generally follow the regional paleoslope, but not necessarily (Potter and Siever, 1956). Longshore current-formed cross-strata probably parallel
the shoreline, but rip currents may cause local deviations away from shore. Cross-strata in tidal deltas should point inland. Tidal channel cross-stratification may show little pattern, because of high degree of sinuosity.

Laboratory Methods: Thin sections were cut of 15 samples of sandstone, although the detailed petrography of the Dakota was not emphasized.

Approximately 17 samples of clay and shale were disaggregated and studied for mineralogy and fossil content. Samples were broken down in a small jaw crusher and a disc crusher and dried for about an hour under heat lamps. They were then soaked in Varsol for 15 to 30 minutes. The Varsol was then decanted and the sample soaked in hot water. The partly disaggregated sample was then washed through a 325-mesh screen to remove some of the clay. The remainder of the sample was boiled in a sodium hydroxide solution for several minutes and then re-screened. The part of the sample retained on the screen was dried and collected for study.

X-ray diffractograms were made of gross samples of each shale and clay to determine mineralogy, particularly of the clay minerals.

A partly successful attempt was made to obtain acetate peels of sandstones and siltstones to supplement thin sections. The method used is similar to that described for making peels of carbonate rocks (Bissell, 1957), except that hydrofluoric acid is used. A sawed, polished, and dried surface is etched about five minutes over acid fumes. This is carried out by supporting the surface on paraffin blocks in a closed plastic container under a hood. After the sample has been etched, washed, and dried, the surface is placed face upward on a clay block and tilted slightly. Acetone is applied and collects at the lower edge of the tilted face. The acetate film is applied at this lower edge and rolled
up the face. The sample is placed face down on a paper towel after several seconds and allowed to remain for a number of hours. Complete drying of the acetate prevents shrinkage and minimizes wrinkling. Best results were obtained with Keuffel and Esser Herculeen (Mylar base) matte finish acetate, 1/2000 inch thick. The method succeeds if the sample is "tight", that is, if it exhibits good grain contacts. Weathering has affected much of the Dakota to such an extent that it has already been etched too much. Therefore, any further etching in the laboratory was unnoticeable in some samples.

Recent Sediment Studies: Three areas near Houston were visited to gain first-hand knowledge of the processes which form some of the features used as criteria of environments of deposition and the relationships among the features and environments. Small trenches were dug to expose the stratification. As the walls of the trenches dry, patterns of stratification develop in response to differential erosion of laminae containing different grain sizes. All features were photographed on color slides. Two shore areas were studied, a tidal flat and beach environment at the west end of Galveston Island, and beaches east of the Brazos River mouth at Freeport. The third locality was the dry, sandy bed of the San Bernard River about 60 miles west of Houston on U. S. highway 90.

Previous Work

The following work has been done on the Dakota and its lithologic equivalents. A synopsis of results will be presented at the end.

The Dakota was first recognized and studied over one hundred years ago during reconnaissance work of early field parties. It was formally named in 1861 by Meek and Hayden, who previously referred to it as "formation No. 1" of the Cretaceous System. Their work, and that of
other early geologists, was mainly paleontological. They met with some
difficulty in assigning an epochal age to the unit, which was named from
what they felt were typical, well-developed exposures near the town of
Dakota in eastern Nebraska. Since then, the Cretaceous age of the Dakota
everywhere has been verified, but epochal boundaries within it are still
highly conjectural.

The type area has since been restudied by Tester (1929), who made an
effort to determine depositional environments.

Plummer and Romary (1942) described the Dakota in central Kansas,
and also attempted to determine its environments.

Schoff (1943) and Rothrock (1925) studied outcrops of Dakota equiva-
lents in Cimmaron County, Oklahoma, and made some speculations pertaining
to environments.

More recently Franks and others (1959) have studied the source, ex-
tent, and environments of the Dakota in central Kansas from cross-bedding.
The Kansas Geological Survey has also described a well core from northwest
Kansas (Merriam and others, 1959).

Loeblich and Tappan (1950) studied the foraminifera in the type Kiowa
shale in Kansas.

Eaton (1960) studied the remains of an armored dinosaur from the
middle of the Terra Cotta clay member of the Dakota formation in Ottawa
County, Kansas.

Anderson (1939) reported dinosaur tracks from the Dakota equivalents
in the Black Hills, South Dakota.

Young (1960) made a rather detailed investigation of the Dakota of
the Colorado Plateau, and went into some detail in environmental inter-
pretation.
Karl M. Waage has contributed two significant papers to detailed knowledge of Dakota stratigraphy in Colorado. The first (Waage, 1953) describes the unit in south central Colorado, where the formation is mined for refractory clay. The second (Waage, 1955) describes more fully the Dakota in the Front Range foothills from about 20 miles south of Denver to the Colorado-Wyoming border. This paper was later supplemented by the publication, in graphic form, of sections measured in the investigation (Waage, 1959a). A third paper by Waage (1959b) describes the Dakota stratigraphy in the Black Hills.

Moerly’s (1960) study of the Dakota equivalents in the northern Bighorn Basin treats depositional environments more thoroughly than any previous study and is well-documented by recent sediment studies.

The most detailed investigation of the Dakota is that of a U. S. Geological Survey project in the Southern Black Hills, where approximately sixteen 7-1/2 minute quadrangles have been mapped at 1:7200, which is also the published scale of the preliminary maps. Individual exposures were plotted on all of the maps, making them an obvious aid to later workers. A few reports and several of the preliminary maps have been published, and the maps are listed below.

MF-55 through MF-60 (Gott & Schnabel, 1956)
MF-61 through MF-66 (Bell & Post, 1957)
MF-67 through MF-70 (Wilmarth & Smith, 1957)
MF-71 through MF-73 (Schnabel & Charlesworth, 1958)
MF-74 (Schnabel, 1958)
MF-75 (Schnabel & Charlesworth, 1958)
MF-77, MF-78 (Brobst, 1958)
MF-180 (Cuppels & Conway, 1958)
MF-207, MF-209 (Post & Cuppels, 1959)
MF-208, MF-210 (Post & Lane, 1959)
MF-211, MF-212 (Post, 1959)

Eventually, manuscripts with accompanying maps will be published. Other reports resulting from this project include a diagrammatic cross-section
(Mapel & Gott, 1959) and the stratigraphic study by Waage (1959b).

Many classic early works by the U. S. Geological Survey included description of the Dakota. Many Geologic Atlas Folios, Professional Papers, and Annual Reports are still the most up to date investigations of the Dakota in many areas. Most of these works are listed in bibliographies of the publications of Waage (1953, 1955, 1959a, 1959b).

O'Boyle (1955), Burton (1955) and Waage (1958, 1959c) have written summaries of regional Dakota stratigraphy for several Rocky Mountain guidebooks.

The Dakota has also been the subject of several theses. Goldstein (1948) studied the Dakota of the Colorado Front Range area, but his work has been superceded by Waage's (1955) report. The clay mineralogy of the Dakota was investigated by Larsen (1953), who included some environmental interpretations of his results. Breed (1956) made a rather regional study of the Dakota in northwestern Colorado. Curry's (1959) study of the Dakota in central Wyoming is one of the more detailed theses on the subject.

Remaining literature on the Dakota can be divided into three categories: 1) reconnaissance maps and reports of early geologists, such as those of Hayden (1876) and King (1876); 2) paleontologic studies, to which Reeside (1923) and others have contributed; and 3) incidental description of the Dakota in various investigations, such as the study of the origin of South Park (Stark and others, 1949) and Lovering's (1934) investigation of the Breckenridge mining district.

Based on these investigations, the Dakota has been interpreted as continental and near-shore in origin. Waage (1953, 1955) concluded that the Dakota of the Colorado Front Range foothills contains floodplain,
deltaic, estuarine, littoral, and neritic deposits. The lower part is fluvial, and is overlain by transgressive sands and black shales which are most prominent in the northern part. At the top is a series of regressive sands which, to the south, are definitely fluvial in character. In the Denver Basin these sands are thought to be sand bars of the offshore island type (Fentress, 1955).

The Dakota of the Northern Bighorn Basin differs slightly in that it contains large amounts of altered volcanic ash in the lower, fluvial part (Moberly, 1960). Nearshore sands and shales overlie the continental sediments and are succeeded by marine black shales of the Thermopolis.

The Black Hills area contains some of the thickest Dakota. The base is a thick sequence of superposed channels, overlain by near-shore sands and black shales (Waage, 1959b). In the center is the marine Skull Creek Shale, and at the top is the Newcastle sandstone, which is interpreted as a series of offshore bars (Skolnick, 1958).

In central Kansas the lower Dakota consists of three parts, a lower strand-line continental sand (Cheyenne), a middle brackish or marine shale (Kiowa), and an upper fluvial-lake-swamp unit (Dakota), (Plummer and Romary, 1942). Loeblich and Tappan (1950) conclude that the large number of individuals of a relatively small number of species of arenaceous foraminifera in the type Kiowa shale indicate a brackish environment. Based on associated dinosaur remains and hardwood leaves in the Dakota of central Kansas, Eaton (1960) interprets the vertebrate-bearing beds as a warm, temperate, deciduous forest. The upper unit was the main subject of Tester's investigation of the type locality (1929), and he concluded that the sediments were deposited in floodplain, deltaic, neritic, and littoral environments.
Rothrock (1925) reached conclusions similar to those of Plummer and Romary (1942), except that he thought that the lower strand-line sand graded from continental on the west to marine on the east.

**General Stratigraphy**

**Lithologic Description**

The Dakota formation in the study area consists of interbedded buff sandstones and conglomerates, buff, grey, maroon, olive, and black siltstones, and grey and black shales. Sandstones comprise 65% to 85%, siltstones 10% to 25%, and shales 0% to 15% of the formation, which varies in thickness from 125 feet at Derby Mesa to 225 feet at Wolcott. The lower one-half to two-thirds consists of several thick sandstone bodies, massive-looking from a distance, but cross-bedded on closer inspection. Thin shales and siltstones are intercalated at various localities. Conglomerate and conglomeratic sandstone are common in this portion and are dominant in the western area. Above the massive sand section are interbedded thin sandstones, siltstones, and shales in varying proportions. This section is commonly characterized by irregular and discontinuous bedding and by disturbed stratification. The siltstones are commonly grey to black, though maroon and olive shades are encountered at some localities. The shales are grey to black. At the top of the formation is a thick body of sand whose thickness is relatively uniform over broad areas. From a distance it appears tabular, but the lower part is thinly and evenly bedded, and the top is cross-bedded.

A typical Dakota sandstone consists of sub-rounded and rounded detrital quartz grains surrounded by secondary quartz in optical continuity, the whole forming an inter-locking pattern. Plant remains constitute several percent of the sandstones at many places. They occur mainly as chunks of charcoal, streaks of vitrain, finely divided carb-
Figure 2: Peels and Thin Sections

a: Acetate peel of Channel conglomerate from basal Dakota at New Castle. About 2 cm. across.

b: Acetate peel of shale pebble conglomerate from upper Dakota at Rocky Point (tidal flat deposits). About 1 3/4 cm. across.

c: Thin section of channel chert pebble conglomerate from basal Dakota at New Castle. Note bryozoan fragment in chert pebble in upper right corner. Plain light.

d: Same as (c), crossed nicols. About 2 cm. across.

e: Thin section, well-sorted quartz sandstone. Crossed nicols. About 1 1/2 cm. across.

f: Thin section, moderately well-sorted quartz sandstone containing chert granules (dark, speckled grains). Crossed nicols. About 1 1/4 cm. across.

g: Poorly sorted cherty sandstones. Crossed nicols. About 1 1/4 cm. across.
Figure 2. Typical acetate peels and thin sections of Dakota rocks.
onaceous matter, and as unidentifiable carbonized plant remains. Mineral
grains larger than sand size are composed of coarsely crystalline quartz,
chert (infrequently fossiliferous), clay pebbles, shale pebbles, and finely
crystalline quartz. Silica overgrowths, vein-like finely crystalline
quartz, and iron oxide are the cementing agents. Feldspar grains are
rarely present. Well-rounded tourmaline and zircon are the most common
heavy minerals. Typical thin sections and acetate peels of Dakota sand-
stones are shown in Figure 2.

The siltstones are probably very similar, mineralogically, to the
sandstones. They commonly are very dark grey in color because of homogeneously
distributed, finely divided carbonaceous matter. No mineral
grains noticeably larger than silt or fine sand size were observed.

Clays and shales in the Dakota consist of kaolinite, quartz, and
carbonaceous matter. The clay minerals were identified by X-ray diffrac-
tion. The quartz is sand size, well-rounded, and detrital. Many samples
contain cellular, vitreous wood fragments whose original vascular chambers
are filled by a white material which may be silica.

Sedimentary units in the Dakota normally exhibit a low degree of
lateral continuity. Large sand bodies in the lower part are generally
lens-shaped or wedge-shaped, and have irregular convex-downward bases and
flat tops. Similar, though smaller, units are found in the interbedded
sandstone-siltstone-shale sequence just below the top of the formation.
Some of these smaller lenses are only a few feet thick. Small lenses are
generally surrounded by shale, and larger lenses are surrounded by sand-
stone and/or shale.

Simple, planar, and trough cross-stratification (McKee and Weir,
1953) are common to abundant in the sandstones and siltstones of the
Dakota. Planar and trough cross-bedded sets from several inches to a few feet thick are characteristic of many sandstones, while all three types occur in the siltstones, usually in sets only an inch or less in thickness.

Several varieties of ripple marks are abundant in the upper third of the Dakota. This same part of the formation is also characterized by tube-shaped sand stringers in black shale, strongly suggestive of burrows or organisms.

Plant impressions, some of tree-truck proportions, are common in the lower Dakota.

Correlation

The Dakota and its lithologic equivalents present difficulties in dating and correlation nearly everywhere. Problems of nomenclature have sprung from these difficulties. The formation has a sparse fossil content in most places, though land plant remains are abundant at some localities and marine invertebrates at others. Few, if any, sections contain chronologically significant fossils through the entire formation. Hence, the ages of the various units in the Dakota are often 1) estimates, 2) based on a fossil found in only a small part of the total thickness, 3) based on fossils found in the base of the overlying marine shale. A glance at the GSA Correlation Chart (Cobban and Reeside, 1952) reveals the results of some of these dating methods. More accurate results must await new methods of dating, reevaluation of presently used index fossils, more complete knowledge of the physical stratigraphy of the Dakota, and regional synthesis of the information thus gained. The correlation chart (figure 3) summarizes the state of knowledge about the physical relationships of the Dakota lithology at several well-studied localities in the Western Interior of the United States.
Figure 3: Source of Information

Colorado Plateau-Young, 1960
Northwestern Colorado-This paper
Northern Front Range Foothills-Waage, 1955
South-Central Colorado-Waage, 1953
Northern Bighorn Basin-Moberly, 1960
Black Hills-Waage, 1959b
Kansas, Oklahoma-Merriam and Others, 1959
Northeastern Nebraska-Tester, 1929
<table>
<thead>
<tr>
<th></th>
<th>Colorado Plateau</th>
<th>Northwestern Colorado</th>
<th>Northern Front Range Foothills</th>
<th>South-Central Colorado</th>
<th>Northern Bighorn Basin</th>
<th>Black Hills</th>
<th>Kansas, Oklahoma</th>
<th>Northeastern Nebraska</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dakota Group</td>
<td></td>
<td>Plainview ss.</td>
<td>(sandstone)</td>
<td>Sykes Mountain fm.</td>
<td>Fall River ss.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Lytle ss.</td>
<td></td>
<td>Little Sheep mudstone</td>
<td>Fuson mbr.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Pryor cgl.</td>
<td>Lakota fm.</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Figure 3. Lithologic Equivalency Chart**
ENVIRONMENTAL CRITERIA

Deposits representing fluvial, beach, tidal flat, marsh, and possible deltaic, lacustrine, longshore current, surf zone, and weathering zone environments have been observed in the Dakota formation in the study area. Interpretation has been based mainly on comparison with primary structures found in Recent sediments. An extensive survey of the literature, plus first-hand observation, provides most of the documentary evidence. The following section summarizes these findings. The terminology follows that suggested by McKee and Weir (1953).

