THE DEPOSITIONAL ENVIRONMENT
OF THE UPPER JURASSIC SALT WASH MEMBER OF THE MORRISON FORMATION
SLICK ROCK DISTRICT, SAN MIGUEL COUNTY, COLORADO

by

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ABSTRACT

The depositional environment of the Salt Wash Member of the Morrison Formation (Upper Jurassic) near Slick Rock, Colorado is determined by semiquantitative methods. These methods include analyses of stratigraphy, sandstone petrography and clay mineralogy, and paleocurrent distributions. Results of these analyses are then compared to documented examples and depositional models.

Thirteen stratigraphic sections of the Salt Wash Member and adjacent units are measured and described in detail. The Salt Wash Member is subdivided into three informal units: the lower sand unit, the middle silt unit and the upper sand unit. The subdivision is based on the thickness and lateral continuity of sandstone strata and on the percentage of interbedded mudstone layers.

The stratigraphic sections are analyzed by a quantitative method to detect vertical cyclicity and nonrandom frequency of certain sedimentary features. After statistical verification, a facies diagram and local model for the Salt Wash Member are developed which illustrate a characteristic cycle of fluvial deposition. The completely preserved cycle begins with a scoured basal surface (channel establishment), consists largely of trough and planar cross-strata (channel filling), and is topped by ripple cross-laminated siltstone and mudstone (channel abandonment/shifting and floodplain/overbank deposition).

Sandstones from the Salt Wash Member are classified as immature and submature, subarkoses and lithic arkoses. The sandstones are characterized by fine- to medium-grain size, moderate-sorting and

subangular to rounded, subequant to equant detrital grains. The detrital fraction is dominated by quartz, with subordinate amounts of potassium feldspar and lithic fragments, and minor percentages of plagioclase, chert and heavy minerals

The clay mineralogy of mudstone samples from the Salt Wash Member and adjacent units is determined by x-ray diffraction. The clay mineral constituents of samples from the Salt Wash Member consist of subequal amounts of illite, mixed layer clays and chlorite. Changes in the relative proportions of clay minerals are shown as a function of stratigraphic position. The most significant changes occur between the Salt Wash Member and adjacent units, and in an upward decrease in kaolinite and an upward increase in chlorite and montmorillonite.

Paleocurrent readings from the Salt Wash Member have unimodal distributions. Mean current directions for all three informal units are dominantly eastward and show an increasingly southerly flow component as deposition of the Salt Wash Member progressed.

The Salt Wash Member near Slick Rock, Colorado is interpreted as a distal braided fluvial deposit. This interpretation is made by comparing the Salt Wash Member of this study to documented examples of ancient and modern fluvial deposits and models. The interpretation is summarized by the following aspects: 1) The gross geometry of the Salt Wash Member is dominated by thick sandstone strata of channel deposition and fine grained sediments of floodplain/overbank deposition are at a minimum, 2) Vertical sequences of textures and sedimentary structures compare closely to cycles described in modern day braided river sediments, 3) Paleocurrent distributions indicate low sinuosity channels, and 4) Stratification ratios (Smith, 1970) indicate deposition in more distal reaches of a braided channel system.

CHAPTER 1 INTRODUCTION

PURPOSE AND METHODS OF STUDY

The purpose of this thesis is to interpret the depositional environment of the Upper Jurassic Salt Wash Member of the Morrison Formation near the town of Slick Rock, Colorado.

The environmental interpretation is developed from the following analyses:

1. Stratigraphy, to determine the vertical sequence, thickness and lateral continuity of lithologic units and major sedimentary structures.

2. Petrography, to augment field descriptions and determine lithologic characteristics and variations.

3. Paleocurrent analysis, to determine directional changes during deposition of the Salt Wash Member and aid in interpretation of the depositional environment.

4. Comparison to depositional models of modern and ancient examples.

AREA OF STUDY AND ACCESSIBILITY

The study area is located in the north-central part of the Slick Rock district near the town of Slick Rock in San Miguel County, Colorado. The investigation is confined to a 10.0 km by 6.5 km area, Figure 1, located in the eastern half of Range 19 West and the western half of Range 18 West, Township 44 North on the Horse Range Mesa 7.5 minute geologic quadrangle map (Cater, 1955).

The area is accessible along its southern end by State Highway 80. Secondary roads and numerous unpaved mine roads traverse the area and provide access to outcrops.

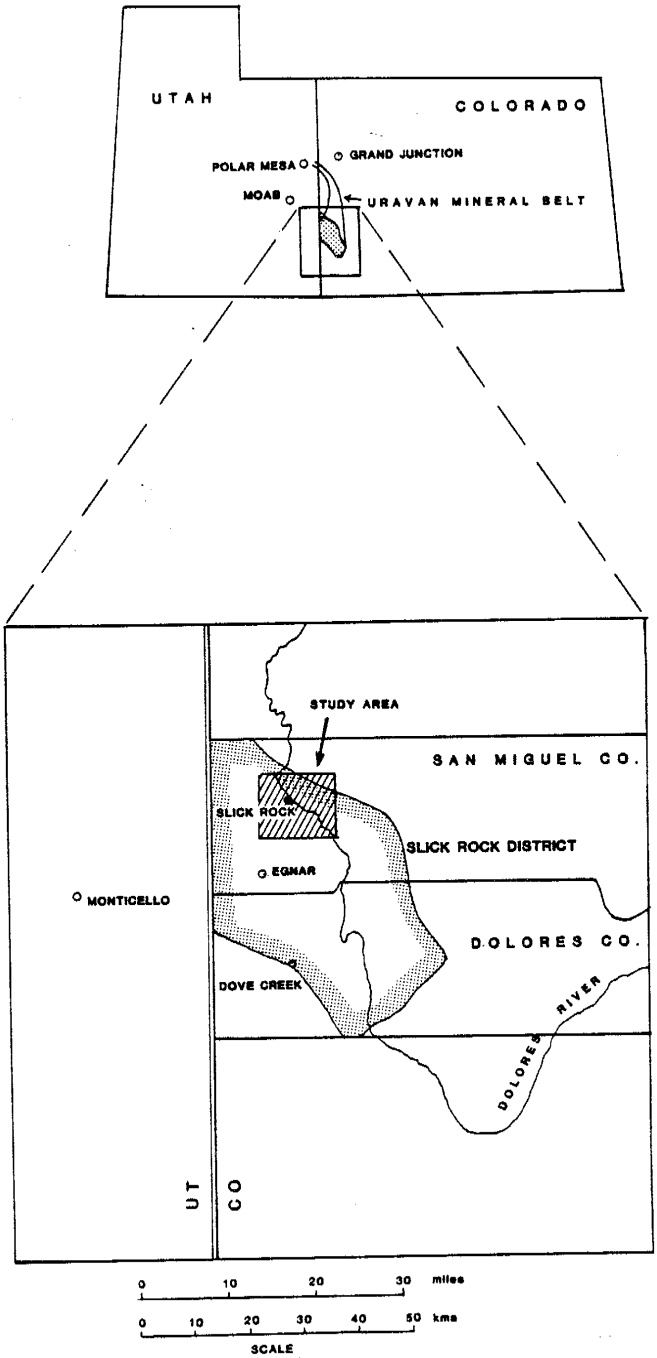


Figure 1. Location of the study area.

The topography of the study area is characterized by a succession of benches and mesas dissected by numerous canyons. The generally north-flowing Dolores River and its tributaries cut deeply into the strata and provide excellent exposures along canyon walls. Fieldwork was begun in May 1978 and continued throughout the summer.

ECONOMIC ASPECTS AND SIGNIFICANCE OF THE STUDY

Since the late 1940's the Salt Wash Member has been of economic importance due to its significant deposits of uranium-vanadium ores. The more productive deposits occur within the Salt Wash Member in a narrow elongate area known as the Uravan mineral belt. The belt extends from Polar Mesa in southeastern Utah to the Slick Rock district in southwestern Colorado (Figure 1).

Because of its economic significance, the geology of the Salt Wash Member has been intensely studied. In this thesis, much detail and information is presented in an effort to understand more fully the paleoenvironment of the Salt Wash Member in the Slick Rock district. Although not a direct concern of this study, it is hoped that semi-quantitative analyses on sedimentary structures, paleocurrent patterns and depositional environment may lead to a better understanding of the stratigraphic distribution and localization of uranium-vanadium deposits within the Salt Wash Member and possibly provide an aid to guide exploration for these deposits.

REGIONAL STRATIGRAPHY

The Jurassic stratigraphy of the southwestern United States is characterized by repeated sequences of eolian, marine and fluvial deposits. In the Colorado Plateau region the Jurassic section has been subdivided into three major lithostratigraphic units. From oldest to youngest they are: the Glen Canyon Group, San Rafael Group and the Morrison Formation. Figure 2 shows the regional correlation and nomenclature of stratigraphic units in the Colorado Plateau area. For a more detailed description of Triassic and Lower and Middle Jurassic rocks of the Glen Canyon Group and lower units of the San Rafael Group of the Colorado Plateau region, the reader is referred to Baker, Dane and Reeside (1936, 1947).

The Summerville Formation

The San Rafael Group was originally described by Gilluly and Reeside (1928) for rocks of the San Rafael Swell in southeastern Utah. At the type locality the group consists of four formations. In ascending order they are: the Carmel Formation, the Entrada Sandstone, the Curtis Formation and the Summerville Formation. From fossil evidence the Carmel Formation is dated as Medial to early Late Jurassic and the Curtis Formation as medial Late Jurassic. The San Rafael Group represents a period of alternating transgressions and regressions over the Colorado Plateau region. Marine deposits of the Carmel and Curtis formations are conformably overlain by the dominantly subaerial deposits of the Entrada Sandstone and the marginal marine deposits of the Summerville Formation respectively.

The Summerville Formation has been recognized in southeastern Utah, southwestern Colorado, and parts of northeastern Arizona and northwestern

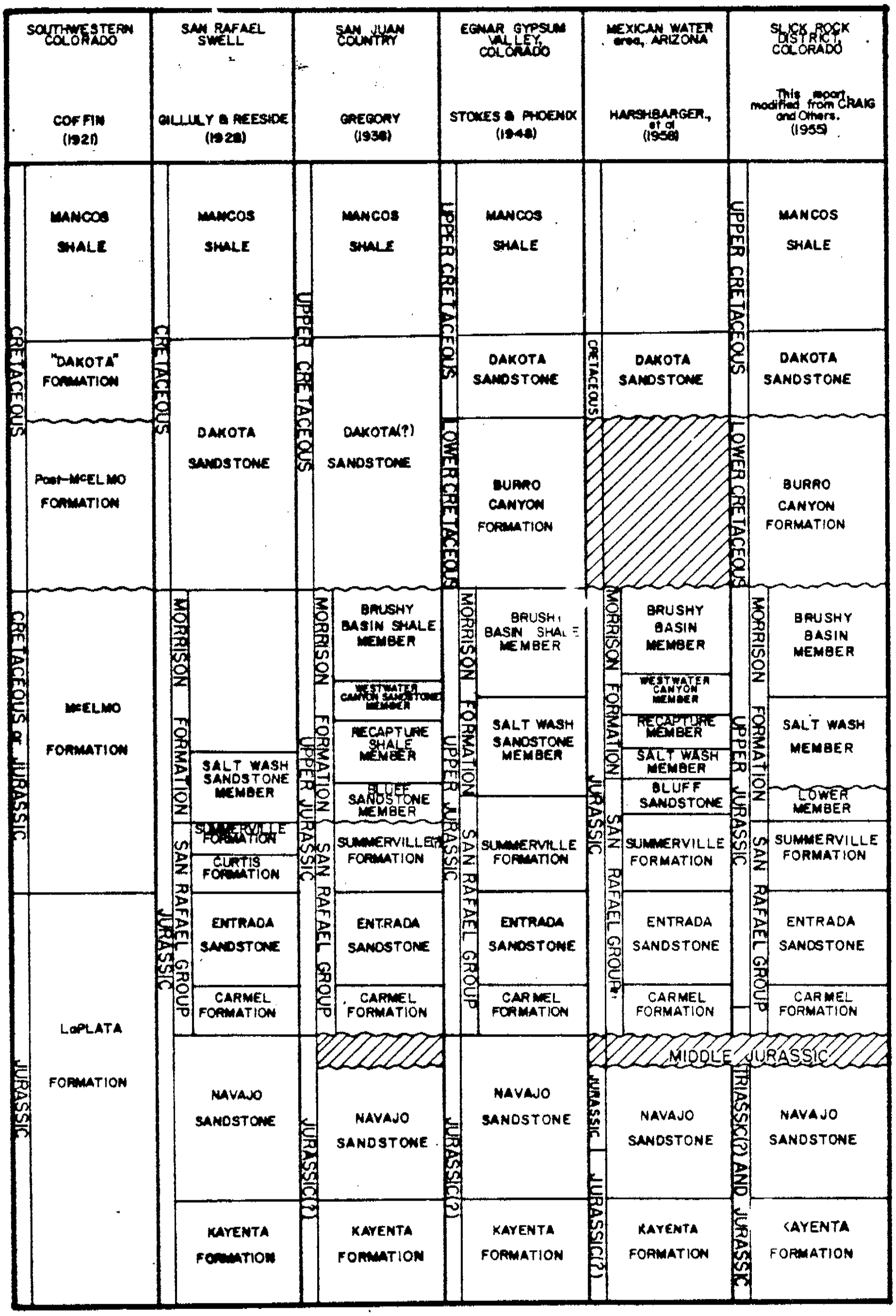


Figure 2. Regional correlation and nomenclature of stratigraphic units in the Colorado Plateau area.

New Mexico. The unit was named by Gilluly and Reeside (1928) for exposures on Summerville Point of the San Rafael Swell. In the type locality, the Summerville Formation conformably overlies the Curtis Formation. Based on fossil dating of the Curtis Formation, the Summerville Formation is considered to be of Oxfordian age (Imlay, 1952). East of the San Rafael Swell, the basal part of the Summerville Formation stratigraphically replaces the Curtis Formation (Baker, Dane and Reeside, 1936). In the Four Corners area, and in the Slick Rock district, the Summerville Formation directly overlies the Entrada Sandstone. The Summerville Formation consists of alternating thin, even beds of chocolate-colored gypsiferous mudstones, red and white sandstones and red to maroon claystones. The formation is regarded as a nearshore marine deposit formed in quiet, shallow water (Wright and Dickey, 1963). Harshbarger, et al., (1957) arbitrarily subdivided the Summerville Formation into a lower silty member and an upper sandy member which indicate a marine regression.

In the Four Corners area and in southeastern and south-central Utah, a prominent sandstone unit occupies the interval between the top of the Summerville Formation and the base of the Morrison Formation. Gregory (1938) defined the unit as the Bluff Sandstone Member of the Morrison Formation from exposures near Bluff, Utah. The Bluff Sandstone Member has since been recognized as a lower tongue of the Cow Springs Sandstone of northeastern Arizona (Harshbarger, et al., 1957). Both the Bluff and Cow Springs sandstones are considered to be eolian in origin (Harshbarger, et al., 1957). Goldman and Spencer (1941) renamed the unit the Junction Creek Sandstone Member of the Morrison Formation in southwestern Colorado, and indicated that it was correlative with the Bluff Sandstone Member of southeastern Utah. In the Slick Rock district, the Junction Creek Sandstone was first recognized by Cater (1955) who mapped it with the Salt Wash Member of the Morrison Formation. Subsequently, Shawe, Simmons and Archbold (1968) mapped it as a separate formation in the southern part of the district, but included it with the Summerville Formation in areas where it is much thinner and where the two units intertongue.

The Morrison Formation

The Morrison Formation has been recognized throughout the western United States and is present over all of Colorado, eastern Utah, northwestern New Mexico and parts of northeastern Arizona. The formation was originally named by Cross (1894) for exposures near Morrison, Colorado.

At the type locality, and in most areas, the Morrison Formation is undifferentiated. On the Colorado Plateau, however, the Morrison Formation has been subdivided into four members: the Salt Wash Member (Lupton, 1914; Gilluly and Reeside, 1928), the Recapture Creek Member, the Westwater Canyon Member and the Brushy Basin Member (Gregory, 1938).

Over most of eastern Utah and western Colorado, including this study area, the lower part of the Morrison Formation consists only of the Salt Wash Member. The Salt Wash Member extends a short distance into Arizona and New Mexico. In most of northeastern Arizona and northwestern New Mexico only the Recapture Creek Member is recognized in the lower part of the Morrison Formation; the Recapture Creek Member does not extend as far north as the Slick Rock district. These two lower members are equivalent in age and intertongue and grade into each other in the Four Corners area.

The upper part of the Morrison Formation is subdivided into the Westwater Canyon and Brushy Basin members. The Brushy Basin Member is the most extensive unit of the Morrison Formation and is present in eastern Utah, western Colorado, northeastern Arizona and northwestern New Mexico. In the Four Corners area, the Westwater Canyon Member underlies the Brushy Basin Member, but northward these two members intertongue and intergrade. The Westwater Canyon Member is absent in the Slick Rock district.

The area of undifferentiated Morrison includes all of central and eastern Colorado and can be traced into western Kansas, Wyoming and Montana. In these areas the Morrison Formation is similar in lithology to the Brushy Basin Member, but no lithologic units are distinguished nor sufficiently laterally continuous to warrant member status.

