BRIGHAM

YOUNG

UNIVERSITY

GEOLOGY STUDIES

Volume 21, Part 3 — October 1974

CONTENTS

Brigham Young University Geology Studies

Volume 21, Part 3 — October 1974

Contents

A publication of the
Department of Geology
Brigham Young University
Provo, Utah 84602

Brigham Young University Geology Studies is published semiannually by the department. *Geology Studies* consists of graduate-student and staff research in the department and occasional papers from other contributors. *Studies for Students* supplements the regular issues and is intended as a series of short papers of general interest which may serve as guides to the geology of Utah for beginning students and laymen.

Distributed October 31, 1974

Price $5.00

(Subject to change without notice)

Sedimentary Structure and Depositional Environment of Paleochannels in the Jurassic Morrison Formation Near Green River, Utah*

MICHAEL E. DERR
Chevron Oil Company, Denver, Colorado

ABSTRACT.—The Morrison Formation near Green River, Utah, contains excellent examples of exhumed fluvial-channel segments that provide a unique opportunity to map their geometries and the sequences of associated sedimentary structures in both horizontal and vertical planes and to compare these features with those defined in theoretical and observational models of modern fluvial sedimentation. Two channels are part of a meander (point-bar) complex, while a third segment is preserved as a result of avulsion, a permanent change in stream course. The general vertical sequence of the point-bar channels is, from upper surface to base: (1) cross-bedded sandstone, (2) horizontally stratified sandstone, (3) cross-bedded sandstone, and (4) cross-bedded conglomerate. The smallest-scale cross-bedding and smallest grain sizes are present near the channel surface, and largest near the channel bases. The sequence compares with those described by Visher (1965), and Harms and Fahnestock (1965) for point-bar sequences. The avulsion channel has an irregular vertical sequence consisting of small-scale and large-scale cross-stratification, and horizontal stratification cosets that vary in order and thickness. Cross-bed and grain sizes vary irregularly. In addition, the avulsion channel was apparently overloaded with sediments and did not meander.

The channels studied show characteristics of a fluvial environment when sediment textures are plotted graphically as coarse to median grain-size ratios. A rose diagram of current direction measurements from all channels exposed in the study area shows that sediment transport was from the west-southwest. According to calculations made with formulae derived by Schumm (1968, 1972), the three channels studied had shallow gradients averaging 2.0 feet per mile, and average annual discharge rates of from 300 to 4,300 cubic feet per second. Climate in the region of the study area was probably hot but may have had moderate rainfall. In any event, vegetation and, therefore, most wildlife was most likely limited to the areas of streams and lakes.

CONTENTS

*A thesis presented to the Department of Geology, Brigham Young University, in partial fulfillment of the requirements for the degree Master of Science, June 1974: W. Kenneth Hamblin, thesis chairman.

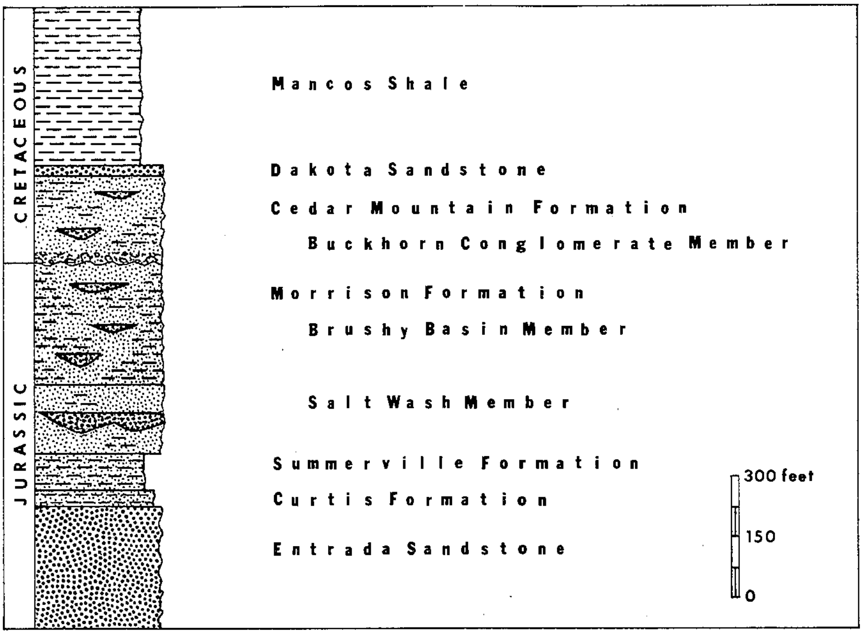
INTRODUCTION

During the early Mesozoic Era an abrupt change occurred in the pattern by which the continent was inundated by epeiric seas. Until late Triassic time, the seas transgressed onto the craton from the west, but with the advent of the Nevadan Orogeny, highlands were raised in central Nevada, and Jurassic seas that moved onto the continent were forced to expand southward from the Arctic through western Canada. Four major transgressive cycles occurred, but only two were extensive enough to deposit marine sediments in the vicinity of the study area located in east-central Utah. The fourth transgressive cycle was the second to move far enough south to reach the study area and formed what is known as the Sundance, or Zuni Sea. The sea was flanked on the east by lowlands of the stable platform. To the west were the highlands of the Nevadan and/or Sevier Orogenies (McKee, 1956; Armstrong, 1968). Marine sediments were deposited as far south as southern Utah and as far east as Nebraska and South Dakota. They consist of the green shale and glauconitic sandstone of the Curtis Formation (Text-fig. 1) to the south and west, and the shale, sandstone, and oolitic limestone of the Sundance Formation to the north and northeast. As the sea began to retreat, these sediments were overlain by thin-bedded red siltstone, shale, and gypsum of the Summerville Formation (Peterson, 1972), which may represent a tidal-flat or lagoonal marginal marine environment. As the sea regressed northward, alluvial sediments were deposited in its wake. This sandstone, variegated shale, and siltstone now comprise the uppermost Jurassic (Kimmeridgian through Portlandian) Morrison Formation and are exposed from northern Arizona to Oklahoma, Kansas, and South Dakota. This formation provides the earliest evidence, on the craton, of Late Mesozoic Cordilleran orogenesis (Dawson, 1970).

The Morrison Formation is well known for its dinosaur fauna, has long been considered a classic example of fluvial sedimentation, and provides an excellent opportunity to study the details of point-bar, floodplain, and associated deposits.

Purpose and Procedure

Examples of fluvial channels contained in the Brushy Basin Member of the Morrison Formation are particularly well exposed near Green River, Utah, where they are both abundant and well defined (Text-fig. 2). The present-day arid climate and limited plant cover of the area have prevented the accumulation of thick soils that would mask the outcrops. Instead, the channel fillings stand starkly exposed to the elements, often having their internal structures readily discernible on their eroded surfaces. The channels are presently exposed in the study area as individual and superimposed exhumed segments. Because exhumed channels of such great extent are not common in the geologic record, these provide an excellent opportunity to study the morphology, geometry, and internal structure of stream channel deposits.

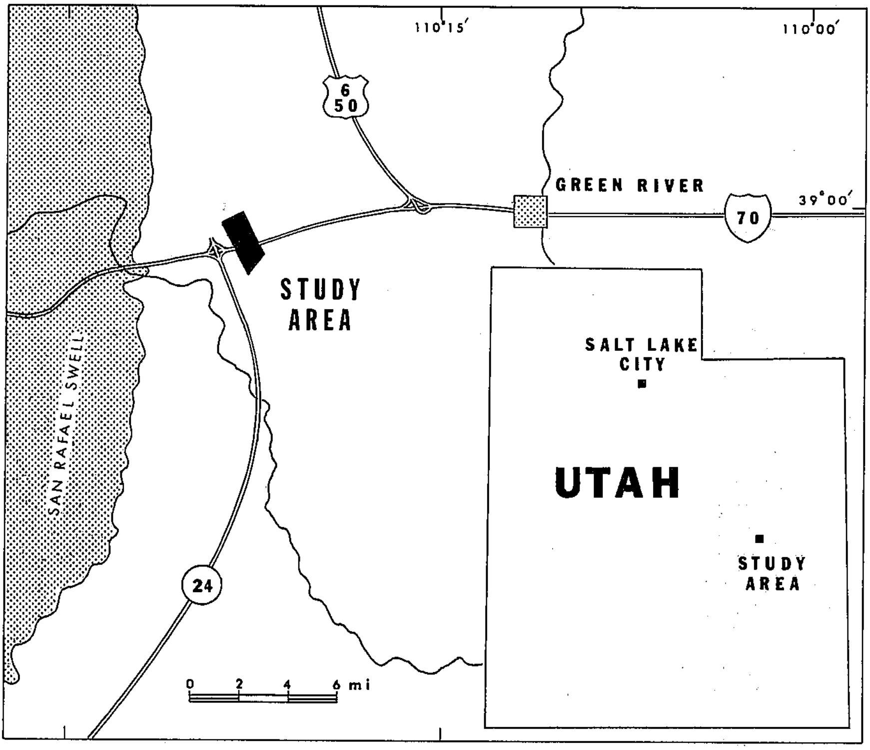


TEXT-FIGURE 1.—Stratigraphic section showing relative thickness and sequence of units present in the vicinity of the study area.

This study was undertaken to define the internal structure of specific channels and the processes responsible for their development and ultimate preservation in the geologic record. Interpretations are made of paleoenvironmental factors which may have influenced channel development. A depositional model is proposed to define the modes of channel preservation in relation to modern sediments.

In three selected groups of paleochannel segments 1,100 to 1,650 feet long, channel geometries, lithologies, and evidences of depositional environment were analyzed. The specific channels to be studied were chosen because they are excellent exposures, are accessible, and appear to demonstrate two contrasting modes of preservation. A road cut of Interstate Highway 70 completed only three months before the study began provided additional fresh exposures for evaluation.

Sedimentary structures and sequences of sedimentary structures are considered to be the key to the type of deposition that has taken place in a particular environment. Sediments are deposited in a systematic way. As discussed under the heading "Depositional Model," there are a finite number of ways that sediment can be deposited in a river. Therefore, composition of the channels chosen for study was determined and compared with that of modern streams to define the environments and the modes of deposition and preservation present. Sedimentary structures and sequences of bedding types were mapped and described in both plan view (Pl. 6, figs. A, B, C)and vertical cross-section (Text-fig. 4) to systematically document the sequences of structures present. Using a Brunton compass and steel tape, grids were constructed



TEXT-FIGURE 2.—Index map.

on the channel fill surfaces to serve as topographic control for the plan-view maps. The original maps were made on a scale of 25 feet to the inch. A stratigraphic section was measured to establish relationships between the units studied, and descriptions were made of the geometry and morphology of the channel segments (Appendix). The general lithologies and sediment characteristics were determined by study of outcrops and thin-sections. A study was made of sediment textural patterns by analysis of coarse to median grain size ratios for all major sediment types present in the channels. The scanning electron microscope was used to describe sand-grain morphology. Current and sediment-transport directions were determined by measuring and averaging cross-bed dips. Estimates of gradient, discharge, meander wavelength, and percent silt-clay in the channel perimeter were made using formulae derived by Schumm (1968, 1972).

Acknowledgments

The author wishes to express gratitude to Dr. W. K. Hamblin, and Dr. J. Keith Rigby, who not only served as thesis committee members, but also provided generous guidance and constant encouragement. Appreciation is also extended to the American Association of Petroleum Geologists and the Society of the Sigma Xi, who provided partial support for this project through grants in aid of research.

Previous Work

The Morrison Formation was originally described by C. W. Cross (1894) but was named by Eldridge and Emmons (1896) from exposures near Morrison, Colorado. C. C. Mook (1916) was first to describe the Morrison Formation on the Colorado Plateau, and he recognized it as a fluvial accumulation on the basis of lithology and sedimentary structures. Subsequent significant descriptions of Morrison stratigraphy and structure on the Colorado Plateau include those by Gilluly and Reeside (1928); Baker, Dane, and Reeside (1936); Craig et al., (1955); and Mullens and Freeman (1957). The most extensive work has been done by W. L. Stokes (1944, 1954, 1958, and 1961) and Stokes and Sadlick (1953), who described the Morrison of the Colorado Plateau with special emphasis on the comparison of sedimentary structure and uranium occurrences in exposures of the Salt Wash Member of the formation. His studies have included thorough descriptions of the composition and structure of the Salt Wash Member principally in northern Arizona and southern Utah.

Location

Today the area around Green River, Utah, stands on the Colorado Plateau at an elevation of about 4,500 feet. Channel segments were studied in an area ten miles west of Green River, Emery County, Utah, near Interstate Highway 70 (Text-fig. 2). The study area lies on the eastern margin of the San Rafael Swell and reflects a local dip of 4.5 to 5 degrees to the east. Two cross sections of channel segments are exposed in road cuts along the westbound and eastbound lanes of the interstate. These channel segments lie nearly perpendicular to the highway and are exposed to the north and the south from it. An additional single channel segment lies west and downsection from the others and is about one-quarter mile south of the highway.

STRATIGRAPHY

The Morrison Formation covers a large section of the west-central United States and is exposed in Arizona, New Mexico, Oklahoma, Kansas, Colorado, Utah, Wyoming, Nebraska, South Dakota, and Montana. In the western Colorado Plateau it is underlain by the marginal marine, Upper Jurassic Summerville Formation (Text-fig. 1). It is overlain by the green, ashy Buckhorn Conglomerate Member of the lowermost Cretaceous Cedar Mountain Formation, which consists generally of river floodplain deposits similar to those of the underlying Morrison. The Cedar Mountain Formation was proposed by Stokes (1944) who also recognized the presence of a Morrison-Cedar Mountain unconformity at the contact.