Fluvial Environments

Stratification: A fluvial interpretation of a sedimentary unit is often rendered on the basis of cross-stratification. However, because this feature also appears in marine deposits, a more detailed inspection is necessary.

Planar and trough cross-strata are the most common types in water-laid sediments (figure 6b, c, d). They are similar in that the lower bounding surfaces of sets of cross-strata are erosion surfaces. They differ in that the planar type has a flat lower surface, the trough type a convex-downward lower surface. The sets are generally a few feet or less in thickness.

Trough cross-lamination formed by the downcurrent migration of small, asymmetrical current ripples is described by McKee (1937) for the upper portion of the Colorado River delta. In some instances the same process forms a pseudo-bedding (see McKee, 1937, Plate ID, figure 3). The sets of cross-strata are roughly an inch or two thick.

Thicker sets of trough cross-strata, one foot or so thick, are formed by the migration of megaripples in the sandy San Bernard River west of Houston, Texas (figure 4, figure 5a). The sets are lenticular, extend
laterally from a few feet to several yards, and are cross-laminated. Angles are relatively steep, about 25° to 30°. This type of cross-lamination is undoubtedly formed during high-water, high-velocity stages which infrequently interrupt the predominantly dry river. McDowell (1960) has observed similar features in point bar deposits of the Mississippi River. McKee (1957a) has produced trough cross-stratification in the laboratory by the filling of troughs formed both during the same and during previous flood stages.

Planar cross-stratification is also formed in rivers. This type was observed in the San Bernard River by the writer. It appears also to form by the downstream migration of megaripples, and by the downstream extension and migration of essentially flat-topped, lobate tongues of sand on point bar deposits (figure 5b). Sand is swept across the top and over the edge of a tongue, some coming to rest on the lee slope in the manner described and reproduced in the laboratory by McKee (1957a). Some growth may also take place by lateral accretion of sand directly from the current to the slope. Fisk (1945, Figure 15A-B) shows thick sets (about 5 feet) of planar cross-strata formed at the heads of point bars on the Mississippi River which probably formed in this way.

Material which settles out of flood waters on broad, flat floodplains develops more or less regular, parallel, and continuous strata. It is thin-bedded (McKee, 1939) to thinly laminated (Dunbar and Rodgers, 1957). Similar bedding may characterize other environments, but may differ in one or more of the following ways: 1) floodplain strata should be more continuous, less lenticular, less well-sorted, and contain more organic matter than beach laminae, and sediments may be finer grained; 2) floodplain strata should lack wave ripples and fossils which may exist in lagoons; 3) lithologic associations would serve to differentiate
Figure 4. Cross-bedding, San Bernard River, Texas. Trench is about 4 feet deep.
Figure 5: San Bernard River

a: Downstream view showing randomly disposed megaripples with gravel concentrated on the stoss sides.

b: Upstream view showing flat-topped sand lobe encroaching on surface covered with megaripples.
floodplain deposits from similar-bedded deposits formed in quiet, deep waters of lakes or seas. Floodplain deposits would occur with channel deposits. Regularly bedded quiet-water lake or sea deposits may be associated with calcareous beds, diagnostic biota, and accumulations of sediments thicker than for floodplain deposits.

**Bedding Surface Features:** A variety of ripple marks is characteristic of current-deposited sediments. Kindle's (1917) early work on this important bedding surface feature remains one of the best summaries. D. W. Johnson's book (1938) also contains a very good summary and historical review of the subject (see pages 489-512).

Small, asymmetrical ripples are probably the most common in fluvial environments, with wavelengths on the order of six inches or less and amplitudes of an inch or less. There may be a large variation in the degree of regularity of the pattern of the ripples. Some are relatively parallel, others more lobate. In the San Bernard River parallel ripples exist where the water flows over shallow, flat areas, and lobate ripples in the deeper, more trough-shaped portions of the channel (see figure 6a).

Larger current ripples, called megaripples and sand waves, form where currents are stronger and the water deeper. Areas affected by strong tides, such as the estuaries around southern England and the Bay of Fundy, are characterized by these features, as are normal rivers in flood. Similar large ripples were observed in the San Bernard River by the writer (see figure 5a). Here the ripple amplitude is about one foot, the wavelength several feet, and length of crests only a few feet. Gravel is concentrated in sheets on the stoss sides of these ripples. In some rivers, these features are as much as 3 feet in amplitude and may be tens of feet in distance between crests (Johnson, 1938; Cornish, 1913). It is the migration of these features which is responsible for the forma-
Figure 6: Stratification and bedding surface features, San Bernard River, Texas

a: Current ripples. Parallel type in shallow water, lobate or cusped type in deeper water.

b, c: High-angle trough and planar cross-stratification in point bar deposits.

d: Trough cross-stratification in point bar deposits.
Figure 6. Stratification and bedding surface features, San Bernard River, Texas.
Figure 7: Flood on the Cheyenne River

a: Low-water stage of river.
b: Wave at front of flood.
c: Wood debris behind flood front.
d: High water stage of flood. About 5' deep.

(Time elapsed between a & d about 20 minutes.)
Figure 7. Flood on the Cheyenne River, southern Black Hills, South Dakota.
tion of the large-scale trough cross-stratification previously described.

Shape of Larger Units: Because stream valleys and channels have a convex-downward cross-axial shape, deposits which fill them should have a convex downward base and a relatively flat top.

Tidal Flat Environment

The tidal flats which have been studied are divisible into three classes, two of which are parts of other environments. The first class, a true tidal flat, is typified by the area along the Dutch and northwestern German coast, where mud flats, fed and drained by sinuous and rapidly migrating channels, exist between a chain of offshore islands and the mainland. Even the mainland may be covered occasionally by exceptionally high tides and, in this case, salt marshes form the landward margin of the flats. A second class is actually the tidal upper surface of a delta. Examples of this are the Frazer River delta in British Columbia (Johnston, 1922), and the Colorado River delta in Mexico (McKee, 1939). The third class is the intertidal estuary, exemplified by the many river mouths around the southern coast of England (Cornish, 1913) and around the Bay of Fundy (Kindle, 1917). Because all three are characterized by channels, many of the features found in fluvial deposits are also found in tidal flat deposits. These will be mentioned again briefly, but emphasis will be on those features which might serve to distinguish tidal flats from other environments.

Stratification: Because tidal flats are affected by both currents and waves, two main types of stratification are formed, cross-stratification and irregular stratification. That cross-strata are quite abundant is evidenced by the works of Haentzschel (1935; 1936; 1955), Van Straaten (1954b) and Richter (1929). Thin sets of trough cross-laminae
are formed by the migration of sand waves and megaripples. Both are similar to the same current-formed features found in terrestrial streams. The principal difference is the thicker sets of cross-strata resulting from sand waves, which are larger than megaripples, because they are formed by more powerful tidal currents.

Sets of planar and trough cross-strata several feet thick are formed by quite a different process. Material accumulates on the inside of each bend in the rapidly migrating and meandering channels, and sets of planar cross-beds result. The process is called lateral sedimentation by Van Straaten (1954a,b). Such cross-beds may be seen in the process of formation in figure 22 of Richter (1929), and a resulting set of cross-beds is shown in figure 21 of Richter (1929). Some of these sets are truncated and superceded by other sets, thus giving the appearance of quite large sets of trough cross-strata (Haentzschel, 1936).

Irregular beds, formed by the preservation of rippled surfaces, are very common in tidal flat environments (Schwarz, 1933; Luders, 1930). Wave and current ripples and combinations of the two abound on tidal flats and in tidal channels. Material which settles out of the water during the slack period at the turn of the tide no doubt helps preserve the ripple marks which have just formed. Many irregularly-beded, discontinuous sand lenses exist on tidal flats. In general, the irregular beds are very thin-beded or thinner (McKee and Weir, 1953). The tidal phenomenon contributes to the thinness of bedding much in the same way as it does on beaches. Once an equilibrium profile is attained, the constructive and destructive forces are very delicately balanced.

Bedding Surface Features: The most abundant feature is the ripple mark, of which many types may be found. Most fall into the category
Figure 8: Beach and Tidal Flat Ripples

a: Asymmetrical current ripples on sand flat, west end of Galveston Island, where beach begins to merge with tidal flat. Current from upper right to lower left. Ripples are about 2 inches across.

b: Low, wide ripples on beach east of Freeport, Texas. Ripples are about 1 foot across.

c: Channel on tidal sand flat, west end of Galveston Island. Not current ripples coming toward observer.

d: Symmetrical ripples on Galveston Island tidal sand flat. Ripples have rounded crests, pointed troughs. Ripples are about 2 inches across.
which McKee (1957b) calls parallel. Some of these have rounded crests and slightly pointed troughs (Richter, 1929, figure 11; figure 8d, this paper). A type similar to this, but which preserves the effects of tidal current action, has slight to pronounced asymmetry (figure 8a). These were observed on the tidal flat on the west end of Galveston Island. In a third type the pointed crests are separated by broad, flat troughs (Kindle, 1917, Plate 21A; McKee, 1957b, Plate 8A). Trusheim (1929) has shown that the formation of ripple marks is not restricted to sandy material, as Kindle (1917) had stated.

Asymmetrical cusp ripple marks (McKee, 1957b) form in shallow channels which drain water from the flats into the main channels. Similar features have been observed at Galveston Island (figure 8c).

Sand waves and megaripples are a distinct feature of many tidal flats. Excellent examples are shown by Cornish (1913) from estuaries around the English coast. In some of these the sand wave crests extend for some distance, and resemble their miniature counterpart, the parallel type of asymmetrical current ripple mark, which usually forms on the sand waves. In other places megaripple crest lengths are short, and the pattern thus developed is that of a series of randomly disposed pockets and mounds. Examples of these features are also known from the eastern coast of North America (Kindle, 1917) and the tidal flats of the north German coast (Richter, 1929). As these sand waves, megaripples, or "grossrippeln" migrate, moderately thick sets of trough cross-strata are formed.

Other ripple marks also form on tidal flats. Intersecting patterns of current and wave ripples are not uncommon (Cornish, 1913). This type was observed at Galveston Island.

A third major category of bedding surface features, and one which
may be very diagnostic, is that of traces of organisms, including tracks, trails, and fecal material. Gastropod trails are abundant on the tidal flats at Cholla Bay, Sonora (McKee, 1957b). The imprints left by a great variety of organisms are mentioned by Van Straaten (1954b) for the Wadden Sea. The alternate wetting and drying of the mud surfaces enhances the chance for preservation of imprints. It is well known that dry or partially dry muds are difficult to erode (Hjulstrom, 1935).

A great variety of other bedding surface features occurs on tidal flats. Important among these are dessication cracks, swash and other waterline marks, crystal impressions (mostly salt or ice), raindrop impressions, rill marks, and load casts. The greater ease with which lithified sediments separate along bedding planes favors the discovery of these features in older rocks rather than in recently deposited sediments.

Channels: Distinctive channel features are found on tidal flats. McKee's (1939) study of the Colorado River delta revealed that mud-filled channels were characteristic of the lower, tidal portion. Because tidal channels are small in comparison to terrestrial streams, superimposed channels of small size should be a criterion of the tidal flat environment.

The rapidity with which tidal channels migrate has already been mentioned (Van Straaten, 1954b, figure 3). Rapid migration results in lateral sedimentation (Richter, 1929). Such relatively mobile streams are not characteristic of terrestrial areas.

Flora and Fauna: As is characteristic of other environments of brackish water and/or variable salinities tidal flats support fairly large quantities of a restricted number of species. Grasses, bacteria,
phytoplankton, and algae, principally green and blue-green, are the dominant plants. In tropical areas mangroves may be abundant. Grasses act as sediment traps (Ginsburg and Lowenstam, 1958) and cause irregular stratification (Van Straaten, 1954b). Their roots may disrupt the previously deposited strata even further. Generally, however, they are more important in the tidal marshes. Algae also may act as sediment traps (Ginsburg and Lowenstam, 1958). Certain types form leathery mats over the mud surfaces. Bacteria are most important for the chemical reactions they cause which have profound effects on the character of the sediments (Van Straaten, 1954b). They are responsible for reducing conditions which cause the formation of iron sulphides, giving the sediments a black color. Bacteria are also important scavengers and are almost exclusively mud dwellers (Sverdrup, Johnson, and Fleming, 1942).

The faunal spectrum is greatly reduced. Here the most important groups are mollusks, particularly pelecypods (clams, oysters, and mussels) and some gastropods, various burrowing marine worms, and crustaceans, mostly crabs and shrimp. Other groups exist, such as birds and the fish which inhabit the lower (lagoonal) parts of the tidal flat.

One of the most important aspects of the fauna, in terms of criteria for recognizing tidal flats, is the burrowing habit of many worms and mollusks, though this feature is not limited to tidal flats (Moore and Scruton, 1957). Burrowing leaves a distinctive imprint on the stratification. Fine laminae of black mud and light silt are disrupted. Many bulges and tubes of silt surrounded by mud are produced. Photographs of these features are included in Van Straaten's (1954b) report on the Wadden Sea.

Lithology: Some gross lithologic features merit attention because
they offer important clues for recognizing tidal flats. Probably the most important is the shale-pebble conglomerate. Muds deposited on tidal flats are well-laminated and have ample opportunity to become slightly lithified through drying during low tide. Succeeding flood tides then erode this hardened material, which breaks up into flat shale pebbles, granules, and cobbles (Haentzschel, 1935). These grains are then transported and re-deposited with coarse sand. It is testimony of the turbulent conditions which accompany flood and ebb tides.

Another distinctive feature of tidal flat lithology is the occurrence of interbedded thinly laminated black muds and very thin-bedded light silt or fine sand. This reflects the alternate turbulent and quiet conditions on the tidal flat. The coarse, light layers are commonly internally thinly cross-laminated but may also appear structureless (Van Straaten, 1954b).

The black color of tidal flat muds is caused, not by organic matter, but by finely divided iron sulphides. Bacteria assume the key role in the production of this material (Van Straaten, 1954b). Their metabolic processes involve the utilization of oxygen attached to SO₄⁻ ions, the end product of which is S²⁻ ions. The later combine with Fe⁺⁺ ions to produce various iron sulphide compounds. Transformations may occur, resulting in the formation of FeS, FeS₂, or limonite. The first two require anaerobic conditions, the last one requires aerobic conditions. The iron sulphide compounds of the Wadden Sea are discussed by Van Straaten (1954b).

Areal Distribution of Features: The features discussed above are not randomly distributed but fall into a definite pattern. Those features which indicate relatively great current velocities occur in and near the main channels which, on true tidal flats, radiate landward from the tidal inlets between barrier islands. Included in this group of features are
the channel scours (wash-outs), large scale cross-bedding, current ripples and sand waves, shale pebble beds, coarse grained sediments, and interbedded laminae of sand and mud. Moving away from the main channels and onto the tidal flats proper, these features become less common and are gradually replaced by ones indicative of quiet water conditions. Important among these latter are burrowing structures and oscillation ripple marks. As the highest portion of the flats is approached, ripples become rare, grain size diminishes, and burrows become extremely abundant. An excellent summary is provided by Van Straaten (1954b) of the characteristics of each part of the tidal flat environment.