The Salt Wash, Recapture Creek and Westwater Canyon members of the Morrison Formation are composed predominantly of interstratified lenticular layers of sandstone and mudstone. All three members have been interpreted as fluvial deposits. The Salt Wash and Recapture Creek members were deposited simultaneously by two fan-shaped alluvial systems that coalesced along the Four Corners area where the two members now intertongue (Craig and others, 1955). The Westwater Canyon Member, also deposited by a fan-shaped alluvial system, is thought to be a continuation of deposition of the Recapture Creek

Member. The Brushy Basin Member consists of variegated claystones, partly derived from volcanic debris, with a few interbedded conglomeratic sandstone lenses and sparse, thinly-bedded limestone layers. The Brushy Basin Member sediments are considered to have been deposited in both fluvial and lacustrine environments (Craig and others, 1955).

The Salt Wash Member

Isopach maps prepared by Craig and others (1955) and Mullens and Freeman (1957), show the Salt Wash Member to be a fan-shaped wedge that covers an area of 75,000 square miles (194,250 sq km). The wedge thins radially to the north and east from an apex in south-central Utah. The western edge of the fan is poorly defined and marks the depositional limit of the Salt Wash Member to the west. Along the southern edge, in the Four Corners area, the Salt Wash Member grades laterally into the Recapture Creek Member of the Morrison Formation. The northern and eastern edges of the fan are near Vernal, Utah and Glenwood Springs and Gunnison, Colorado, beyond which the Salt Wash Member cannot be distinguished from the upper parts of the Morrison Formation.

The basal contact of the Salt Wash Member, at most localities, is an erosional unconformity marked by channels eroded into evenly-bedded strata of the Curtis and Summerville formations. An angular unconformity occurs in the San Rafael Swell and Henry Mountains area of Utah, where convoluted beds in the Summerville Formation are locally bevelled by the Salt Wash Member (Mullens and Freeman, 1957). The Salt Wash Member bevels older units over the crests of salt anticlines in western Colorado; near Gunnison, Colorado the Salt Wash Member overlies Precambrian rocks. Near the Four Corners area, the Salt Wash Member channels into and locally intertongues with the Bluff Sandstone (Mullens and Freeman, 1957).

The Salt Wash Member is composed of interstratified sandstone and mudstone units over most of its areal extent. Conglomerate dominates the Salt Wash Member in south-central Utah, and claystones with minor interbedded lenticular sandstones compose the Salt Wash Member in northeastern Utah and northwestern Colorado. Interstratified claystone and limestone lie to the east of the recognizable Salt Wash Member where the Morrison Formation is not differentiated into members (Craig and others, 1955).

The Salt Wash Member reaches a maximum thickness of 600 ft. (182.9 m) near the apex of the fan and, in general, uniformly decreases in thickness towards the margins. Several irregularities in the thickness of the Salt Wash Member are related to tectonic features that existed during deposition of the Salt Wash Member. The Salt Wash Member thins appreciably over the site of the Monument Upwarp in Utah and over salt anticlines in western Colorado. A pronounced thinning of the Salt Wash Member also exists in western Colorado that is related to the Uncompahgre uplift (Mullens and Freeman, 1957).

PREVIOUS WORK

The Morrison Formation

Definition and Correlation - The Morrison Formation was first named by

Cross (1894) for variegated shales and sandstones near Morrison, Colorado. The formation was originally described and poorly defined by Eldridge (Emmons, *et al.*, 1896) and was later redefined by Lee (1920). However, it was not until 1944 (Waldschmidt, *et al.*, 1944) that the type section of the Morrison Formation was completely described.

For a thorough review of the nomenclature and literature on the Morrison Formation prior to 1935, refer to Baker, Dane and Reeside (1936). Since the early 1900's, numerous workers have described the Morrison Formation in and adjacent to the Colorado Plateau (Gilbert, 1877; Cross, 1907; Gilluly and Reeside, 1928; Gregory, 1938; Stokes, 1944; Harshbarger, *et al.*, 1957; Shawe, *et al.*, 1968; Cater, 1970; and Peterson, 1972).

Age - Age assignments for the Morrison Formation range from the Upper Jurassic to Lower Cretaceous series. Eldridge (Emmons, *et al.*, 1896) originally assigned the formation to the Jurassic System. Based on close relationships of plant fossils in the Morrison Formation to those of the Lower Cretaceous Potomac Group of the Atlantic coast, Berry (1915) and Lee (1915) assigned the Morrison Formation to the Comanchian Stage. Other workers felt that deposition of the Morrison Formation began during the Late Jurassic Epoch but continued well into the Comanchian Age (Mook, 1915; Osburn, 1915). Based on reptile remains the Morrison Formation has been correlated to Portlandian beds in East Africa (Simpson, 1926). Imlay (1952) concluded that parts of the Morrison Formation are Kimmeridgian in age because underlying marine beds contain fossils indicative of the Oxfordian Age but lack characteristic fossils of the Kimmeridgian Age. It is now generally accepted that the Morrison Formation belongs to the Upper Jurassic Series and is Kimmeridgian to early Portlandian in age.

The Salt Wash Member

Definition and Stratigraphy - The Salt Wash Member of the Morrison Formation was originally defined by Lupton (1914) as a member of the McElmo Formation for exposures in Salt Wash, 30 miles southeast of Green River, Utah. Lupton traced the member into the area of the San Rafael Swell but confused it with what was to become the Curtis Formation. Gilluly and Reeside (1928) correctly identified the Salt Wash Member and redefined it as the basal member of the Morrison Formation after abandoning the term McElmo Formation.

In 1947 a program of geologic studies on the Salt Wash Member was begun by the USGS on behalf of the Atomic Energy Commission. The principal concern of these studies was to outline favorable areas for uranium mineralization and to establish ore guides in the Salt Wash Member. Through this work the geology, regional stratigraphy and petrology of the Salt Wash Member became known.

The concept of the Uravan mineral belt of southwestern Colorado and southeastern Utah was developed during this time when it was recognized that uranium-vanadium deposits were localized in an arcuate area by favorable lithology in the Salt Wash Member (Fischer and Hilpert, 1952). The idea was further developed by McKay (1955) who suggested there were two discrete mineral belts in the Salt Wash Member instead of one as outlined by Fischer and Hilpert.

Subsequently, the uranium ore deposits in the Uravan mineral belt and other mineralized area were intensely investigated in pursuit of establishing geologic ore guides. Ore guides brought out in these studies included thickness and color of ore-bearing sandstone, alteration of mudstone associated with ore-bearing sandstone and abundance of carbonaceous material in ore-bearing sandstone (Fischer, 1950; Weir, 1952; Shawe, 1956; and Wood and Lekas, 1958).

Interest in the occurrence of uranium has encouraged much petrologic and petrographic work on the sediments of the Salt Wash Member. Petrographical studies of the Salt Wash Member are included in reports by Craig and others (1955), Bilbey, et al., (1974), Cater (1970) and Shawe, (1968, 1976a). The mineralogy and geochemistry of claystones and siltstones of the Salt Wash Member have been investigated by Weeks (1953), and Keller (1959, 1962). Other petrographic studies have been concerned with establishing the depositional environment and source areas of the Salt Wash Member (Cadigan, 1967; Furer, 1970).

The most extensive work on primary structures in the Salt Wash Member has been done by Stokes (1944, 1954, and 1961), Stokes and Sadlick (1953) and Jones (1954). The main purpose of these studies was to relate sedimentary trends and structures in the sandstones of the Salt Wash Member to occurrences of uranium mineralization.

Depositional Environment and Source Areas - Most previous workers agree that the Salt Wash Member is a fluvial deposit. The member has long been attributed to a system of aggrading streams flowing over a broad, flat surface very near sealevel (Lee, 1915; Gilluly and Reeside, 1928; Baker, *et al.*, 1936; and Stokes, 1944). Mook (1915) describes the Salt Wash Member as deposited by a number of large streams in the form of flat, alluvial fans accompanied by the development of lakes in abandoned stream valleys and between principal stream areas.

The depositional outline and lithofacies of the Salt Wash Member became well known from regional studies of Craig and others (1955) and Mullens and Freeman (1957). Both studies conclude that the Salt Wash Member was deposited as a fan-shaped alluvial plain by a single distributary system of braided streams, diverging to the north, east and southeast from an apex in south-central Utah.

Stratigraphic maps prepared by Mullens and Freeman (1957) indicate structural control on deposition of the Salt Wash Member. Upward movement of salt anticlines in west-central Colorado and east-central Utah presented topographic barriers to low gradient streams causing them to deposit their sediment near the flanks of the anticlines. The slight topographic relief of the Uncompahgre highlands may also have formed a barrier to flow of streams during deposition of the Salt Wash Member.

Shawe (1962) attributes the localization of the Uravan mineral belt to local subsidence of a basin in southwestern Colorado. He concludes that the subsidence initiated the development of a smaller alluvial fan upon the much larger fan of the Salt Wash Member and that differences in sedimentation provided favorable lithology for uranium mineralization. Significantly, the toe of the smaller fan coincides with the position of the Uravan mineral belt. Shawe points out that east of the belt, strata of the Salt Wash Member are more flat-bedded and contain more mudstones, suggesting deposition in floodplain and lacustrine environments. Within the Uravan belt and to the west, sedimentation occurred under fluvial conditions.

Recently Peterson (1977, 1979) has studied the Salt Wash Member in the Henry Mountains of south-central Utah in an attempt to relate depositional environments to the localization of uranium deposits. Peterson has recognized a series of fluvial and lacustrine beds in an informal lower member of the Morrison Formation and the Salt Wash Member and has subdivided them into three fluviolacustrine sequences. The three sequences were deposited on an extensive alluvial plain by braided streams originating in highlands to the southwest and west of the Henry structural basin, and in lakes that formed in the depositional low of the basin. Locally meandering streams formed on the topographically low distal end of the alluvial plain. Peterson believes the uranium deposits of the Henry Mountains region were localized within an offshore-lacustrine mudstone facies.

Craig and others (1955) conclude that the major source area for the Salt Wash Member was in west-central Arizona and southeastern California. They suggest a provenance of older sedimentary rocks, chiefly clastics, with little exposed igneous and metamorphic rocks. Craig also notes erratic distributions of opaline tuff, feldspar and apatite along the western edge of the Salt Wash Member which indicate minor sources to the west and northwest of central Utah. Cadigan (1967) believes that the major source area of the Salt Wash Member was high lands in the Basin and Range province of east-central and southern Nevada that rose during the late Paleozoic. Cadigan proposes the presence of a minor source of dominantly sodic tuffaceous material to the west of the Colorado Plateau region.

Previous Work in the Study Area

The earliest work in the Slick Rock district and the study area dealt with the occurrence of uranium-vanadium ore deposits. Among the earlier workers were Fleck and Haldane (1907), Moore and Kithel (1913) who briefly sketched the geology of the area, then known as the McIntyre district, and described the ore deposits, the mines and the locations of mining claims.

Coffin (1921) first mapped the area to prepare a base map of "exploited carnotite districts of southwestern Colorado". His study in the Slick Rock district included the geology of the area, the economic geology of the carnotite ores and the stratigraphy of the McElmo Formation which was comprised of the Summerville and Morrison formations.

From 1939 to 1945 the Colorado State Geological Survey made a study of the ore deposits and geology of the Slick Rock district as part of a national appraisal of uranium-vanadium resources. Fischer (1944) published a simplified geologic map of the uranium-vanadium region of southwestern Colorado and southeastern Utah. This map includes the study area and shows the generalized distribution of sedimentary rocks and locations of uranium mines in the Slick Rock district.

In 1947 the USGS on behalf of the Atomic Energy Commission initiated a series of studies in conjunction with extensive exploratory drilling along the Uravan mineral belt and in the Slick Rock district.

These studies included geologic mapping of eighteen 7.5 minute quadrangles in southwestern Colorado. Cater (1955) mapped the geology of the Horse Range Mesa Quadrangle in which the study area is located. Craig and others (1955) measured stratigraphic sections in the Slick Rock district to include in their regional study of the Morrison Formation. Cadigan (1959, 1967) analyzed samples of the Salt Wash and Brushy Basin members from the study area to include in his study of the regional petrology of the Morrison Formation. Other petrographic studies of samples of the Morrison Formation collected from the Slick Rock district include Archbold (1959), Shoemaker, et al., (1959), and Bowers and Shawe (1961).

The most extensive work in the study area is that done by Shawe, et al., (1968) and Shawe (1968, 1970, 1976a and 1976b) who published a series of geologic investigations on the stratigraphy, structure, petrography of sedimentary rocks, sedimentary rock alteration and geologic history of the Slick Rock district.

Cater (1970) published a report on the stratigraphy and structural and geomorphic development of the salt anticline region of Colorado that includes the study area.

CHAPTER 2 GENERAL GEOLOGY OF THE STUDY AREA

LOCAL STRATIGRAPHY

Rocks exposed in the study area are Mesozoic in age and are dominantly clastics. The oldest exposed rocks in the study area are the Upper Triassic red beds of the Chinle Formation which outcrop only in Summit Canyon. Late Triassic and Jurassic rocks that form the canyon walls, benches and slopes below the mesas, conformably overlie the Chinle Formation and consist in ascending order of the Glen Canyon Group, the Entrada Sandstone, the Summerville Formation and the Morrison Formation. The Burro Canyon Formation and the Dakota Sandstone, of Early and Late Cretaceous age, conformably overlie the Morrison Formation and cap the mesas in the study area.

For a complete description of pre-Summerville and post-Morrison rocks in the Slick Rock district, the reader is referred to Shawe, *et al.*, (1968).

The Summerville Formation

In their stratigraphic study of the Slick Rock district, Shawe, *et al.*, (1968) describe the Summerville Formation as consisting of evenly-bedded, sandy, reddish brown mudstone and siltstone and reddish brown and light gray, very fine-grained to fine-grained sandstone. They note that sandstone is most abundant in a transitional unit at the base of the Summerville Formation and in a persistent "upper marker bed" in the upper part of the formation.

The author adopts the terminology and redefinition of the base of the Morrison Formation informally proposed by Peterson (1977) which is discussed in more detail below. As a result, the Summerville Formation, as identified in this study, is more restricted than that defined by Shawe, et al., (1968) and Cater (1955; 1970) in the Slick Rock district. The Summerville Formation in the study area is divided into a lower sandy unit, consisting of thin intervals of fine-grained structureless sandstone alternating with thinner intervals of sandy siltstone and mudstone, and an upper silty unit, consisting of dominantly red, sandy siltstone and mudstone with thin interbeds of silty sandstone. The lower sandy unit corresponds to the transitional unit described by Shawe. The basal contact of the Summerville Formation is placed at the base of the lowest red siltstone or mudstone layer. This formation in the study area averages 19.0 m thick and conformably overlies the Slick Rock Member of the Entrada Sandstone.

Redefinition of Contact Relations Between the Summerville and Morrison Formations

Recently Peterson (1977, personal communication 1979), based on his work in the Henry Mountains and Green River, Utah, has informally redefined the base of the Morrison Formation so that it includes the upper beds of the Summerville Formation and refers to the unit as the lower member of the Morrison Formation. According to Peterson, the basis for the redefinition is to clarify the nature of the basal contact of the Morrison Formation. The base of the Morrison Formation over most of the Colorado Plateau region is defined as the lower contact of the Salt Wash Member and placed at the base of the lowest cross-bedded sandstone layer. In parts of Utah and Colorado this lowest sandstone is lenticular and laterally discontinuous so that beds of the Salt Wash Member interfinger with horizontally bedded units of the Summerville Formation. In such areas the base of the Morrison Formation is placed in a zone of limy nodules and lenses which occur up to several meters below the lowest cross-bedded sandstone (Cater, 1970). Peterson retains the definition of the lower contact of the Salt Wash Member and distinguishes an informal lower member of the Morrison Formation whose basal contact he believes corresponds to a regional angular unconformity between the Summerville and Morrison formations.

Peterson places the basal contact of the lower member at the lowest occurrence of a chert granule layer overlying the red sands and silts of the Summerville Formation. Commonly the chert granule layer is only a few granules thick and occurs in a white, fine-grained sandstone unit. Although locally discontinuous, the layer has been correlated regionally by Peterson. A similar unit recognized by Goldman and Spencer (1941) near Uravan, Colorado was termed by them the "mixed grain sandstone unit" which they found to be "unusually persistent" in the upper half of the Summerville Formation (see Unit B of their Uravan section, pg. 1756). The "mixed grain sandstone unit" near Uravan, Colorado has been correlated by Cater (1970) to the "upper marker bed" in the Slick Rock district described by Shawe, et al., (1968).

The Lower Member of the Morrison Formation

Criteria used to distinguish strata of the Summerville Formation from that of the lower member of the Morrison Formation in the study area include: (1) change in the sedimentary structures from dominantly structureless to laminated and/or small-scale cross-stratified, (2) change in the predominant color of the sandstone from pale red to light gray, white and/or yellowish gray, (3) an increase in the percentage and variety of colors of chert grains in the sandstone, and (4) an increase in the degree of induration of the sandstone.

In the study area the basal contact of the lower member of the Morrison Formation is placed directly below a 4.5 m thick, fine-grained, silty sandstone unit which is tabular in shape and traceable laterally for several miles. Internally the unit is horizontally and wavy laminated, ripple cross-laminated and locally displays small-scale, low-angle cross-bedding. This basal sandstone unit corresponds to the "upper marker bed" of the Summerville Formation described by Shawe, et al., (1968). Reasons for choosing this sandstone unit as the basal contact are the following: (1) the chert granule layer as described by Peterson (1978) for areas farther west was not found in the study area, (2) the basal sandstone unit is extremely persistent and can be correlated easily within and adjacent to the study area, and (3) the basal sandstone unit often represents the lowest occurrence of internal sedimentary structures above the base of the Summerville Formation.

The lower member of the Morrison Formation in the study area consists of the basal sandstone unit and an overlying interval of thin, evenly-bedded pale grayish red and greenish gray siltstone and mudstone and light gray sandstone. Strata above the basal sandstone unit commonly are horizontally laminated and ripple cross-laminated. The lower member conformably overlies the Summerville Formation and averages 13.0 m thick in the study area.