Of the four members regionally recognized in the Morrison Formation, only two, the Salt Wash and Brushy Basin, are present in the study area. In the Four Corners area the Westwater Canyon and Recapture Members underlie the Brushy Basin and overlie the Salt Wash. The Salt Wash Member is less extensive than the Brushy Basin but has been studied more intensively because of relatively large accumulations of uranium minerals present. Craig et al. (1955) described the Salt Wash Member as an interstratified sandstone and claystone, the sandstone being grayish yellow, very pale orange, and white and having a fine to medium grain. In the Green River area the Salt Wash Member is between 100 and 200 feet thick (Stokes, 1944). The Brushy Basin Member consists of variegated shale and siltstone with sandstone channel segments of fluvial origin distributed throughout. The sandstone ranges from light gray yellow to light red brown, and is medium to fine grained. The larger of the channels often have conglomerate at their bases. The Brushy Basin Member is about 300 feet thick in the study area (Stokes, 1944). Discontinuous lacustrine limestone representing local lakes on the Morrison alluvial plain have been recognized by Craig (1955).

Of the three groups of channels chosen for study, two are genetically related; the third has distinct differences that suggest a separate mode of preservation. In the following sections the two types are discussed individually and their vertical sequences of sedimentary structures documented. Comparison of vertical sequences provides a definition of relationships between the sedimentary systems originally present. The three groups of channels chosen for study are numbered in order of their stratigraphic position in relation to each other (Appendix). In plan view the oldest is exposed farthest west (channel 1). The others (channels 2 and 3) are exposed consecutively upsection to the east (Text-fig. 3). The channels have distinctive geometries and morphologies, which aid in interpretation of their development.

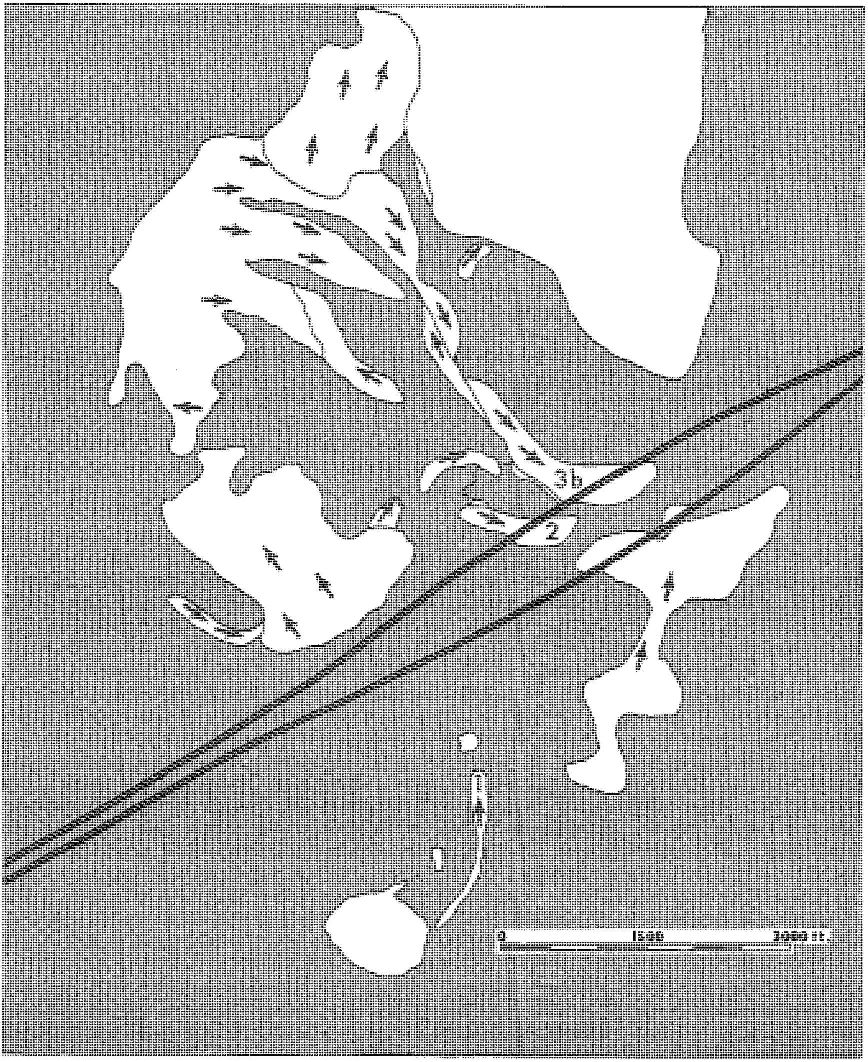
POINT-BAR CHANNELS

Geometry and Morphology

The maximum widths of channels 2 and 3 are exposed on the north side of the I-70 westbound lane road cut. Channel 2 has a maximum exposed width of 237 feet and a maximum depth of 13 feet. It is exposed for 700 feet north of the westbound lane road cut and in patches for 400 feet south. The cross-section of channel 3 has a maximum exposed width of 653 feet and a maximum thickness of 27 feet. It is, however, a compound channel consisting of two separate channel segments with the uppermost (3b) superimposed on and eroded into the east side of the lower (3a) (Pl. 1, fig. 1; Pl. 6, fig. D). The maximum exposed width of channel 3a is 225 feet, and its maximum exposed depth is 18 feet. Channel 3b has a maximum exposed width of 393 feet, and a maximum exposed depth of 22 feet. Channel 3b is exposed for 1100 feet north of the westbound road cut before being truncated by erosion, although some exposures further north may also be related. It is exposed in patches for 500 feet to the south before being covered by alluvium. Channel 3a is not well exposed in plan view and therefore could not be studied in detail. Channels 2 and 3 approach being parallel. Channel 2 forms a gentle curve along its length and trends from about 105° to 120°. Channel 3b forms a gentle curve that trends from about 110° to 130°.

Channels 2 and 3 are generally lens shaped in cross section and have convex bases. In cross section the exposed channel bases show minor irregularities of up to two feet in relief. The base of channel 2 forms a broad trough which is exposed to a depth of 4.5 feet below the point of maximum channel width (the point of the tongue described below). The base of channel 3 broadly undulates, with the lowest point on the base channel 3a lying 7.5 feet below (downsection from) the lowest point on the base of channel 3b.

Channels 2 and 3 appear to have been entirely surrounded by siltstones and shales prior to erosion (Pl. 4, fig. 2). The original western margin of channel 2 and the original western margins of channels 3a and 3b have been removed by recent erosion. The east margin of channel 2 forms a sandstone-and-conglomerate wedge or tongue, which in cross section tapers to a rounded point



TEXT-FIGURE 3.—Outcrop and current direction map, showing average directions of sediment transport.

(Pl. 1, fig. 4). The original eastern margins of channels 3a and 3b are covered by alluvium and not exposed.

Upper portions of channels 2 and 3 have been eroded, forming irregular surfaces and exposing internal structures. In plan view, channel 3a forms an alluvium-covered ledge that is exposed about five feet below the western margin of the channel 3b surface. With the exception of this small ledge, channel 3b forms the entire plan-view exposure of channel 3. A sandstone-and-conglomerate channel not exposed in the westbound road cut underlies channel 2 about 400 feet to the southeast (Pl. 1, fig. 3). It is exposed in the eastbound road cut, and is separated from channel 2 by gray siltstone varying in thickness from 2 to 7 feet. A small sandstone channel erosional remnant (unit 37) overlies channel 3 and is exposed in the north side of the westbound road cut (Pl. 1, fig. 2). It is separated from channel 3b by about 9 feet of dark brown to gray siltstone. These and other related segments suggest the presence of a floodplain channel complex.

Lithology

As exposed in the study area, the Brushy Basin Member is about 300 feet thick (Craig et al., 1955) and consists of moderate to thin-bedded variegated shale and siltstone with intermittent lenses of sandstone and conglomerate (Appendix). Rapid facies changes occur over areas of small lateral extent. Shale and siltstone surrounding channels 2 and 3 range from light and dark gray to red gray and red brown. Thin beds (averaging about one foot thick) of green and yellow brown shale are present at the exposed channel bases and represent a reduction zone at the channel-floodplain interface. Shale and siltstone consist primarily of clays, although as much as 70 percent of the composition may be quartz grains of silt and very fine sand sizes. Small percentages of calcite, limonite, and feldspars are also present.

Sandstone and conglomerate of the study area are generally very light gray but weather red brown. They form lenses that range in thickness from about one inch to nearly thirty feet. Those thicker than one to two feet generally contain characteristic sedimentary structures. Sedimentary structures are best exposed in the thickest channels and are well exposed in channels 2 and 3. Quartz grains are the main composition of the sandstone. Sandstone texture varies from silt to coarse sand size, and cement consists of both calcite and silica. Sandstone of channels 2 and 3 averages 98 percent quartz. Traces of calcite, limonite, clay, and feldspar are present. In channel 3b some individual cross-beds and entire sets have been selectively cemented by limonite (Pl. 2, fig. 1). Conglomerates of channels 2 and 3 consist of quartzite and chert pebbles ranging up to about 2 inches in diameter. The pebbles are generally well rounded with occasional angular admixtures. Occasional angular clay pebbles are present in channel 2. Griffiths (1952) believes clay pebbles to be reworked former sediments. Fossils are rare in channels 2 and 3 and in the surrounding siltstone and shale. Rooted sediments and other evidences of bioturbation were not observed.

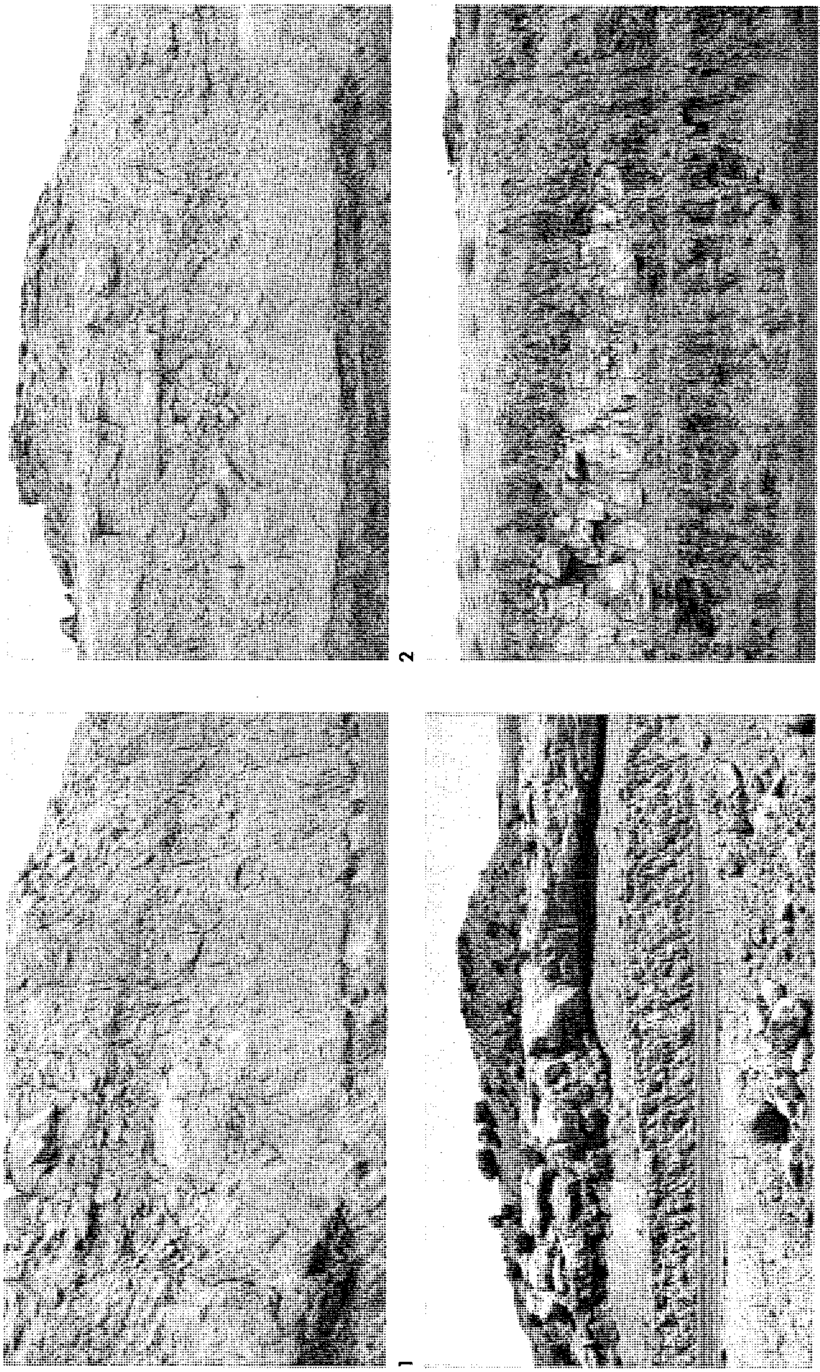
EXPLANATION OF PLATE 1
CHANNEL OUTCROPS

Fig. 1.—Sandstone and conglomerate sequence of channel 3b overlying (and eroded into) that of channel 3a below. Exposure lies on the north side of the I-70 westbound lane road cut.

Fig. 2.—Small sandstone channel remnant overlying, and separated by siltstone from, channels 3b and 3a below. Location is the same as that of Fig. 1.

Fig. 3.—Part of channel 2 overlying siltstone and another channel segment on the south side of the I-70 eastbound lane road cut.

Fig. 4.—Sandstone and conglomerate tongue of channel 2 surrounded by siltstone. Location is the same as that of Fig. 1.



1 2 3 4

PLATE 1

Sedimentary Structures

Three major types of bedding are present in channels 2 and 3: planar (tabular) cross-beds, trough-shaped cross-beds, and horizontal bedding. All are present to some extent in both channels. Two types of planar cross-beds are present in channels 2 and 3. Planar cross-beds, which dip toward the channel margin and strike nearly parallel to the average current direction of the channel are present only near the western erosional margin of channel 3b (Pl. 6, fig. C). They are straight in the strike direction and have parallel strata. Examples of planar-type cross-beds, which dip parallel to the channel trend (Pl. 2, fig. 2), are moderately well exposed on the eroded surfaces of the channels. Such cross-beds often appear to coalesce with trough-shaped cross-beds near channel margins. They consist of parallel strata which vary from straight to sinuous in the strike direction. There appears to be a gradational sequence between the planar and the trough cross-bed forms. They cannot be reliably discerned from one another in vertical cross-sections exposed parallel to the current direction, because at that angle they often look similar (Potter and Pettijohn, 1963, p. 70-71).