Beach Environment

Beaches have long been of interest to scientific observers, but surface features and morphology have received the most attention. Beach deposits and their characteristic features, particularly stratification, have been intensively studied only recently. Thompson's (1937) investigation of California beaches was the first comprehensive work, but his findings have been but little supplemented since then. McKee (1957b) reported on the types of stratification in beach deposits on Texas, Sonoran, and California beaches. Most recently, beaches of offshore bars adjacent to the Mississippi coast have been under scrutiny (Friddy and Smith, 1960). The writer has visited and noted features of beaches at Galveston Island and Freeport, Texas, near Pensacola and at Daytona Beach, Florida, and at the southern end of Lake Michigan, Indiana. The following summary incorporated these reports and observations.

For convenience, beaches are divided into a foreshore, between low water and the landward limit of effective wave action, and a backshore, covered only during abnormally high water. A crest normally marks the
decrease in slope from foreshore to backshore. For a more complete discussion on terminology, the reader is referred to Shepard (1948) or Johnson (1938).

Beaches are elongate parallel to the strand, narrow normal to the strand, and contain relatively thin deposits. As McKee (1957b) has pointed out, beach deposits "...can not expand both in thickness and in width with sedimentation." Thus, a distinctive feature of ancient beaches is their blanket-like shape which results from either transgression or regression.

Stratification: Beach deposits are most clearly recognizable from their stratification. They generally contain regular, parallel, laminae and thin laminae (McKee and Weir, 1953). In the upper part of the foreshore (above the zone of permanent saturation: see Thompson, 1937), laminae dip seaward at low angles. If the beach is cusped, sets of laminae form shallow troughs which truncate each other (Thompson, 1937). On flat beaches, laminae extend for long distances along the shore. Wedge-shaped sets of strata are superimposed and are separated by fairly flat surfaces of erosion or deposition (Thompson, 1937, figure 2). Regular, thin laminae of other environments are generally more continuous.

If the permanently saturated lower foreshore is flat and continuous with the upper foreshore, lamination similar to that found in the upper foreshore should exist. However, many lower foreshore beaches consist of a low ridge and shallow trough. Some troughs always contain water, others only during high tides. Some ridges and troughs are quite wide and of low relief, while others are narrow and have steeper sides. Examples of the latter were observed on a beach near Pensacola, Florida, by the writer, while that area was under the strong influence of a hurricane. The troughs are connected to the sea by channelways that cut across
the ridges. These troughs may act as sites for the formation of small sets of high-angle cross-lamination by the extension of miniature deltas into them as material is carried seaward by backwash. Trough cross-lamination may also result from the even filling of the troughs. Currents, which also affect the lower foreshore, add to the intricacy of cross-lamination which is intercalated with the regular lamination already described.

Backshore deposits exhibit other types of lamination. In general, laminae dip landward or toward an intervening lagoon. Angles vary, but highestones are greater than the highest angles in seaward-dipping foreshore beaches. Where beaches border directly on land, backshore deposits may take the form of small deltas encroaching upon marine swamps or other land environment (Johnson, 1938, Plate 61). This would result in thin sets of high-angle cross-laminae dipping landward. Similar structures may appear where backshore beach deposits border lagoons (Thompson, 1937; McKee, 1957b). Backshore deposits investigated by McKee (1957b) also contained numerous channels trending parallel to the beach. Some channels were flattened, others steep-sided. A few contained large fragments of a partially lithified, stratified sandstone (intraformational conglomerate).

Bedding Surface Features: Numerous features which form on the surfaces of beaches may serve to distinguish that environment. Rill marks, swash marks, gas bubble pits or bubble impressions, ripple marks, backwash marks, and lineations caused by backwash flowing over larger particles such as fossil fragments are probably the most common features. Of these, ripple marks deserve special attention.

Johnson (1938), Kindle (1917), and Trefethen and Dow (1960) all depict parallel current ripples on beaches. The writer has seen similar
ripples at Galveston Island (figure 8a). However, such ripples are formed on areas which are actually sand flats or where beaches begin to merge with sand flats. The writer has neither read of nor seen any instance in which ripples of this type form on a normal, narrow foreshore beach. Near Freeport, Texas, however, large symmetrical ripples were observed on such a beach (figure 8b). They have gently rounded crests and sub-angular troughs. Crests are parallel and are commonly transected by channels by which the swash returns to the sea. Coarse particles, mostly shell debris, and heavy minerals are concentrated in troughs and on the landward sides of crests by the backwash.

Lithologic Features: Beach material is among the best sorted of sedimentary products, but some beaches contain lenses of poorly sorted material derived from nearby source material of the same nature, or from abundant shell material. Well-sorted sands show highest values of sorting in individual laminae, although bulk samples also show excellent sorting (Thompson, 1937). Many beaches show concentrations of darker heavy minerals into distinct, sometimes thick bands (Van Straaten, 1954b). It is this difference in color, plus the slight textural variations between laminae, that impart to beach sands their remarkable stratification.

Although quartz is nearly ubiquitous in beach sands, some beaches contain large proportions of other materials. Heavy minerals, such as magnetite, ilmenite, and zircon are abundant enough in some sands to make the deposits commercial or at least feasible. Some of the New England beaches are composed mainly of gravels. Others, as in Florida, contain considerable amounts of shell fragments, and form coquinas. Part of the beach at Cholla Bay, Sonora (McKee, 1957b), is composed of granite fragments and minerals from nearly outcrops.
Fossils: Many modern beaches are graveyards for large quantities of biotic material derived from deeper marine waters, from estuaries and lagoons, and from outcrops, both subaerial and subaqueous. Hard parts of marine invertebrates are abundant, and include pelecypods, gastropods, corals and bryozoans as important constituents. Fish are often washed up onto beaches, and it is possible for their teeth to be preserved. Individual vertebrae are rarely seen at Galveston Island beaches. The backshore beach near Freeport, Texas, is littered with wood of all sizes from tree trunks to small fragments. This material was evidently transported by river to the Gulf and later cast up on the beach by storm waves. Thus, a large number of species and ecologic types may be preserved in beach deposits. This diversity is probably the most diagnostic biologic property.

Lagoonal Environment

It is difficult to develop reliable criteria for the recognition of ancient lagoonal deposits. One obstacle to the formation of common criteria is the great variety of lagoon types. Information on primary structures is hard to obtain. Cores provide about the only access to this important feature, and far too few are available. Some inferences about the nature of the stratification may be made, however, based on the knowledge of processes affecting lagoons. Studies of the lithologic and textural characteristics of lagoonal sediments have been made, but none has revealed any really diagnostic features. Biologic constituents may be the most useful.

Morphologically, lagoons are usually shallow bodies of water, elongate parallel to the coast. A barrier island or similar feature offers protection from the forces of the open ocean, and streams may enter from the landward side. Some barriers are continuous for over
100 miles, though more commonly they are only a few miles or tens of miles long, separated by inlets through which tidal waters pass.

The prevailing condition over most of the floor of a coastal lagoon is quiescence. Sediments brought into lagoons are predominantly fine-grained and are spread evenly over the bottom, most likely in thin layers composed of silt, clay, or both, and perhaps some fine sand.

Investigations of Texas Gulf coastal lagoons have included descriptions of stratification in cores. Mottled (i.e. boring) structures are the most common in bays of the Central Texas coast (Shepard and Moore, 1960), and fine, homogeneous (structureless) sediments are found in deeper parts of bays. The sediments of elongate Laguna Madre, however, are predominantly regularly layered (Rusnak, 1960) except at the ends of the lagoon, where mottles and irregular structures dominate.

McKee (1957b) noted that some of the lagoonal sediments at Corpus Christi, Texas, consist of thin beds of fine sand and coquina near a major channel. In places, this material exhibits low-angle, simple cross-stratification, indicating weak, but persistent, currents.

Strong currents exist near inlets. Coarser sediments are encountered there, and one would expect cross-bedding, formed in tidal deltas. Some lagoonal inlets have a delta built into the lagoon and one built onto the sea floor. Other lagoons may have only one delta, or none at all. The seaward-facing deltas are smaller and, because of wave action, have arcuate fronts. They appear as bulges on the sea floor. Deltas in the lagoon, however, grow into quiet water, and are more like a bird-foot delta. Cross-bedding and current ripples are probably formed in both types of tidal deltas, and the outer ones may have oscillation ripples. As Jacka (1960) suggests for surf zone deposits, sets of cross strata probably are bounded by wavy surfaces.
A variety of biota exists in lagoons, but "reefs" built up by colonies of oysters or other pelecypods are among the more conspicuous sedimentological features. Fish are abundant, and some of their remains may be preserved, particularly teeth, scales and other boney material.

The margins of lagoons are, in places, the environmental equivalents of high tidal flats and should exhibit many of the same features: burrows, algal mats, mud cracks, ripple marks, tracks and trails, raindrop and crystal impressions, and root structures, to list a few.

Waves which disturb the waters of lagoons are much smaller than those in larger bodies because of shorter fetch. Consequently, bottom deposits may be affected only occasionally, if at all, and the result is symmetrical oscillation ripple marks. Subsequent quiet conditions should be favorable for the preservation of these ripples by burial under later sediments.

Evaporation products are conspicuous in regions of high aridity, and distinct layers of salts may form under optimum conditions. Salt crystals can form and be preserved only as impressions. Salt crusts form around the margins of some lagoons.

Black color characterizes many lagoonal sediments, as it does in tidal flat deposits, and for similar reasons.

Marsh Environment

Many types of swamps and marshes exist. The ones discussed below refer to those which border lagoons, estuaries, and tidal flats, or which lie landward of backshore beaches, and are occasionally affected by tides or storms.

Abundant plant life is a most noticeable feature of any marsh. Another is coincidence with, or proximity to, the water table. Both have
important effects on the character of the sediments, and on the type of stratification.

Plants serve three main functions. First, they act as a sediment trap (Ginsburg and Lowenstam, 1958; Van Straaten, 1954b). Grasses cause the sediment to have a somewhat irregular stratification. Second, roots of grasses can burrow into the sediment and leave it disrupted where they do so. Third, grass may be contributed to the sediment itself, and in great abundance in some marshes. The plants are more easily preserved if they fall and accumulate in water, otherwise they may be decomposed.

Examples of marsh stratification are shown in Richter (1929) and Van Straaten (1954b).

Shallow Marine Environments

Included in the shallow marine environments are sediments which have accumulated within the zone permanently affected by waves. The depth to which the effects of waves are felt depends on the relationships between bottom slope and wavelength, wave height, and wave period (Keunen, 1950, pp. 69-86). The depth of this zone is still the subject of much speculation, but 50 feet seems to be the right order of magnitude. This limits the width of the zone to a relatively narrow strip along most shores. The exact width depends, of course, on the relationship between bottom slope and the depth of wave agitation.

Johnson (1956) points out that about 80% of nearshore sediment movement occurs landward of the breaker zone. Most, if not all, coasts are affected by longshore currents, which reflect the movements of the major wind-driven ocean currents adjacent to land areas. Sand grains are easily moved by suspension and saltation by longshore currents. Thus, conditions in the surf zone are favorable for the formation of cross-
bedding by the migration of small, dune-like structures. Longshore currents affect the bottom beyond the surf but become weaker seaward. Other currents, such as rip currents and density currents, probably form cross-bedding, but these would have an orientation away from shore and may reverse directions with changing seasons.

Many shallow sub-littoral zones have one or more submerged offshore bars, commonly marked by breaker zones, which may serve to modify the general conditions discussed above. These bars migrate seasonally. Cross-stratification formed in these areas by longshore currents and surf conditions should likewise migrate, causing an interlayering of cross-bedded units and rippled units, or of units showing markedly different sizes of cross-bedded sets.

Ripple marks are common on shallow sea bottoms. Symmetrical ripples, formed by wave motion, are abundant. Whether they would be detectable in a well-sorted, lithified rock is a matter for debate. They may not even be preserved, because of the destructive effect of current action and general turbulence on the shallowest portions of the sea floor, where these processes predominate over wave activity. Ripples ought to be more common away from the breaker zone(s) and also are more likely to be preserved there. The changing competency of wave-induced motion of the water allows sediments of varying textures to become interbedded, and the variation may render rippled structures visible. Current ripples can form in the surf zone, where translation waves occur, but these may be obliterated in subsequent transgression by the turbulence at the plunge point of breakers.

One might expect that sets of marine cross-strata would be rather thin (one foot or less) and contain low-angle foreset strata, in com-
parison with similar features formed by currents in terrestrial streams. They are also probably bounded by wavy and relatively continuous surfaces (Jacka, 1960). These speculations are based on the morphology and processes which occur in shallow sub-littoral zones. Currents over shallow bottoms are generally too slow to produce the megaripples associated with rivers. In rivers, the migration of these features produces thick sets of high-angle cross-beds, as previously discussed. Shallow sea bottoms are more or less flat, containing only low-relief features, the most pronounced of which are the gently arched submerged bars. Other areas contain small mounds and shallow depressions, and probably small dune-like structures. Thus, conditions are more likely to favor thin sets of low-angle cross-beds.

The writer will not attempt to summarize the voluminous literature pertaining to either the biota or the gross lithologic aspects of these environments. For the former, suffice it to say that a large and varied array of forms exists. The reader is referred to the Treatise on Marine Ecology and Paleoecology (Hedgepeth, ed., 1958).

A summary of environmental characteristics is given in table 1.
<table>
<thead>
<tr>
<th>Stratification</th>
<th>Bedding Surface Features</th>
<th>Lithologic Features</th>
<th>Biota</th>
<th>Other Features</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fluvial - High-angle cross-beds in tabular to lenticular sets 1-2' thick. Regular, thin laminated.</td>
<td>Parallel &amp; cuspatate current ripples; parallel and irregular megaripples. Tracks, trails, wood and other impressions.</td>
<td>Poorly sorted conglomerates. Wood; clay pebbles; coal.</td>
<td>Mainly land plants; rare vertebrate remains.</td>
<td>Channels; sub-aerial erosion and weathering features Irrregular thickness</td>
</tr>
<tr>
<td>Tidal Flat - Thin, irregular bedding; thick sets of cross-beds; ripple cross-laminae; burrows of organisms.</td>
<td>Many types wave and current ripples in sand and mud; impressions of many kinds; tracks, trails; flow casts</td>
<td>Shale pebble conglomerates; interbedded sand, silt, and shale; iron oxides and sulphides; fecal pellets.</td>
<td>Molluscs; algae; fish; worms; crustaceans.</td>
<td>Small channels. Irregular thickness and character.</td>
</tr>
<tr>
<td>Lagoon - Thinly laminated to structureless sand, silt, and clay. Regular and irregular beds. Burrowing structures.</td>
<td>Wave ripples. Trails tracks; algal mats; mud cracks and crystal impressions on margins.</td>
<td>Fine grained except near rivers and inlets. Iron sulphides; carbonates; evaporites; fecal pellets.</td>
<td>Molluscs; algae; worms; crustaceans; fish</td>
<td>Irregular thickness and character.</td>
</tr>
</tbody>
</table>

Table 1. Summary of environmental characteristics
DAKOTA ENVIRONMENTS

In this section the Dakota formation at each locality studied is described. Environmentally significant features are discussed and interpreted.