The Salt Wash Member of the Morrison Formation

Due to the recognition of the lower member and redefinition of the base of the Morrison Formation, the basal contact of the Salt Wash Member no longer corresponds to the base of the Morrison Formation as previously defined. In the study area the contact between the lower member and the Salt Wash Member of the Morrison Formation is generally a gently to sharply undulatory scour surface. The basal contact of the Salt Wash Member is placed at the base of the lowest sandstone unit that meets the following criteria: (1) the unit is the lowest sandstone that displays medium-scale cross-stratification, (2) the unit overlies an erosional surface, (3) the unit has a thickness equal to or greater than 1.2 m, and (4) the unit has a lateral extent of greater than 4.6 m. The contact is well exposed, readily recognized and laterally persistent throughout the study area.

In the study area the Salt Wash Member is informally subdivided into three units consisting of a lower sand unit, a middle silt unit and an upper sand unit. Such a three part division of the Salt Wash Member is not unique and has been described by early miners as the three "rims" and utilized by previous workers in the Slick Rock district (Shawe, et al., 1968). The subdivision as used by the author is based on the visual surface appearance of the member as a whole, especially the lateral continuity and thickness of sandstone strata, and the percentage of interbedded siltstone and mudstone. The division is made in an attempt to facilitate discussion of the Salt Wash Member and to help in the interpretation of depositional environments.

In the study area the Salt Wash Member of the Morrison Formation consists of sandstone layers interbedded with layers of siltstone and mudstone. Salt Wash Member sandstones are well- to moderately-sorted, fine- to medium-grained and contain greater than 70% quartz. Sandstone strata are traceable for considerable distances, particularly in the lower sand and upper sand units, and are internally composed of coalescing lenses that display complex bedding types and scour and fill structures.

The thickness of the Salt Wash Member of the Morrison Formation ranges from 75.0 m to 100.0 m in the study area.

The Brushy Basin Member of the Morrison Formation

The Brushy Basin Member of the Morrison Formation was first named by Gregory (1938) for exposures in Brushy Basin, west of Blanding, Utah. In the study area the Brushy Basin Member is similar to that at its type locality and consists dominantly of variegated, bentonitic mudstone with interbedded lenses of sandstone and conglomerate and thin layers of limestone. Mudstones are nonfissile and contain an abundance of volcanic derived sediment, shard structures and sharp angular grains of quartz, plagioclase and potassium feldspar. Sandstones range from very fine- to fine-grained and are commonly cemented by silica. Conglomerates consist of pebbles of red and green chert and quartzite with interstitial clay and commonly contain silicified saurian bone fragments and petrified wood. Lenses of sandstone and conglomerate are cross-bedded and display scour and fill structures. Limestone layers, up to several centimeters thick, are lenticular to tabular and are dominantly structureless.

The contact between the Salt Wash and Brushy Basin members is gradational and is arbitrarily located. Cater (1955) and Craig and others (1955) place the lower contact of the Brushy Basin Member at the base of the lowest layer of conglomeratic sandstone with red and green chert pebbles. Shawe, et al., (1968), however, place the lower contact of the Brushy Basin Member exclusively at the top of the ore-bearing sandstone (or upper sand unit) of the Salt Wash Member since it is more laterally persistent and is a more recognizable horizon. The thickness of the stratigraphic interval between the contact used by Craig and others (1955) and Cater (1970) and the contact defined by Shawe, et al., (1968) varies from 3.0 m to 12.2 m. In the study area, layers of conglomeratic sandstone in the Brushy Basin Member are not laterally continuous, are locally absent and vary in stratigraphic position from place to place. The author places the contact between the Salt Wash and Brushy Basin members at the top of the stratigraphically highest sandstone unit that retains typical Salt Wash lithology (see Chapter 4). Commonly this coincides with the contact as defined by Shawe, et al., (1968) but locally does occur several meters higher in the section. The Brushy Basin Member of the Morrison Formation ranges from 100.6 m to 129.5 m thick in the study area.

STRUCTURAL GEOLOGY

The structural interpretation of the study area is not a primary objective of this study. For a detailed description of the structural geology of the Slick Rock district refer to Shawe (1970) on which the following is based.

Three major northwest-trending features have influenced the structure of the study area. These include the Gypsum Valley anticline, the Disappointment syncline, and the Dolores anticline, all of which are a part of a sequence of salt-cored anticlines and intervening synclines whose axes trend northwest-southeast along the Utah-Colorado border. Much of the deformation in the study area is a result of uplift and subsequent collapse of the anticline crests due to intrusion and removal of the underlying salt cores.

The Gypsum Valley anticline borders the northeast edge of the study area. A zone of high angle, normal faults in the vicinity of Steamboat Hill and Grassy Hills, bound the southwest edge of the collapsed crest of the anticline. Individual faults strike N45°-60°W, are less than four miles long, and have a displacement of less than 152.4 m with their northeast sides downthrown. Investigations by Shawe (1970) indicated that there were episodes of faulting associated with the anticline. The first occurred during uplift of the anticline core and the second during collapse. A small sharp anticline and syncline, no more than two miles long, is located at the northeast end of Steamboat Hill and parallels the bounding faults of the Gypsum Valley anticline.

From the northeast corner of the study area strata dip southwestward toward the Disappointment syncline. The syncline is a broad, asymmetrical fold that plunges southeast and extends across the eastern half and into the northwest corner of the study area where the fold begins to flatten out. The average trend of the syncline axis is S55°E. Beds associated with the syncline in the study area generally dip less than 5°. The syncline averages five miles wide and parallels the Gypsum Valley and Dolores anticlines. Southwest of Cape Horn, in the northeast corner of the study area, three minor normal faults trending northeast cut the flank of the Disappointment syncline.

The Dolores anticline is the most conspicuous structural feature in the Slick Rock district and is the southeast extension of the Lisbon Valley anticline in Utah. The Dolores anticline lies approximately seven miles southwest of the Gypsum Valley anticline and is separated from it by the Disappointment syncline. Unlike other salt-cored anticlines of the Colorado Plateau, the crest of the Dolores anticline has not collapsed.

In the study area, two systems of faults cut the northeast limb of the Dolores anticline. One system of faults trends N55°W parallel to the anticline axis and is located between Summit and Bush Canyons in the south-central and southeastern parts of the study area. The other system of faults occurs northwest of Summit Canyon, in the vicinity of Horse Range Mesa; faults strike N70°-85°W. Individual faults in these systems are less than one mile to several miles long and generally have a displacement of less than 30.5 m. The faults bound small en echelon grabens with no consistent pattern or direction of displacement (Shawe, 1970). According to Cater (1970) the faults associated with the Dolores anticline formed in response to either adjustments of the underlying salt core during collapse of the Lisbon Valley anticline or to tensional stresses developed during folding.

A few minor faults trend northeastward and normal to the Dolores anticline system of faults. These include three normal faults near Cape Horn, two faults in the Lower Group mining claims located in the center of the study area, and one fault in Summit Canyon.

A major set of joints is oriented approximately N60°-70°W, parallel to the principal bordering faults of the Gypsum Valley and Dolores anticlines in the study area. A less pronounced set of joints is also parallel to the minor northeasterly trending faults and strikes about N45°E.

Structural History

The structural events that deformed the rocks in the study area began during the Early Pennsylvanian Epoch. Compressive forces involving basement rock gently warped and faulted the region and gave rise to the ancestral Uncompahgre highland and the Paradox Basin, in which thick accumulations of sediments, including marine evaporites of the Pennsylvanian Hermosa Formation, were deposited. These features ultimately controlled the northwest-trending grain of the salt anticlines.

During the Permian Period renewed activity along basement faults initiated flowage and intrusion of salt from the Hermosa Formation into overlying sediments (Cater, 1970). Until the Late Jurassic Epoch, when flowage stopped, the salt intrusions stood as topographic highs and all Mesozoic formations older than the Morrison Formation pinch out against their flanks. During deposition of the Morrison Formation sediments began to cover the salt domes.

Major folding in the study area began near the end of the Cretaceous Period associated with the Laramide Orogeny (Cater, 1970). A series of broad, northwest-trending folds developed along pre-existing salt intrusions. Although the salt cores influenced their shape, the folds developed in response to regional compression and deep-seated Paleozoic basement structures.

Younger faulting in the study area occurred during two episodes. At the close of the Late Cretaceous Epoch, normal faulting developed when salt flowage was renewed during folding, and crests of anticlines were locally dropped as grabens. The second of these episodes of faulting occurred after the uplift of the entire Colorado Plateau during the Middle to Late Tertiary Epochs. The uplift rejuvenated streams and increased groundwater circulation causing anticline crests to be breached and salt cores to be removed by solution. The final collapse of the anticlines occurred during readjustments and removal of salt cores. Where salt was removed, overlying unsupported sediments slumped along fractures and joints. Small faults and folds noted by Shawe (1976) displacing Quaternary deposits of the Slick Rock district indicate that collapse and local readjustments may still be continuing.

CHAPTER 3 DETAILED STRATIGRAPHY OF THE SALT WASH MEMBER WITHIN THE STUDY AREA

INTRODUCTION

Thirteen stratigraphic sections of the Salt Wash Member and adjacent units are measured and described in detail within a 10.0 km by 6.5 km square area. They constitute two lines of sections that run north-south along the Dolores River and southwest-northeast in Summit Canyon (Plates 1 and 2). The measured sections include: seven complete sections of the informal lower member and the Salt Wash Member, five partial sections of the upper two-thirds of the Salt Wash Member, and one incomplete section of the Brushy Basin Member. All the stratigraphic sections include the gradational contact between the Salt Wash and Brushy Basin members. Stratigraphic sections are divided into units characterized by lithology and major sedimentary structures and are traced laterally wherever possible.

SALT WASH MEMBER

Sedimentary Structures

The reader is referred to Appendix 1 for definitions of the terminology used in the following descriptions.

Channel cut and fill structures - Channel cut and fill structures of various sizes and shapes are abundant throughout the Salt Wash Member. Small channels occur within the middle silt unit and within thinner mudstone sequences of the lower sand and upper sand units. They occur as thin, elongated lenses of very fine- to fine-grained sandstone.

with an average width of 7.6 m to 9.0 m and range from 0.2 m to 1.2 m in thickness. Small channels are typically filled by medium-and small-scale trough-shaped sets, ripple cross-laminations and horizontal laminations (Fig. 3).

Channel deposits of the thicker cliff-forming sandstone layers, particulary in the lower and upper sand units, are much larger in size. Channels of the lower sand and upper sand units range from 4.6 m to greater than 91.0 m in width and from 0.9 m to 9.0 m in thickness. These channels have a trough-like cross section and are usually symmetrical in shape (Fig. 4). The channels truncate each other, with successively younger channels truncating strata of adjacent and underlying older channels. The bases of channel structures are characterized by scour surfaces overlain with poorly-sorted sandstone and numerous mudstone clasts. Where channels directly overlie mudstone, the contact is sharp with some scours up to 0.9 m in depth. Above the base, channels consist of fine- to coarse-grained sandstone. The upper contacts of channel structures are typically planar and horizontal where they are not eroded by overlying channels.

Cross-stratification - Cross-stratification is the most common type of sedimentary structure in the Salt Wash Member. The cross-strata are predominantly thinly-bedded to thinly-laminated.

Trough cross-stratification

Medium-scale, low angle, trough-shaped sets of concordant cross-laminae with erosional lower contacts (hereafter referred to as medium troughs) are the most abundant sedimentary structures in

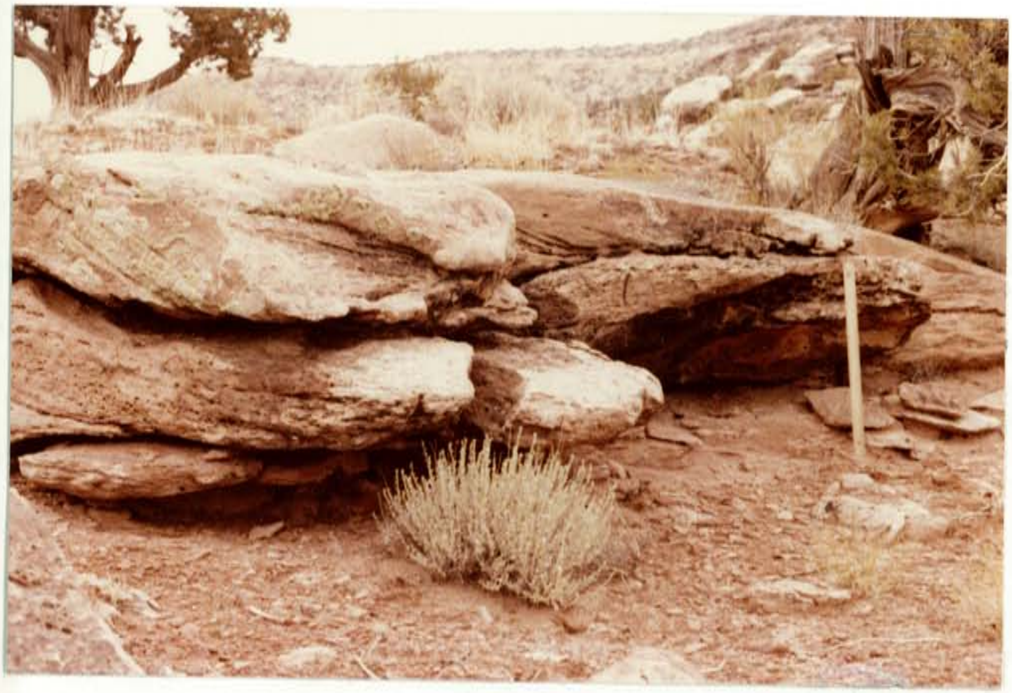


Figure 3. Small channel in the middle silt unit.
Channel is filled by medium- and small-scale,
trough-shaped sets. (Scale is 0.6 m long.)

Figure 4. Large channels in the upper sand unit. Channels are approximately 6.0 m to 10.0 m thick.

major cliff-forming sandstones. Medium troughs commonly occur in grouped sets and can constitute entire fill of channel cut and fill structures. Individual sets of medium troughs range from 0.2 m to 1.2 m in thickness and are usually from 2.4 m to 4.9 m in lateral extent. Cross-strata within medium troughs are concordant with the lower bounding surface of the set and have dips of less than 20^{o}. Lower contacts of troughs are always erosional and scour into underlying sets as much as 0.3 m locally (Fig. 5).

Large-scale, low angle, trough-shaped sets of concordant cross-laminae (large troughs) typically occur at the bases of channel cut and fill structures. Where present at the base of channels, large troughs usually occur in solitary sets and are replaced vertically by grouped sets of medium troughs (Fig. 6). Many channels are filled only by large troughs with no development of other stratification types. Such channels are themselves trough-shaped and consist of solitary sets of conformable laminae. Commonly these are truncated by overlying channels with similar conformable laminae, forming a vertical sequence of cross-cutting large trough sets. These structures are termed channel-fill cross-bedding by Reineck and Singh (1975). The large troughs have characteristically high width to depth ratios, and range from 0.3 m to 1.8 m in thickness and up to 23.0 m in lateral extent.

Grouped sets of medium troughs of this study correspond to the pi-cross-stratification of Allen (1963); the solitary large troughs and solitary medium troughs correspond to theta- and iota-cross-

Figure 5. Overlapping medium-scale, trough-shaped sets.

Figure 6. Large-scale, trough-shaped sets, in lower half of channel deposit, are overlain by horizontal laminations and medium-scale, trough-shaped sets.

stratification of Allen (1963); the solitary large troughs and solitary medium troughs correspond to theta- and iota-cross-stratification. The large troughs that conformably overlie channel bases most likely correspond to Allen's zeta-cross-stratification. The trough-shaped sets of this study are similar to festoon cross-beds described in modern rivers (Harms, McKenzie and McCubbin, 1963; Harms and Fahnstock, 1965).

Small—scale trough-shaped sets are not as common in the major channel structures of the Salt Wash Member as are the larger sizes. Within thinner sandstone layers, however, small troughs are abundant and are often associated with ripple cross-lamination. Small trough sets range from 8.0 cm to 16.0 cm in thickness and average 0.3 m in lateral extent.

Scour and fill structures

Scour and fill structures occur with the channel cut and fill structures as solitary, medium and small scale trough sets that truncate other strata. They are typically asymmetrical in cross section, possess steep slopes, and are filled by tangential laminae that flatten downdip. Commonly, the material in these troughs is coarser grained than the surrounding material and contains sparse granules and small mudstone clasts along the lower portions of cross-strata.

Planar cross-stratification

Large-and medium-scale, low angle, tabular- and wedge-shaped sets of planar cross-laminae occur within sandstones of the Salt Wash Member.

Wedge- and tabular-shaped sets usually have erosional lower contacts and occur as both isolated and grouped sets. They are most commonly associated with medium-scale trough sets and horizontal laminae. Wedge- and tabular-shaped sets occur within channel structures and are more common in the upper half of the channel structure than the lower half (Fig. 7). Small-scale wedge and tabular sets of cross-strata are rare in the Salt Wash Member.

Wedge and tabular sets of this study correspond to beta- and xi-cross-stratification of Allen (1963).