Horizontal stratification (current lamination) in channels 2 and 3 is well exposed only in cross section and was not observed on the channel surfaces, as it was in channel 1. When present, it often appears to stratigraphically separate small-scale cross-beds (with sets less than 0.2 feet thick) or large-scale cross-beds exposed near the top of the channel sequences from larger-scale cross-beds below (Pl. 2, fig. 3). Though present in the sands near the surfaces of channels 2 and 3, horizontal stratification is not present in the grits and conglomerates near the channel bases. Horizontal bedding predominates in the siltstone and shale that surround channels 2 and 3. The siltstone and shale range from thick to thin bedded but are also microcrosslaminated within these beds.

Trough-shaped cross-beds are the predominant bedding type on the surfaces of channels 2 and 3 and in the conglomerates near the channel bases. Elsewhere in the sequence, planar and trough cross-beds are not differentiable from each other because they are well exposed only in vertical cross-section parallel to the current flow. The sets of trough cross-beds are trough- or scoop-shaped bodies that taper in the downstream direction (Pl. 2, fig. 4). Set troughs may be scours in the channel bed that have refilled with nearly parallel cross-strata (forest beds) of nearly uniform thickness that taper toward set margins. These are concave, and they dip approximately parallel to the channel trend. Dip of the cross-strata ranges from approximately 35° to 5°

EXPLANATION OF PLATE 2
STRATIFICATION TYPES

Fig. 1.—Limonite spots and individual cross-beds that have been selectively cemented by limonite on the surface of channel 3b at its western margin.

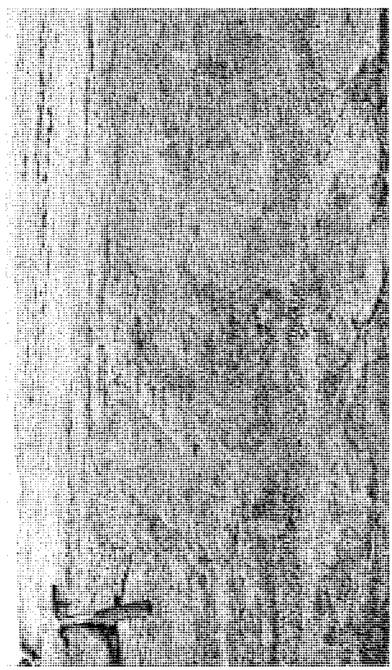
Fig. 2.—Planar (tabular) cross-beds on the surface of channel 3b. The apparent downstream direction is from lower left to upper right.

Fig. 3.—Horizontal stratification overlain by small-scale cross-beds. Outcrop is located on the western margin of channel 3b.

Fig. 4.—Eroded trough cross-bed set (foreground) surrounded by other cross-bed remnants on the surface of channel 3b.


1


2


3

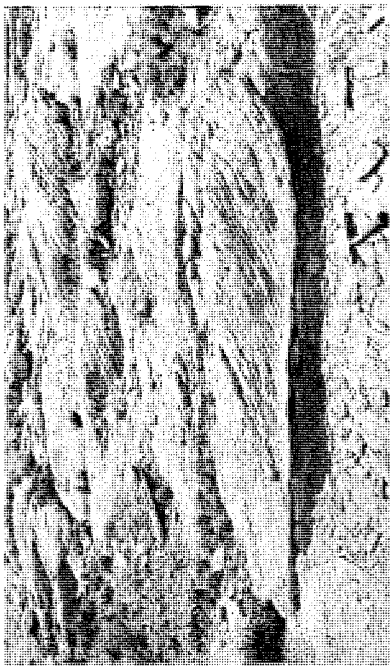

4

PLATE 2

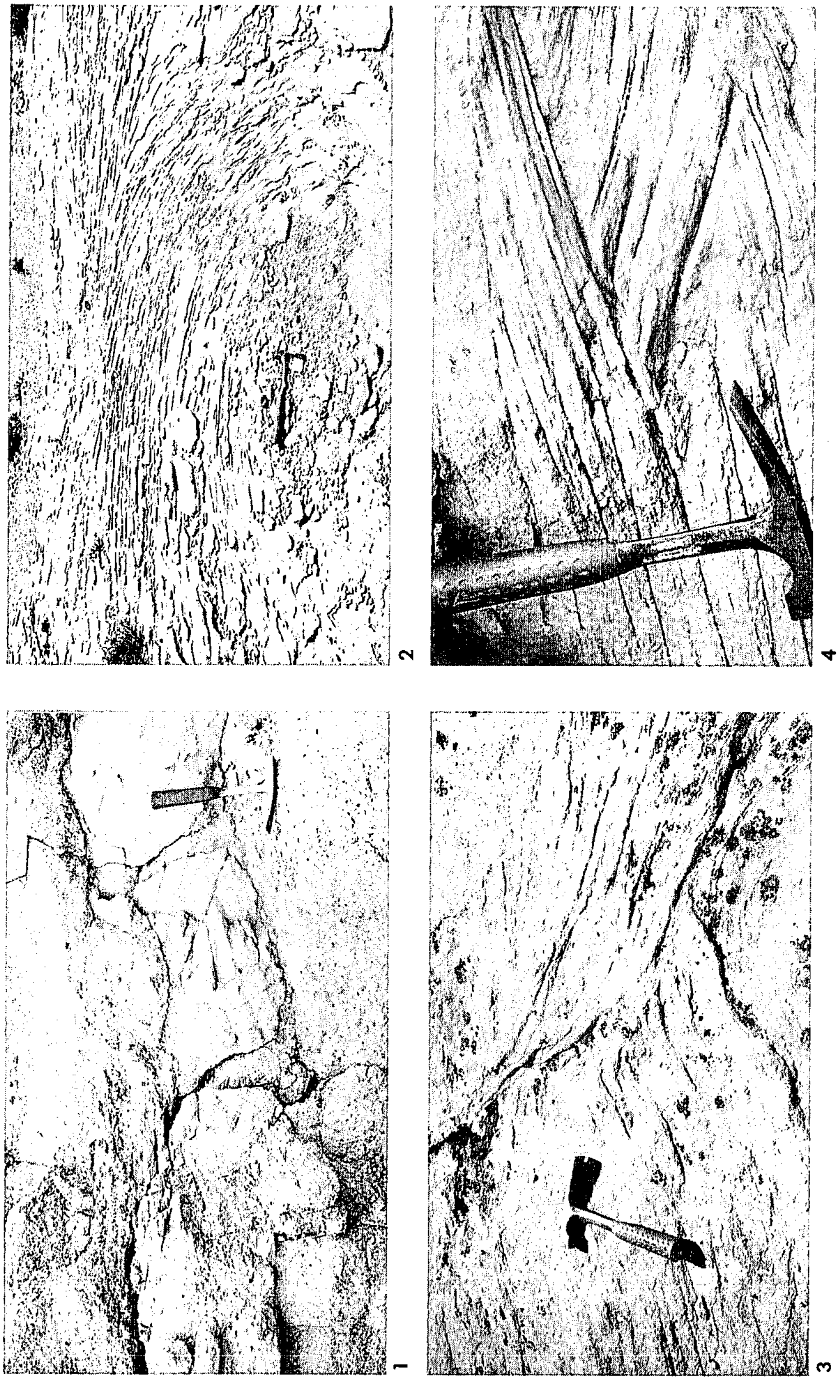


PLATE 3

but is generally from 10° to 30°. Thickness of individual cross-strata ranges from 4 inches in coarse conglomeratic sediments (Pl. 3, fig. 1) to 1 inch or less in sand-sized and finer sediments (Pl. 5, fig. 3). Troughs of cross-bed sets in channel sediments range in width from less than 1 foot to greater than 20 feet. In plan view the set margins have eroded into and truncated cross-beds of older surrounding sets (Pl. 3, fig. 3). Each stratigraphically higher and younger set has eroded into those below and beside it. Cross-beds are best exposed in fine sediments and become least well exposed in sediments of grit and pebble sizes.

The trough-shaped cross-beds of the study area are generally similar to festoon cross-beds described in modern streams (Harms and Fahnestock, 1965). Cross-bed size and shape are dependent on the volume and velocity of the water in the stream and on the sizes of sediment present. Many of the cross-bed sets exposed on the surfaces of channels 2 and 3 have been partially dissected by erosion.

Single examples of atypical cross-strata sets in which the cross-beds appear as whirls (Pl. 3, fig. 2) and as uniquely shaped truncations are present on the exposed surface of channel 3b. These features may be attributable to current eddies. Whirls are present in the modern Green River, east of the study area, and often form downstream from rapids where obstructions are present in the channel bed. Shoreward currents are also common in the river.

Vertical gradations in grain size are present on two scales. Channels 2 and 3 grade from conglomeratic bases to medium and fine sand at their upper exposed surfaces. Channels 2 and 3 contain small textural gradations in the bedding planes between cross-bed strata and sets. Minor imbrications are also present, also generally between cross-bed strata and sets. Although channel bases are not well exposed in the study area, rare examples of sole markings have been identified. Load casts along the base of unit 20 (Appendix) represent differential settling of channel sediments into underlying material prior to lithification.

Microcrosslaminations, common throughout the siltstone and shale that surround the channels of the study area, appear to represent deposition by low-energy currents on the interchannel floodplains. Microcrosslaminations are best exposed in siltstone and shale with the highest sand content. A few examples of massive, apparently structureless sandstone are also present. This feature occurs within sequences of cross-beds in channels 2 and 3. Where present, it separates larger-scale cross-beds near the base of the sequence from smaller-scale cross-beds near the top.

EXPLANATION OF PLATE 3
CROSS-BED RELATIONSHIPS

Fig. 1.—Large-scale trough cross-beds in conglomerate near the base of channel 3b. Exposure is located on the south side of the I-70 westbound lane road cut.

Fig. 2.—Cross-beds forming a circular pattern on the surface of channel 3b.

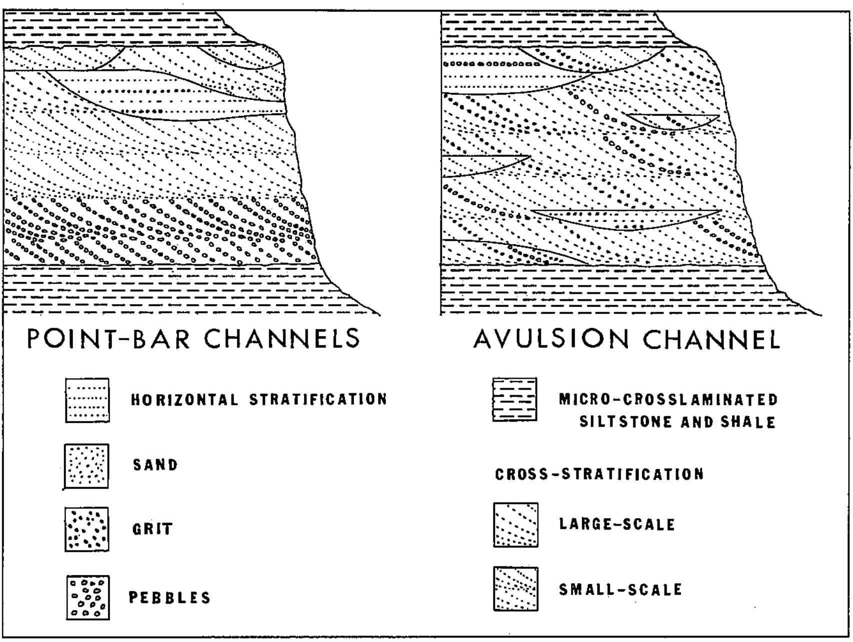
Fig. 3.—Trough cross-beds truncated by a stratigraphically younger set on the surface of channel 3b. The apparent downstream direction is approximately from lower right to top center of the photograph.

Fig. 4.—Trough cross-beds truncating each other in an outcrop near the north end of channel 1.

A boulder, probably rafted, is present in the shale of unit 34 (Appendix) on the south side of the westbound road cut. The boulder is a well rounded, highly lithified conglomerate about 3.5 feet in diameter. It lies in shale about one foot below the base of channel 3a. Pebbles within the boulder consist of chert and quartzite and average about one-quarter inch in diameter.

Vertical Sequence

A characteristic vertical sedimentary sequence is readily defined in channels 2 and 3 (Text-fig. 4). Generally, sediment and cross-bed sizes decrease upward through the sequence. Horizontal stratification is always found in the sands near, but never on, the channel surfaces. It was not observed in the conglomerates near the channel bases. At the channel bases where sediments are coarsest (pebble conglomerate), the largest-scale cross-stratification is present (Pl. 3, fig. 1). Some intermixing and interfingering occurs to vary the rates at which the sizes of cross-beds, sets, and sediments decrease upward from the channel base. Large-scale cross-beds are overlain by sequences that include horizontal stratification, beds of massive, apparently structureless sandstone, and small-scale cross-stratification. Small-scale cross-beds with sets up to 0.2 feet thick are most common near the channel surfaces. Small-scale cross-beds are often underlain and separated from the large-scale cross-beds below by horizontal stratification or massive, structureless sandstone. However, as Hamblin (1965) points out, most if not all massive-appearing rocks contain some internal structure even though it may not be readily recognizable on exterior surfaces.



TEXT-FIGURE 4.—Vertical sequences of sedimentary structures and lithologies in point-bar and avulsion channels of the study area.

Small- and large-scale trough and planar cross-beds are present on the upper exposed surfaces of the channels. Only large-scale cross-beds, however, are large enough to be shown on the channel surface maps (Pl. 6, figs. B, C). The presence on the channel surfaces of isolated patches of small-scale cross-beds, possible dissected small-scale cross-beds, and their presence only near the channel surfaces makes it possible that they could have predominated prior to erosion. Where horizontal strata and massive sandstone are absent, large-scale cross-strata are overlain by small-scale cross-strata or, as is now most common (due to erosion), exposed on the channel surfaces.