East Rifle Creek Locality

Of the 165 feet measured at the westernmost locality (see index map), only about 88 feet are exposed. The exposure, however, is better than any others between Rio Blanco and Glenwood Springs. Diagnostic structures are revealed in three sand ledges of the lower 120 feet. The sandstones exposed in this interval are medium-grained and conglomeratic and are characterized by trough and planar cross-stratification with apparent dips of up to 30°. Units containing cross-strata are tabular to lenticular. Foresets are marked by pebbles and, commonly, by coalified wood. The upper sand ledge is actually two sandstone units, the dark, upper sand filling a channel in the light, lower sand (figure 15b). It appears that one channel deposit has been partly eroded, and the channel has been filled by deposits of a later stream. Cross-stratification, coarse grain size, poor sorting, and the relatively high angle of cross-stratification characterize both sandstone units and are all very similar to features in modern streams. It is difficult to imagine a process other than subaerial erosion which could produce a feature like the 30-foot channel, another strong argument for a fluvial origin for the lower 120 feet.

Twenty feet of very thin-bedded to thinly laminated, grey, carbonaceous sediments are exposed above the fluvial beds. Grey siltstone and dark grey shale predominate. Thin sandstone beds containing charcoal wood fragments occur in the upper 10 feet. A very dark grey shale in this interval contains irregular, lenticular laminae of sandstone. These
features are not inconsistent with a lagoonal or related origin (marsh, mud flat). The fine lamination, fine grain size, and plant and other organic constituents all support this hypothesis. It seems likely that irregularly laminated sand lenses may be shaped by wave oscillation in shallow water.

The next highest unit is a 2-foot sandstone with thin, horizontal, even lamination. It contains a small amount of fine carbonaceous matter. The stratification suggests the possibility that this unit is a beach deposit. It is thinly-laminated, similar to present beaches. However, 2 feet are insufficient for a conclusive interpretation.

At the top of the exposure is an 11-foot-thick sandstone containing fine, medium, and coarse sand and conglomeratic material. Cross-beds are abundant and may indicate a surf zone deposit. Here, again, because of lack of exposure, the evidence is inconclusive.

The remaining 33 feet of covered slope to the top of the hill are littered with chips and blocks of a medium grey siltstone, presumably the basal deposits of the Mancos shale.

Although good evidence for the top one-fourth of the formation is lacking, the units exposed do exhibit features which fit a logical sequence, and no contrary evidence refutes the idea of a transgressive sedimentary sequence. Features in the Dakota exposed to the east suggest that a similar sequence is, in fact, present.

Elk Creek Locality

The resistant Dakota forms a steeply dipping ridge along Elk Creek, but only the bottom 100 feet of sandstone are exposed. The basal contact with the Morrison can be picked within a few feet, but no clues to an upper contact are to be found. A thick black shale sequence is exposed
toward the foot of the dip slope. It undoubtedly belongs to the Mancos shale. Only a rough estimate of the thickness could be made.

The exposed Dakota sandstones are relatively coarse grained. Conglomerates and conglomeratic sandstones are common, although much fine-grained sandstone is present. The structures in these deposits suggest that they are a continuation of the fluvial environment exposed at the base of the Rifle Creek locality. Cross-bedding of the trough and planar types is common throughout. All of these features have their counterparts in modern sandy streams. No floodplain deposits were detected. They may have been destroyed by migration of contemporaneous channels, or they may be eroded more easily and thus be covered at present.

New Castle Locality

A prominent ridge of Dakota sandstone begins on the southeast side of the gap cut by the Colorado River east of New Castle, and extends southeast and then south toward Placita. The ridge is similar to the one along Elk Creek in that only the bottom 100 feet, approximately, of the formation are exposed. In most places the exposed Dakota is highly fractured and is partially covered by lichens and/or iron oxide stain, which prevent any detailed study of primary features. However, at the west end of this ridge the lowest 85 feet are well exposed and were studied by the writer.

The basal 4 feet of this section contain silt and fine sand and an 8 inch clay layer. The remainder of the section contains material from fine sand to pebble conglomerate, and is predominately medium sand or coarser. Chert pebbles in a conglomerate near the base contain fossil bryozoan fragments (see figure 2d). Permian fossils have been identi-
fied from Dakota chert pebbles of other localities (Chronic, 1954). The Dakota-Morrison contact was picked at the top of a maroon siltstone, the upper few inches of which are light grey.

Except for two units, totalling less than 5 feet, the entire section is cross-stratified. The exceptions are a 2.7 foot pebble conglomerate (in which bedding is obscured by the coarse particle size) and a 1.2-foot fine sand (which is irregularly bedded.) Cross-stratified units are similar to those of the Elk Creek and Rifle Creek (basal part) localities. Angles are steep, units are lenticular and non-continuous to tabular, and foresets are marked by coarse grains. Planar and trough cross-strata are the most common types. These features and lithologies are conspicuous features of modern stream deposits.

Some features are present which indicate that the strata in question were subaerially exposed at least for part of their history. One conspicuous feature is the light grey top of the maroon siltstone which is assumed to be the top of the Morrison formation. The maroon siltstone may have been bleached by exposure to subaerial weathering to produce the light grey color at the top. The contact is irregular, not sharp as would be expected for a depositional contact in homogeneous material which must have been horizontal originally. The top of the grey siltstone is irregular, also, having been subject to subaerial erosion. Other units from the base of the Dakota up contain similar erosional tops.

Conglomerates higher than four feet above the base of the Dakota contain sometimes conspicuous amounts of more or less rounded clay pebbles. These were probably eroded from a stream bank of older material and buried fairly rapidly. The clay is similar to Morrison formation clay. Clays in marine cliffs may be attacked by waves and thus eroded, but
such particles may break up eventually because of wave action. No features associated with beaches or surf zones were observed at this locality, however, so the clay pebbles are assumed to be a product of terrestrial erosion and deposition. Flat pebbles of laminated shale (generally dark grey) are found in recent tidal flat deposits, but neither the pebbles nor associated features of tidal flats were found here.

Plant fragments are present in many parts of the section. Though not unique to stream deposits, they add weight to the proposed fluvial origin of the deposits exposed here.

Burns Locality

In the vicinity of Burns, in Eagle County, the Dakota is a well-exposed rim rock for many miles. Figure 15a shows a typical exposure. Unfortunately these nearly vertical cliffs are inaccessible from top to base and therefore of little use in the detailed observation of primary structures. The outcrop is crossed by roads in a few places, and nearly complete sections were measured in two localities. The first to be described is at the east end of Derby Mesa, above the junction of Derby Creek with the Colorado River. The second section is along Big Alkali Creek just up stream from its junction with the Colorado River.

Derby Mesa Section

Approximately 120 feet of Dakota were measured at Derby Mesa. The contacts of the Dakota are not exposed, but very little of the section is missing. Typically variegated Morrison shales and siltstones are visible just below the lowest exposed sand. McElroy (1953, map in pocket) has mapped patches of the Mancos shale exposed just east of the highest sand exposed in the road cut.

Several features in the lower 55 feet of the section indicate that
Figure 9: Burns Locality

a: Surf zone low-angle cross-strata. Scale is graduated in tenths of a foot.

b: Beach laminations, slightly curved, perhaps representing low-angle beach ripples.

c: Small stream channel in shale beds.

d: Typical trough cross-stratification in channel sandstone. Float block.
much of that part is fluvial in origin. Bedding similar to that in modern streams is present in several of the sandstone bodies. Trough and planar cross-stratification are both common (see figure 9d), occurring in sets less than one foot thick with angles up to 25 degrees. The siltstones and clays in this interval of channel sandstones could well be clay plugs (Fisk, 1944), floodplain deposits (McKee, 1937), or any number of continental environments associated with stream valleys. No conclusive evidence is present.

A 20-foot sandstone at the base of the Dakota is medium to coarse grained and contains pebbles and granules. Laminations are commonly marked by carbonaceous matter. Smaller sandstone bodies between 30 and 55 feet above the base exhibit convex downward bases and fill channels in the underlying shale (see figure 9c).

Structures in the next highest 12 feet are slightly different. Some units are irregularly thin-beded to laminated and may represent floodplain deposition. It is also possible that they are part of a lagoonal or tidal flat association, although little other evidence of these environments was found. They are interbedded with dark carbonaceous siltstones and plant-bearing black shales, both of which are found in recent lagoonal sediments.

The next highest 10 to 12 feet contain structures similar to backshore beach deposits of barrier islands. The basal sandstone is a 3 to 6 foot, bi-convex, lenticular unit containing wedge-shaped sets of both low angle planar cross-stratification and thin, even, horizontal lamina-
tion. (McKee (1957b) describes interbedded deposits such as these from backshore beaches of Texas.) Grey siltstones containing wood fragments are interbedded with the sandstones.
The most conspicuous feature of the next highest unit, a 13-foot fine-to medium-grained sandstone, is thin, regular lamination. These thin laminae are slightly curved upward (see figure 9b), probably representing low, symmetrical ripple marks. Also, the thin laminae and the sets containing them are discontinuous. Sets are 50 to 75 feet long, and lens-shaped. All of these features are found in modern foreshore beach deposits and have not been detected elsewhere. The top of the unit is irregular.

At the top of the section is a 25-foot sandstone whose base fills in the lows of the unit below it. The base is cross-bedded, and irregular beds are common in the bottom 10 feet. The strata become more tabular, parallel, and regular upward. Faint cross-beds are visible near the top. These features indicate that the top unit is a surf zone deposit.

As mentioned earlier, the Dakota here contains a transgressive sequence of deposits. Even though evidence is lacking to identify positively the origin of every foot of section, enough features are present to identify the major events and to indicate the general sedimentary framework.

Big Alkali Creek Section

There are many similarities between the Derby Mesa and Big Alkali Creek sections. They are separated only by about 5 miles. However, one or two noteworthy differences exist.

As at Derby Mesa, the basal part of the Big Alkali Creek section is fluvial. Most of the sandstone in the basal 40 feet is medium-to coarse-grained granular, and contains abundant planar cross-lamination of about 25° dip. Pebbles and granules are common on cross-laminated surfaces. Sets of cross-strata are normally about 1 foot thick or less, but reach 2 to 3 feet in one or two places. Associated with these
deposits are some fine sandstones and siltstones, which commonly are carbonaceous and contain larger chips and fragments of charcoal. They are regularly and irregularly laminated, and show some fine cross-lamination and ripple bedding. One friable sandstone near the base is heavily iron-stained, which may indicate subaerial weathering prior to deposition of units which lie on it.

In the center of the measured section is a 20-foot sandstone composed of overlapping lenticular sandstone units. Stratification sets are tabular, discontinuous, and, near the top, internally cross-stratified. The type of stratification in the rest of the unit could not be determined. The top of the sandstone is irregular and slabby. Apparently, this unit is a series of superimposed small stream channels. There are no remnants of bank deposits. There is no evidence to suggest an origin other than fluvial.

Above the 20-foot sandstone just described are an 8-inch, very dark grey, silty shale and a 2-foot sandstone. Both are thinly laminated and contain abundant small plant impressions similar to grass blades, on bedding surfaces and charcoal fragments. The two units may represent a swamp or marsh environment, and the sand may have been deposited by a small stream.

Overlying the swamp deposits are 7 feet of interbedded sandstone, siltstone, and black shale. These units contain very abundant boring structures throughout and were deposited either on a small tidal flat or in a small shallow bay or lagoon.

Above the interbedded sandstone, siltstone, and shale are 10 to 15 feet of thinly laminated sandstone, contained in thin, discontinuous, lenticular sets. This material was probably deposited on a beach as the
shoreline moved landward over the tidal flat or lagoonal deposits found just below it.

At the top of the section is a 25-foot slabby sandstone unit containing cross-lamination of about 10° dip near the base (see figure 9a). This unit probably represents surf (near the base) and associated shallow sub-littoral deposits.

**Toponas Locality**

Approximately 120 feet of Dakota were measured in vertically exposed beds along Egeria Creek, just south of Toponas. The beds are not only upturned but highly weathered and slightly faulted. Nonetheless, some very important features were noted in the upper one-half of the exposed Dakota.

The lower one-half of the exposure is nearly all sandstone. An 18-foot sand at the base and a 15-foot sand at the top of the lower half are pebbly and granular. All others are very fine to medium grained. The 17 feet of sand above the basal unit consist of alternating resistant buff-colored sandstone and soft grey sandstone. Carbonaceous siltstone, sandstone, and clay are present in the upper third of the lower one-half of the section. No diagnostic primary structures were noted in this part of the section. Poorly sorted, carbonaceous, coarse clastics partly support a fluvial origin for these sands, as was suggested for deposits at adjacent localities.

The upper half of the exposure is thin-bedded to thinly laminated and consists predominantly of interbedded sandstone or siltstone and black, fissile shale. In detail, much of the material is thinly and irregularly laminated, and cross-lamination is present in many thin sandstone beds. The most diagnostic feature is found in the upper 50
feet of the section. Most of this material contains abundant boring structures. All the evidence exposed in the upper half points to a tidal flat origin.

No beach or surf zone sands were found. Above the tidal flat deposits were several feet of very dark grey, thinly interlaminated siltstone, sandstone, and shale. Either the top of the Dakota is faulted out (a strong possibility, though no fault was detected), or the sea transgressed without depositing beach or offshore sands.

Wolcott Locality

The exposures studied at Wolcott contain some of the most significant features of any locality included in the investigation. Approximately 220 feet of Dakota are present, and the section measured included a 22-foot and a 35-foot covered interval. Figure 15c shows the exposure, and it may be seen on the vertical cliff that silt or sand occurs in both the covered intervals.

The bottom 160 feet of the formation contain several fluvial features. Above the Morrison contact is a 10-foot, structureless chert-pebble conglomerate containing thin lenses of cross-laminated sandstone, which probably represents a stream gravel bar. This, together with the overlying 30 feet of sandstone, appears to have been the first of three channel phases. The basal conglomerate gives way to about 25 feet of sandstone, exhibiting relatively high-angle (25° to 30°) trough and planar cross stratification in sets ranging from about 1 to 1-1/2 feet. At the top of the channel phase is a 10-foot slabby sandstone with horizontal, regular, continuous laminations (figure 10c). This is interpreted as a flood plain deposit because of the stratification and position overlying channel deposits. These beds are unevenly truncated (subaerial erosion) and overlain by a cross-
stratified conglomerate which is the basal deposit of channel phase two. Only the bottom 15 feet and the top 15 to 18 feet of this phase are exposed, out of approximately 65 feet. However, the sequence is nearly identical to phase one. The conglomeratic base contains high-angle planar cross-stratification and trough cross-stratification (figure 10d). The finer-grained top 15 feet of the phase contains thin sets (a few inches thick) of low-angle cross-laminated sandstone at the base and horizontal, regular, continuous laminae at the top. This part also exhibits impressions of pieces of logs. Again, the top is unevenly truncated and overlain by non-conglomeratic sandstone containing planar and trough cross-strata. Unfortunately, only about 20 feet of the third channel phase are exposed, the top 20 to 22 feet being covered.

Above the third channel phase are 6 to 10 feet of friable carbonaceous siltstone and fine sandstone. These deposits also contain wood fragments and coal seams up to 1/2 inch thick and some thinly-laminated, papery black shales. Lamination is generally irregular. A small channel is present within the interval, the base of which is filled with coaly shale material. These deposits probably represent a marine swamp or salt marsh environment.