Horizontal lamination - Horizontal lamination is the second most abundant type of stratification in the sandstones of the Salt Wash Member. Horizontal laminations most commonly occur in larger channel structures that are greater than 15.2 m in lateral extent. They can occur anywhere within a channel structure but are more common in the upper parts than basal parts. Near the top of channels, horizontal laminations commonly overlie medium troughs and underlie sets of ripple cross-lamination. Horizontal laminations found near the top of channels are commonly burrowed and show slight disturbance of original bedding (Fig. 8). Larger channel structures in the lower and upper sand units have thick sequences of horizontal laminations at their bases which occur in layers up to 2.0 m thick and that extend laterally for over 61.0 m (Fig. 9). Horizontal laminations are also well developed in the thinner sheetlike sandstone layers interbedded with mudstone and siltstone, particularly in the middle silt unit. These layers are usually less than 1.2 m thick and extend laterally for 9.1 m to 15.2 m.

Figure 7. Large-scale, wedge-shaped set of planar cross-strata.

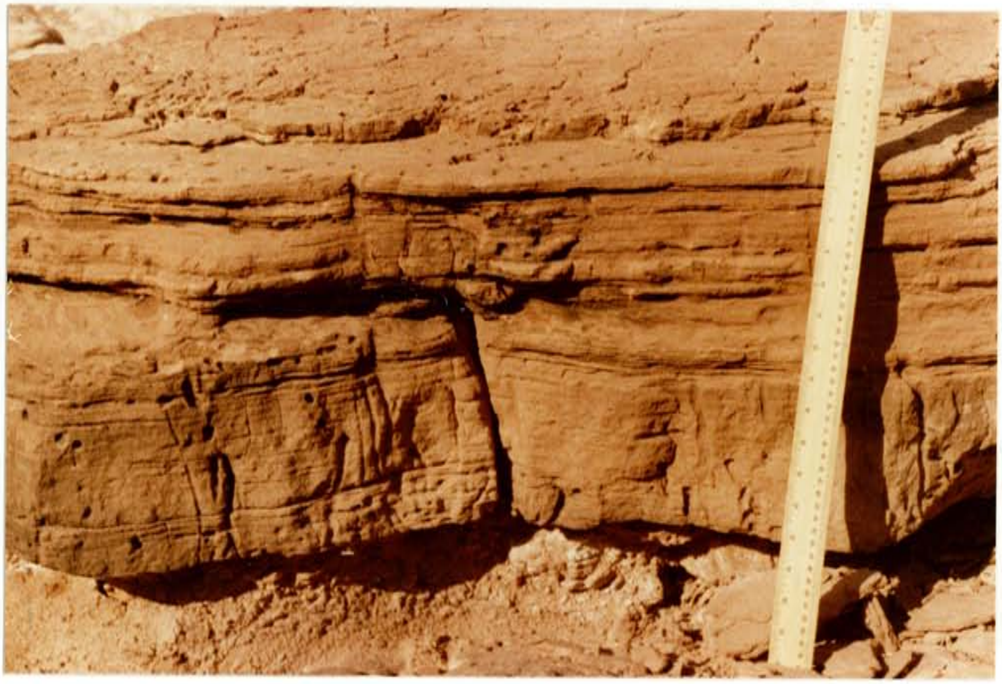


Figure 8. Horizontal laminations with burrows normal to the stratification surface.

Figure 9. Thick sequence of horizontally laminated sandstone in lower sand unit.

Horizontal laminations of these sheetlike sandstones grade upward and laterally into ripple cross-lamination.

Ripple cross-lamination - Ripple cross-lamination is best developed in interbedded very fine- to fine-grained sandstone and siltstone that occur as layers between channel structures and within the mudstone sequences of the middle silt unit. Ripple cross-lamination is also well developed within the upper portions of channel structures where they generally overlie horizontal laminae and/or medium-scale trough sets.

Ripple cross-lamination in the rocks of the Salt Wash Member are present in the form of small ripple bedding described by Reineck and Singh (1975) and as climbing-ripple or ripple drift lamination. Small ripple bedding occurs as trough-shaped sets with erosional lower and upper contacts, and with tangential foreset laminae that are concave upward. The trough sets average 2.0 cm to 3.0 cm thick and range from 3.0 cm to 10.0 cm in lateral extent. Small ripple bedding is formed where relatively less sediment is available in suspension and where reworking is stronger (Reineck and Singh, 1975) compared to climbing-ripple or ripple drift lamination.

Ripple cross-lamination is also present as climbing ripple drift cross-lamination (Jopling and Walker, 1968). Climbing ripple cross-lamination in the Salt Wash Member is composed of climbing sets of leeside laminations with no preservation of stoss side laminations. They are characterized by grouped, tabular-shaped sets of tangential cross-laminae and are classified as Type A ripple laminae-in-drift by

Jopling and Walker (1968) (Fig. 10). In some cases, Type A ripple drift is associated with climbing sets of ripples that have preserved stoss sides. These latter structures are called Type B ripple drift by Jopling and Walker (1968) and are very similar to wavy, parallel stratification as described by Campbell (1967). Cosets of climbing ripple cross-lamination in the study area range up to 0.3 m in thickness. Climbing ripple cross-lamination is best developed where abundant sediment is continually available, especially from suspension (Reineck and Singh, 1975). McKee (1966) found climbing ripple laminations to be extremely abundant in areas of overbank flows, floodplains and natural levees of fluvial systems.

Structureless - Structureless as used here means no internal structures are apparent to the naked eye. Several examples of structureless sandstone occur in the Salt Wash Member. Structureless sandstones occur anywhere within sequences of cross-stratification. Structureless sandstone commonly occurs in layers up to 0.6 m thick at the erosional base of channel structures. These bases are also associated with load structures indicating that soft sediment deformation may have destroyed any pre-existing structures. Many of the thin, lenticular sandstone layers interbedded with mudstone-siltstone sequences are structureless.

Hamblin (1962) demonstrates with x-radiography that most structureless sandstones do contain some internal structure. In the Salt Wash Member, the absence of internal structures in some sandstones may be due to extensive bioturbation. In such cases, structureless sandstone

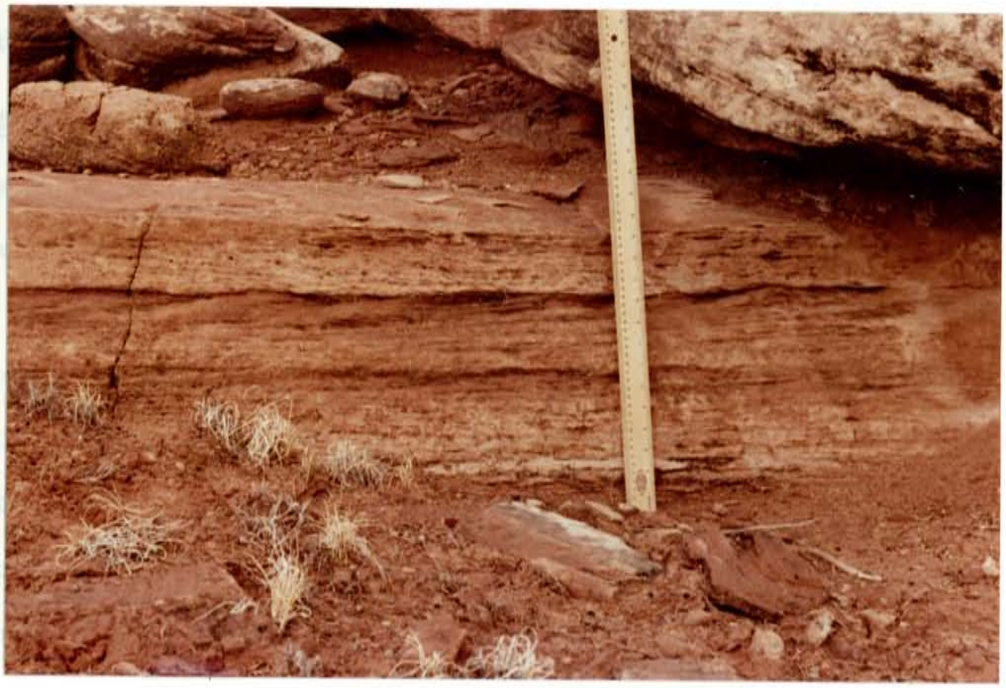


Figure 10. Sets of ripple laminae-in-drift, Type A, in middle silt unit.

is closely associated with burrowed strata. It has also been suggested that beds originally lacking any lamination can be formed by rapid deposition of sediment from suspension (Blatt, Middleton and Murray, 1972).

Soft sediment deformation - Soft sediment deformation is present in the Salt Wash Member as load structures, convolute bedding and overturned cross-strata. Load structures are common along basal contacts of channel cut and fill structures where they directly overlie mudstone. On the basal surfaces, load structures occur as swellings and bulbous protrusions of sandstone extending into the underlying mudstone (Fig. 11). Locally, convolute lamination and overturned cross-strata occur as small antiforms in very fine- to fine-grained sandstone (Fig. 12).

Stratification plane structures - Primary current lineations (or parting lineations) are common features in the sandstones of the Salt Wash Member. Current lineations are well developed on stratification surfaces of horizontally laminated, medium- to fine-grained sandstone within channel structures and in the thinner sheet-like sandstone bodies within the mudstone intervals. Primary current lineations are often used as paleocurrent indicators in this study.

Rib-and-furrow structures are the stratification plane and/or weathering plane expression of ripple cross-lamination. Rib-and-furrow structures are particularly abundant in very fine-grained sandstone layers of the mudstone intervals.

Although rib-and-furrow structures and ripple cross-lamination

Figure 11. Load structure in a mudstone interval.

Figure 12. Soft sediment fold in small channel deposit of upper sand unit.

frequently occur throughout the Salt Wash Member, ripple marks are not a common feature. Due to their sparse occurrence, data on type and size were not collected on ripple marks in the Salt Wash Member.

Carbonaceous plant remains

Carbonaceous plant fragments are most abundant in the upper sand unit, ranging from minute acicular flakes to larger branches up to 15.0 cm in diameter. Such plant remains occur along bedding planes in light gray sandstone and in greenish gray to medium gray mudstone. The occurrence of carbonaceous material is closely associated with the uranium-vanadium mineralization of the upper sand unit.

Trace fossils

Burrows are locally present in siltstones and fine-grained sandstones and occur at all orientations relative to stratification. The burrows are cylindrical to subcylindrical in shape, ranging from 0.3 cm to 1.0 cm in diameter and up to 0.9 m in length. The burrows are predominantly straight and often intersect one another at various angles. Burrow walls are smooth.

No positive identification of the organism responsible for the burrows could be determined by this author. However, the types of structures these burrows most closely resemble are Paleophycus, Hall, 1847 and Planolites, Nicholson, 1873. These structures and their possible modes of origin are discussed in more detail by Hantzchel (1966).

Stratigraphy

The general features that distinguish the lower sand unit, middle silt unit and upper sand unit of the Salt Wash Member are shown in Table 1. Sandstone percentages are calculated from the sum of the thickness of individual sandstone layers (each greater than 1.2 m thick) divided by the total thickness of the unit times 100%. Although the middle silt unit contains numerous interbedded sandstone layers, they are predominantly discontinuous over 15.0 m to 30.0 m and are less than 1.2 m in thickness and are not included in the sum of sandstone layers for calculation of sandstone percentages.

The lower sand and upper sand units are very similar in geometry, lithology and sedimentary structures. Both units consist of stacked, multilateral sandstone lenses (terminology follows Potter, 1967) that group to form thick, tabular bodies that are laterally continuous for several kilometers. Both the lower and upper sand units average 69% or more sandstone. The bases of the tabular sandstone bodies are always sharply defined scour surfaces that locally truncate underlying strata of mudstones and sandstones. Mudstone layers interbedded within the lower sand and upper sand units are few, thin, laterally discontinuous over 5.0 m to 15.0 m and end abruptly against basal scour surfaces of laterally adjacent and overlying sandstone lenses.

Internally, the tabular sandstone bodies of the lower sand and upper sand units are composed of two scales of sedimentary structures. The largest structures are the individual lenses of sandstone which

		LOWER SAND UNIT	MIDDLE SILT UNIT	UPPER SAND UNIT
UNIT THICKNESS	Range Average	17 m to 31 m 23 m	26 m to 42 m 32 m	18 m to 41 m 32 m
PERCENT SANDSTONE	Range Average	69% to 100% 90%	19% to 68% 39%	46% to 89% 69%
MAJOR SANDSTONE BODIES	Average Number Average Thickness	2 11 m	2 6 m	3 8 m
MUDSTONE INTERVALS	Average Thickness	2 to 3 m	7 m	5 m
RELATIVE ABUNDANCE OF SEDIMENTARY STRUCTURES AND FACIES*		Tm > tw > H > 0 > T_L > R	0 > Tm > H > tw > T_L = R	0 > Tm > tw = T_L > H > R

*For explanation of symbols, see Page 66.

Table 1. General features and characteristics of the lower sand, middle silt and upper sand units of the Salt Wash Member.

are channel cut and fill structures. Internally the channels display a variety of stratification types, as discussed in the preceding section.

The ratio of sandstone to mudstone intervals of the middle silt unit helps to distinguish it from the lower sand and upper sand units. The middle silt unit averages 39% sandstone and is composed dominantly of interstratified siltstone and claystone layers that are laterally continuous for 150.0 m or more. Unlike the other two units, sandstone layers of the middle silt unit are lenticular and laterally discontinuous.

The lower sand, middle silt and upper sand units are outlined in Fig. 13 and are correlated on Plates 1 and 2. The following descriptions are general but characterize the three informal units of the Salt Wash Member in the study area. For more detailed descriptions the reader is referred to Appendix 1.

<u>Lower sand unit</u> - The basal contact of the Salt Wash Member corresponds with the contact of the lower sand unit with the underlying lower member of the Morrison Formation (Fig. 14). The contact is an erosional surface marked by a distinct, undulating scour surface. In some places this contact must be traced laterally to note truncation of lower member beds. Locally, the lower sand unit interfingers with strata of the lower member. In such areas, cross-stratified sandstone lenses of the Salt Wash Member, appear to intertongue with mudstone layers of the lower member.

Within the study area, the lower sand unit consists of the

Figure 13. The three informal units of the Salt Wash Member as defined in the study area.

Figure 14. View of the Summerville Formation, the lower member of the Morrison Formation and the lower sand unit of the Salt Wash Member.

thickest, most prominent sandstone strata of the Salt Wash Member. The unit forms a vertical cliff that is typically split into two major sandstone layers by a thin mudstone interval. Sandstone of the lower sand unit is pale red to light brown in color.

Vertical successions of lithology and associated sedimentary structure in the lower sand unit are variable from one section to the next. All sections, however, are characterized by channel cut and fill structures; the fill is composed of alternating cosets of medium troughs, planar cross-strata and horizontal laminae. Channel structures begin with a scour surface at the base which is usually overlain by one to several large troughs. In general, channel structures show an overall upward decrease in scale of sedimentary structures. Cosets of ripple cross-laminae which overlie horizontal laminae tend to occur at the top of channel sequences.

The relative abundance of sedimentary structures of the lower sand unit are given in Table 1. The predominant structures are medium troughs with set width/thickness ratios (W/T) ranging from 6 to 30. Locally, individual troughs are separated by discontinuous, grayish red mudstone and claystone seams. Sets of planar cross-strata vary from medium-to large-scale with W/T ratios of 3 to 143. These latter sets are observed in Section C, where individual sets extend laterally for 45.7 m. Horizontal laminae occur in layers that range up to 1.2 m in thickness and up to several meters in lateral extent.

The least abundant structures are large troughs and ripple cross-laminae. Large troughs usually occur at the base of channel deposits where they average 0.6 m in thickness and have W/T ratios of 12.5 to 20.

Cosets of ripple cross-laminae occurring at the top of channels are up to 1.5 m in thickness.

Mudstone intervals that split the lower sand unit into two sand bodies consist of alternating layers of grayish red mudstone and thin lenses of pale red very fine-grained, silty sandstone. Lenses of sandstone range from 1.5 m to 4.0 m in lateral extent and up to 0.5 m thick. These sandstone layers locally display ripple cross-laminae, horizontal laminae and small troughs, but commonly are structureless with load structures along their lower surfaces.

Middle silt unit - Upper and lower contacts of the middle silt unit are difficult to define since the unit locally intertongues with the upper sand unit and more rarely with the lower sand unit. In such places mudstone strata of the middle silt unit merge laterally and intertongue with sandstone strata of the other two units. The lower contact of the middle silt unit is placed at the base of a mudstone interval, 1.5 m to 9.0 m in thickness, that directly overlies the thick, cross-stratified sandstone strata of the lower sand unit. In most places, this contact is a planar, gradational or sharp nonerosional surface.