Individual cross-beds are not graded but appear to be generally uniform in grain size and thickness, implying deposition under more continuous and less variable transport conditions than those found in channel 1. Planar cross-bed sets do not extend across the surface widths of channels 2 and 3 to the extent that they do in channel 1; instead, they are confined to smaller areas (Pl. 6, figs. A, B, C). Trough-shaped cross-beds predominate on the present surface exposures of channels 2 and 3, while planar cross-bedding is most common in channel 1. The divisions of the vertical sequence present in channels 2 and 3 vary in thickness and appear to be partially interrelated with the size range of sediments present at specific positions in the sequence.

AVULSION CHANNEL

Geometry and Morphology

Channel 1 is exposed as a single, isolated, and somewhat sinuous channel segment south of the Interstate (Text-fig. 3). It appears to stand alone, no closely related channel segments being exposed nearby. The maximum width of channel 1 is exposed in plan view where the uneroded portion of the channel varies from 20 feet in width at its south end to nearly 100 feet on the north. It is exposed continuously for 1,650 feet and varies up to 10 feet thick. A small patch of cross-beds is also exposed about 200 feet north at the level of the alluvium and in line with the channel trend. Between these cross-beds and the main channel body the area has been dissected by a small, modern ephemeral stream. Channel 1 terminates abruptly at its southern end and does not continue into a nearby hillside. Measurements of channel-outline and cross-bed dip directions are generally coincident, and show that the channel forms a moderate curve along its length, trending from about 50° to about 350°.

Channel 1 appears to have been entirely surrounded by siltstone and shale prior to erosion. Both original margins of channel 1 have been moderately eroded. The base of the channel is poorly exposed, although the channel appears to be lens shaped in cross-section. The upper portion of the channel has been eroded to form an irregular surface and expose internal structures.

Lithology

The siltstone and shale that surrounded channel 1 when it was originally preserved in the geologic record have been removed by modern erosion and are not presently exposed. Shale on a nearby hillside at about the same stratigraphic level as channel 1 (Appendix) consists of clay with very fine sand and ranges from gray to red brown. A small percentage of calcite is also present in the shale.

Sandstone and conglomerate of channel 1 range from light gray to red brown. The sandstone consists primarily of quartz grains ranging from fine to coarse sand size and cemented by both calcite and silica. Sandstone in channel 1 averages 95 percent quartz. Traces of calcite, limonite, clay, and feldspar are present. Limonite spots are present in the channel sandstone and conglomerate. Limonite cements sand and finer pebbles, making them more resistant so that they weather out of the surrounding sediments as brown spheres 1 to 3 inches in diameter. Conglomerate in channel 1 consists of chert and quartzite pebbles ranging up to about 2 inches in diameter. Sorting in the conglomerate is fair to poor. Pebbles are generally well rounded with occasional angular admixtures. The sediments of channel 1 are generally finer grained though more poorly sorted than those of channels 2 and 3. A few clay pebbles were observed. Fossils in channel 1 apparently are rare and were not observed.

Sedimentary Structures

As with channels 2 and 3, three major types of bedding were observed in channel 1: planar (tabular) cross-beds, trough-shaped cross-beds, and horizontal bedding. Also as with channels 2 and 3, planar cross-beds were, because of the exposures present, generally only differentiable on the channel surface. Planar cross-beds dipping toward the channel margin, such as those exposed in channel 3b, were not observed in channel 1. Planar cross-beds with dip parallel to the channel trend are common and appear to predominate on the surface of channel 1 (Pl. 6, fig. A). They consist of parallel strata which vary from straight to sinuous in the strike direction. Planar cross-beds often appear to coalesce with trough-shaped cross-beds near the channel margins or to grade into trough cross-beds in the direction of current flow.

Horizontal stratification in channel 1 is well exposed in cross section but poorly exposed on the channel surface, where, unlike in channels 2 and 3, it is present. Where exposed in channel 1, horizontal stratification appears to be irregularly spaced throughout the vertical sequence and may be both overlain and underlain by large- and small-scale cross-beds (Pl. 5, fig. 1). Horizontal stratification may be present anywhere in the vertical sequence from the channel base to its surface.

Trough-shaped cross-beds are less common in channel 1 than in channels 2 and 3, where they predominate. These trough-shaped cross-beds are similar in general form to those exposed in channels 2 and 3. These cross-beds are common and well exposed on the channel surface. Sets are trough- or scoop-shaped and taper in the downstream direction. Set troughs may be scours in the channel bed which have refilled with nearly parallel cross-strata that are concave and dip approximately parallel to the channel trend. Cross-strata taper toward the set margins. As exposed in channel 1, thickness of individual

EXPLANATION OF PLATE 4
CROSS-BED AND LITHOLOGIC RELATIONS

Fig. 1.—Graded cross-beds in an outcrop near the east margin of channel 1.
Fig. 2.—Contact between the conglomeratic base of channel 3a and underlying siltstone.
Fig. 3.—Large-scale trough cross-beds overlain by horizontal stratification in an outcrop near the north end of channel 1.
Fig. 4.—Outcrop of channel 2 as viewed from the surface of channel 3b looking west. Compare with Text-figure 3.

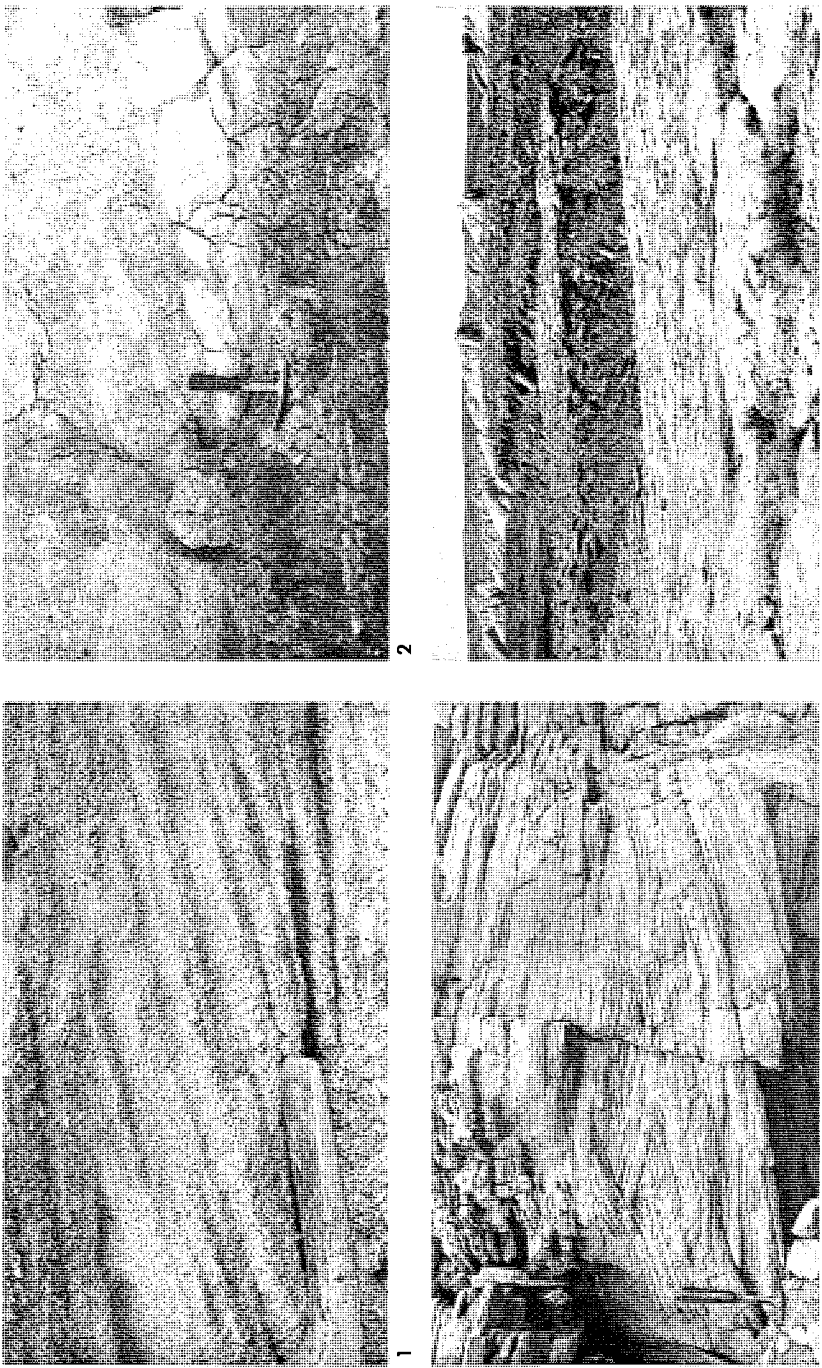


PLATE 4

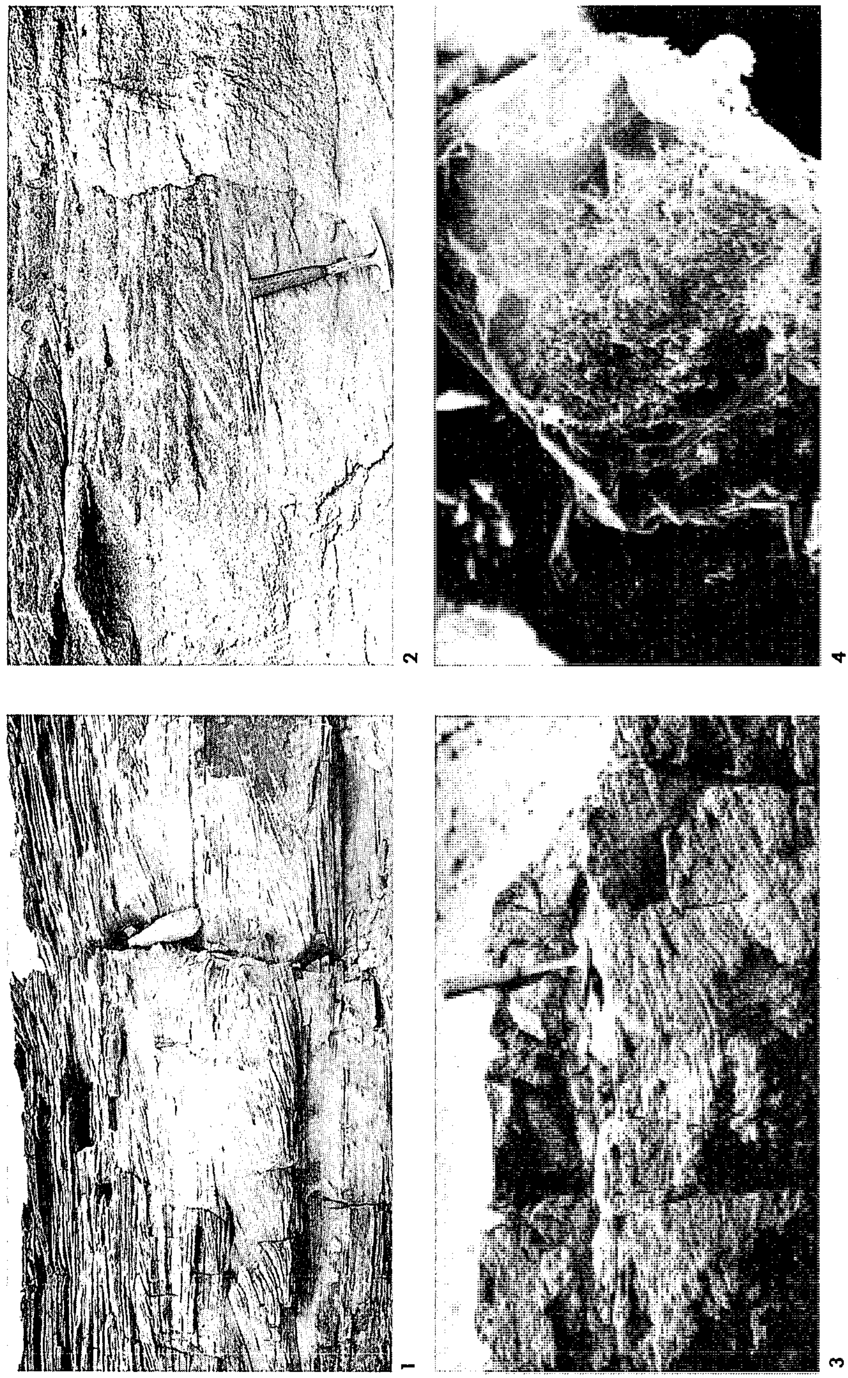


PLATE 5

cross-strata ranges from 3 inches in coarse, conglomeratic sediments to 1 inch and less in sand-sized and finer sediments. Sets are generally 1 to 3 feet thick and 1 to 30 feet wide. In channel 1, cross-beds form a discernible pattern only on the channel surface where, at a moderate bend in the channel, the cross-strata are broadened and flattened toward the outside of the bend (where current velocity would have been greatest).

Atypical cross-strata sets similar to those present in channel 3b were not observed; however, in channel 1, cross-bed dips abruptly reverse over a surface about 40 feet long. This feature, like those of channel 3b may also be attributable to current eddies. Reverse currents are common in the modern Green River east of the study area, generally occurring near shore. However, recent experimental work by Shepherd (1973) suggests the possibility that such backset stratification may also result from deposition in an area of the stream where the bed is locally inclined upstream and may occur under lower flow-regime conditions. Because the reverse cross-beds in the channel entirely replace all others where present, the latter explanation seems more likely. Dips of the backset range from 15° to 25° which, according to Harms and Fahnestock (1965), would preclude the possibility that the reverse cross-beds could be the result of antidune formation under upper flow-regime conditions.

Vertical gradations in grain size in channel 1 are irregular. The sediments of channel 1 do not grade from coarse to fine upward as do those of channels 2 and 3. Small textural gradations in the bedding planes between cross-bed strata and sets are present, however. In addition, many individual cross-bed strata are also graded (Pl. 4, fig. 1). Minor imbrications are also present, generally between the cross-bed sets.