The top 50 feet of Dakota are marine. The bottom 15 feet of this contain beach structures, grading from backshore beach at the base to foreshore beach at the top and, finally, merging with surf zone deposits. The sands are medium grained and, in places, granular. The base contains wedge-shaped and lens-shaped sets of thinly and regularly laminated and cross-laminated sandstone, and some small-scale channel or cut and fill structures, a foot or so thick, characterized by trough cross-lamination. This grades upward into the thin, regular, horizontal lamination
Figure 10: Wolcott Locality

a: Surf zone low-angle cross-strata. Note continuous, irregular sets, about 1 foot thick.

b: Wedge-shaped sets of thinly laminated beach deposits.

c: Thin-bedded, regular, and parallel floodplain strata. Base of overlying channel shown in upper left corner.

d: Trough cross stratification in channel sandstone. Compare with figure 4.
Figure 10. Wolcott
of foreshore beach deposits. Both backshore and foreshore deposits con-
tain charcoal fragments, but the sands are otherwise clean. The presumed
beach structures are shown in figure 10b).

The foreshore beach laminae grade into thin sets (less than 1 foot)
of very thinly cross-bedded sands. The sets become thicker, reaching 1
to 1-1/2 feet upward in the interval. These deposits also contain charcoal
fragments. Angles are generally much lower than in the channel sands
(although angles up to 25° are recorded), the foreset laminae are curved,
and cross-stratified sets are bounded by wavy surfaces. These sands are
very likely surf zone and related shallow sub-littoral deposits.

The top of the Dakota grades into thinly interlaminated and cross-
laminated grey siltstone and black shale of the Mancos shale.

Dillon Locality

Approximately 150 feet of Dakota were studied at a locality about
1/2 mile north of Dillon. Primary features are largely obscured by iron
staining, silica cement, lichen growths and fracturing across the beds.
Nonetheless, a few significant features were found which tend to support
the previously suggested hypothesis of a transgressive sequence, grading
from fluvial beds at the base, through lagoonal and beach deposits, to
surf zone and shallow sub-littoral deposits at the top.

A 45-foot sand near the base contains generally lens-shaped and
irregular sets of beds. From a short distance, a thick, structureless
lens of material may be seen in the middle and upper part, possibly a
channel fill. Its lens shape and basal Dakota position support this
origin.

The next highest 50-foot interval is mostly carbonaceous siltstone
and sandstone, both dark grey to light grey, and a small percentage of
black shale. Coalified wood fragments are common in the lower half. Sandstones occur in beds from about 1.3 to 6 feet thick. However, no internal stratification or other structures were seen in any of the interval. It is possible that they are floodplain, swamp or marsh, or lagoonal deposits. They may be any or all of these.

A 19-foot sandstone which overlies the highly carbonaceous interval contains structures suggestive of beach deposits. Thin lamination is present in places. Thick and thin sets of cross-laminae and some irregular bedding are also present. Sets are lens-shaped. The thin lamination represents possible foreshore or backshore beach environments. The thicker sets of cross-lamination near the base suggest a possible backshore beach origin. Thin sets of cross-laminae and irregular beds may be either backshore or lower foreshore beach features.

Above the proposed beach is an 18-foot, covered to poorly-exposed interval. It appears to contain sandstone in the lower half (probably a continuation of the underlying sandstone) and very dark grey carbonaceous siltstone and black shale in the upper half. This description is based on float.

At the top of the section is a 15-to 20-foot, slabby, cross-laminated sandstone. Cross-laminae are of low (10° to 20°) dip and occur in sets 1.5 to 2.0 feet thick, which are continuous along the outcrop. This may be a surf zone deposit. The top sandstone forms a tabular ledge typical of the upper Dakota over most of the study area.

Rocky Point Section

Approximately 160 feet of well-exposed Dakota were measured in a road cut (formerly a railroad cut of the now abandoned Colorado and Southern Railroad) about 1-1/2 miles southeast of Breckenridge. Much of the outcrop is affected by fracturing and small faults which tend to
obscure primary features, especially in the lower half. Several significant features are present in the upper half, and a few manage to show through the tectonically affected lower half.

The lower 100 feet are predominantly sandstone, from fine to coarse and pebbly. Much of it is in thick (20 to 25 feet) units with thinner units of siltstone and fine sandstone in between. Eroded tops overlain by channel fill are common. In one sand, the base of the channel fill contains pebbles of an underlying clay bed. Carbonaceous material is common throughout, and some units, particularly siltstones and shales, are dark grey or black. Some coaly clay material is present in one unit. Where cross-bedding can be seen, the dip is about 25°, and bedding sets are generally wedge-or lens-shaped. A channel phase is present near the base, grading from cross-bedded, coarse, conglomeratic sandstone at the base to evenly and thinly bedded sandstone and siltstone at the top. This probably represents a change from channel to floodplain conditions. An 11-foot sandstone, which is the basal unit of the entire section below the channel, is evenly and thinly bedded and may represent the floodplain stage of a channel phase begun in the upper Morrison. All of this evidence points to a fluvial origin for the lower 100 feet.

The fluvial deposits are overlain by approximately 15 feet of dark grey carbonaceous sediments. Where stratification can be seen, it is thin-bedded and sometimes irregular. These deposits may well be near-shore floodplain or inter-fluvial swamp deposits.

At the top of the section are 46 feet of carbonaceous sandstone, siltstone, and black shale. The 21 feet at the base contain thinly cross-laminated fine sandstone and siltstone interbedded with thinly and irregularly laminated black shale. The ratio of sandstone: shale
grades from about 1:2 at the base to about 2:1 at the top. The cross-
lamination is characteristic of a fluvial environment and is nearly
identical to that found in modern tidal flat channels. The gradation
in the sandstone: shale ratio could represent a change from high to low
tidal flat conditions, which is a change from lower to higher current
velocities.

These deposits are overlain by 14 feet of cross-bedded sandstone.
Planar cross-strata are inclined about 25°, and trough cross-stratifica-
tion is observed near the top. Interference ripples are present near
the base. This is another fluvial unit and is no doubt a more turbulent
continuation of the tidal channel environment.

The top 10 feet contain thinly and irregularly bedded, carbonaceous,
fine to coarse sandstone, shale pebble conglomerate, and black shale.
Beds are laterally continuous up to 100 feet, which is the limit of the
outcrop. The fine sandstones are cross-laminated and irregularly inter-
bedded with black shale. Most material coarser than medium sandstone
contains quartz granules and flat pebbles of black shale. Most of the
latter are small, but some are of cobble size (see figure 11d). Large
current ripples, with an 8-to 12-inch wavelength, are present at the top
in what was originally a black mud and is now a black shale. In places
the beds are disturbed by thin, tubular burrowing structures. Features
in the top 10 feet indicate that the material accumulated on a tidal flat,
probably between channels, as the thin continuous irregular bedding
suggests.

No higher deposits were seen, either because of non-deposition or
faulting. A fault which lies at a small angle to the dip of the beds
cuts through the top of the Dakota, and may well explain the absence of
Figure 11: Rocky Point Locality

a: Thin, continuous beds of tidal flat deposits.
b: Sub-parallel current ripples on bedding surface of tidal flat shale.
c: Organism burrows on bedding surface of tidal flat shale.
d: Mold of 6" shale pebble in tidal flat shale. Scale graduated in tenths of a foot.
Figure II. Rocky Point
beds above the tidal flats deposit.

Alameda Parkway Locality

Several exposures in the northern Front Range Foothills were examined with the aid of U.S.G.S. Oil and Gas Investigation Chart 00-60 (Waage, 1959a). The southernmost of these is the section at Alameda Parkway, supplemented by some exposures at Morrison.

The basal 55 feet of Dakota in the Alameda Parkway roadcut contain three sandstones, each 10 to 15 feet thick, separated by two siltstone-shale units 7 and 10 feet thick. The sandstones exhibit planar and trough cross-stratification. Each type occurs in both thin, irregular sets (a few inches) and in slightly thicker sets (up to 1 foot) which, for the planar type, are somewhat tabular. Cross-strata dips attain 25° to 30°. The siltstone-shale units have irregular, eroded tops. The lower one is a maroon-colored unit whose top 1 to 2 feet are yellowish, as if the maroon material had been bleached by weathering and subjected to subaerial erosion. These appear to represent channel cycles, similar to those observed at other localities, except that the material is finer grained. This part of the Dakota contains features indicative of a fluvial origin—channel, floodplain, and so forth. All but the top 10 feet of the basal 55 feet of the Dakota comprise the Lytle sandstone.

The succeeding 10 feet consist of lignitic, carbonaceous shaly siltstone with a medial sandstone. These features suggest a possible marsh or swamp deposit. The top is irregular, either because of erosion or differential compaction or both.

Overlying the lignitic deposits is a thick section of sandstone, siltstone, and black shale bearing features of tidal flat deposition. A 20-foot sand at the base has several types of stratification. The
Figure 12: Alameda Parkway Locality

a: Casts of dinosaur footprints on underside of sandstone bed at Morrison.

b: Small channel showing upstream-curved current ripples, bank of channel, and debris impressions on bank.

c: Parallel current ripples in probable tidal estuarine deposits.

d: Two types of symmetrical ripple marks in probable tidal estuarine deposits. Type on right has pointed crests, rounded troughs. Ripples are about 3 inches across.
Figure 12. Alameda Parkway
basal 2 feet are more or less structureless, and may be a marsh creek deposit which fills channels in the underlying lignitic siltstone. The structureless base is succeeded by about one foot of irregular, continuous, thin-bedded sandstone layers separated by shale. These are followed by several feet of tabular sets of very thinly cross-bedded sandstone. The foreset strata have low dips, about 10° to 15°, and they are slightly concave upward. The tabular layers are overlain by wedge-shaped sets of thin-bedded sandstone for one or two feet. At the top are 10 feet of irregular, continuous, thin-bedded sandstone. Other important features within this unit include rippled bedding surfaces (irregular beds of above), trails of organisms, and boring structures in laminated sand and black shale partings between thin-bedded sandstone layers. These primary features suggest a tidal flat origin, but some of the stratification and its sequence is somewhat puzzling. The cross-bedding indicates substantial current agitation, and the wedge-shaped units indicate either weak, persistent currents or beach conditions. Possibly this sand body was built by stream deposition into a lagoonal body with sufficient tidal range and/or wave action to produce a thin beach zone (wedge-shaped sets of thin-bedded sandstone) and extensive ripples. The cross-strata and wedge-shaped units may both be the products of stream deposition, or of weaker stream currents which have just entered a standing body of water.

The 20-foot sandstone just described, the 10 feet of marsh deposits, and the top 10-foot sandstone of the fluvial beds comprise the Plainview Sandstone member of the South Platte formation, as defined by Waage (1955).

Above the Plainview are about 50 feet of irregular, continuous,
very thin-bedded siltstone layers separated by thin laminae of black shale. Boring structures are abundant throughout but are most abundant in the basal 15 feet. Irregular bedding indicates ripple marks. The upper part is sandy and has thin sets of cross-lamination. From the base to the top of the 50 feet of section above the Plainview is a probably high to low tidal flat gradation.

The lower of two parts of the Kassler sandstone member overlies the tidal flat deposits. This 30-foot sandstone is cross-laminated and contains both trough and planar types. About 10 feet from the base is a small channel cut into sandstone and filled by shale-pebble conglomeratic sandstone. This strongly suggests proximity to a tidal flat. The unit most likely represents a channel environment somewhat nearer the tidal inlet than the underlying deposits.

Above the lower unit of the Kassler sandstone member is the lower unit of the Van Bibber shale member. The few feet of thin-bedded siltstone and black shale were probably deposited on a tidal flat on the lee side of a barrier island.

The upper unit of the Kassler occurs next and consists of 15 feet of predominantly even, continuous, and thinly laminated sets of tabular sandstone. This is a beach deposit which marks nearly the zenith of transgression within the Dakota at this locality.

The upper unit of the Van Bibber shale may record the beginning of a regression. Thirteen feet of thin, irregular, continuous beds of sandstone and siltstone interbedded with shale, are covered by ripple marks. Two types of symmetrical ripple marks are common: those with sharp, parallel, continuous crests separated by broad troughs, and those with rounded crests separated by sharp troughs (figure 12d).
Both are abundant on modern tidal flats.

The remaining 35 feet of Dakota show similar evidences of tidal effects and also exhibit several features of stream deposition. In addition to the symmetrical wave ripple marks, many bedding surfaces are covered by parallel type asymmetric current ripple marks (see figure 12c). Many of these are also marked by plant impressions and organism trails. One small channel in an excellent state of preservation is present. In it, parallel current ripples below low water line are refracted upstream at the edge of the channel, and abundant plant impressions occur above the low water line (see figure 12b). Asymmetric ripple marks identical to those on Galveston Island tidal flats are present. The sandstones in this interval are thinly cross-bedded in planar sets up to about 2 feet thick, very thinly trough cross-bedded up to 2 to 3 feet thick, and irregularly thin-bedded. The cross-bedding shows highly turbulent, swiftly moving currents. Siltstones and shales are very thinly and evenly bedded. A broad, shallow channel filled with very thin-bedded siltstone and shale is present in the upper part. Casts of dinosaur footprints are present in the top of the upper (unnamed) sandstone unit at Morrison (see figure 12a). This unit is the lithologic equivalent of the upper sandstone at Alameda Parkway. The intimate mixture of stream and tidal features suggests a tidal, sandy estuary, similar to those in southern England. A generally deltaic framework is indicated by deposits from the upper Plainview sand to the top. Over 150 feet of sediments were deposited in these shoreline environments.

Van Bibber Creek Locality

The Van Bibber shale member of the South Platte formation was examined at its type section. Thinly laminated clay shale (refractory),
siltstone and sandstone, both regularly and irregularly laminated, comprise the entire 50 feet of Van Bibber shale. The sandstone above it is cross-stratified. Sandstones in the upper half are regularly laminated. Sandstone and siltstone in the lower half are irregularly laminated, and clay shale regularly laminated. This may show a change from tidal flat (lower part) to beach environment (upper part) overlain by surf zone sediments (unnamed upper sandstone).

Plainview Locality

An excellent lower Dakota section is exposed in a railroad cut at Plainview, about two miles southwest of Eldorado Springs.

The 70-foot Lytle formation contains two prominent sandstones, each about 20 feet thick and each filling channels in underlying siltstones and silty shales which may be floodplain deposits. The basal channel fill is a red sandstone with no obvious bedding, probably because of the newness of the cut. Overlying the red sandstone is a maroon siltstone with a yellow, bleached, irregular, deeply eroded top, overlain by the upper, buff-colored channel fill. The upper channel fill shows a bi-convex, sand-bar-like feature near the base, which is covered by tabular layers of sandstone. The top of the formation consists of about 10 feet of thinly-bedded, friable sandstone and siltstone. The Lytle is a fluvial deposit.

The overlying Plainview sandstone is about 45 feet thick. Immediately over the Lytle are several feet of black shale with thin lenses of light grey siltstone. Burrows and trails of organisms are abundant. Twelve feet of sediments over the black shale consist of slabby, irregular sets of thin-bedded and very thin-bedded (McKee and Weir, 1957) siltstone and sandstone. Some casts of trails are present. A gradation
Figure 13: Plainview Locality

a: Thinly laminated beach deposits

b: Irregularly and thinly laminated backshore beach or tidal flat deposits.

c: Thinly and irregularly bedded siltstone and dark grey shale of tidal flat deposits.

d: Channel sandstone in silt or shale, with possible sand bar at base.
Figure 13. Plainview
from high tidal flat (lower part, black shale) to low tidal flat (upper sandy part) deposition is indicated. The sediments become coarser, and burrows and trails become less abundant upward.