The unit is a sequence of thick mudstone intervals and laterally discontinous layers of cross-stratified sandstone. Mudstone intervals of the unit consist of dominantly grayish red interbedded mudstone, siltstone, claystone and numerous lenses of very fine-grained, silty sandstone (Fig. 15). Locally mudstone is mottled and has thin interlayers of greenish gray mudstone. Within the mudstone intervals, sandstone lenses are grayish red to greenish gray in color and range from

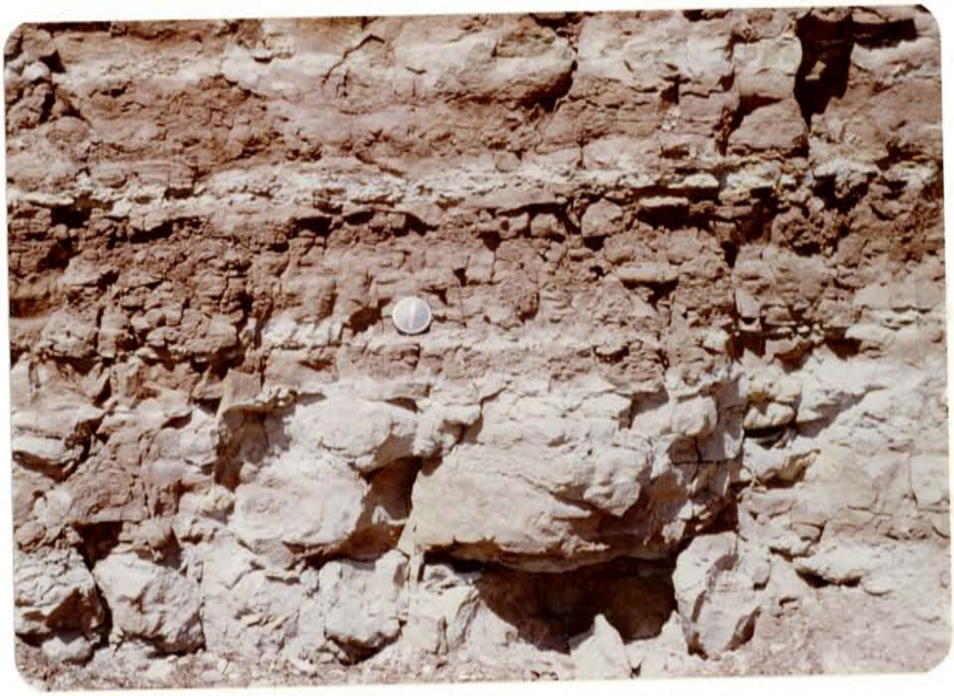


Figure 15. Mudstone interval, of the middle silt unit, consisting of grayish red and greenish gray, mudstone, siltstone and lenses of fine-grained sandstone.

several centimeters to 1.2 m in thickness and 0.6 m to 5.0 m in lateral extent. Internally the lenses are either structureless, ripple cross-laminated and/or horizontally laminated. Sets of ripple cross-laminae range from 2.5 cm to 15.0 cm thick. Thicker sandstone lenses display small and medium troughs and sets of planar cross-strata. Troughs and planar sets average 15 cm thick and range from 0.3 m to 1.8 m in lateral extent. Carbonized plant fragments occur rarely and locally along stratification planes of sandstone and mudstone. Rib-and-furrow marks are an abundant and widespread structure on weathering surfaces of the middle silt unit.

The extreme lateral variability of the middle silt unit is due to the discontinuity and varying thicknesses of major interstratified sandstone layers. The layers are lenticular in shape and range from 1.5 m to 12.8 m thick and from 18.0 m to 300.0 m in lateral extent. Larger sandstone strata must be traced laterally to note their discontinuity. The layers are characterized by erosional bases and by outer edges that grade into or interfinger with surrounding mudstone. In a given vertical succession, the middle silt unit contains an average of two major sandstone strata. The sandstone is typically fine- to medium-grained and pale red to light brown in color.

Channel structures in the middle silt unit are similar in size, shape and sedimentary structures to those in the lower sand unit. Within the middle silt unit, however, channels do not form thick, laterally continuous, tabular bodies of sandstone; rather they form discontinuous layers or single lenticular channel deposits surrounded by mudstone.

Unlike the lower sand unit, alternating or repeating sequences of medium troughs, planar cross-strata and horizontal laminae are not as common in the channel deposits of the middle silt unit. Sedimentary structures within channel deposits generally decrease in scale upward. Channels are dominated by cosets of medium troughs and by thick layers of horizontal laminae. Medium troughs range up to 1.2 m in thickness with W/T ratios of 5 to 25. Horizontal laminae occur in layers that average 4.0 m thick, but can range up to 7.0 m. Tabular- and wedge-shaped sets of planar cross-strata are not as abundant in the middle silt unit.

The least abundant sedimentary structures in the channel deposits are large troughs, which typically occur as isolated sets at the base of channels, and ripple cross-laminae. Cosets of ripple cross-laminae are generally thicker than in the lower sand unit and tend to occur at the top of channels where they reach thicknesses of approximately 2.0 m.

Upper sand unit - Contacts of the upper sand unit are somewhat difficult to place due to intertonguing with the middle silt unit and to the gradational contact with the overlying Brushy Basin Member of the Morrison Formation. The contact of the upper sand unit with the middle silt unit is typically marked by a laterally extensive scour surface of a channel structure. The scour surface underlies a sandstone layer that is greater than 3.4 m in thickness. Locally, however, lenses of sandstone split from the main strata of the upper sand unit and intertongue with mudstone layers of the middle silt unit.

The upper contact of the Salt Wash Member corresponds to the contact of the upper sand unit with the Brushy Basin Member. This contact is gradational and consists of a transitional sequence of mudstone, sandstone and conglomeratic sandstone. In all cases the upper contact is placed at the top of the stratigraphically highest sandstone that has a lithology typical of the Salt Wash Member (i.e., moderately-sorted, $\geq$85% quartz, and $<$5% brown, black or gray chert fragments). The change to lithology of the Brushy Basin Member is easily recognized by its coarser grain size (coarse sand to conglomerate) and/or by an increase in red, orange, and green chert grains. The upper contact of the Salt Wash Member varies in stratigraphic position from section to section and occurs anywhere from 0.0 m to 16.2 m above the top of the prominent, vertical cliff-forming, tabular sandstone body of the upper sand unit.

Aside from containing the only economically significant uranium-vanadium deposits in the study area, the upper sand unit has several features that distinguish it from the lower units of the Salt Wash Member.

The upper sand unit is distinguished from the lower sand unit by a greater number and thickness of interbedded mudstone layers, by the relative abundance of certain sedimentary structures and by a general increase in overall grain size (Fig. 16).

Sandstone in the upper sand unit has an overall coarser grain size than that of the lower sand unit. Sandstone in the upper unit

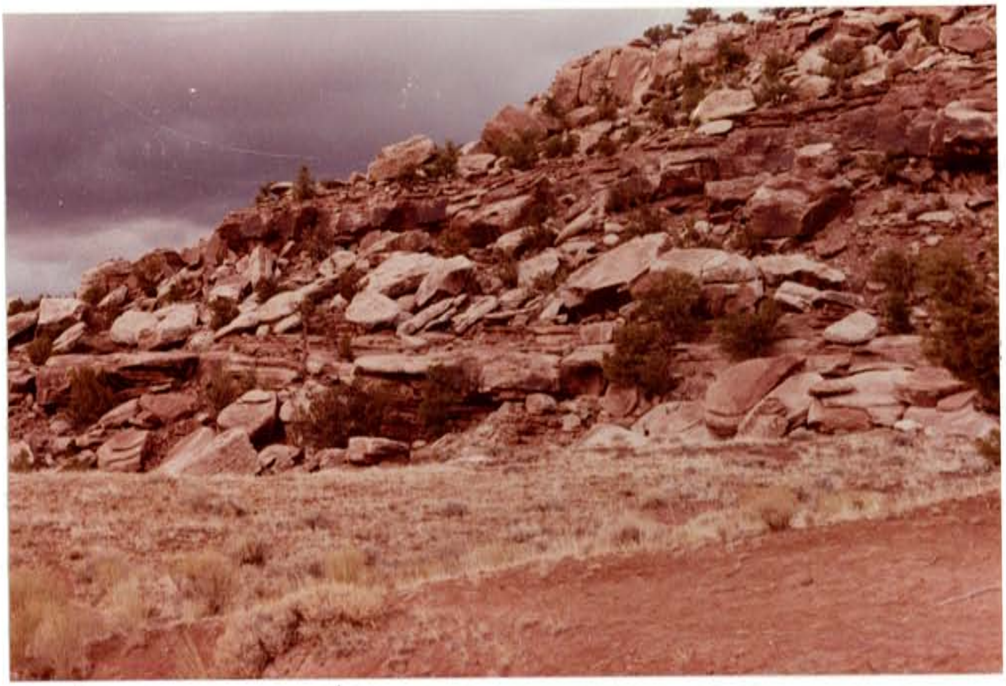


Figure 16. The upper sand unit. Major channel deposits form ledges and cliffs, while interbedded mudstone layers form talus-covered slopes.

ranges from fine- to coarse-grained and has an average size of medium sand. Coarse lag deposits of granules and sparse pebbles of white, tuffaceous lithic fragments and altered feldspar are common along the lower parts of medium and large troughs (Fig. 17). Such coarse-grained material is uncommon in the lower sand unit.

The thickest and most laterally extensive channel structures in the Salt Wash Member occur in the upper sand unit (Fig. 18). Channel cut and fill structures extend up to 61.0 m laterally and from 2.7 m to 14.0 m in thickness. Scouring by channel structures is pronounced.

The most abundant sedimentary structures in the channel deposits of the upper sand unit are medium troughs. Medium troughs have W/T ratios of 14 to 20. Large troughs, planar cross-strata and horizontal laminae make up approximately equal proportions of the upper sand unit. Unlike the lower sand and middle silt units where large troughs occur as isolated sets overlying channel bases, large troughs of the upper sand unit are much more common. They typically occur in thick cosets and are described as channel-fill cross-bedding by Reineck and Singh (1975). Large troughs of the upper sand unit have W/T ratios of 17 to 30.

Planar cross-strata occur in medium- and large-scale, wedge- and tabular-shaped sets and have W/T ratios of 12 to 150. Horizontally laminated sandstone occurs in layers of 0.3 m to 6.7 m in thickness and

Figure 17. Coarse lag deposits of tuffaceous lithic fragments and altered feldspar in a channel of the upper sand unit.

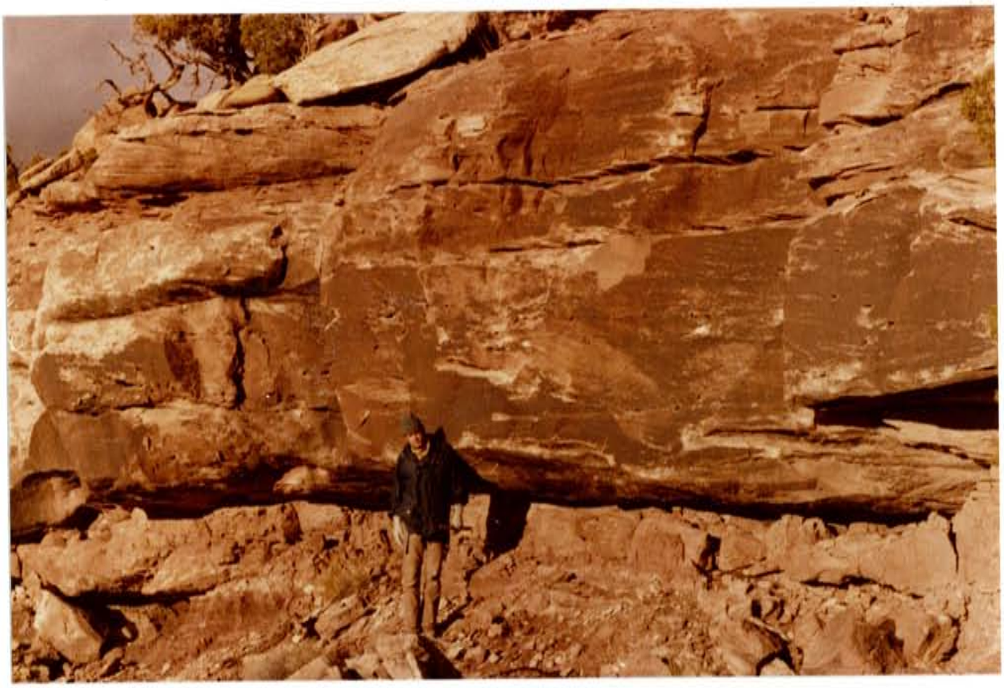


Figure 18. A channel in the upper sand unit consisting of large troughs at the base, medium troughs, sets of planar cross-strata, and horizontal laminations at the top.

are associated with abundant parting lineations.

Sandstones within the transitional upper contact form lenticular strata that range from 0.6 m to 3.4 m in thickness. The sandstone lenses are laterally discontinuous, extending from 6.1 m to 2.3 m, and interfinger with mudstone strata. Locally, the uppermost sandstone layers are tongues of the major sandstone body in the upper unit, but elsewhere they appear to be totally separate from it.

Interbedded mudstone intervals in the upper sand unit are laterally discontinuous and are scoured by overlying and adjacent channel structures. Mudstone intervals are similar to those in the lower units, consisting of grayish red (locally greenish gray) mudstone, claystone, siltstone and very fine-grained, silty sandstone. In the upper sand unit, mudstone occurs in layers that are generally thicker and more abundant than in the lower sand unit.

The local occurrence of greenish gray mudstone is characteristic of the upper sand unit and seems to be uncommon to virtually absent in the lower units of the Salt Wash Member. Layers range from thin films to 1.0 m in thickness and are laterally continuous for no more than 9.1 m. They typically occur at the base of channel structures where overlying and adjacent channels scour deeply into them (Fig. 19). These mudstones contain fragments of carbonized plant material ranging in size from minute flakes to several cm in diameter. Because of the occurrence with carbonized debris, the gray mudstones of the upper sand unit are probably deposited under reducing conditions and their color is, therefore, primary in origin. Greenish gray mudstone of the lower

Figure 19. Primary greenish gray mudstone interval scoured by overlying channel of upper sand unit. (Mudstone interval is approximately 1.0 m thick.)

units are most likely due to diagenetic alteration of originally red mudstone since they locally show alternating greenish gray and grayish red mottling, are more green than gray in color, and typically do not contain carbonized plant material. Diagenetically altered greenish gray mudstone also occurs in the upper sand unit.

Quantitative Analysis of Stratigraphic Sections

Introduction - To facilitate interpretation of the Salt Wash Member, the twelve measured stratigraphic sections have been analyzed by a quantitative method which is a useful technique for detecting vertical cyclicity in a sequence of sedimentary rocks. The quantitative method used in this study is described by Harbaugh and Bonham-Carter (1970), and Miall (1973), and has been applied to a Devonian fluvial deposit by Cant and Walker (1976). The process consists of: 1) defining specific facies or features, 2) quantitatively analyzing their vertical sequence, 3) statistically substantiating predicted transitions, and 4) presenting their sequence in a facies or "tree" diagram and in the form of a local model. The following discussion shows the development of the facies diagram and local model for the Salt Wash Member based on this quantitative method which is verified statistically. Although some of the final interpretations are subjective, they are reasonable and consistent with the observed data.

Identification of facies and features - Seven distinct features or facies of the Salt Wash Member are defined according to lithology and primary sedimentary structures. The features or facies are given code letters and are as follows:

(S) scoured surface. This feature is an erosional surface which is the base of a channel cut and fill structure and does not include erosive basal surfaces of cross-stratified sets.

(T_L) large trough cross-stratified sandstone.

(T_m) medium trough cross-stratified sandstone.

(tw) planar cross-stratified sandstone. This facies consists of both large and medium, tabular- and wedge-shaped sets.

(H) horizontally laminated sandstone. This facies commonly exhibits current lineations.

(R) ripple cross-laminated sandstone and/or siltstone.

(O) interbedded mudstone and thin discontinuous lenses of sandstone that are less than 1.2 m in thickness. Sedimentary structures within these sandstones are variable but typically consist of small to medium troughs, horizontal laminae and ripple cross-laminae.

Analytical procedure - Analysis of the Salt Wash Member begins by recording from the measured stratigraphic sections (Plates 1 and 2) only the upward changes or transitions in facies. From this data a transition count matrix is tabulated, showing the number of times that each type of vertical transition occurs within the given stratigraphic section. The lower facies of each transition is given by the row number of the matrix, and the upper facies by the column number. Owing to their similarity and low total number of transitions, data from each stratigraphic section of the Salt Wash Member are combined to form the transition count matrix.

From the transition count matrix, two probability matrices are derived. The first (transition probability matrix) is constructed by converting the observed data in the transition count matrix to probabilities. This is done by dividing each entry in the transition count matrix by the sum of the row in which it occurs. The second matrix (random probability matrix), is calculated assuming the same abundance of facies but in a random (i.e., "equal likelihood of each transition occurring") sequence. Each entry (r_{ij}) in the random probability matrix is calculated by the following equation:

$$r_{ij} = s_j/(T - s_i')$$

where: s_j = column sum for each entry of the transition count matrix

T = total number of facies transitions

s_i' = column sum for each corresponding row of the transition count matrix.

A difference matrix is then derived by subtracting the random probabilities from the transition probabilities. Positive entries in the difference matrix indicate those transitions that have occurred with greater than random frequency. To test for stationarity (as described below), separate transition probability matrices are also calculated for each unit of the Salt Wash Member. The data and matrices are presented in Appendix 2.

Statistical verification - A statistic, which follows the X^2 (Chi squared) distribution, can be used to test for nonrandom frequency in the transition probability matrix. The null hypothesis is that the observed facies transitions are independent, or that they occur randomly. The alternative hypothesis is that the transitions are not independent and that they occur with significantly greater than random frequency. The statistic is calculated as follows:

$$X^2 = 2 \sum_{ij}^{m} n_{ij} \left[\log_e \; (p_{ij}/r_{ij}) \right]$$

where: m = the number of states (rows or columns) in the matrix

n_{ij} = entry in the transition count matrix

p_{ij} = entry in the transition probability matrix

r_{ij} = entry in the random probability matrix

and where: $(m - 1)^2 - m$ = degrees of freedom.

A X^2 test (with significance level of 0.05) on the transitional probabilities rejects the null hypothesis that the observed facies transitions of the Salt Wash Member occur with random frequency.