Vertical Sequence

The vertical sequence of channel 1 consists of irregularly spaced cosets of cross-beds interbedded with horizontal stratification from base to upper exposed surface. This sequence is summarized and compared with that of channels 2 and 3 in Text-figure 4. Small-scale cross-stratification appears to occur irregularly throughout the channel sequence (Pl. 5, fig. 2). Large-scale cross-strata and horizontal strata also appear throughout the vertical sequence and are the most common bedforms present (Pl. 4, fig. 3; Pl. 5, fig. 1). General ranges of cross-bed and sediment grain sizes vary irregularly and do not appear to form systematic patterns throughout the vertical sequence or horizontally along the channel length.

Poorly sorted sediments from clay to conglomerate are present as strata consisting of variable sediment sizes in cross-bed sets rather than as a vertical

EXPLANATION OF PLATE 5
VERTICAL SEQUENCES AND ELECTRON PHOTOMICROGRAPH

Fig. 1.—Cross-strata irregularly interbedded with horizontal stratification in an outcrop near the north end of channel 1.

Fig. 2.—Cross-strata having a wide variety of forms exposed in an outcrop near the east margin of channel 1.

Fig. 3.—Cross-beds exposed on the west margin of channel 2.

Fig. 4.—Electron photomicrograph of sand grains, showing crystal faces of quartz overgrowths. Magnification is 200x.

gradation from base to channel surface, as is present in channels 2 and 3. Sediment sizes vary within and between cross-bed sets. In addition, the sediments present in many individual cross-beds are graded both vertically and horizontally (center to margins). Cross-beds often vary in thickness within sets. These factors imply that transport and deposition occurred in pulses rather than under conditions of continuous flow. More sediment was apparently present than the stream was capable of transporting continuously. Clay and silt separate many cross-strata and weather to leave open spaces between cross-beds (Pl. 3, fig. 4). This suggests wider variations in flow than appear to have been present in channels 2 and 3, where cross-beds are usually separated by sand and grit. In addition, planar cross-beds, which appear to predominate on the surface of channel 1, often extend across much of the channel width (Pl. 6, fig. A), while often remaining no more than 1 to 2 feet thick. These cross-beds may represent the remnants of migrating transverse bars (sand waves) that are common in streams which are overloaded, containing more sediments than they can transport continuously (Ore, 1965). Channel 1 curves, but does not appear to form a meander loop. As compared with the reaches of meandering streams, its reaches are remarkably straight upstream and downstream from the actual curve. There is no evidence in the channel of point-bar sequences, or substantial lateral erosion.

These sequences, as defined for the three channels studied, will be summarized, further discussed, and compared with those derived by other workers from depositional models. Although vertical sequences provide the most precise definition of depositional environment, other factors have also been shown to provide useful information. Some of these factors are discussed in the following sections.

CHANNEL CLASSIFICATION

The conclusion that channels 1, 2, and 3 are of fluvial origin is supported by the following observations: (1) they have convex bases, are generally lenticular in cross section, have lengths greater than their widths, and widths greater than their depths (Finch, 1959), (2) they have eroded into the surrounding sediments, disrupting bedding, (3) they consist of sandstone and conglomerate and are entirely surrounded by siltstone and shale, (4) conglomerate pebbles have fair to good size sorting and are generally well rounded, (5) minor admixtures of angular pebbles are present in the rounded pebble conglomerate (Sames, 1966), (6) sand and conglomerate, of which they are composed, are often cross-bedded, (7) only one general current direction is present in each channel (Yeakel, 1962), (8) a rose diagram of current directions in these and other channels throughout the study area indicates a single sediment transport direction, (9) a plot of coarse to median grain-size ratios for a series of samples produces a pattern that generally resembles patterns formed from plots of modern stream sediments (Passega, 1957), and (10) they lack discrete horizontal bedding in the gravels (Clifton, 1973).

TEXTURAL PATTERNS

Until fairly recently, little work had been published on interpretations of graphically derived textural patterns and their use in defining the depositional environment of modern and ancient sediments. In a pioneer study, Passega (1957) found that textural patterns of clastic sediments are generally sharply defined when plotted graphically and that they vary considerably with the type of depositional agent. Further work by Bull (1962, 1972) and Ahlborn and Hamblin (1973) have amplified Passega's original findings with emphasis on alluvial fan sedimentation. Passega described the textural pattern as a geologic tool that can be used to analyze deposition of recent sediments and to reconstruct conditions under which ancient sediments, including stream channels, lake sediments, tidal flats, turbidites, and beaches, were deposited. Passega produced type textural patterns for each. A few of these patterns are represented in Text-figure 5. The textural pattern consists of logarithmic plots of the coarsest one-percentile grain size (C), on the vertical axis, and the median grain size (M), on the horizontal axis. The median grain size is the 50th percentile. The resulting pattern is termed a CM ratio.

In rivers and in most currents of flowing water, which are the most common agents of transportation, loads of fine and coarse sediment are largely independent of each other. As a result, texture of sediment composed of fine and coarse fractions is a function of two independent factors. Therefore, parameters such as skewness and the coefficients of sorting, which measure attributes of the total sediment, cannot be used to express the character of this type of deposition because they are likely to be a function of two independent variables.

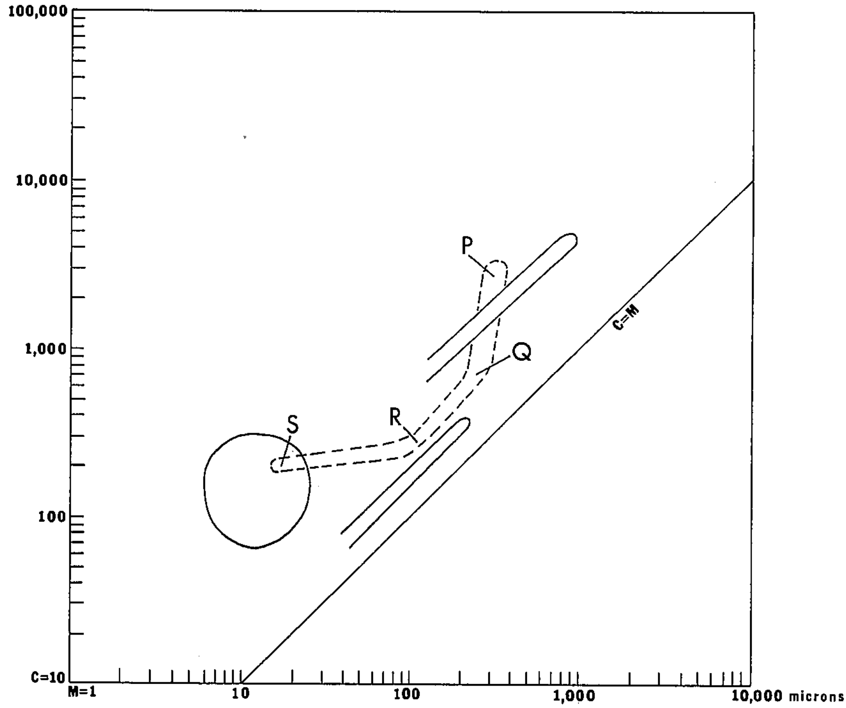
Passega (1957) gave preference to the coarse fractions. The only overall parameter of texture used in his method is the median, which expresses the average coarseness of the sediment. The maximum grain size, or coarsest one-percentile, measures the stream's competency. He chose the coarsest one-percentile because he reasoned that a few large grains may have been introduced by extraneous agents.

A turbidity current, a mud flow, and a river may have equivalent energy and may transport particles of the same size range, but each would transport different proportions of fine and coarse material. This proportion or ratio, the coarse to median ratio, is believed to be a signature of the transporting and depositing medium.

As shown in Text-figure 5, turbidities (labeled TC) form an open linear pattern. Quiet-water deposits form the circular pattern with CM ratios of about 10:1. Rivers and current systems form a "dog-leg" linear pattern with three separate segments. Segment PQ represents the pattern produced by the coarsest material in the main channel. Segment QR represents subaqueous bank, or braided stream deposits, and RS represents the finest sediments in the protected bank zone.

Passega collected unconsolidated samples and conducted grain-size analyses using sieves and weight-percent measurements. This was impractical for use in the present study of Brushy Basin Member sediments. Most of the Morrison sedimentary rocks are tightly cemented and range from pebble conglomerate to sandstone, siltstone, and shale.

Two methods were used to determine the CM ratios of the Morrison facies. First, as suggested by Ahlborn and Hamblin (1973), color slides were taken of individual representative outcrops containing sediments from conglomerate to coarse sand sizes, then projected onto graph paper. Horizontal and vertical counts across the projection were then tabulated and analyzed. A scale was placed on the outcrop so that each picture included a control for pebble measurement. Second, smaller diameter sediments, from medium sand to clay sizes, were counted microscopically, on thin-sections, using a calibrated eye-



TEXT-FIGURE 5.—Basic CM patterns modified from Passega (1957). Turbidity currents are represented by open-ended patterns, quiet water sediments by the circular pattern, and streams by the segmented pattern. The letters are for convenience when discussing individual segments in the text.

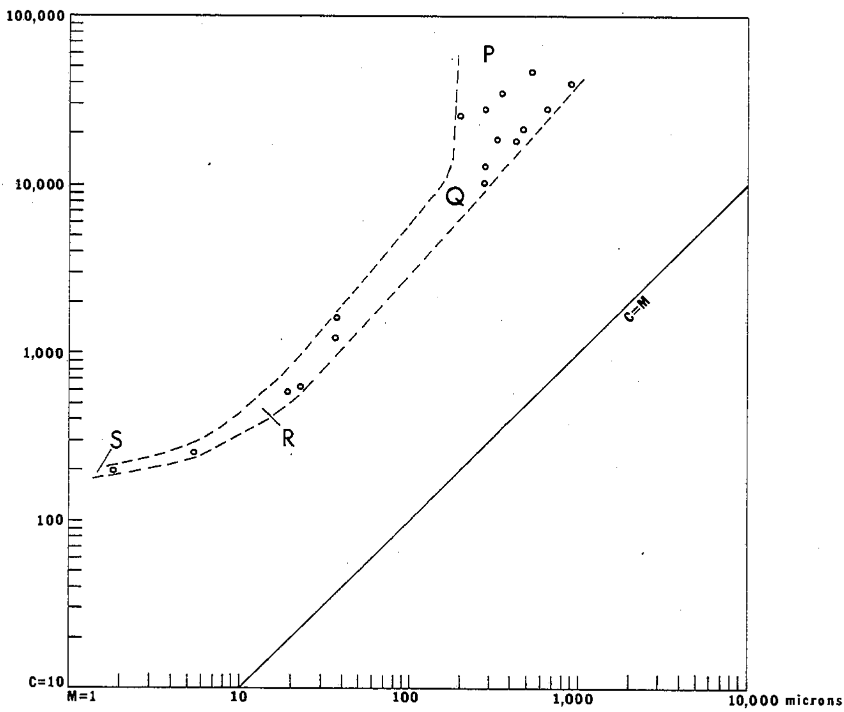
piece scale. In both methods maximum observable diameter was recorded for each count and care was taken to define a grid-spacing larger than the diameter of the largest grain or pebble present.

Determination of CM ratios in ancient sediments is limited by a number of factors that are not as apparent when working with their modern analogs. Complete data is required to form a meaningful pattern. Therefore, samples must be numerous and varied enough to be representative of all sediment depositional types present in the study area. Because of the large sediment sizes present, conglomerates are the least difficult of the ancient sediments to evaluate. When working with thin-sections, counting accuracy is reduced by the presence of overgrown and intergrown quartz grains, or interstitial calcite. The thin-sectioning process cuts the grains at various levels. As a result, the maximum grain diameter will not normally be measured. Though the basic shape of the pattern would be expected to remain the same, the data values would tend to be reduced, elongating the portion of the textural pattern that the values represent. In shale, when clay content approaches 50 percent, median grain size can no longer be calculated because of difficulty in measuring sizes of clay particles. The presence of carbonates or of fossil materials in the samples is also a factor requiring further evaluation and limiting the usefulness of CM ratios in ancient sediments.

In the study area 23 samples were taken, with one or more of the samples representing each of the sediment types present in and around each of the three paleochannel sand bodies studied. Samples were analyzed and logarithmic plots made of resulting data. Six of the shale thin-sections had clay contents of 50 percent or more, making them unsuitable for evaluation. As shown in Text-figure 6, the CM ratios of the study area sediments form an elongated three-segment pattern. The pattern is similar to that formed by fluvial sediments but extends upward and is somewhat broadened at the top. The uppermost segment corresponds to the main channel sediments defined by Passega as segment PQ. The lowermost segment corresponds to the quiet-water-protected bank deposits designated RS, and the center segment corresponds to sub-aqueous bank or braided stream deposits designated QR. The sediment samples from the study area used in this analysis empirically correspond with this interpretation.

GRAIN MORPHOLOGY

Characterization of surface textures by the study of Pleistocene and Recent quartz sands under the electron microscope has demonstrated that particular surface textural features appear to be characteristic of specific erosional environments from which the samples have been taken (Krinsley and Margolis, 1969; Stieglitz, 1969; Krinsley and Donahue, 1968). Sand samples from each of the three channels studied were inspected with a scanning electron microscope



TEXT-FIGURE 6.—CM patterns of study area sediments.

to determine the type of surface features present and their relationship to environments of erosion to which they have been subjected. Because fluvial transport does not impress characteristic surface textures on quartz sand grains, the surface texture of any other environments through which the grains may have passed would be visible (Krinsley and Donahue, 1968).

In all samples, however, the grains were shown to have been diagenetically altered by extensive secondary quartz overgrowths. All traces of the original predepositional surface texture have been destroyed by a mask of chemical deposition (frosting)—a process recognized and described by Kuenen and Perdok (1962) (Pl. 5, fig. 4). Apparently, common diagenetic alteration rapidly modifies the surface textures of quartz grains masking characteristic features (e.g., Marzolf, 1973). In most cases, therefore, analysis of grain texture in ancient sediments by electron microscopy may not be of significant value.

CURRENT AND SEDIMENT TRANSPORT DIRECTIONS

Detailed maps were made of cross-bed orientations as expressed on the surface exposures of channels 1, 2, and 3b (Pl. 6, figs. A, B, C). Channel 3a is not well exposed in plan view. Current flow in channel 1 averaged just east of north, and ranged from about 50° to 350°, around a moderate bend. Channels 2 and 3 show current flow to the east-southeast. Cross-bed dips in channel 2 trend around a gentle curve from about 105° to 120°. Those in channel 3b also trend around a gentle curve and range from about 110° to 130°.