The upper 25 feet of the Plainview is a sandstone with wedge-shaped to planar bedding sets. Internally, these sets are cross-laminated at a very low angle (less than 10°). Bedding surfaces between sets are covered by very low relief, symmetrical ripples. The unit appears to be a backshore beach deposit, bordering on a tidal flat.

Approximately 16 feet of sandstone above the Plainview has stratification similar to the Plainview, except that the material is nearly all thinly laminated in tabular sets, indicating that the material was probably deposited on an upper foreshore beach.

Some thin-bedded sandstone with abundant organic trails is present at the top of the exposure. Tidal flat deposition is suggested, but too little is exposed to draw any conclusion.

Spring Canyon Dam Locality

In the roadcut at Spring Canyon Dam near Ft. Collins about 312 feet of Dakota are exposed. A lower hogback 109 feet thick is separated from an upper hogback 133 feet thick by a 70-foot, grass-covered "saddle."

The lower hogback consists of the Lytle formation and the Plainview sandstone member of the South Platte formation. No formal names are applied to the remainder of the South Platte this far north.

The Lytle formation is entirely fluvial. More specifically, it is entirely channel fill. A lower 49-foot sandstone and conglomerate is separated from an upper 24-foot sandstone by about 2-1/2 feet of shale. The lower unit is a chert-pebble conglomerate in the basal 10 feet. Above this clay pebbles become an abundant constituent. Both units are charac-
terized mainly by trough cross-stratification, but planar cross-stratification is not uncommon. Bedding in the lower unit is obscured in places because of coarse grain size and poor sorting. Floodplain deposits may have been laid down and later eroded by migrating Dakota streams.

The bottom 19 feet of the Plainview consist of irregularly laminated to thin-bedded sandstone and siltstone with partings of shale. Ripple marks are present on bedding surfaces (but are recognized mainly in cross-section as irregular bedding), and organic bores are present. This part of the Plainview was probably deposited on a tidal flat.

The top 15 feet of the Plainview contain thin, regular, and continuous laminae, characteristic of beaches. Most of this interval is weathered into sharply defined tabular layers about one foot thick, but bedding in parts of the interval is slightly lenticular. Upper foreshore beach deposition is the probably origin for the upper Plainview.

The upper hogback contains some features not seen at previous localities. At the base, calcareous, irregular, laminated sandstone and black shale are interbedded. Above this is a zone about 15 to 25 feet thick containing limey concretions about one foot thick and a few feet across. These concretions contain abundant pelecypods (*Inoceramus comancheanus* Cragin), and have a one-inch layer of cone-in-cone structure at the base. The *Inoceramus comancheanus* fauna is generally regarded as indicative of a marine environment, but the writer knows of no study in the literature which would substantiate this ecologic interpretation. It seems possible that *Inoceramus comancheanus*, like some modern mollusks, could have been euryhaline. The fossil occurs in 4.9 feet of thinly-laminated black shale with relatively well-developed bedding. This zone is succeeded by 63 feet of black shaly siltstone and very fine sandstone with very poorly
Figure 14: Spring Canyon Dam Locality

a: Thinly laminated beach deposits.

b: Thinly and regularly laminated beach deposits overlying thin, irregular tidal flat deposits.

c: Thinly and irregularly bedded tidal flat deposits. Note rippled beds.

d: Trough and planar cross-stratification in channel sandstone.
Figure 14. Spring Canyon Dam
developed bedding. The top of this zone is about 15 feet of greenish grey sandstone which is very similar to sediments immediately below the Kassler sandstone member at both Alameda Parkway and Morrison. At Alameda Parkway the greenish material was part of a tidal flat sequence, and there is a good possibility that it had a similar origin at Spring Canyon dam site. In this case, the bulk of black shale and siltstone is probably part of a large lagoonal body. The greenish material may have been deposited on the lagoonal margin of a barrier island which is the environmental equivalent, at many places, of a tidal flat. The upper 20-to 25-foot sandstone would then record the second passage of the Dakota beach and surf over this area. Sublittoral marine sediments would occur in the covered interval.

If, however, the molluscan fauna indicates a marine environment, then the top sandstone is a regressive unit of shallow, sub-littoral sands. The paleogeography interpreted from these upper Dakota sediments depends, of course, on the correct identification of events recorded by the sediments. Unfortunately, dependable primary structure evidence is lacking for such a purpose. The outcrop is fresh enough that weathering has not had a chance to etch out stratification in the upper sandstone, which is one key to the problem.

A summary of features found in various Dakota environments interpreted by the writer is given on page 55.
Figure 15: Dakota Sections

a: Near Burns

b: Channel fill at East Rifle Creek locality.

c: Wolcott

d: Possible river cut-bank slump block, overlain by channel sandstone deposits. Southern Black Hills, South Dakota, Inyan Kara Group (Lakota).
<table>
<thead>
<tr>
<th>Stratification</th>
<th>Bedding Surface Features</th>
<th>Lithologic Features</th>
<th>Biota</th>
<th>Other Features</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thin bedded and structureless strata, regular and irregular.</td>
<td>Surfaces not exposed.</td>
<td>Black shale and siltstone. Iron sulphides and organic matter.</td>
<td>None observed</td>
<td>Irregular thickness and distribution</td>
</tr>
<tr>
<td>Thin, irregular beds, with possible root traces.</td>
<td>Surfaces not exposed.</td>
<td>Siltstone and iron oxides. Possible sandy creek channels.</td>
<td>Plants, mostly grasses.</td>
<td>Erratic distribution.</td>
</tr>
<tr>
<td>Tabular to irregular sets of low-angle cross-beds.</td>
<td>Surfaces not exposed.</td>
<td>Sandstone</td>
<td>Wood fragments</td>
<td>Widespread. Uniform thickness and character.</td>
</tr>
</tbody>
</table>

Table 2. Summary of significant features in Dakota rocks.
CONCLUSIONS

As a result of the present study it is concluded that sedimentary environments can be identified by the primary structures they contain, aided by other features such as gross lithology, organic content, and geometric configuration.

The chronological sequence of environments identified in the Dakota is: 1) fluvial, floodplain and other, unidentifiable, continental environments; 2) near shore continental and transitional (brackish) environments, including salt marsh, tidal flat, and lagoon; and 3) barrier island environments, including backshore and foreshore beach and shallow sub-littoral (surf zone) environments.

Fluvial deposits are characterized by trough and planar cross-stratification channel shape, and coarse grain size. Floodplain deposits are thinly and regularly laminated, and may be sand, silt, or shale. Marsh, tidal flat, and lagoonal deposits are thin-bedded, regularly and irregularly bedded, commonly contain abundant organic structures, especially burrows of organisms, and consist of interbedded, dark grey, carbonaceous sandstone, siltstone, and shale. Beach deposits most commonly consist of thinly and regularly laminated, wedge-shaped sets of strata, though they also contain some trough cross-bedding. Shallow, sub-littoral deposits contain low angle cross-laminae in wavy, continuous sets.

Deposits of the Dakota sandstone in the study area were laid down prior to and during the latter of two Early Cretaceous marine transgressions which affected the western interior of the United States. Fluvial and related continental deposits were being formed at the time of the first transgression and regression, which affected areas to the north and east of the study area.
REGIONAL SUMMARY

Summary of Environments in Study Area

It has been demonstrated in a preceding section that the Dakota sandstone is composed of a series of transgressive deposits. The ideal chronological sequence, not entirely present at any one locality studied, is: 1) channel and floodplain, 2) salt marsh or near-shore swamp, 3) tidal flat and/or lagoon, 4) beach, and 5) surf zone. Channel deposits are everywhere present and vary mainly in thickness. The marsh-tidal flat-lagoon is the most variable in character, and also varies considerably in thickness. The beach and surf deposits are the most uniform, both in character and thickness. They are absent only at Rocky Point and at Toponas.

Some ideas about the nature of Dakota streams may be gained from the materials and structures they contain. Sand, commonly granular or pebbly, is the most abundant channel sediment. The most common structure is high-angle cross-stratification in sets about 1 foot thick. The cross-stratification and abundance of coarse-grained sediment suggest two things. 1) Streams had high competencies. Hjulstrom's curves (Hjulstrom, 1955) indicate velocities from 0.5 to 200 cm/sec. for material in the sand-granule-pebble size range. The cross-strata support this hypothesis. 2) Streams were wide and flat and were probably braided. Data by Schumm (1960) indicate that streams low in silt-clay are relatively wide and shallow. Model stream studies (Friedkin, 1944) indicate that braided streams tend to form where streams cut into non-cohesive bank material. If, as Moberly (1960) suggests, the climate was periodically dry in the middle Rocky Mountain area, streams would have been seasonal. Because they usually transmit great quantities of water during a restricted period of time, seasonal streams are not uncommonly wide, flat, and sandy.
No indications were found of either 1) regressions caused by uplift, withdrawal of the sea, or delta-building, or 2) regional erosional disconformity between marine and continental deposits, as proposed by Waage (1953, 1955, 1959a, 1959b) for the Front Range foothills, south central Colorado, and the Black Hills. The longest hiatuses are probably those at the bases of channel phases. No large breaks occur between marine and continental rocks in the Dakota between East Rifle Creek and Rocky Point. Apparently there was continuous deposition from continental conditions straight through into marine conditions.

Comparison with Dakota of Adjacent Areas

Primary features and environmental sequences similar to those in the study area are present in the Dakota of other areas. However, it should be noted that, because of the interrupted transgressions of the Cretaceous sea, sequences are not exactly equivalent across the entire Rocky Mountain geosyncline (geologic history will be discussed more fully in a later section). In the present discussion similarities and differences will be pointed out for several selected areas. The reader is referred to the correlation chart, page 11.

South Park, Colorado: Descriptions of two sections measured by J. H. Johnson and H. W. Miller (Stark and others, 1949) indicate that the upper Dakota hogback on the western side of South Park may have been deposited on tidal flats. Thin, irregular beds are ripple marked, cross-bedded, and contain worm burrows and suggestions of mud cracks. The absence of beach or surf structures above the tidal flat may mean that the top beds at Rocky Point are also tidal flat, and that beach and surf sands are not faulted out. The lower Dakota contains features suggestive of channel sandstones and grades upward into thin-bedded floodplain sand-
stones. Limestone and mudstone pebbles are present near the base, as at New Castle.

Colorado Plateau: Carbonaceous deposits of the upper Dakota of the Colorado Plateau are near-shore continental (Young, 1960; Houser and Ekren, 1959). Worm burrows and trails, ripples, and cross-lamination are common features of probable tidal flat deposits, while lignites probably accumulated in swamps. The lower Dakota, or Cedar Mountain formation (Burro Canyon of Houser and Ekren, 1959), is a fluvial unit containing cross-bedded conglomeratic sandstone and mudstone which often contains limestone nodules. Sandstones contain mudstone pebbles and limestone pebbles.

South Central Colorado: Waage (1953) describes thin-bedded carbonaceous sandstone and shale in the upper Dakota of the Canon City embayment which are ripple marked and contain worm trails at the top and local coal beds up to 18 inches thick in the middle and base. The evidence seems to indicate tidal flat and swamp conditions. However, the upper Glencairn also contains several molluscan fossils which, in the equivalent Kiowa shale, are interpreted as marine. Possibly they are actually lagoonal or tidal flat organisms. The Lytle member of the Purgatoire is a channel sandstone deposit, as in the northern Front Range foothills.

Western Oklahoma and Central Kansas: The Cheyenne sandstone is equivalent to the Lytle and has features similar to it, such as channel-shaped base, conglomerate, and high-angle planar cross-stratification. Judging from descriptions by Schoff (1943), who notes marine fossils in the Cheyenne in Texas County, Oklahoma, the top may be marine or littoral, which would make it the counterpart of the Plainview sandstone member of the South Platte formation in the northern Front Range foothills. The
Kiowa shale, which overlies the Cheyenne sandstone, is a fossiliferous unit interpreted by most workers as marine. Iceblich and Tappan (1950), however, consider it to be brackish. The Omadi formation (formerly called Dakota), above the Kiowa, is a thin-bedded, coal-bearing unit. Thin bedding, interbedded sandstone, shale, and siltstone, and abundant carbonaceous matter suggest that the Omadi represents several near-shore environments. Planar and trough cross-stratification of a fluvial nature is also common and has been studied quantitatively by Franks and others (1959). They conclude "...that the currents that transported the Dakota sediments traveled mainly from northeast to southwest,..."

Northeastern Nebraska: The section here contains only the upper part of the Dakota formation. The lower exposed part contains conglomeratic sandstones with high-angle cross-beds and channel bases (Tester, 1929). The irregular, thin beds of the upper Dakota are ripple marked and contain mollusc shells, fish bones, gypsum, glauconite, dark carbonaceous sediments, mud cracks, cross-lamination, plant remains, lignite, and iron sulphides and oxides. All are indicative of a near-shore origin, mainly including lagoonal, marsh and swamp, tidal flat, beach, and surf zone.

Denver Basin: The "D", "J", and upper "M" sands (Fentress, 1955; Dakota equivalents) and intervening shales were deposited in near-shore continental and marine environments. Cores from two wells, one near Fort Morgan, Colorado (Fentress, 1955) and the other in northwestern Kansas (Merriam and others, 1959) show structures of tidal flats, such as burrows of organisms, thin and irregular lamination, shale pebbles, carbonaceous material, and cross lamination. Fish teeth and scales, shell fragments, glauconite, spores, brachiopods, and pelecypods are
present above the "M" sand in the Kansas core. No information was given concerning features below the upper part of the "M" sand. The features shown indicate that the upper "M" sand is the eastward extension of the Plainview member of the South Platte formation.

**Black Hills:** The shoreline origin of the Newcastle sandstone has been summarized by Skolnick (1958). Some of the features present are thin, irregular bedding, ripple marks, lignite, dinosaur bones, wood fragments, cross-lamination, and highly discontinuous nature of the sand bodies. Skolnick's figures 11, 12, and 14 show stratification and bedding surface features typical of tidal flats. His figure 13 shows thin, regular stratification suggestive of a beach environment.

The marine origin of the Skull Creek Shale is known from its marine foraminiferal content (Skolnick, 1958). It is black, thinly laminated, and contains cone-in-cone concretions, selenite crystals, and septarian nodules.

The Fall River sandstone contains numerous tidal flat features. Ripple marks, thin and irregular interbedded carbonaceous sediments, lignite, gypsum, and worm trails and burrows are present at most localities described by Waage (1959b).

The Lakota formation includes typically fluvial structures. Channel sandstones, rarely conglomeratic, all contain planar and trough cross-stratification. Petrified logs are present in places. At two localities in the southern Black Hills apparent river cut-bank slump blocks underlie channel sandstones (figure 15d). Anderson (1939) has described dinosaur tracks from near Rapid City, which support a subaerial origin. The channel-shaped base of the Lakota contains pebbles of the underlying white Jurassic Unkpapa sandstone.
Northern Bighorn Basin: In one of the most comprehensive studies of depositional environments in the Dakota or its equivalents, Moberly (1960) has described features of tidal flat origin in the Sykes Mountain formation, and of fluvial and lacustrine origin for the Cloverly formation. The Sykes Mountain contains thin-bedded carbonaceous sediments with organism burrows and cross-lamination. The Cloverly contains both structureless clay and conglomeratic channel sandstones. The latter are characterized by abundant high-angle planar and trough cross-stratification. The clays are of volcanic origin, and are interpreted as extensive lake deposits (Moberly, 1960).

Summary of Paleogeography

Cretaceous Seaways: Two marine invasions occurred in the Lower Cretaceous, the second larger one extending into the Upper Cretaceous (Waage, 1955). Their approximate positions are shown on figure 16. They lay in a trough extending roughly northwest-southeast (first) and north-south (second).