A question arises as to whether or not different depositional processes or mechanisms are responsible for each unit of the Salt Wash Member. A test for stationarity is applied to test the null hypothesis that the transition probabilities calculated from each unit are equal to the transition probability matrix from the entire Salt Wash Member. The alternative hypothesis is that the depositional processes are non-stationary or have changed through time. The test statistic follows the X^2 distribution and is calculated as follows:

$$X^2 = 2 \sum_{t}^{T} \sum_{ij}^{m} n_{ij\,t} \left[\log_e \; (p_{ij\,t}/p_{ij}) \right]$$

where: m = the number of states (7 for this study)

T = the number of units in the Salt Wash Member

$n_{ij\,t}$ = entry in the transition count matrix for each unit

$P_{ij\,t}$ = entry in the transition probability matrix for each unit

P_{ij} = entry in the transition probability matrix for the entire Salt Wash Member

and where: $(T - 1)\ (m\ (m - 1))$ =degrees of freedom.

Results of this test accept the null hypothesis and indicate that the depositional history and processes that deposited each unit of the Salt Wash Member are similar. The facies diagram (Fig. 20), therefore, is applicable to the entire Salt Wash Member. Deviations from the diagram that appear to be but are not unique to any particular unit are pointed out only for purposes of discussion.

For the complete computational details on these statistical methods, the reader is referred to Harbaugh and Bonham-Carter (1970) and Miall (1973).

Facies diagram for the Salt Wash Member - After verifying nonrandom frequency, positive entries in the difference matrix are used to construct a facies (or "tree") diagram. The diagram depicts preferred transitions with varying arrow widths to show subjectively how much more frequently certain transitions occur. To simplify the diagram and to exclude transitions that occur with near random frequency, only those entries in the difference matrix which are greater than + 0.10 are shown.

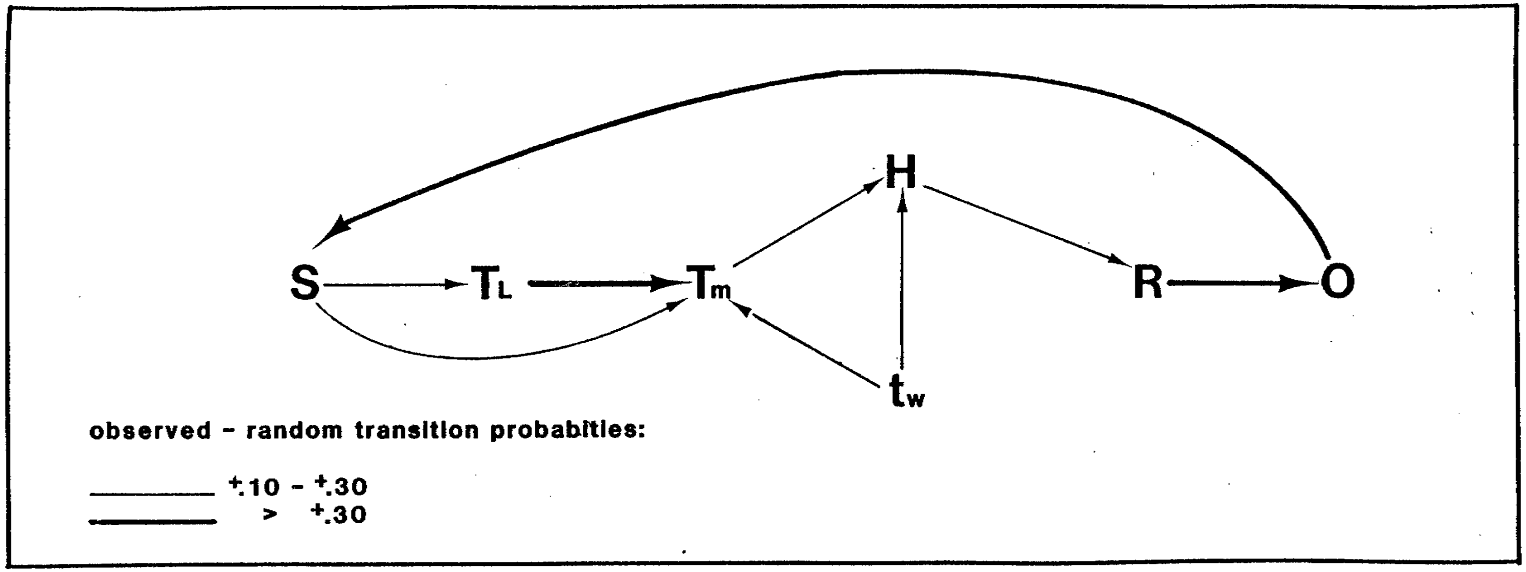


Figure 20. Facies diagram for the Salt Wash Member based on transitions that occur with greater than random frequency.

Values lower than this are numerically close to values derived from truly random data. It should be noted, therefore, that some of the types of transitions have been arbitrarily omitted from the diagram.

The facies diagram of the Salt Wash Member depicts a cycle with a scour surface (S) at the base and with interbedded mudstone (0) at the top. A noteworthy feature of this cycle is a gross, overall upward decrease in grain size (i.e., mudstone clasts in sandstone to mudstone) and scale of sedimentary structures (i.e., large and medium troughs to ripple cross-laminae).

The fluviatile origin of the Salt Wash Member cannot be argued against. The sandstone bodies display textures, sedimentary structures, stratigraphic sequences, and trace fossils (and lack of marine fossils) that compare closely with channel deposits of modern streams (Harms, et al., 1963; Allen, 1965; Harms and Fahnestock, 1965; Visher, 1972). The mudstone intervals are similar to modern floodplain and overbank sediments as described by Reineck and Singh (1975).

A cycle developed by channel filling would result in sediments and scale of sedimentary structures fining upward due to decreases in water velocity and stream competency (Allen, 1965). Where completely preserved, each cycle represents the establishment of a channel, abandonment by the stream and finally burial beneath floodplain or overbank deposits. The Salt Wash Member, therefore, is characterized by repeated episodes of channel establishment, channel filling and abandonment or shifting.

The transitions shown in Fig. 20 are used to form a local model

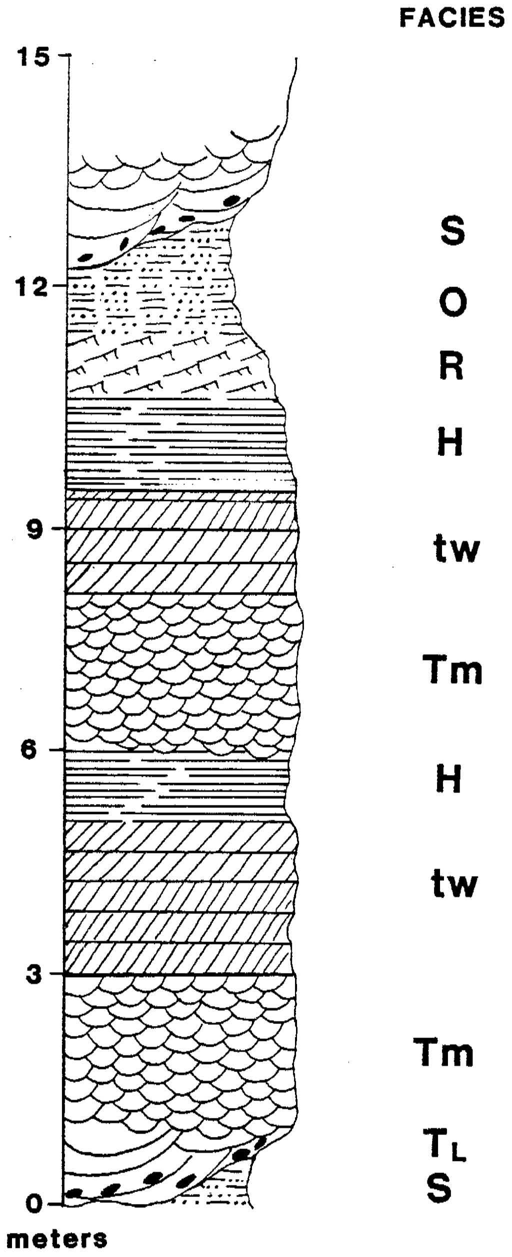


Figure 21. Facies model for the Salt Wash Member showing the average sequence and thicknesses of facies.

for the Salt Wash Member in the study area. The model is expressed as a stratigraphic column (Fig. 21).

The model begins with a scour surface overlain by a basal zone of poorly-sorted sand with mudstone clasts and trough (theta- and pi-) cross-stratification. The zone indicates initial channeling and represents bedload material in transport primarily by traction (Visher, 1972). The origin of theta-cross-strata has already been discussed; cosets of theta-cross-strata are constructed by repeated cutting and filling of channels. Such processes must have been common during deposition of the upper sand unit where cosets of large troughs reach 12.0 m in thickness. Some of the very large troughs of the Salt Wash Member (30.5 m in lateral extent) probably represent deposits by the largest bedforms present in the channel and may result from migration of large dunes or sandwaves.

Medium troughs (pi-cross-strata) overlie large troughs and represent migration of dunes along the channel floor (Reineck and Singh, 1975). Allen (1963) describes pi-cross-strata as a result of the migration of crescentic dunes under lower flow regime conditions. Harms and Fahnestock (1965) found large and medium troughs to be the most volumetrically important stratification types in a modern river, particularly within point bar deposits.

Planar cross-strata of fluvial deposits represent the downcurrent migration of bars or solitary banks (Allen, 1963 and Harms and Fahnestock, 1965). Extensive trenching of modern braided river sediment shows that tabular sets of planar cross-strata are the dominant structures (Collinson, 1970; Williams, 1971; Smith, 1972). Well-documented studies by Smith (1970, 1971) show that transverse bars, which are characteristic of distal braided streams, are predominantly composed of planar cross-strata. Sandwaves as described by Harms, et al., (1963) can also give rise to sets of planar cross-strata. Planar cross-strata make up approximately one-third of the lower sand unit and one-seventh of the sandstone of each the middle silt and upper sand units.

The facies tw, T_m and H are closely associated in a given vertical succession through the Salt Wash Member and represent processes taking place within channels (i.e., bar progradation). The frequent transition, tw $\rightarrow T_m$, implies channel filling to and above the level of bars (Miall, 1977). In the lower sand unit, planar cross-strata frequently overlie medium troughs suggesting aggradation of the channel floor prior to bar formation.

The upward transition, tw $\rightarrow$ H $\rightarrow$ R, is pronounced throughout the Salt Wash Member. Horizontal laminae can be generated on bar surfaces by plane bed movement under conditions of higher flow regime. A decrease in depth from the bar front to the bar surface can produce the increase in flow necessary for plane bed movement. Horizontal laminae overlain by ripple cross-laminae indicate deposition in topographically higher parts of the fluvial system and/or diminishing flow velocities (Harms and Fahnestock, 1965). Picard and High (1973) found the vertical succession, tw $\rightarrow$ H $\rightarrow$ R, to be common in ephemeral braided stream deposits. Smith (1970) describes similar bed transitions in deposits of the Lower Platte River. In both studies, the sequence is developed by linguoid bar progradation followed by low water accretion. The transition of large troughs to horizontal laminae, observed in the middle silt unit, possibly results from planar bed movement in channels of shallow water during flood stages (Miall, 1977).

Cosets of ripple cross-laminae develop by the migration of ripples and where diminished flow allows for deposition of suspended sediment. Ripples can develop on bar surfaces in shallow water, in the uppermost parts of channels after the channel is filled and outside the channel in overbank and floodplain areas.

Facies 0 occurs stratigraphically above all other facies. The interbedded very fine-grained sandstone, siltstone and mudstone that characterize this facies closely resemble modern floodplain or overbank deposits. Sediment deposition is primarily from suspension and forms vertical accretion deposits from waning floods. The common occurrence of rib-and-furrow marks, local bioturbation, and local occurrence of limestone nodules along stratification planes, support the interpretation. Allen (1974) records the occurrence of caliche nodules in shallow standing water of overbank areas. Horizontally laminated sandstones within facies 0, locally display parting lineations and probably represent vertical accretion during flood stage. Facies 0 is always succeeded by a scour surface, a result of renewed channeling.

Mudstone intervals can also develop by lateral migration of a channel or by channel abandonment followed by filling with fine sediment. Such processes would form lenticular, shoestring-like deposits, where mud settles out in pools of standing water. Low oxygen content or reducing conditions would preserve plant material within settling muds. This may be a possible origin for the gray mudstones and claystones of the upper sand unit. Preservation of these deposits would be low due to shifting and erosion by the channel system.

Of course, not all vertical successions are as complete as the facies diagram and local model depict. For example, the transitions, $S \rightarrow T_L \rightarrow T_m \rightarrow tw \rightarrow T_L$, as observed in the upper sand unit, suggests channel scouring, bar migration and renewed channel scouring before topographically higher facies could be formed or preserved. Other differences from the local model are exhibited by the middle silt and upper sand units. The middle silt unit consists of a greater proportion and thicker deposits attributed to floodplain or overbank sedimentation. The upper sand unit consists of facies T_L that are much thicker and 4 to 5 times more abundant than in the lower units. The most complete cycles are developed in the lower sand unit.

CHAPTER 4 PETROGRAPHIC AND X-RAY ANALYSES

PETROGRAPHY

Procedures

An optical petrographic study is made to augment lithologic descriptions, to determine diagenetic alterations and to aid in the interpretation of depositional environment. The samples chosen for thin section analyses were selected from 45 hand specimens and are representative of the major lithologies of each member of the Morrison Formation. Sample labels give the section and stratigraphic position (in meters) within the section from which the sample was collected (e.g., sample A-10.3 was collected from measured Section A at 10.3 meters above the base).

A total of 19 thin sections is analyzed. Two samples of the lower member of the Morrison Formation include siltstone and very fine-grained sandstone collected from the basal sandstone unit and the upper ripple cross-laminated, interbedded siltstone-sandstone unit. Petrographic study of the Salt Wash Member is largely confined to the major sandstone strata of the lower sand, middle silt and upper sand units. Two samples of siltstones from the middle and upper units are also studied. Samples of the Brushy Basin Member include sandstone, mudstone and claystone.

Point counts are made to determine percentages of detrital and interstitial components of all thin sections except for three mudstones and a claystone of the Brushy Basin Member. Counts are made of 300 points per section utilizing a petrographic microscope and a mechanical click stage with traverses approximately 1.0 mm apart. Components of Brushy Basin Member mudstones and claystone are visually estimated using the charts of Terry and Chilingar (1955).

Mineral identification is aided by Kerr (1959). Five thin sections of Salt Wash Member sandstones were stained to facilitate identification of potassium feldspar. Sections were etched with hydrofluoric acid and treated with sodium cobaltinitrite. A resulting greenish yellow stain, however, only delineated the more altered potassic detrital grains of microcline and potassic lithic fragments and did not effectively stain unaltered orthoclase. This may be explained by the etching process which is more rapid on altered than fresh grains of feldspar causing altered grains to absorb more of the stain.

Grain size is determined by averaging random measurements from thin section. Roundness, sphericity and sorting of detrital grains are determined by comparisons to charts of Pettijohn (1957), Krumbein and Sloss (1963) and Folk (1968) respectively.

Classification of sandstone samples is based on their mineralogy and textural maturity and is modified from Folk (1968). The samples are plotted on the classification diagram in Fig. 22.

Results

Sandstones

Salt Wash Member - Based on petrography, the samples show no significant

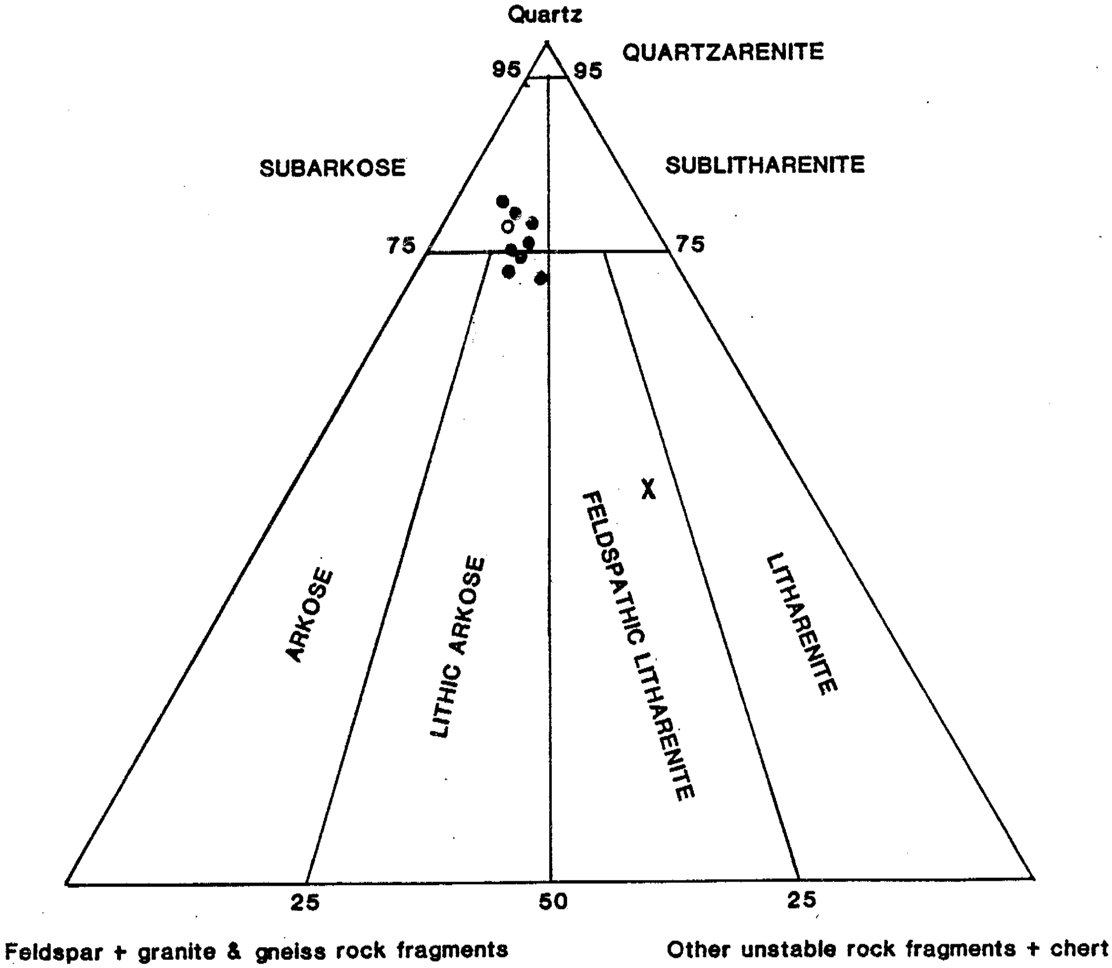


Figure 22. Plots of sandstone compositions of the lower member, Salt Wash Member and Brushy Basin Member of the Morrison Formation (o = lower member, ● = Salt Wash Member, X= Brushy Basin Member). (Classification modified from Folk, 1968).

differences in mineralogic composition or petrogenesis to allow distinction between sandstones of the lower sand, middle silt and upper sand units. The discussion that follows generally pertains to all sandstone samples that were studied from the Salt Wash Member; data on individual samples can be found in Tables 2 and 3.