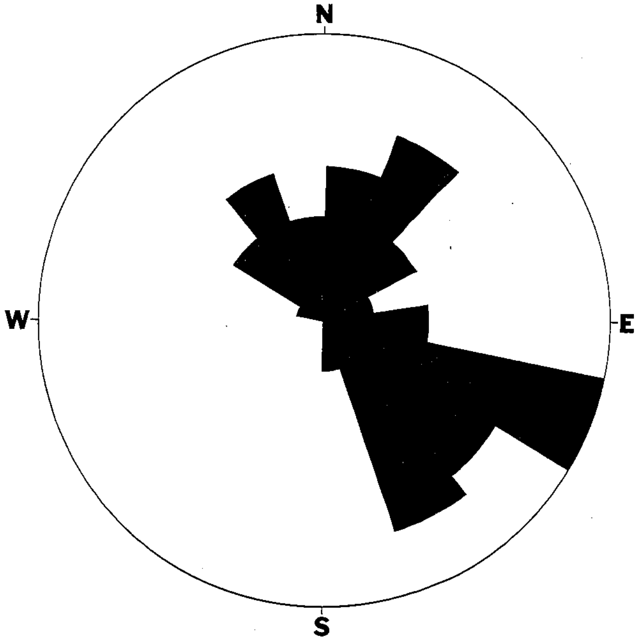
Results of current direction measurements over a larger area of about 1.5 square miles are partially represented in Text-figure 3. Each arrow represents the average of cross-bed dip directions at that point. The shaded area represents shale and alluvial cover, while the clear areas represent sandstone and conglomerate channel outcrops. Arrows are present only where cross-beds are exposed. A rose diagram of the current directions was plotted to determine the transport direction of the sediments (Text-fig. 7).

Due to the relative scarcity of cross-beds per unit area, measurements were taken at all exposures present rather than at points in a predetermined grid. The southwest direction, between 180° and 280°, was notably barren of measurements, indicating this to be the general direction from which sediment was transported into the study area.

ESTIMATES OF STREAM CHARACTER

Channel pattern and cross-sectional dimensions of streams are related to hydraulic variables. Width, depth, meander wavelength, gradient, shape (width vs. depth) and sinuosity of stable alluvial stream channels are dependent on the volume of water moving through the channel and on the type of sediment being transported (Schumm, 1972). Many equations used to determine hydrology and third-dimension character of modern streams have been inappropriate for paleochannel use because they often require parameters such as water discharge, current velocity, and slope (e.g., Leopold and Maddock, 1953), which are normally not obtainable in the geologic record.

In 1968 and 1972 Schumm proposed equations, developed from empirical data collected along modern alluvial streams, which permit estimation of paleochannel gradient, meander wavelength, discharge, and percent silt-clay (particles <0.074 mm) in the channel perimeter from dimensions of paleochannels exposed in cross section.



TEXT-FIGURE 7.—Average sediment transport directions shown as a rose diagram representing 72 measurements.

Channels described in the study area are well exposed in cross section, but have undergone moderate erosion. An attempt was made to determine their original dimensions by drafting their present cross-sectional shapes on graph paper and extending their bases and upper surfaces to complete their forms. Because the results of this approach were inconclusive, cross sections of the channels as they are presently exposed were used with Schumm's equations to provide approximate values of the calculated parameters. Results of the calculations are recorded in Table 1. The bank-full width (w) and the depth (d) were measured directly from the channel cross sections. Only the value of Qm would be affected by climate. If the Brushy Basin streams drained an arid area, Qm may be as little as one-half the calculated value. As Schumm (1972) points out, the equations provide only reasonable estimates of paleochannel character.

Meander wave-length (1) ranges from 1,500 to 5,100 feet in the channels studied. Calculated stream gradient (s) is low, averaging 2.0 feet per mile. Flow during mean annual flood (Qma) ranges from 4,600 to 27,000 cubic feet per second. The calculated values for silt-clay in the channel perimeter (M) ranges from 4.5 to 10.3 percent. In comparison with major modern streams, the channels studied are relatively small. The Missouri River at Kansas City, Missouri, averages 1,093 feet in width and 11.7 feet in depth and has a mean annual discharge of 43,710 cubic feet per second. The Mississippi River at Saint Louis, Missouri, averages 1,586 feet in width and 28.0 feet in depth and has a mean annual discharge of 166,700 cubic feet per second. The Yellowstone River, near Sidney, Montana, averages 308 feet in width and 11.9

TABLE 1
STREAM CHARACTER RELATIONSHIPS

Channel	F (w/d)	w (ft.)	d (ft.)	l (ft.)	s (ft./mi.)	Qma (cfs)	Qm (cfs)	M (%)
1	10.0	100	10	1500	2.9	4600	300	6.6
2	18.2	237	13	3600	2.2	12000	1200	10.3
3a	12.5	225	18	2900	1.6	14000	1700	5.6
3b	17.9	393	22	5100	1.3	27000	4300	4.5

$l = 18\,(F^{.53}\,w^{.69})$ where l = meander wavelength in feet; F = width to depth ratio of channel; w = channel bank-full width in feet

$s = 30\left(\frac{F^{.95}}{w^{.98}}\right)$ where s = channel gradient in feet per mile

$Qma = 16\left(\frac{w^{1.56}}{F^{.66}}\right)$ where Qma = flow during mean annual flood in cubic feet per second

$Qm = \frac{w^{2.43}}{18\,F^{1.13}}$ where Qm = mean annual discharge in cubic feet per second

Schumm (1972)

$F = 225\,M^{-1.08}$ where M = percent silt-clay (<0.074mm) in the channel perimeter

Schumm (1968)

feet in depth and has a mean annual discharge of 11,860 cubic feet per second (Leopold and Maddock, 1953). For thirty-three modern streams representing a variety of climates and having mean annual discharges within the range of those determined for the study area channels, drainage area was calculated to average 3,700 square miles.

CHANNEL PATTERN

Three major types of channel pattern are recognized in modern streams (Leopold and Wolman, 1957). Meandering and straight channels are texturally and structurally similar, but braided channels form a series of stream reaches that are divided into two or more anastomosing channels by islands or bars of alluvium (Brice, 1960). According to Leopold and Wolman (1957), truly straight channels are so rare in the field as to be almost nonexistent. Short segments or reaches of a channel may be straight, but reaches extending for distances exceeding ten times the channel width are rare and are probably the result of topographic control. Such straight channels exhibit a tendency for the flow to follow a sinuous path within the confines of their straight banks. Channels described in the study area each exhibit some curvature and cannot be considered truly straight.

Differentiation of meandering from braided streams among ancient sediments has been an uncertain procedure, although recent studies by Schumm (1968) have shown that the frequency of braided streams in the geologic record may be quite high. Identifications of ancient braided stream deposits not involving regional studies have generally been provisional and based on evidences that could also represent superimposed, highly sinuous fluvial systems (Kessler, 1971). Doeglas (1962) considers steep gradient an important factor in the formation of braided streams. Gole and Chitale (1966), however, have described braided reaches in the Kosi River of India that have shallow gradients, less than 0.3 feet per mile. Most of the features found in modern braided streams are also present in those that predominantly meander.

Although no single features appear to be clearly diagnostic of braided streams in the geologic record (Kessler, 1971), they have been shown (1) to have coarser sediments than meandering streams of equal sizes (Brown, 1969), (2) often to contain poorly sorted sediments, though there are usually vertical textural gradations (Smith, 1970), (3) to have vertical sediment sequences separated by clay drapes (thick-bedded clays) (Kessler, 1971), (4) to have uneven bedding planes (Doeglas, 1962), (5) to lack point-bar sedimentary sequences (though they may be present if the stream is meandering with only intermittent braided reaches) so that festoon and tabular cross-stratification would alternate randomly with horizontal strata in a vertical sequence (Waechter, 1970), (6) to be associated with arid or semiarid climates (Doeglas, 1962), (7) to have strong fluctuations between high and low discharge (Smith, 1970), and (8) to consist of anastomosing or overlapping channel sequences (Kessler, 1971).

Channels described in the study area conform only partially to these characteristics of braided streams. They vary in sediment sizes, but only channel 1 has distinctly coarser sediments than the others. Sorting is fair to good in all channels studied, except for channel 1, in which it is fair to poor. None of the channels studied have clay drapes separating sediment sequences, nor do they have distinctively uneven bedding planes. All but channel 1 appear to form point-bar sequences. In channel 1, cross-beds and horizontal stratification appear to alternate irregularly. As discussed under the heading "Climate," rainfall in the study area may have been little enough to produce a semiarid environment. Regardless, an overall cover of vegetation was probably not present. Within the channels described in the study area, grain-size variations, both vertical and lateral, are often rapid and extreme. Some interbedding occurs among the sandstones and coarse conglomerates. According to Smith (1970), these are indicators of strong variations in flow conditions. None of the channels appear to consist of clearly anastomosing or overlapping sequences, although the irregular vertical sequence of channel 1 could be a reflection of these characteristics.

It is possible that braided conditions were present from time to time in the channels studied, though these conditions may not have been well preserved. Only the channel pattern present during the channel preservation process would have been recorded in the geologic record. The channel preservation process would normally have been initiated and carried on during periods of high water, though flow through the abandoning channel would have varied with the process involved and the type and amount of sediment deposited. Evidence of fluvial conditions such as braiding, which could have been present during low-water periods, would not necessarily have been recorded.

Also, as Leopold and Wolman (1957) point out, the physical characteristics of all three channel types discussed (meandering, straight, and braided) are similar and suggest that all natural channel patterns intergrade. They state that although braids and meanders are strikingly different, they actually represent extremes in an uninterrupted range of channel pattern. Because the pattern of a stream is controlled by the mutual interaction of a number of variables (and because the range of these variables in nature is continuous), a complete range of channel patterns varying only by degree and magnitude should be potentially present. As Russell (1954) points out, the Meander River in Turkey, from which the term *meandering* was derived, has both braided and straight reaches.

DEPOSITIONAL MODEL

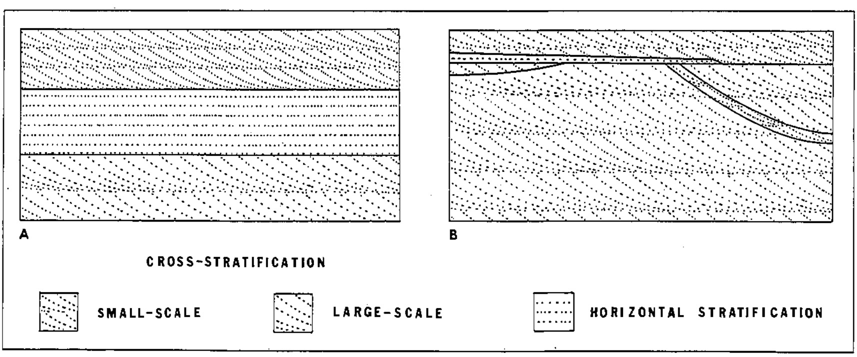
During late Jurassic time the study area consisted of an aggrading sequence of alluvial clay, silt, and sand that covered the former floor and margins of the Zuni (Sundance) Sea (Peterson, 1972). Streams from the late Nevadan/early Sevier mountains to the west (Armstrong, 1968) produced a large alluvial plain which aggraded seaward as the sea retreated to the north and mean sea level fell relative to the continent. The lateral migration of the channels, especially in this rapidly aggrading situation, caused the deposits to be widespread geographically, and to have considerable stratigraphic thickness (Ore, 1965), making the formation highly time transgressive. In addition, sediments built up by aggradation were at least partially reworked as local and regional base levels varied intermittently throughout Morrison time.

Channels preserved in the study area by this situation have depositional environments closely analogous to those of modern streams. Modern streams consist of three basic systems: a tributary or water and sediment collection system, a main trunk transportation system (which moves water and sediments downstream), and a distribution system (in which sediments are ultimately deposited when the stream is in equilibrium) (Fisher, et al., 1967; Allen, 1965). Channel preservation is a depositional feature and is, therefore, limited to the distributary or lower transport systems near base level. There are two basic ways in which channels are abandoned, making possible their incorporation into the geologic record: meander cut-off and avulsion.

Meander cut-off occurs whenever a stream can shorten its course and, thus, locally increase its slope. Two types of cut-off are recognized by Fisk (1944, 1947). Both chute cut-off and neck cut-off involve incremental filling of the old channel by bed and suspended load sediments (Allen, 1965). These sediments necessarily fine upward because the decrease in water velocity and the corresponding decrease in stream competency will transport decreasingly coarse sediments as the channel fills. As the channel fills, it requires periods of higher and higher water to complete the process—until finally the filling is capped by fine suspended sediments brought in by overbank floods (Allen, 1965). The channel bodies become surrounded and initially separated by overbank sediments, which, in the study area, consist of sandy siltstone and shale.

Flow in channels is classified into an upper flow regime and a lower flow regime with a transition in between. This general classification, originated by Simons and Richardson (1961), provides a useful characterization of bed forms present in a stream channel. High stream velocities produce bed forms characteristic of the upper flow regime, while low velocities produce lower flow-regime bed forms. Stream competency also increases from lower to upper flow regime. Lower to upper flow-regime bed forms follow an orderly sequence (Harms and Fahnestock, 1965; and Visher, 1965). The lower flow regime is characterized by (1) ripples (producing microtrough and small-scale trough cross-bedding), (2) dunes (producing large-scale trough cross-bedding), and (3) planar (tabular) cross-stratification (which intermixes with all bed-form types from ripples to horizontal stratification). The upper flow regime is characterized by (1) horizontal stratification (current lamination) and (2) antidunes (having low-angle [<10°], downstream-dipping cross-strata). The bed forms of the upper and lower flow regimes are characteristic but grade from one to another. In channels abandoned by meander cut-off and associated point-bars, then, a specific sequence of flow-regime bed forms should be apparent. Visher (1965) produced a model in which he proposed that the vertical sequence of preserved channel sediments is (from top to base) (Text-fig. 8): (1) ripples, (2) horizontal stratification, and (3) trough cross-beds (or sand waves). In the modern Rio Grande River, Harms and Fahnestock (1965) found the following sequence in trenches made in point-bars for their study: (1) ripples, (2) small-scale trough cross-stratification, (3) horizontal stratification (occurring at or near the base of the small-scale cross-strata), (4) large-scale trough cross-stratification (stratigraphically lowest in the sequence), and (5) tabular sets (which occur intermittently in the upper part of the sequence). According to Harms and Fahnestock (1965), upper flow regime horizontal stratification present within the sequence represents high flow velocity produced by either a narrowing of the channel and a high discharge or a flow along channel-bar margins at lower discharge rates.