Source Areas: On the western side of the trough lay a volcanic mountain chain which extended to Alaska. Many Paleozoic and Mesozoic sedimentary formations were exposed off the flanks of these mountains. To the east lay the Canadian shield and Paleozoic lowlands of the eastern United States. Highland areas may have existed in the Ozark-Ouachita area of southern Missouri, northwestern Arkansas, and eastern Oklahoma. In some areas Cretaceous rocks rest directly upon basement (Precambrian) rocks, and these were probably subordinate, local areas within the trough. The Sioux uplift in eastern South Dakota (Reeside, 1944) and various ranges of the Ancestral Rockies (Haun, 1959) are areas of Dakota-Precambrian contacts.
Figure 16: Cretaceous Seaways

Source of Information for Stream Directions:
Wyoming-Moberly, 1960
South Dakota-Ryan, 1958
Kansas-Franks and others, 1959
Utah-Young, 1960
Figure 16. Cretaceous Seaways

- First Cretaceous seaway, represented by Kiowa, Glencairn, Skull Creek, & Thermopolis shales
- Second Cretaceous seaway, represented by Graneros, Benton, Mowry, & Mancos shales
- Approximate shoreline at end of Albion time
- Stream directions
Geographic Location: Various studies have located the positions of the wandering poles at various times in Earth history. There is good agreement between positions determined magnetically and positions determined from ancient wind directions, indicating approximate coincidence of magnetic and geographic poles, respectively (Opdyke and Runcorn, 1959). During the Cretaceous, the study area lay approximately 15° to 20° nearer the equator than it does at present. Such a location would have placed northwestern Colorado at about 20° north latitude, rather than its present 38° north latitude. That is a latitudinal position similar to that of the Yucatan Peninsula today.

Climate: Owing to its low latitude during the Cretaceous, northwestern Colorado must have enjoyed somewhat warmer temperatures than it does at present. The climate near shore was probably tropical and rainy. According to Moberly (1960), who studied apparent soil profiles in the Cloverly formation, the climate was periodically dry (savannah). Eaton (1960) suggest a warm, temperature climate. The climate probably graded inland to a more temperate type of climate as it does on the present western border of the Gulf of Mexico.

Summary of Pre-Benton Cretaceous Geologic History in the Western Interior of the United States

The earliest Dakota sediments were deposited in river channels, on flood plains, and probably in other, related continental environments such as lakes, abandoned meanders, and swamps. Late Jurassic sediments had been deposited under similar conditions. There is no evidence for a post-Morrison major disconformity, although an erosional interval, as indicated by channels and "basal conglomerates", is present at many localities. The fluvial deposits of the Lower Dakota and Lytle record
less a change in environments than they do a change in supply of sedimentary material in the source areas. Volcanism and tectonism were active in the mountain ranges to the west, as evidenced by thick gravel deposits and volcanics in southeastern Nevada, southern Arizona and New Mexico, and Utah, and by volcanic ash deposits in the Dakota equivalents (Moberly, 1960). Stream directions detected in various areas are shown on Figure 16.

As the initial invasion of the Cretaceous sea reached Colorado from the north, different types of sedimentary environments made their appearances. Salt marshes, coal swamps, lakes, lagoons, and tidal flats were common on the landward sides of beaches and barrier islands. In some areas, apparently, beaches were absent and marine deposits rest directly upon those of tidal flat origin. Beaches are absent at places along the present Texas Gulf Coast, and small tidal flats are the sole representatives of the intertidal zone, as shown in Gulf Coast Association of Geological Societies Field-Trip Guidebook for 1959.

The transgression of the sea was impeded in western Colorado by north-south trending mountain ranges of the Ancestral Rockies (Haun, 1959) and covered principally eastern Colorado and the North Park area in Colorado. The sea eventually extended into northeastern New Mexico, northern Texas, and western Oklahoma (see figure 16). Sediments of the Skull Creek, Glencairn, Kiowa, Thermopolis and lower South Platte were deposited.

Renewed activity in the source areas resulted in the deposition of near-shore sands over the marine black shales of the first sea invasion. Newcastle, Muddy, and upper South Platte sands were deposited in Colorado and to the north and east. In Kansas a period of erosion into the Kiowa shale may have preceded the deposition of Dakota sands (Franks and others, 1959).
Following this influx of clastics just described, a second advance of the sea began. It was during this episode that the near-shore sediments of the upper Dakota in the study area were deposited. Fluvial sandstones were being laid down during the first advance and the succeeding retreat. The ensuing transgression culminated in the Arctic-to-Gulf Cretaceous seaway which extended as far east as Minnesota and Iowa, and as far west as eastern and Northeastern Arizona (Pike, 1947), central Utah, eastern Idaho, and western Montana (Reeside, 1944).
APPENDIX

Description of Sections

1. East Rifle Creek Section; Sec. 3, T5S, R92W.

<table>
<thead>
<tr>
<th>Unit</th>
<th>Feet</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>11</td>
<td>Covered interval at top of hill.</td>
</tr>
<tr>
<td>2</td>
<td>11</td>
<td>Sandstone; fine, medium, and coarse-grained; conglomeratic layers; planar cross-bedding.</td>
</tr>
<tr>
<td>3</td>
<td>10</td>
<td>Sandstone (orthoquartzite); sparsely and finely carbonaceous; horizontal, even beds. (2') Shale; very dark grey; slightly silty; thinly and poorly laminated. (0.5') Sandstone; very fine-grained; light grey; some yellow iron staining; carbonaceous fragments. (0.4') Claystone; very light brownish-grey; soft. (0.3') Sandstone; very fine-grained; light grey; charcoal wood fragments. (1.7') Shale; very dark grey; silty; thinly and irregularly laminated; middle one foot contains white, very fine-grained sandstone lenses up to 5mm. thick, irregularly laminated, and a 6&quot; bed of thin sandstone lenses about 6&quot; from top. (3.1') Sandstone; very fine-grained; very light grey; hard; iron-stained in places. (2')</td>
</tr>
<tr>
<td>4</td>
<td>12</td>
<td>Siltstone or very fine grained sandstone; medium grey; carbonaceous matter both in layers and distributed evenly; 6&quot; lens of non-carbonaceous, very fine-grained sandstone near center.</td>
</tr>
<tr>
<td>5</td>
<td>32</td>
<td>Sandstone; medium-grained and conglomeratic; very light grey; coalified wood on high-angle cross-bedded surfaces in basal 3'; heavily iron-stained in places; iron oxide concentrated around some grains which may be chert. This unit consists of two sandstone bodies, the upper one filling a channel in the lower one.</td>
</tr>
<tr>
<td>6</td>
<td>0.5</td>
<td>Conglomerate; pebbles up to 15 mm.</td>
</tr>
<tr>
<td>7</td>
<td>28</td>
<td>Covered interval.</td>
</tr>
<tr>
<td>8</td>
<td>20</td>
<td>Sandstone; medium grained and conglomeratic; buff; trough and planar cross-bedding.</td>
</tr>
<tr>
<td>Unit</td>
<td>Feet</td>
<td>Description</td>
</tr>
<tr>
<td>------</td>
<td>------</td>
<td>-------------</td>
</tr>
<tr>
<td>9</td>
<td>38</td>
<td>Covered interval</td>
</tr>
<tr>
<td>10</td>
<td>3</td>
<td>Sandstone; medium-grained and conglomeratic; buff; pebbles mark traces of planar cross-beds; friable. Covered interval to base of hill.</td>
</tr>
</tbody>
</table>

2. Elk Creek Locality; Sec. 23, T5S, R91W.

The Dakota at this locality is a ridge of highly-weathered, poorly exposed conglomerate, fine-grained sandstone, and conglomeratic sandstone. Trough and planar cross-beds and rare irregular beds are exhibited. The measurement is an estimation based on rough tape measurement. Only about 80 to 100 feet are exposed on the dip slope. The entire Dakota above the part exposed is too poorly exposed to identify the lithology or the Mancos shale contact.

3. New Castle Locality; Sec. 5, T6S, R90W.

<table>
<thead>
<tr>
<th>Unit</th>
<th>Feet</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>30</td>
<td>Sandstone; fine to medium-grained; very light grey; very heavily iron-stained in places; scattered clay and chert pebbles; plant fragments 25 feet above base, some as impressions, some as charcoal; high-angle planar cross-beds.</td>
</tr>
<tr>
<td>2</td>
<td>30</td>
<td>Covered interval.</td>
</tr>
<tr>
<td>3</td>
<td>9</td>
<td>Sandstone; medium-grained; light tan; lenses of pebbles (pebbles up to 4 mm); high angle trough and planar cross-bedding; unit hard and orthoquartzitic.</td>
</tr>
<tr>
<td>4</td>
<td>3</td>
<td>Conglomerate; lens-shaped unit; bedding not apparent; predominantly chert pebbles 2 to 10 mm.; a 1&quot; lens of medium-grained sandstone 2.2' below top.</td>
</tr>
<tr>
<td>5</td>
<td>9</td>
<td>Conglomerate, medium-grained and conglomeratic sandstone; very light tan; high-angle planar cross-beds; contains pebbles of underlying claystone.</td>
</tr>
<tr>
<td>6</td>
<td>4.2</td>
<td>Claystone; light to medium grey. (0.7); Siltstone; light grey. (0.3')</td>
</tr>
<tr>
<td>Unit</td>
<td>Feet</td>
<td>Description</td>
</tr>
<tr>
<td>------</td>
<td>------</td>
<td>-------------</td>
</tr>
<tr>
<td>6</td>
<td></td>
<td>Sandstone; fine-grained; very light grey; high-angle planar cross-beds; irregular beds; selenite crystals in joints; fractured; iron-stained; becomes thin-bedded laterally. (2') sandstone; fine-grained; very light grey; irregularly bedded; cuts into underlying unit; iron-stained. (1.2')</td>
</tr>
<tr>
<td>7</td>
<td>5</td>
<td>Siltstone; maroon; top 3' light grey; contact between maroon and light grey irregular; Morrison formation (?).</td>
</tr>
</tbody>
</table>

4. Derby Meas Locality; Sec. 21, T2S, R85W.

<table>
<thead>
<tr>
<th>Unit</th>
<th>Feet</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>16</td>
<td>20</td>
<td>Sandstone; medium to coarse-grained, pebbly and granular; light tan; weathering of textural differences shows cross-bedding of units less than 1' thick; angle of cross-beds about 25°; near base, beds more parallel and thin-bedded; Morrison-Dakota contact covered, but Morrison formation can be seen near the exposed base of the Dakota.</td>
</tr>
<tr>
<td>15</td>
<td>15</td>
<td>Shale; medium to dark grey; soft and clayey with blocky fracture on surface; structureless; fine sandstone near center; becomes siltstone near top. (5' to 8') Sandstone; medium grained; buff; iron-stained; thin-bedded, irregular base, faint cross-beds in upper part, top thinlly laminated. (2') Interbedded siltstone and fine grained sandstone; buff to reddish sand and dark grey siltstone; siltstone carbonaceous; thin-bedded; top 2' a dark grey carbonaceous siltstone. (8')</td>
</tr>
<tr>
<td>14</td>
<td>4</td>
<td>Sandstone; fine grained; buff; base irregular; high angle trough cross-stratification.</td>
</tr>
<tr>
<td>13</td>
<td>3</td>
<td>Siltstone; light to medium grey; soft.</td>
</tr>
<tr>
<td>12</td>
<td>6</td>
<td>Sandstone; fine grained; buff; low angle trough and planar cross-strata; unit has flat top and convex downward base; pinches out within 20'.</td>
</tr>
<tr>
<td>11</td>
<td>2</td>
<td>Siltstone; medium grey; charcoal fragments.</td>
</tr>
<tr>
<td>10</td>
<td>3</td>
<td>Sandstone; similar to unit 5; thin-bedded with trough cross-stratification; pinches out within 20'.</td>
</tr>
<tr>
<td>Unit</td>
<td>Feet</td>
<td>Description</td>
</tr>
<tr>
<td>------</td>
<td>------</td>
<td>-------------</td>
</tr>
<tr>
<td>9</td>
<td>3</td>
<td>Siltstone; orange to grey; soft and iron-stained at base, becomes grey 1' up; top 1' is a very dark grey shale containing plant fragments.</td>
</tr>
<tr>
<td>8</td>
<td>6</td>
<td>Sandstone; fine grained; buff; thin, irregular beds; base slightly irregular; basal 1' is soft, iron-stained.</td>
</tr>
<tr>
<td>7</td>
<td>2</td>
<td>Siltstone; very dark grey at base to grey and buff at top; no structures observed.</td>
</tr>
<tr>
<td>6</td>
<td>6</td>
<td>Sandstone; fine grained; medium grey; low-angle lens-shaped unit; planar cross-beds; thins to 3' within 10'.</td>
</tr>
<tr>
<td>5</td>
<td>1.4</td>
<td>Siltstone; medium grey below, very dark grey above; dark unit poorly laminated, soft, and contains some iron staining.</td>
</tr>
<tr>
<td>4</td>
<td>3</td>
<td>Sandstone; fine to medium grained; buff; basal beds are horizontal, unit becomes cross-bedded and coarser 1' up; cross-beds dip 22°.</td>
</tr>
<tr>
<td>3</td>
<td>1.8</td>
<td>Siltstone; medium and dark grey laminae; top 6&quot; is irregularly bedded sandstone containing wood fragments.</td>
</tr>
<tr>
<td>2</td>
<td>13</td>
<td>Sandstone; fine to medium grained; buff; thin, parallel laminae, slightly convex upward; sets of strata are 50 to 75 feet long, lenticular; three 1' zones of siltstone at 4', 6.5', and 8.5' above base.</td>
</tr>
<tr>
<td>1</td>
<td>25</td>
<td>Sandstone; fine grained; buff; base irregular; cross-bedded near base, and faintly cross-bedded above base; sets irregular at base, but are more regular above.</td>
</tr>
</tbody>
</table>

5. Big Alkali Creek Locality; Sec. 17, T28, R84W.

<table>
<thead>
<tr>
<th>Unit</th>
<th>Feet</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>22</td>
<td>Sandstone; fine grained; buff, base not exposed; but Morrison sediments are not far below the lowest exposed Dakota sandstone; beds not apparent; sets irregular. (12') Sandstone; medium grained; medium light grey; soft; contains spheroidal masses of hard sand in an iron-stained sand groundmass; charcoal at the top. (5') Sandstone; fine to medium grained, granular; light grey; base irregular; top thinly and irregularly laminated, contains carbonaceous matter; fine cross-laminae present throughout. (3') Siltstone; light grey; thinly laminated. (2')</td>
</tr>
<tr>
<td>Unit</td>
<td>Feet</td>
<td>Description</td>
</tr>
<tr>
<td>------</td>
<td>------</td>
<td>---------------------------------------------------------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>6</td>
<td>25</td>
<td>Sandstone; medium to coarse grained, pebbly; light tan; pebbles concentrated along bedding surfaces; planar cross-beds dip about 25°; sets are wedge or lens shaped; very dark grey, carbonaceous siltstone near top.</td>
</tr>
<tr>
<td>5</td>
<td>6</td>
<td>Siltstone; light grey.</td>
</tr>
<tr>
<td>4</td>
<td>20</td>
<td>Sandstone; fine to medium grained; buff; consists of superimposed plano-convex downward sandstone units containing tabular and wedge shaped sets.</td>
</tr>
<tr>
<td>3</td>
<td>10</td>
<td>Interbedded fine to medium grained sandstone, siltstone, and very dark grey shale; contains burrows of organisms throughout.</td>
</tr>
<tr>
<td>2</td>
<td>12</td>
<td>Sandstone; fine grained; buff; thin, parallel laminae in sets which are long and lenticular, and which cut into adjacent and underlying sets.</td>
</tr>
<tr>
<td>1</td>
<td>25</td>
<td>Sandstone; fine grained; buff; unit contains tabular sets which, at least in the basal part, are cross-bedded at low angles.</td>
</tr>
</tbody>
</table>

Toponas Locality; Sec. 24, T1N, R84W.