Sandstones of the Salt Wash Member are classified as immature and submature subarkoses and lithic arkoses. In hand specimen the sandstones are pale red (10 R 6/2) to light gray (N 7) in color, fine- to medium-grained and moderately- to well-indurated. Quartz comprises 70% to 90% of the detritus in any hand sample.

In thin section detrital components (those greater than 0.02 mm in diameter) make up 63% to 81% of Salt Wash Member sandstone. Detrital grains are moderately-sorted, subangular to rounded and sub-equant to equant in shape. Grain sizes range from 0.05 mm to 0.60 mm with a mean grain size of about 0.25 mm, which is the boundary between fine and medium sand. Long axes of grains are generally randomly oriented, however, in some samples intermediate-shaped grains are poorly imbricated. Line and point contacts are the most common types of grain-to-grain contacts. The detrital grains are dominantly of quartz with subordinate amounts of potassium feldspar and various lithic fragments. Plagioclase, chert and heavy minerals compose a minor percentage of sandstones in the Salt Wash Member.

Quartz and Chert

Monocrystalline grains of quartz with nonundulatory to slightly undulatory extinction make up 72% to 81% of detrital components in

	Sample Number	COMPOSITION				GRAIN SIZE (mm)			TEXTURE					CLASSIFICATION
		Detritus	Cement	Matrix	Porosity	Range	Average	Wentworth	Sorting	Roundness	Sphericity	Grain-to-grain contacts	Textural Maturity	
LOWER SAND UNIT	A-21.3	81%	15%	3%	1%	.05-.20* / .10-.30	.10 / .30	very fine / medium	moderate	subrounded	subequant	line, point	submature	subarkose
	C-45.7	75	12	12	1	.10-.30	.20	fine	moderate	rounded	subequant	line, point	immature	subarkose
	F-33.8	79	20	tr**	1	.20-.50	.30	medium	moderate	subrounded	equant	line, point	submature	lithic arkose
MIDDLE SILT UNIT	A-68.6	67	20	12	1	.15-.30	.20	fine	moderate	subrounded	intermediate	line, point	immature	subarkose
UPPER SAND UNIT	C-76.2	63	25	12	0	.05-.50	.10	very fine	poor	subrounded	subequant	line, point	immature	subarkose
	C-106.7	69	30	tr	1	.20-.50	.30	medium	moderate	rounded	subequant	point, line	submature	subarkose
	D-100.6	76	9	15	0	.20-.60	.40	medium	well	rounded	equant	sutured, line	immature	lithic arkose
	C-96.0	80	14	5	1	.10-.50	.25	fine-medium	moderate	rounded	subequant	line, point	submature	subarkose

*Sample has two distinct size populations.

**Tr = trace amount.

Table 2. Texture and composition of the sandstones from the Salt Wash Member.

	Sample Number	Quartz	Potassium Feldspar	Plagioclase	Lithic Fragments	Chert	Opaque Heavy Minerals	Nonopaque Heavy Minerals	Number of Points
LOWER SAND UNIT	A-21.3	77% (±6)	13% (±4)	0% (0)	9% (±4)	tr% (0)	tr% (0)	tr% (0)	243
	C-45.7	74 (±6)	14 (±5)	tr (0)	10 (±4)	0 (0)	2 (0)	0 (0)	225
	F-33.8	73 (±6)	17 (±5)	0 (0)	10 (±4)	tr (0)	0 (0)	0 (0)	236
MIDDLE SILT UNIT	A-68.6	74 (±7)	14 (±5)	1 (0)	9 (±4)	1 (0)	1 (0)	0 (0)	201
UPPER SAND UNIT	C-76.2	81 (±6)	13 (±5)	tr (0)	6 (±3)	tr (0)	0 (0)	0 (0)	190
	C-106.7	79 (±6)	12 (±5)	tr (0)	8 (±4)	1 (0)	0 (0)	0 (0)	207
	D-100.6	72 (±6)	14 (±5)	0 (0)	13 (±5)	1 (0)	0 (0)	0 (0)	228
	C-96.0	75 (±6)	14 (±5)	tr (0)	10 (±4)	1 (0)	tr (0)	0 (0)	240

Table 3. Mineral composition of the detrital components of the sandstones from the Salt Wash Member.

thin sections. A few polycrystalline grains of quartz also occur. Quartz grains are rounded to subrounded in coarser size fractions and subangular in finer sizes. Small, euhedral to subhedral crystals of zircon, feldspar, rutile and apatite occur as inclusion in quartz. Smaller, rounded grains of chert compose tr% to 2% of the detrital components.

All thin sections show secondary quartz overgrowths that are optically continuous with the detrital monocrystalline quartz grains. Quartz overgrowths are usually thin, ragged and incomplete over the detrital grain surfaces and locally fill the surrounding interstices. In one sample (D-100.6) grains are tightly cemented together by secondary quartz overgrowths that completely fill interstitial spaces. The overgrowths show euhedral faces on detrital grains and linear sutures with each other. Very thin, dustlike films of iron oxide (hematite) and/or clay separate original grains from their overgrowths. Locally, grains of quartz exhibit concave-convex contacts following Taylor (1950). Calcite commonly embays the borders of quartz and chert grains and partially replaces microcrystalline quartz in the chert grains.

Feldspar

Potassium feldspars compose 12% to 17% of detrital components in Salt Wash Member sandstones. The most abundant variety is orthoclase, with microcline constituting less than 2% of detrital grains in any thin section. Grains of orthoclase are similar to quartz grains in size, roundness and elongation. Several thin sections show orthoclase with thin, ragged overgrowths that incompletely cover original grain surfaces and are nonoriented. Secondary enlargement of orthoclase is not as common or extensive as that of quartz. Microcline occurs as smaller grains that display polysynthetic twinning and that generally do not have secondary overgrowths. Microcline, and some detrital orthoclase, are clouded by flecks of white, fine crystalline material (kaolinite and/or sericite). The potassium feldspars also show varying degrees of replacement by calcite - from embayments along grain borders to nearly total replacement.

Plagioclase makes up only a minor percentage of detrital components and ranges from tr% to 1%. Plagioclase occurs as much smaller, more rounded, equant grains that are commonly twinned according to the albite law. Determination of An content is made using the Michel-Levy method and utilizing all twinned grains. Measurements along extinction angles indicate plagioclase compositions to be predominately albite with some oligoclase (An_0 to An_{30}). Plagioclase has also partially altered to a white, finely crystalline mica (sericite) and is partially to totally replaced by calcite.

Other Detrital Minerals

Heavy minerals and micas also constitute a very minor percentage of Salt Wash Member sandstones, ranging from tr% to 2% of the detritus. Trace amounts of detrital muscovite and biotite occur as elongate, crinkled grains interstitial to more abundant equant to subequant grains. Nonopaque heavy minerals include small, rounded grains of zircon, tourmaline, rutile and garnet. The most abundant heavy minerals are iron oxides (magnetite and hematite) which occur as small, dark, rounded and fibrous grains interstitial to coarser detritus. The hematite probably results from diagenetic oxidation of the original detrital magnetite. Small euhedral crystals of pyrite occur in some thin sections but these are more likely to be of secondary origin and not original detritus.

Lithic Fragments

Lithic fragments compose 6% to 13% of the detrital grains. The most abundant types are derived from volcanic rocks and include subrounded rhyolitic, vitrophyric and tuffaceous particles. Rhyolitic grains are optically similar to chert but the former contain microcrystals and patches of potassium feldspar which in some thin sections have been stained by the cobaltinitrite. Vitrophyric particles are composed of tiny, euhedral microcrystals of quartz, potassium feldspar and minor opaque heavy minerals that are often preferentially oriented in a black glassy groundmass. Tuffaceous fragments appear nearly isotropic and faintly show elongated flow textures and shard-like structures. Most volcanic grains have been devitrified and replaced by silica, calcite and/or clay minerals to various degrees. Nearly isotropic silica (opaline) and microcrystalline quartz (chert) appear to selectively replace the groundmass and vesicular structures of many volcanic fragments. Replacement by calcite ranges from partial to complete - from corroded borders to "ghosts" of original grains. Many volcanic lithic fragments have altered to micaceous clay (montmorillonite).

Sedimentary lithic fragments are represented in the thin sections by cloudy, dark brown argillaceous grains, some of which contain rounded, silt-sized particles of quartz, feldspar and opaque minerals. These fragments are commonly plastically deformed and have been squeezed between more competent grains. Deformation ranges from slight to extreme so that the former rock fragments can be confused with clay matrix and give rise to a false or pseudomatrix (Allen, 1962 and Dickenson, 1970). Although difficult, it is possible to recognize squashed lithic fragments, or pseudomatrix, even when the original grain outlines are gone. Pseudomatrix is distinguished from matrix by its distribution and nonuniform character from one area of the thin sections to the next. Pseudomatrix seems to fill only some intergranular spaces; matrix tends to fill all pores. Lithic fragments, though deformed, are not alike in color, composition or texture, whereas matrix displays more uniformity. Many argillaceous grains retain some relict layering even after deformation. If clay-filled areas could be recognized as pseudomatrix they were counted as lithic fragments.

A few grains of detrital carbonate are observed in several thin sections. The carbonate grains are micritic and contain unidentifiable microfossils that exhibit tubular structures. Microcrystalline quartz (chert) partially replaces detrital carbonate grains and selectively replaces some microfossils.

Lithic fragments of uncertain origin are composed predominantly of microcrystalline quartz (chert) with varying amounts of finely crystalline feldspar, mica, clay and opaque minerals. The microcrystalline quartz of these fragments is in turn replaced by isolated blebs of calcite.

Several grains are composed of interlocking crystals of quartz, potassium feldspar and biotite and suggest a possible plutonic source rock.

Matrix

Matrix, as defined by this study, includes all interstitial material less than 0.02 mm in size (excluding precipitated mineral cement). In thin section this material includes trapped detrital clay, microcrystalline particulate iron oxide, fine silt-sized debris, authigenic clays derived from feldspars and other detrital minerals, diagenetic alteration and replacement products of detrital clays, and small particles produced by plastic and brittle deformation of framework grains. Matrix ranges from tr% to 15% of the analyzed sandstones of the Salt Wash Member. In thin section the matrix appears as structureless dark brown and gray areas that commonly contain very fine to fine silt-sized particles of quartz, feldspar and fibrous opaque heavy minerals. Locally, patches of matrix are disseminated and stained by iron oxides (limonite and hematite). In one sample, tiny microcrystals of secondary pyrite and/or marcasite have impregnated matrix clay and impart a golden sheen to the matrix under reflected light. In other samples the matrix appears dark gray under crossed micols and contains aggregates of fibrous, micaceous grains with single mica crystals oriented normally to each other and tangentially to borders of framework grains. The texture and orientation of the micaceous crystals indicate that they are probably diagenetic and have developed by alteration of detrital clays. Locally, the matrix has been replaced by gray, nearly isotropic silica (opaline) and by isolated blebs of calcite.

Cement

Cement includes all minerals that show evidence of having been precipitated in pore spaces following deposition of the sediment. Cement ranges from 9% to 30% of the total composition of the sandstones studied. Cementing materials consist predominately of calcite and of optically continuous quartz overgrowths on detrital quartz grains. Phyllosilicates, silica (chert and opaline), iron oxides and authigenic orthoclase overgrowths on detrital orthoclase grains make up a minor percentage of cementing constituents.

Calcite is by far the most abundant cement and is present in all thin sections in varying amounts except for sample D-100.6. It occurs with poikilotopic texture, that is as large single crystals that enclose detrital grains, and with blocky texture in isolated, irregular patches that occupy intergranular spaces. Locally areas of poikilotopic calcite cement display polysynthetic twinning. Interstitial calcite also occurs as subhedral microcrystals disseminated in the matrix; however, it is felt that this is a result of replacement by calcite and not by precipitation of calcite cement in pore spaces. Several thin sections show replacement of calcite cement by microcrystalline quartz (chert).

Silica cement is predominantly present as authigenic overgrowths on original quartz grains which have been previously discussed. Silica cement occurs to a much lesser extent as microcrystalline silica (chert) and as nearly isotropic silica (opaline) that locally fill interstitial spaces. In several thin sections, opaline silica is observed between pore-filling calcite cement and quartz overgrowths, indicating its intermediate development in the sequence of cementation.

A number of workers have determined the presence of phyllosilicate cements in thin section studies and have supported the probability of direct precipitation of clay minerals as cement (Carrigy and Mellon, 1964; Suttner, 1969; Dickenson, 1970; Pettijohn, Potter and Siever, 1973; Almon, Fullerton and Davies, 1976). Recognition of phyllosilicate cement is based on textural evidence and is distinguished from other authigenic clay and clay matrix by its crystalline habit and mono-mineralogy. In the samples studied, phyllosilicate cements occur as thin rims of uniform thickness that surround framework grains. The rims are clear and devoid of impurities and are internally composed of radially-oriented microcrystals. The cementing clay minerals are bright green and/or red in color, optically continuous and pleochroic. Based on their optical characteristics, it seems probable that the cementing clays of the Salt Wash Member are in part chlorite.

Hematite and/or limonite cements are present in all thin sections in trace amounts. They occur as coatings on detrital grains and their overgrowths, and as pore-filling patches. Iron oxides have locally impregnated the matrix material and have filled veinlets in earlier calcite cement. Hematite is observed to radiate outward from many opaque grains, indicating a local origin for some of the iron-oxide cement.

Due to the widespread occurence of calcite and other cementing minerals, the porosity of the Salt Wash Member sandstones is low, ranging from tr% to 1%.

The clay mineralogy of the sandstones of the Salt Wash Member was not directly determined for this study. Work by Keller (1959) shows that the clay-sized fraction of the sandstones is dominantly illite with kaolinite and chlorite. This is compatable with results obtained in this study for mudstones and claystones of the Salt Wash Member.

Lower Member - Sample D-30.5 is from the interbedded siltstone-sandstone unit above the basal sandstone of the lower member of the Morrison Formation. This sandstone, based on petrographic analysis, is a mature subarkose. In hand specimen it is a yellowish gray (5 Y 7/2), very fine-grained sandstone. Subangular grains of quartz compose approximately 75% of the detritus.

Grain sizes of sample D-30.5 range from 0.05 to 0.12 mm in diameter with a mean grain size of 0.10 mm, very fine-grained sand. The detrital grains are well-sorted, subangular and subelongate to intermediate in shape. (Tables 4 and 5).

In thin section the samples of the Salt Wash and lower members are almost identical in their detrital, matrix and cement components. The main detrital grains in the sandstone of the lower member are of quartz, potassium feldspar and various lithic fragments. Lithic fragments include particles of volcanic, argillaceous and carbonate rocks that are very similar to those in sandstones of the Salt Wash Member. Minor detrital constituents include plagioclase, chert and heavy minerals (opaques and tourmaline). Cementing minerals consist dominantly of calcite with only minor amounts of silica as secondary overgrowths on quartz grains and as interstitial opaline cement. No phyllosilicate cement is

	SAMPLE NUMBER	COMPOSITION				GRAIN SIZE (mm)			TEXTURE					CLASSIFICATION
		Detritus	Cement	Matrix	Porosity	Range	Average	Wentworth	Sorting	Roundness	Sphericity	Grain-to-grain Contacts	Textural Maturity	
LOWER MEMBER	D-30.5	68%	27%	4%	1%	.05-.12	.10	very fine	well	subangular	intermediate	line	mature	subarkose
BRUSHY BASIN MEMBER	BB-80.8	76	18	6	0	.05-1.3	.45	medium	poor	rounded	subequant	line, point	submature	feldspathic litharenite

	SAMPLE NUMBER	Quartz	Potassium Feldspar	Plagioclase	Lithic Fragments	Chert	Opaque Heavy Minerals	Nonopaque Heavy Minerals	Number of Points
LOWER MEMBER	D-30.5	78% (±6)	13% (±5)	1% (0)	5% (±4)	tr (0)	2% (0)	1% (0)	204
BRUSHY BASIN MEMBER	BB-80.8	45 (±7)	12 (±5)	2 (0)	30 (±6)	7 (±3)	3 (0)	1 (0)	228

Table 4 (top). Texture and composition of the sandstones from the lower member and Brushy Basin Member.

Table 5 (bottom). Mineral composition of the detrital components of the sandstones from the lower member and Brushy Basin Member.

observed.