Avulsion is defined by Allen (1965, p. 119) as the sudden abandonment of a part or the whole of a meander belt by a stream for some new course at a lower level on the floodplain. I propose to extend this definition to include any channel abandonment that results in a permanent change in stream course downstream from the point of occurrence. The definition would now include distributary cut-off that occurs on the deltaic plain. As periodic floods move downstream in a river, they build natural levees by depositing sediments as flood waters top the channel banks and are reduced in velocity and competency (Coleman, 1969). As successive floods increase the height of the natural levees, the channel becomes more and more confined, raising the stream, during floods, higher and higher above the flood (or deltaic) plain. In the floodplain, floods which top the natural levee are normally confined to the floodplain by the stream valley. Avulsion usually occurs when, during a particularly catastrophic flood, flood waters break out of the stream valley to find a new, more advantageous course. Major avulsions occur regularly in modern streams, particularly in semiarid regions and even in humid regions (Leopold,



TEXT-FIGURE 8.—Vertical point-bar sequences modified from (A) Visher (1965), and (B) Harms and Fahnestock (1965).

Wolman, and Miller, 1964, p. 84). In rapidly aggrading alluvial streams, stream valleys are shallow and easily overrun. In the deltaic plain, however, floods that top the natural levee are rarely confined at all and, instead, spread away from the channel, forming crevasse splays. These deposits consist of flat-bottomed, convex-upward sand lenses having coarse central cores (Lawyer, 1972). Eventually the stream at flood stage is confined high enough above the deltaic plain to divert the entire channel to a more favorable gradient when it overruns the natural levee. Because avulsion occurs as a more-or-less continuous event, channel fill consists of bed load that has been frozen in place and of suspended load that has been dropped into it. As the water flow and transportation rate diminish, suspended load material mixes with the bed load being transported.

Channel sediments preserved by avulsion would have preserved within them only bed forms (and flow regimes) present at the time of channel abandonment. They would not generally show a vertical sequence similar to that of point-bars in meander channels. Instead, the preserved sediments would be a poorly sorted mixture of suspended and traction load sediments.

The channels of the study area consist of sandstones and conglomerates the best exposed of which were chosen as examples and studied in detail. Two distinct types are present. Channels 2 and 3 are interpreted to have been preserved as a result of meander cut-off, while channel 1 appears to be the result of avulsion.

Channels 2 and 3 have vertical sedimentary sequences characteristic of point-bars and cut-off meanders (Text-fig. 4). They are morphologically and structurally related. Both are broad and shallow, having width-to-depth ratios of about 25:1. Channel 3 is a pair of superimposed channels (3a and 3b). They are closely overlain by the erosional remnant of another channel segment (unit 37). In the south (eastbound) road cut of I-70, channel 2 is closely underlain by another channel segment not present to the north. These and other channels in the area (Text-fig. 3) appear to form part of a channel-segment complex characteristic of deposition in a meandering fluvial environment.

Comparison of the fluvial models of sedimentation proposed by Harms and Fahnestock (1965) and Visher (1965) indicates that a sequence of lower and upper flow-regime bed forms are present in channels 2 and 3b of the study area (the sedimentary structures of channel 3a were not well-enough exposed for study). The sequence of sedimentary structures exposed on the surfaces and eroded margins of the channels is generally (from surface to base): (1) small-scale cross-beds (ripples), (2) horizontal stratification, which occurs in the upper part of the sequence but never at the channel surface, and (3) large-scale trough cross-stratification, which increases in size toward the channel base. Only small evidences of ripples are present, as they have apparently been mostly eroded from the channel surfaces. Both channels have conglomeratic bases (tractive load sediments) grading generally to fine sand at their upper exposed surfaces (suspended load sediments) (Sunborg, 1956). Mineral and sediment-size sorting are good. All channels of the study area were surrounded by microcrosslaminated siltstone and shale prior to erosion.

Channel 1 stands isolated with no evidence of superposition or related channels. At greatest exposed width, its width-to-depth ratio is about 10:1. Large-scale cross-bed sets predominate in channel 1 and have an apparently irregular variation in set sizes. They are interbedded with horizontal strata at varying intervals. The sediments of channel 1 show no regular or systematic gradations either vertically or horizontally (Text-fig. 4). The sediments range in size from coarse sand to pebble conglomerate and generally consist of various mixtures of the two. Conglomerate is often present as layers in cross-bed sets. The sediments appear to grade randomly from one size range to another, forming textural patches throughout the channel. Mineral and size sorting in the sediments range from fair to poor. The poorly sorted sediments probably represent a mixture of both tractive and suspended load particles.

In addition, channel 1 apparently does not form part of a meander loop but has unusually straight reaches upstream and downstream from a moderate curve. The channel appears to have been overloaded with sediment and, if so, would have lacked the capacity to erode laterally as meander formation requires. Unlike channels 2 and 3, where trough cross-beds dominate the channel surfaces, planar cross-beds are most common on the surface of channel 1. Unlike the cross-beds of channels 2 and 3, they often extend entirely across the channel surface. They may represent bed forms which have coalesced, as a result of the abundant sediment supply, to form migrating sand waves (transverse bars). In an overloaded stream, sediment transport would be expected to occur intermittently rather than more or less continuously as appears to have occurred in channels 2 and 3. This would explain the presence, in channel 1, of many cross-beds which are graded, having coarse sediments at their bases grading to fine both vertically and horizontally toward their margins. Graded cross-beds were not observed in channels 2 and 3.

Channel 1 may have been strictly fluvial or perhaps deltaic, as Craig and others (1955) report the presence of discontinuous beds of limestone in the Brushy Basin Member, beds which they interpret to have been deposited in temporary freshwater lakes.

CLIMATE

Continental reconstruction by Dietz and Holden (1970) has demonstrated that in the late Jurassic the study area was located between 35° and 40° north latitude. Its present position of 39° north lies within this range. Because North America was rotated in relation to its present position, the west-to-east weather pattern of the northern hemisphere normally would have brought storms into the region of the study area from the direction that is southwest today. Southwest to west was probably the direction of source area for the Brushy Basin sediments present in the study area (Stokes, 1944, p. 975; Craig et al., 1955, p. 157; Hintze, 1973, p. 67). It may therefore have been the direction of the nearest major highland. According to Armstrong (1968), the last of the Nevadan orogeny and the beginning of the Sevier orogeny occurred during Brushy Basin time. Mountains to the southwest and west would have produced a substantial rain shadow, and as a result, the climate of the study area was probably dryer than it would otherwise have been. It was perhaps semiarid, but such a conclusion remains uncertain because abnormally high temperatures may have been present throughout the world at that time.

Fossil reptiles, including dinosaurs, turtles, and crocodiles, have been found as far north as the present-day 44th parallel (Kay and Colbert, 1965). Today they are quarried from the Brushy Basin Member at numerous sites from Wyoming to Arizona. Because reptiles operate most efficiently at tropical and subtropical temperatures, similar temperatures may have been present in the region of the study area during Brushy Basin time.

Elevated temperatures of the late Jurassic appear to have been worldwide (Kay and Colbert, 1965). The increased worldwide rate of evaporation resulting from these temperatures could have resulted in high rates of precipitation. The presence of a rain shadow to the southwest under these conditions may therefore have had only a moderating effect, with the study area region still receiving substantial rainfall. Conversely, there as an apparent lack of plant-fossil material in the study area, implying barren conditions. It is possible that had plants been abundant there, they could have been preserved in the extensive undeformed and unaltered siltstone and shale. Evidences of rooted sediments and bioturbation are not present. In any event, vegetation was probably limited to areas near lakes and streams. Stokes (1944) believes that desert conditions may have surrounded the streams and lakes that existed on the Brushy Basin alluvial plain.

CONCLUSIONS

1. Channels described in the study area are channels of fluvial origin and consist of two distinct morphological and structural types.
2. Channels 2 and 3b fit the general flow-regime models of Harms and Fahnestock (1965) and Visher (1965) and were apparently channel segments of a meandering stream in the lower part of the transporting segment of a river system.
3. Channel 1 probably was abandoned and preserved as a result of avulsion in a flood or deltaic plain, because it has an irregular sedimentary sequence, was apparently overloaded with sediment, and did not meander.
4. The channels studied show characteristics of a fluvial environment when sediment textures are plotted graphically as coarse to median grain-size ratios.
5. A rose diagram of current direction measurements from all channels exposed in the study area shows that sediment transport was from the west-southwest.
6. According to calculations made with formulae derived by Schumm (1968, 1972), the three channels studied had shallow gradients averaging 2.0 feet per mile and average annual discharge rates of from 300 to 4,300 cubic feet per second.
7. Climate in the region of the study area was probably hot, but there may also have been moderate rainfall. In any event, vegetation (and therefore most wildlife) was most likely limited to the areas of streams and lakes.
8. Sand grains in the study area channels are thoroughly overgrown with secondary quartz and could not be used for determining depositional environment by observation of surface textures with the scanning electron microscope.

APPENDIX

MEASURED STRATIGRAPHIC SECTION OF THE LOWER BRUSHY BASIN MEMBER, MORRISON FORMATION, NEAR THE HANKSVILLE I-70 INTERCHANGE

Beginning at base of member near the interchange (Marshall, 1955; Orkild, 1955) and continuing with offsets northwestward parallel to and north of the westbound highway lane.

Unit	*Description*	*Feet/ Unit*	*Total Feet*
37	Sandstone: quartzitic, medium-grained sand to grit, moderately sorted, red brown to white, cross-bedding common, highly eroded, forms resistant cap	4.5'	254.5'

36	Siltstone: clay to fine sand, dark brown to medium gray, forms slope	9.0'	250.0'
35b	Sandstone (channel 3b): quartzitic, medium sand to grit, 2.5 to 7 feet of pebble conglomerate at base, fines upward, fair to good sorting, white, weathers light red brown, limonite spots, superimposed on and eroded 13 feet into unit 35a (channel 3a) below, cross-bedded, jointed, forms ledge in natural exposures, moderately calcareous	22.0'	241.0'
35a	Sandstone (channel 3a): quartzitic, medium sand to grit, 4 to 6 feet of pebble conglomerate at base, fines upward, fair to good sorting, interfingering lenses, light gray green shaly lens, white, weathers light red brown, jointed, cross-bedded, calcareous, forms ledge	18.0'	219.0'
34	Shale: clay with very fine sand; green with 1- to 4-inch yellow brown bed at top; contains 3.5-foot-wide, 1-foot-thick conglomerate boulder, possibly rafted; noncalcareous; forms slope	2.0'	201.0'
33	Shale: clay with very fine sand, medium to dark gray, forms slope, slightly calcareous	7.5'	199.0'
32	Siltstone: clay to fine sand, white, lens, forms slope	.5'	191.5'
31	Shale: clay with very fine sand, medium to dark gray, forms slope, slightly calcareous	2.0'	191.0'
30	Siltstone: clay to fine sand, white, lens, slope former	.5'	189.0'
29	Sandstone (channel 2): quartzite, medium sand to grit, 2 to 6 feet pebble conglomerate at base, sorting fair to good, interfingering lenses, fines upward, white, weathers light red brown, cross-bedded, jointed, minor clay pebbles, forms ledge, moderately calcareous, stratigraphically overlaps lowest 13 feet of units above, best exposed on south side of road cut	(13.0')	
28	Shale: clay with very fine sand, light green with 2-inch yellow brown bed at top, forms slope	.5'	188.5'
27	Siltstone: clay to fine sand, red brown, highly variegated (mottled with white patches), microcrosslaminations, medium bedded, forms slope, slightly calcareous	17.0'	188.0'
26	Shale: clay with fine sand, light to dark gray, variegated, medium bedded, forms slope, moderately calcareous	8.0'	171.0'
25	Siltstone: clay to fine sand, red gray to red brown, slightly variegated, forms slope, noncalcareous	6.0'	163.0'
24	Sandstone: quartzitic, medium sand to pebble conglomerate, interfingering lenses of sandstone and conglomerate, fair sorting, light red brown, cross-bedded jointed, forms ledge	35.0'	157.0'
23	Shale: clay with very fine sand, light green with 1-inch yellow brown bed at top, forms undercut slope, slightly calcareous	.5'	122.0'