<table>
<thead>
<tr>
<th>Unit</th>
<th>Feet</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>12</td>
<td>18</td>
<td>Sandstone; fine to medium grained, pebbly; buff; highly fractured; base covered.</td>
</tr>
<tr>
<td>11</td>
<td>17</td>
<td>Sandstone; very fine to medium grained; consists of alternating soft grey beds and hard buff beds.</td>
</tr>
<tr>
<td>10</td>
<td>7.5</td>
<td>Siltstone; greenish grey; blocky fracture.</td>
</tr>
<tr>
<td>9</td>
<td>6</td>
<td>Sandstone; fine grained; base conglomeratic; thin laminae containing carbonaceous material near top.</td>
</tr>
<tr>
<td>8</td>
<td>1</td>
<td>Siltstone; very dark grey; carbonaceous; contains dark carbonaceous clay.</td>
</tr>
<tr>
<td>7</td>
<td>15</td>
<td>Sandstone, fine to medium grained, granular, pebbly; carbonaceous; highly fractured; conglomeratic near base only.</td>
</tr>
<tr>
<td>6</td>
<td>12</td>
<td>Interbedded fine grained sandstone, siltstone, and very dark grey shale; carbonaceous matter common throughout; thinly and irregularly laminated; cross lamination rarely observed.</td>
</tr>
<tr>
<td>Unit</td>
<td>Feet</td>
<td>Description</td>
</tr>
<tr>
<td>------</td>
<td>------</td>
<td>-------------</td>
</tr>
<tr>
<td>5</td>
<td>1.2</td>
<td>Shale, black; thinly and irregularly laminated.</td>
</tr>
<tr>
<td>4</td>
<td>23</td>
<td>Sandstone; fine grained; greenish grey; irregular, thin beds containing burrows of organisms.</td>
</tr>
<tr>
<td>3</td>
<td>1</td>
<td>Shale; black.</td>
</tr>
<tr>
<td>2</td>
<td>8</td>
<td>Sandstone; fine grained; greenish grey; thin-bedded at top, grades into overlying unit.</td>
</tr>
<tr>
<td>1</td>
<td>11</td>
<td>Interbedded fine grained sandstone, clay, and black shale; thinly laminated and thinly cross-laminated sandstone.</td>
</tr>
</tbody>
</table>

Wolcott Locality; Sec. 15, T4S, R33W.

<table>
<thead>
<tr>
<th>Unit</th>
<th>Feet</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>35</td>
<td>Sandstone; very fine grained; light tan; tabular unit consisting of irregular sets of low angle cross-beds; sets are about 1' thick and are relatively continuous laterally; wood fragments.</td>
</tr>
<tr>
<td>2</td>
<td>15</td>
<td>Sandstone; medium grained; light tan; intersecting and overlapping wedge shaped sets of thinly laminated sandstone near base; upward, beds mostly thinly and evenly laminated; wood fragments and granules common.</td>
</tr>
<tr>
<td>3</td>
<td>8</td>
<td>Interbedded fine grained sandstone and grey siltstone; carbonaceous matter abundant; wood stems are preserved on some bedding surfaces; vitreous coal seams up to 1/2&quot; near top; beds irregular and discontinuous; a siltstone near the base fills a channel in the underlying material, which is covered just below the base of the channel; the base of the unit is a black fissile shale.</td>
</tr>
<tr>
<td>4</td>
<td>22</td>
<td>Covered interval.</td>
</tr>
<tr>
<td>5</td>
<td>35</td>
<td>Sandstone; very fine grained; buff; top half contains high angle trough and planar cross-stratification and impressions of logs; lower half contains thin, regular, continuous laminae which gradually merge with thin sets of cross-laminated sandstone toward the base of the unit; top half channels into lower half.</td>
</tr>
<tr>
<td>6</td>
<td>35</td>
<td>Covered interval.</td>
</tr>
</tbody>
</table>
| 7    | 55   | Sandstone; fine grained, granular, and pebbly; top 15' are conglomeratic and contain high angle trough and planar cross-stratification; the base of the top 15'
<table>
<thead>
<tr>
<th>Unit</th>
<th>Feet</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>(7)</td>
<td></td>
<td>channels into the underlyng sandstone, which is thinly and regularly laminated; thin laminae below channel grade downward into trough cross-laminae, and sets of trough and planar cross-strata are predominant in the basal 20'.</td>
</tr>
<tr>
<td>8</td>
<td>10</td>
<td>Conglomerate; tan; pebbles up to 1&quot;; contains thin lenses of cross-bedded sandstone.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Morrison formation.</td>
</tr>
</tbody>
</table>

**Dillon Locality; Sec. 18, T5S, R77W.**

<table>
<thead>
<tr>
<th>Unit</th>
<th>Feet</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>15</td>
<td>Sandstone; very light grey; orthoquartzite; tabular beds about 1.5' to 2' thick, internally cross-bedded at low angles; top is thinbedded as it grades into Mancos shale.</td>
</tr>
<tr>
<td>2</td>
<td>5</td>
<td>Poorly exposed and covered interval; float indicates interbedded grey siltstone and very dark grey carbonaceous shale.</td>
</tr>
<tr>
<td>3</td>
<td>20</td>
<td>Sandstone; fine grained; light grey; faint low angle cross-beds in irregular and discontinuous sets; carbonaceous material.</td>
</tr>
<tr>
<td>4</td>
<td>20</td>
<td>Poorly exposed; float and some rock in place indicate carbonaceous siltstone, fine grained sandstone, and black shale.</td>
</tr>
<tr>
<td>5</td>
<td>6</td>
<td>Sandstone, light grey; slightly carbonaceous.</td>
</tr>
<tr>
<td>6</td>
<td>4.5</td>
<td>Siltstone; light to medium grey; carbonaceous; fractured.</td>
</tr>
<tr>
<td>7</td>
<td>4</td>
<td>Sandstone; fine grained; dark grey; carbonaceous; wood fragments; orthoquartzite.</td>
</tr>
<tr>
<td>8</td>
<td>2.6</td>
<td>Siltstone; dark grey; carbonaceous; coaly wood fragments.</td>
</tr>
<tr>
<td>9</td>
<td>1.3</td>
<td>Sandstone; fine grained; dark grey; highly carbonaceous; wood fragments; orthoquartzite.</td>
</tr>
<tr>
<td>10</td>
<td>12</td>
<td>Siltstone; dark grey; coaly wood fragments; highly fractured.</td>
</tr>
<tr>
<td>Unit</td>
<td>Feet</td>
<td>Description</td>
</tr>
<tr>
<td>------</td>
<td>------</td>
<td>-------------</td>
</tr>
<tr>
<td>11</td>
<td>45</td>
<td>Sandstone; fine to medium grained, granular; light grey; beds lenticular and discontinuous; granular zone about 10' above base; contains some thin mudstones; unit as a whole appears lenticular from a distance, with a convex-downward base.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Talus slope.</td>
</tr>
</tbody>
</table>

Rocky Point Locality; Sec. 8, T7S, R77W.

<table>
<thead>
<tr>
<th>Unit</th>
<th>Feet</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>10</td>
<td>Sandstone; medium to coarse grained; grey; mixture of quartz sand and shale pebbles; highly carbonaceous; beds irregular and discontinuous; burrows of organisms present on some bedding surfaces; shale pebbles up to 6&quot;; though most are 1&quot; or less; sub-parallel current ripples with wavelength of about 1' observed on one bedding surface.</td>
</tr>
<tr>
<td>2</td>
<td>14</td>
<td>Sandstone; fine grained; light grey; orthoquartzite; planar cross-beds inclined 25° in various directions; interbedded with shale in center; interference ripples at base.</td>
</tr>
<tr>
<td>3</td>
<td>21</td>
<td>Interbedded very fine grained sandstone, siltstone, and shale; grey and dark grey; thin beds of cross-laminated sandstone and siltstone interbedded with black shale; at base shale comprises about 2/3 of the unit, grading up to 1/2 in the center and to 1/3 at the top; at the top the sandstone beds become thicker than at the base; beds continuous within the outcrop (about 30').</td>
</tr>
<tr>
<td>4</td>
<td>3</td>
<td>Siltstone; very dark grey; carbonaceous; thin-beded.</td>
</tr>
<tr>
<td>5</td>
<td>5</td>
<td>Sandstone; fine grained; medium dark grey; grades to siltstone in center and dark grey shale at top; irregularly bedded; light yellow clay at top.</td>
</tr>
<tr>
<td>6</td>
<td>7.5</td>
<td>Sandstone; fine grained; light to dark grey; carbonaceous streaks; thin-beded at base; interbedded with dark grey carbonaceous siltstone.</td>
</tr>
<tr>
<td>7</td>
<td>18</td>
<td>Sandstone, medium to coarse grained; light grey; appears laminated near base; interbedded with black shale in places; planar cross-beds.</td>
</tr>
</tbody>
</table>
| 8    | 2.3  | Sandstone; very fine grained; carbonaceous; thinly laminated.
<table>
<thead>
<tr>
<th>Unit</th>
<th>Feet</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>9</td>
<td>26</td>
<td>Sandstone; buff; carbonaceous; irregular base; faint ripples on one bedding surface too high to reach.</td>
</tr>
<tr>
<td>10</td>
<td>3.5</td>
<td>Siltstone; very dark grey; thin-bedded caly clay at top; contains some very thin beds of fine grained sandstone.</td>
</tr>
<tr>
<td>11</td>
<td>2.3</td>
<td>Sandstone; dark grey; carbonaceous; contains pebbles of underlying clay.</td>
</tr>
<tr>
<td>12</td>
<td>1.5</td>
<td>Siltstone; very dark grey; grades upward to medium grey claystone.</td>
</tr>
<tr>
<td>13</td>
<td>5.5</td>
<td>Sandstone; fine grained; medium to light grey; carbonaceous streaks; trough cross-beds; base irregular.</td>
</tr>
<tr>
<td>14</td>
<td>3.5</td>
<td>Interbedded fine grained sandstone, siltstone, and shale; light grey to very dark grey.</td>
</tr>
<tr>
<td>15</td>
<td>11.5</td>
<td>Sandstone; very fine grained; medium grey; grades upward through grey siltstone in center to black shale at top.</td>
</tr>
<tr>
<td>16</td>
<td>10</td>
<td>Sandstone; coarse grained; orthoquartzite; granules and pebbles up to 1-1/4&quot;; pebbles on planar cross-bedded surfaces inclined about 25° in sets about 1' thick; channels into underlying unit; becomes finer grained at top.</td>
</tr>
<tr>
<td>17</td>
<td>11</td>
<td>Sandstone; fine to medium grained; white; thinly and evenly laminated, as shown by slight color changes.</td>
</tr>
</tbody>
</table>

Covered interval

All units in measured sections are numbered consecutively from top to base.
REFERENCES


Haentschel, Walter, 1935, Fossile schragschichtungs-bogen, "flyesswulste" and rieselmarken aus dem Nama-Transvaal System (Sudafrika) und ihre Rezente gegenstucke, Senckenbergiana, Bd. 17, pp. 167-177

---------, 1936, Die schchtungs-formen Rezenter flachmeer-ablagerungen im Jade-gebiet, Senckenbergiana, Bd. 18, pp. 316-356

---------, 1955, Tidal flat deposits, in Recent Marine Sediments, A.A.P.G., Tulsa, Okla., (pp. 195-206)


Hayden, F. V., 1876, Remarks on the Cretaceous rocks of the West known as the Dakota Group, American Jour. Sci., ser. 2, v. 43, pp. 171-179


Hjulstrom, Filip, 1955, Transportation of detritus by moving water, in Recent Marine Sediments, A.A.P.G., Tulsa, Oklahoma (pp. 5-31)


Johnston, W. A., 1922, The character of the stratification of the sediments in the Recent delta of Fraser River, British Columbia, Canada, Jour. Geol., v. 30, no. 2, pp. 115-129


King, Clarence, 1876, U. S. Geological Exploration of the 40th Parallel, Atlas, Washington, D. C.


Lovering, T. S., 1934, Geology and ore deposits of the Breckenridge mining district, U.S.G.S. Prof. Paper 176

Luders, K., 1930, Entstehung der gezeitenschichtung auf den Watten in Jadebusen, Senckenbergiana, Bd. 12, pp. 229-254


McKee, E. D., 1939, Some types of bedding in the Colorado River delta, Jour. Geol., v. 47, no. 1, pp. 64-81

---------, 1957a, Flume experiments on the production of stratification and cross-stratification, Jour. Sed. Pet., v. 27, no. 2, pp. 129-134

---------, 1957b, Primary structures in some Recent sediments, Bull. A.A.P.G., v. 41, no. 8, pp. 1704-1747


Meek, F. B., and Hayden, F. V., 1861, Descriptions of new Lower Silurian, (Primordial), Jurassic, Cretaceous, and Tertiary Fossils, collected in Nebraska,***; with some remarks on the rocks from which they were obtained, Proc. Acad. Nat. Sci. Phila., pp 415-447


Opdyke, N. D., and Runcorn, Keith, 1959 Paleomagnetism and ancient wind directions, Endeavor, v. 18 no. 69, pp. 26-34

Plummer, Norman, and Romary, J. F., 1942, Stratigraphy of the Pre-Greenhorn Cretaceous Beds of Kansas, State Geol. Survey of Kansas., Bull. 41, part 9, pp. 313-348


Priddy, R. R., and Smith, B. L., 1960, Recent sedimentation on Horn Island, Mississippi, G.C.A.G.S. Guidebook, pp. 4-8


---------, 1944, Maps showing thickness and general character of the Cretaceous deposits in the Western Interior of the United States, U.S. G.S. Oil and Gas Inv. Prelim. Map 10


Schwarz, Albert, 1933, Meerische gesteinsbildung. I, Senckenbergiana, Bd. 15, pp. 69-160


---------, and Moore, D. G., 1960, Bays of central Texas coast, in Recent Sediments, Northwest Gulf of Mexico, A.A.P.G., Tulsa, Okla. (pp. 117-152)


Thompson, W. O., 1937, Original structures of beaches, bars, and dunes, Bull. G.S.A., v. 48, no. 6, pp. 723-752


Trusheim, F., 1929, Rippeln in schlick, Natur und Museum, Bd. 59, pp. 72-79

Van Straaten, L. M. J. U., 1954a, Sedimentology of Recent tidal flat deposits and the Psammites du Condroz (Devonian), Geologie en Mijnbouw, nieuwe ser., 16e Jargang, nummer 2, pp. 25-47

---------, 1954b, Composition and structure of Recent marine sediments in the Netherlands, Leidsche Geol. Meded., v. 19


---------, 1955, Dakota Group in northern Front Range foothills, Colorado, U.S.G.S Prof. Paper 274-b

---------, 1958, Regional aspects of Inyan Kara stratigraphy, W.G.A. Guidebook, pp. 71-76

---------, 1959a, Stratigraphy of the Dakota Group along the northern Front Range foothills, Colorado, U.S.G.S. Oil and Gas Invest. Prelim. Chart OC-60