22	Sandstone: quartzitic, medium grained, white, cross-bedded, red brown siltstone cut-and-fill structures, forms ledge, noncalcareous	2.0'	121.5'
21	Siltstone: clay to fine sand, dark red brown to black, thin bedded, forms slope, moderately calcareous	7.0'	119.5'
20	Sandstone: quartzitic, medium grained, white, load casts at base, forms small ledge, noncalcareous	4.0'	112.5'
19	Siltstone: clay to fine sand, variegated, white to red brown, limonite staining along bedding planes, 6-inch resistant white sandstone bed, forms slope	3.0	108.5'
18	Sandstone: quartzitic, medium grained, white, forms ledge	4.5'	105.5'
17	Siltstone: clay to fine sand, medium gray, 0.1- to 0.2-inch pebbles, forms slope	3.0'	101.0'
16	Sandstone: quartzitic, medium grained, white, forms ledge	2.0'	98.0'
15	Siltstone: clay to fine sand, medium gray, forms slope, slightly calcareous	31.0'	96.0'
14	Sandstone: quartzitic, fine to medium grained, white, two sandstone lenses 3 and 5 inches thick with 3-inch interbedded red gray siltstone	1.0'	65.0'
13	Siltstone: clay to fine sand, medium gray to red gray, forms slope, slightly calcareous	8.0'	64.0'
12	Shale: clay with minor very fine sand, medium gray, forms shallow slope	3.0'	56.0'
11	Siltstone: clay to fine sand, light to medium gray, 1- to 2-inch white sandstone lenses, thin bedded, forms slope, slightly calcareous	5.0'	53.0'
10	Siltstone: clay with moderate fine sand, red brown, forms resistant bed	1.0'	48.0'
9	Shale: clay with moderate fine sand, light gray, thin bedded, forms slope, slightly calcareous	5.0'	47.0'
8	Siltstone: clay with fine sand, red brown at base to orange red brown at top, brown to white coarse sand-sized grains, thin bedded, forms slope	7.0'	42.0'
7	Siltstone: clay with minor fine sand, light gray to slightly green gray, slightly variegated near top, scattered brown to white coarse sand-sized grains, forms slope	5.0'	35.0'
6	Siltstone: clay with fine sand, red brown, single bed, forms slope	.5'	30.0'
5	Siltstone: clay with fine sand, light gray to slightly gray green, bedding of this and lower units obscured by weathering, scattered white to red brown coarse sand-sized grains, forms slope	4.0'	29.5'
4	Sandstone: quartzitic, fine grained, variegated, white to red brown, lens, forms small ledge	2.5'	25.5'
3	Shale: clay with very fine sand; light gray; scattered		

	coarse sand-sized, angular, white to red brown grains; forms slope; moderately calcareous	12.0'	23.0'
	Unit 3 above approximately corresponds with channel 1, which is exposed as an isolated unit 800 feet south of this composite section: Sandstone (channel 1): quartzitic; medium sand to grit; pebble conglomerate and sand form lenses, interfinger, and are intermixed; fair to poor sorting; light red brown; cross-bedded; jointed; limonite spots common; occasional clay pebbles, base poorly exposed; moderately calcareous	(10.0')	
2	Shale: clay with fine sand; light gray, scattered coarse sand-sized, angular, white to red brown grains; forms slope; moderately calcareous	8.0'	11.0'
1	Siltstone: clay with fine sand, light red gray, forms slope, slightly calcareous	3.0'	3.0'

REFERENCES CITED

Ahlborn, R. C., and Hamblin, W. K., 1973, Textural characteristics of the North Horn Conglomerate as an indicator of depositional environments (abstr.): Geol. Soc. Amer., Abstr. Prog., v. 5, no. 6, p. 459.

Allen, J. R. L., 1965, A review of the origin and characteristics of Recent alluvial sediments: Sedimentology, v. 5, no. 2, p. 89-191.

Armstrong, R. L., 1969, Sevier orogenic belt in Nevada and Utah: Geol. Soc. Amer. Bull., v. 79, no. 4, p. 429-58.

Baker, A. A., Dane, C. H., and Reeside, J. B., Jr., 1936, Correlation of the Jurassic formations of parts of Utah, Arizona, New Mexico, and Colorado: U.S. Geol. Surv. Prof. Paper 183, 66 p.

Brice, J. C., 1964, Channel patterns and terraces of the Loup River in Nebraska: U.S. Geol. Surv. Prof. Paper 422-D, 41 p.

Brown, L. F., 1969, Geometry and distribution of fluvial and deltaic sandstones (Pennsylvanian and Permian), north-central Texas: Gulf Coast Assoc. Geol. Socs., Trans., v. 19, p. 23-47.

Bull, W. B., 1962, Relation of textural (CM) patterns to depositional environment of alluvial-fan deposits: Jour. Sed. Pet., v. 32, no. 2, p. 211-16.

———, 1972, Recognition of alluvial-fan deposits in the stratigraphic record: *in* Rigby, J. K., and Hamblin, W. K. (eds.), Recognition of ancient sedimentary environments: Soc. Econ. Paleont. Mineral. Spec. Pub. 16, p. 63-83.

Clifton, H. E., 1973, Pebble segregation and bed lenticularity in wave-worked versus alluvial gravel: Sedimentology, v. 20, no. 2, p. 173-87.

Coleman, J. M., 1969, Brahmaputra River: channel processes and sedimentation: Sedimentary Geol., v. 3, p. 129-239.

Craig, L. C., Holmes, C. N., Cadigan, R. A., Freeman, V. L., Mullens, T. E., and Weir, G. W., 1955, Stratigraphy of the Morrison and related formations, Colorado Plateau region, a preliminary report: U.S. Geol. Surv. Bull. 1009-E, p. 125-68.

Cross, C. W., 1894, Description of the Pikes Peak sheet: U.S. Geol. Surv. Atlas, Folio 7, 5 p.

Dawson, J. C., 1970, The sedimentation and stratigraphy of the Morrison Formation (Upper Jurassic) in northwestern Colorado and northeastern Utah: unpub. Ph.D. dissertation, Univ. Wisconsin, 142 p.

Doeglas, D. J., 1962, The structure of sedimentary deposits of braided rivers: Sedimentology, v. 1, p. 167-90.

Eldridge, G. H., and Emmons, S. F., 1896, Geology of the Denver Basin in Colorado: U.S. Geol. Surv. Monograph 27, 556 p.

Finch, W. I., 1959, Geology of uranium deposits in Triassic rocks of the Colorado Plateau region: U.S. Geol. Surv. Bull. 1074-D, 164 p.

Fisher, W. L., Brown, L. F., Scott, A. J., and McGowen, J. H., 1969, Delta systems in the exploration for oil and gas: Bureau Econ. Geol., Univ. Texas, Austin, Texas, 77 p.

Fisk H. N., 1944, Geological investigations of the alluvial valley of the lower Mississippi River: Mississippi River Commission, Vicksburg, Miss., 78 p.
———, 1947, Fine-grained alluvial deposits and their effects on Mississippi River activity: Mississippi River Commission, Vicksburg, Miss., 82 p.
Gilluly, J., and Reeside, J. B., 1928, Sedimentary rocks of the San Rafael Swell and some adjacent areas in eastern Utah: U.S. Geol. Surv. Prof. Paper 150, p. 61-110.
Gole, C. V., and Chitale, S. V., 1966, Inland delta-building activity of the Kosi River: Proc. Amer. Soc. Civil Engineers, Jour. Hydraulics Div., HY-2, p. 111-26.
Griffiths, J. C., 1952, The megascopic and field examination of samples from the Salt Wash sediments in southwest Colorado and southeast Utah, a preliminary report: U.S. Atomic Energy Comm., Tech. Info. Service, RME-3023, 54 p.
Hamblin, W. K., 1965, Internal structures of "homogeneous" sandstones: State Geol. Surv. Kansas Bull., 175, pt. 1, 37 p.
Harms, J. C., and Fahnestock, R. K., 1965, Stratification, bed forms, and flow phenomena (with an example for the Rio Grande): *in* Middleton, G. V. (ed.), Primary sedimentary structures and their hydrodynamic interpretation: Soc. Econ. Paleont. Mineral, Spec. Pub. 12, p. 84-115.
Hintze, L. F., 1973, Geologic history of Utah: Brigham Young Univ. Geol. Studies, v. 20, pt. 3, 181 p.
Kay, M., and Colbert, E. H., 1965, Stratigraphy and life history: John Wiley and Sons, New York, 736 p.
Kessler, L. G., 2nd, 1971, Characteristics of the braided stream depositional environment with examples from the South Canadian River, Texas: Earth Sci. Bull., v. 4 no. 1, p. 25-31.
Krinsley, D. H., and Donahue, J., 1968, Environmental interpretation of sand grain surface textures by electron microscopy: Geol. Soc. Amer. Bull., v. 79, no. 6, p. 743-48.
Krinsley, D. H., and Margolis, S., 1969, A study of quartz sand grain surface textures with the scanning electron microscope: New York Acad. Sci. Trans., ser. 2, v. 31, no. 5, p. 457-77.
Kuenen, P. H., and Perdok, W. G., 1962, Experimental abrasion 5. Frosting and defrosting of quartz grains: Jour. Geol., v. 70, p. 648-58.
Lawyer, G. F., 1972, Sedimentary features and paleoenvironment of the Dakota Sandstone (Early Upper Cretaceous) near Hanksville, Utah: Brigham Young Univ. Geol. Studies, v. 19, pt. 2, p. 89-120.
Leopold, L. B., and Maddock, T., Jr., 1953, The hydraulic geometry of stream channels and some physiographic implications: U.S. Geol. Surv. Prof. Paper 252, 57 p.
———, and Wolman, M. G., 1957, River channel patterns braided, meandering, and straight: U.S. Geol. Surv. Prof. Paper 282-B, 51 p.
———, Wolman, M. G., and Miller, J. P., 1964, Fluvial processes in geomorphology: W. M. Freeman and Co., San Francisco, 522 p.
McKee, E. D., Oriel, S. S., Swanson, V. E., MacLachlan, M. E., MacLachlan, J. C., Ketner, K. B., Goldsmith, J. W., Bell, R. Y., Jameson, D. J., and Imlay, R. W., 1956, Paleotectonic maps of the Jurassic System: U.S. Geol. Surv. Misc. Geol. Inv. I-175, 6 p.
Marshall, C. H., 1955, Photogeologic map of the Tidwell-3 Quadrangle, Emery County, Utah: U.S. Geol. Surv. Misc. Geol. Inv. I-88, 1 p.
Marzolf, J. E., 1973, Surface textures of quartz sand grains from the Navajo Sandstone: Geol. Soc. Amer. Abstr. Prog., v. 5, no. 6, p. 495.
Mook, C. C., 1916, A study of the Morrison Formation: N.Y. Acad. Sci. Annual 27, p. 39-191.
Mullens, T. E., and Freeman, V. L., 1957, Lithofacies of the Salt Wash Member of the Morrison Formation, Colorado Plateau: Geol. Soc. Amer. Bull., v. 68, no. 4, p. 505-26.
Ore, H. T., 1965, Characteristic deposits of rapidly aggrading streams: Wyoming Geol. Assoc., 19th Field Conf. Guidebook, p. 195-201.
Orkild, P. P., 1955, Photogeologic map of the Tidwell-4 Quadrangle, Emery County, Utah: U.S. Geol. Surv. Misc. Geol. Inv. I-112, 1 p.
Passega, R., 1957, Texture as characteristic of clastic deposition: Bull. Amer. Assoc. Petrol. Geol., v. 41, no. 9, p. 1952-84.
Peterson, J. A., 1972, Jurassic System: *in* Mallory, W. W. (ed.), Geologic atlas of the Rocky Mountain region: Rocky Mtn. Assoc. Geol., p. 177-89.

Potter, P. E., and Pettijohn, F. J., 1963, Paleocurrent and basin analysis: Springer-Verlag, Berlin, 296 p.
Russell, R. J., 1954, Alluvial morphology of Anatolian rivers: Ann. Assoc. Amer. Geog., v. 44, p. 363-91.
Sames, C. W., 1966, Morphometric data of some Recent pebble associations and their application to ancient deposits: Jour. Sed. Pet., v. 36, p. 126-42.
Schumm, S. A., 1968, River adjustment to altered hydrologic regimen—Murrumbidgee River and paleochannels, Australia: U.S. Geol. Surv. Prof. Paper 598, 65 p.
———, 1972, Fluvial paleochannels: *in* Rigby, J. K., and Hamblin, W. K. (eds.) Recognition of ancient sedimentary environments: Soc. Econ. Paleont. Mineral Spec. Pub. 16, p. 98-107.
Shepherd, R. G., 1973, Backset stratification at lower regime flow: Geol. Soc. Amer., Abstr. Prog., v. 5, no. 7, p. 804.
Simons, D. B., and Richardson, E. V., 1961, Forms of bed roughness in alluvial channels: Proc. Amer. Assoc. Civil Engrs., Jour. Hydraulic Div., v. 87, p. 87-105.
Smith, N. D., 1970, The braided stream depositional environment: comparison of the Platte River with some Silurian clastic rocks, north-central Appalachians: Geol. Soc. Amer. Bull., v. 81, p. 2993-3014.
Stieglitz, R. D., 1969, Surface textures of quartz and heavy-mineral grains from fresh-water environments—an application of scanning electron microscopy: Geol. Soc. Amer. Bull., v. 80, no. 10, p. 2091-94.
Stokes, W. L., 1944, Morrison Formation and related deposits in and adjacent to the Colorado Plateau: Geol. Soc. Amer. Bull., v. 552, no. 8, p. 951-92.
———, 1954, Some stratigraphic, sedimentary, and structural relations of uranium deposits in the Salt Wash Sandstone—final report, April 1, 1952 to June 30, 1954: U.S. Atomic Energy Comm., Tech. Info. Service, RME-3102, 50 p.
———, 1958, Continental sediments of the Colorado Plateau: Intermtn. Assoc. Petrol. Geol., 9th Ann. Field Conf., Guidebook, p. 26-30.
———, 1961, Fluvial and eolian sandstone bodies in the Colorado Plateau: *in* Peterson, J. A., and Osmond, J. C. (eds.), Geometry of sandstone bodies—a symposium: Amer. Assoc. Petrol. Geol., 45th Ann. Mtg., p. 151-78.
———, and Sadlick, W., 1953, Sedimentary properties of Salt Wash sandstones as related to primary structures: U.S. Atomic Energy Comm., Tech. Info. Service, RME-3067, 26 p.
Sunborg, Ake, 1956, The River Klaralven—a study of fluvial processes: Geografiska Annaler, ser. A, v. 38, p. 127-316.
Visher G. S., 1965, Use of vertical profile in environmental reconstruction: Bull. Amer. Assoc. Petrol. Geol., v. 49, no. 1, p. 41-61.
Waechter, N. B., 1970, Braided stream deposits in the Red River, Texas panhandle (abstr.): Geol. Soc. Amer. Abstr. Prog., v. 2, p. 713.
Yeakel, L. S., 1962, Tuscarora, Juniata, and Bald Eagle paleocurrents and paleogeography in the central Appalachians: Geol. Soc. Amer. Bull., v. 73, p. 1515-40.