Brushy Basin Member - Sample BB-80.8 is from a lenticular layer of conglomeratic sandstone near the top of the Brushy Basin Member of the Morrison Formation. The sample is a submature feldspathic litharenite in hand specimen, which is pale yellowish brown (10 YR 6/2) in color, coarse-grained sand to granular, poorly-sorted and well-indurated. Subangular to rounded granules and pebbles (up to 15.0 mm in diameter) include red, green, brown and black chert, potassium and plagioclase feldspar and lithic fragments of quartzite and silicified volcanic rocks. Quartz makes up 50% of the coarse sand-sized components in hand specimen.

Grain sizes in thin section range from 0.05 to 1.3 mm with a mean diameter of 0.45 mm, medium sand. Detrital grains are poorly-sorted, subangular to well-rounded and subequant in shape. Long axes of grains are randomly oriented. Grain-to-grain contacts are largely line and point contacts.

Detrital Minerals

Detrital components of the Brushy Basin Member are generally similar to those found in the lower and Salt Wash members. However, probably due to the coarser mean grain size, the conglomeratic sandstone contains a smaller proportion of detrital quartz and a larger proportion of lithic fragments plus detrital chert than the other sandstones studied. Unlike the sandstones of the lower and Salt Wash members, large, isolated subhedral grains of potassium feldspar, twinned according to the Carlsbad Law, occur in the conglomeratic sandstone of the Brushy Basin Member. Plagioclase occurs both as rounded detrital grains and as bunches of euhedral, lathlike crystals randomly oriented in the matrix. These laths are localized, cutting across silica cement and penetrating into detrital grains, and thus appear to be authigenic in origin. All detrital feldspars are altered by finely crystalline mica and are being partially replaced by opaline silica.

Lithic Fragments

Lithic fragments are derived from volcanic and sedimentary rocks and are very similar in composition and texture to those in the Salt Wash Member. Replacement by opaline silica and chert is far more extensive in the lithic fragments of the conglomeratic sandstone.

Matrix

The matrix of sample BB-80.8 consists of a mixture of detrital clays, finely crystalline iron oxides, fine silt-sized debris, diagenetically produced clays, and finely disseminated microcrystalline quartz (chert).

Cement

Cementing materials are dominantly microcrystalline quartz and nearly isotropic silica that fill intergranular spaces. These minerals also replace the matrix and are difficult to distinguish from pore-filling cement. Phyllosilicate cement occurs as thin crystalline rims surrounding some detrital grains. The clay rims are reddish orange in plane light and constitute less than 1% of the cementing minerals. Minor amounts of iron oxide (hematite) cement are present as grain coatings and as thin patches filling some pore spaces.

Siltstones and Finer Grained Rocks

Lower and Salt Wash Members - Samples of siltstones were collected from the basal sandstone unit of the lower member and from the middle silt and upper sand units of the Salt Wash Member. The siltstones are yellowish gray (5 Y 8/1) and pinkish gray (5 YR 8/1) in color and are moderately indurated. Petrographic data for the siltstones and finer grained rocks of the lower, Salt Wash and Brushy Basin members are shown in Tables 6 and 7.

Grain sizes of the siltstones range from 0.02 mm to 0.24 mm, with a mean grain size for all three thin sections of 0.06 mm, which is coarse silt. The siltstone from the lower member is more poorly-sorted and contains a greater proportion of very fine to fine sand grains than the siltstones of the Salt Wash Member. Detrital grains greater than 0.02 mm constitute 45% to 50% of the siltstones and are scattered in a matrix of detrital and diagenetic clay-sized material. The siltstones generally do not show preferred orientation of grains in thin section, however, sparse elongate muscovite and biotite grains show some alignment of their long axes parallel to stratification. Finer grained rocks of the lower and Salt Wash members contain similar mineral components as the sandstones described previously, and are distinguished only by their finer grain size, higher proportion of feldspars and clay and more angular detritus.

	SAMPLE NUMBER	COMPOSITION				GRAIN SIZE (mm)			TEXTURE		
		Detritus	Cement	Matrix	Porosity	Range	Average	Wentworth	Sorting	Roundness	Sphericity
LOWER MEMBER	C-22.0	45%	38%	17%	0 %	.06-.24	.06	very fine sand —coarse silt	poor	subangular	subequant
MIDDLE SILT UNIT	K-19.5	49	34	16	1	.05-.10	.06	very fine sand —coarse silt	moderate	angular - subangular	subequant
UPPER SAND UNIT	A-109.7	50	44	6	0	.02-.15	.06	very fine sand —coarse silt	moderate	angular - subangular	subequant
	BB-24.4	47	18	35	tr	.06-.50	.20	fine sand	poor	rounded	equant
	BB-25.0	35	33	32	0	.06-.12	.06	very fine sand —coarse silt	moderate	subrounded	subequant
BRUSHY BASIN MEMBER	BB-35.5*	40	5	55	tr	.06-.12	.06	very fine sand —coarse silt	moderate	subangular	subequant
	BB-52.0*	40	10	50	tr	.03-.06	.04	coarse silt	moderate	subangular	subequant
	BB-74.7*	45	5	50	tr	.02-.06	.04	coarse silt	moderate	subangular	subequant
	BB-91.4*	3	4	93	tr	.02-.06	.03	coarse - medium silt	moderate	subangular	subequant

*Based on visual estimations.

Table 6. Texture and composition of finer grained rocks from the lower member, Salt Wash Member and Brushy Basin Member.

	SAMPLE NUMBER	Quartz	Potassium Feldspar	Plagioclase	Lithic Fragments	Chert	Opaque Heavy Minerals	Nonopaque Heavy Minerals	Number of points
LOWER MEMBER	C-22.0	70% (±8)	15% (±7)	tr% (0)	12% (±6)	0% (0)	2% (0)	1% (0)	135
MIDDLE SILT UNIT	K-19.5	72 (±8)	14 (±6)	2 (0)	11 (±6)	tr (0)	0 (0)	1 (0)	147
UPPER SAND UNIT	A-109.7	73 (±8)	13 (±6)	1 (0)	10 (±5)	0 (0)	0 (0)	3 (0)	150
BRUSH BASIN MEMBER	BB-24.4	61 (±9)	17 (±7)	1 (0)	18 (±7)	3 (0)	tr (0)	0 (0)	141
	BB-25.0	46 (±10)	11 (±7)	8 (±6)	35 (±10)	0 (0)	0 (0)	0 (0)	105
	BB-35.5*	60	20	5	15	tr	tr	tr	
	BB-52.0*	65	20	5	10	tr	tr	tr	
	BB-74.7*	65	15	7	13	tr	tr	tr	
	BB-91.4*	45	2	1	2	tr	40	10	

*Based on visual estimation.

Table 7. Mineral composition of the detrital components of the finer grained rocks from the lower member, Salt Wash Member and Brushy Basin Member.

Detrital Minerals

Grains of quartz, potassium feldspar and lithic fragments are the main detrital constituents.

Detrital quartz occurs as angular to subangular monocrystalline grains with nonundulatory to slightly undulatory extinction. Quartz grains in the siltstones generally do not have extensive secondary overgrowths, but where overgrowths do occur, they form optically continuous sawtoothed projections on original grains. Feldspars appear to make up a larger proportion of detrital grains in the siltstones than in the sandstones. Feldspars include orthoclase with minor amounts of microcline and plagioclase (tr% to 2%). Calcite replaces quartz and feldspars by corroding and embaying grain borders and small blebs of calcite are found along twin planes of plagioclase. Flakes of finely crystalline mica occur as alteration products in grains of potassium feldspar and plagioclase.

Lithic Fragments

Lithic fragments (ranging from 10 to 12% of the detritus) include those derived from volcanic and sedimentary rocks and are similar in appearance and diagenetic changes to those in the sandstones. Siltstones from the Salt Wash Member contain rhyolitic and vitrophyric grains, that are partly replaced by microcrystalline quartz, dark brown argillaceous material and micritic, carbonate. Lithic fragments derived from volcanic rocks were not observed in the siltstone of the lower member.

Other Detrital Minerals

Heavy minerals occur in minor amounts and consist chiefly of subrounded to rounded silt-sized grains of magnetite and hematite and elongate, bent grains of biotite and muscovite. Rare small grains of tourmaline also occur.

Matrix

Matrix composes 6% to 17% of the siltstones studied. Matrix material of the siltstones is very similar in appearance and composition to that of the sandstones and consists of detrital and diagenetic clays and very fine silt-sized debris. Matrix occurs as large dark brown and dark gray areas containing aggregates of fibrous micaceous crystals (up to 0.02 mm in length) dispersed throughout. These micaceous grains lie tangentially against silt-sized detritus and appear to be oriented normally to each other where two crystals are in contact. Finely crystalline iron oxides locally impregnate matrix clays. Calcite replaces matrix material in the form of tiny disseminated blebs.

Cement

Cement is chiefly calcite with only minor amounts of silica as quartz overgrowths and as interstitual, pore-filling cement. Sparry calcite cement surrounds detrital grains and is present as irregular patches throughout the matrix. Sparse, isolated rhombic crystals are observed embedded in the calcite cement of all three thin sections. These are probably crystals of authigenic dolomite. Locally calcite is replaced by microcrystalline quartz and in samples C-22.0 and K-19.5, quartz has selectively replaced some of the rhombic crystals of dolomite. Hematite occurs as coatings on detrital grains, as "halos" radiating outward from rounded grains of magnetite, and as rare local pore-filling patches in calcite cement.

Brushy Basin Member - Samples of five mudstones and one claystone were collected from the Brushy Basin Member at vertical intervals of approximately 10.0 m to 20.0 m. The mudstones are greenish gray (5 GY 6/1) in color and poorly-indurated. The claystone was collected from the top of the Brushy Basin Member and is medium dark gray (N 4) in color and very well indurated.

The mudstones are composed of subequal amounts of clay-sized material and silt-sized detritus; both size fractions are nearly identical in composition and proportions of mineral constituents to each other. Detrital grains constitute 35% to 47% of the mudstones and are chiefly coarse silt-size, but some fine and medium sand grains are also present. Grain sizes range from 0.02 mm to 0.50 mm in thin section. Detrital grains are angular to rounded, poorly to moderately-sorted and subequant in shape. Long axes of grains are randomly oriented. Quartz, feldspars and lithic fragments are the major detrital components with chert and heavy minerals making up a minor percentage. The mudstones have a greater proportion of potassium feldspar and lithic fragments than the conglomeratic sandstone of the Brushy Basin Member (see Tables 5 and 7).

Detrital Minerals and Lithic Fragments

Quartz occurs as subangular to rounded, monocrystalline grains that generally do not show secondary overgrowths. Feldspars include orthoclase and plagioclase (albite) that are altered to microcrystalline flecks of mica and clay. Heavy minerals and micas are present in trace amounts and consist of fibrous opaque grains (magnetite) and rare thin flakes of muscovite. Lithic fragments observed in the mudstones consist principally of volcanic debris. They include devitrified glass shards and tuffaceous fragments that show poorly developed vesicular flow textures.

Many grains of quartz, feldspar, chert and lithic fragments have corroded borders that have been replaced by silica and/or calcite. In samples BB-24.4 and BB-25.0 the replacing minerals are chiefly calcite with some microcrystalline quartz which embay grain borders and totally replace some plagioclase grains and volcanic shards. In samples BB-35.5, BB-52.0 and BB-74.7, microcrystalline quartz replaces feldspars and lithic fragments revealing only isolated blebs and ghosts of original grains.

Matrix

The matrix of the mudstone samples consists of detrital and diagenetic clay-sized material, fine silt-sized detritus, finely crystalline iron oxides, and minute disseminated particles of authigenic quartz. The matrix and detrital grains of samples BB-35.5, BB-52.0 and BB-74.7 have been extensively replaced by microcrystalline quartz making estimations of components difficult. In thin section, the matrix is dark gray in plane light and contains faint outlines of shards and angular grains (volcanic fragments ?). Fibrous shreds of highly birefringent micaceous grains are observed cutting across the silicified matrix and are oriented tangentially to silt-sized detrital grains, indicating the micaceous grains are diagenetic in origin.

Cement

Calcite occurs as cement in small, irregular patches, as a replacement mineral of silt-sized detrital grains and as minute blebs replacing matrix material. Calcite as cement ranges from tr% to 30% of the rock in the mudstones studied.

Iron oxides (hematite and limonite) are present as fine dustlike grains that are disseminated within the matrix. Iron oxides also occur as cementing material which have filled small pore spaces and hairline cracks in the matrix. The maximum amount of iron oxide cement in any thin section of Brushy Basin Member mudstones is 4%.

Sample BB-91.4 is a claystone that contains approximately 3% medium silt-sized debris of quartz, muscovite and opaque heavy minerals. The long axes of fibrous, elongate grains of opaques and muscovite are preferentially oriented along bedding planes. Minute isolated patches of calcite have replaced approximately 5% of the clay minerals. Microcrystalline quartz, that was a common replacement mineral in the mudstones, does not occur in the claystone.

The clay mineralogy of the siltstones and finer-grained rocks of the lower, Salt Wash and Brushy Basin members is determined by x-ray diffraction and is discussed in the following section.

X-RAY ANALYSIS

Procedures

The clay mineralogy of 15 claystone and mudstone samples is determined semiquantitatively by x-ray diffraction methods. The purpose of this analysis is fourfold: 1) to identify clay mineral constituents, 2) to determine relative proportions of clay constituents in each sample, 3) to ascertain variations in mineralogy and relative proportions of clay constituents with respect to stratigraphic position, and 4) to determine if such variations can be used to aid the interpretation of depositional environment.

Samples are from measured stratigraphic Sections C and BB and range in stratigraphic position from the base of the Summerville Formation to the top of the Brushy Basin Member of the Morrison Formation. Intervals between sample locations range from 6.0 to 25.0 m. Sample numbers give the section and stratigraphic position (in meters) from which the claystone or mudstone sample was collected.

After the samples are pulverized in the lab, approximately 25 grams of each sample are added to 250 ml of distilled water, mixed thoroughly by an electrosonifier and allowed to settle. Clay-sized material ($\leq 2\mu$) that remains in suspension is drawn off, placed on a glass slide and allowed to dry. Samples that contain calcium carbonate or other salts are boiled in EDTA solution, centrifuged and remixed with distilled water before preparation of sedimented slides.

Carroll (1970) provided the guidelines for analytical procedures and identification of clay minerals used in this study. Each sample was analyzed four times on an x-ray diffractometer; once after being air-dried, again after treatment with ethylene glycol, and after being heated to 350° C and finally to 550° C. Diffraction patterns were obtained by using nickel-filtered copper K-alpha radiation at settings of 40 KV and 20 ma and with a 1^{o} collimator, a 4^{o} soller slit and a 1^{o} receiving slit. Slides were scanned from 2^{o} to 37^{o} 2θ at a scanning rate of 2^{o} per minute.

Relative proportions of clay mineral components are calculated from methods modified from Johns, Grim and Bradley (1954) by Austin (personal communication, 1979) which uses peak heights instead of peak areas. The proportions of clay constituents are reported in parts per ten and only to one significant figure after recommendations by Austin and Leininger (1976). The semiquantitative method for clay mineral analysis used in this study is as follows:

$$I = Ig/T \times 10$$

$$M = (Mg/4)/T \times 10$$

$$C = C_3/I_2 \times I$$

$$Mx = (I_h - (Ig + Mg/4))/T \times 10$$

$$K = K_1/T \times 10 \text{ or if chlorite is present } = K_2/2C_4 \times C$$

$$T = I_h + K_1 \text{ or if chlorite is present } = I_h + \left[(C_3 \times Ig)/I_2\right] + \left[(K_2 \times C_3 \times Ig)/2C_4 \times I_2\right]$$

where

I = calculated proportion of illite
M = calculated proportion of discrete montmorillonite
C = calculated proportion of chlorite
Mx = calculated proportion of mixed illite-montmorillonite clays
K = calculated proportion of kaolinite
Ig = glycolated illite peak at 8.8^{o} 2θ
Mg = glycolated montmorillonite peak at 5.2^{o} 2θ
C_3 = air-dried chlorite peak at 18.4^{o} to 18.9^{o} 2θ
I_2 = air-dried illite peak at 17.8^{o} 2θ
I_h = heated illite peak at 8.8^{o} 2θ
K_1 = air-dried kaolinite peak at 12.4^{o} 2θ

K_2 = air-dried kaolinite peak at 24.9° 2θ
C_4 = air-dried chlorite peak at 25.1° 2θ

Clay Mineralogy

Figure 23 shows the changes in relative proportions of clay mineral constituents as a function of stratigraphic position. The most significant changes in the clay mineral assemblages occur between the formations and members and in an upward decrease in kaolinite and an upward increase in chlorite and montmorilonite. Mixed layer clays are largely composed of randomly layered illite and montmorillonite.

The clay mineral assemblage of samples from the Summerville Formation is dominated by illite (ranging from 3 to 7 and averaging 5 parts in ten) with lesser mixed layer clays (range 1 to 3, average 2.5) and kaolinite (range 0 to 6, average 2.5). Discrete montmorillonite and chlorite are insignificant components of the clay mineral assemblage of all three samples.

The clay mineral assemblages of both samples from the lower member of the Morrison Formation are characterized by zero parts in ten discrete montmorillonite and mixed layer clays. This is an anomalously low proportion of mixed layer clays compared to all fifteen samples which combined with the low proportion of discrete montmorillonite distinguishes the samples of the lower member of the Morrison Formation from the samples of all the other stratigraphic units.

The clay mineral assemblages of samples from the Salt Wash Member of the Morrison Formation are commonly dominated by subequal proportions of illite, mixed layer clays and chlorite with minor kaolinite and no discrete montmorillonite.

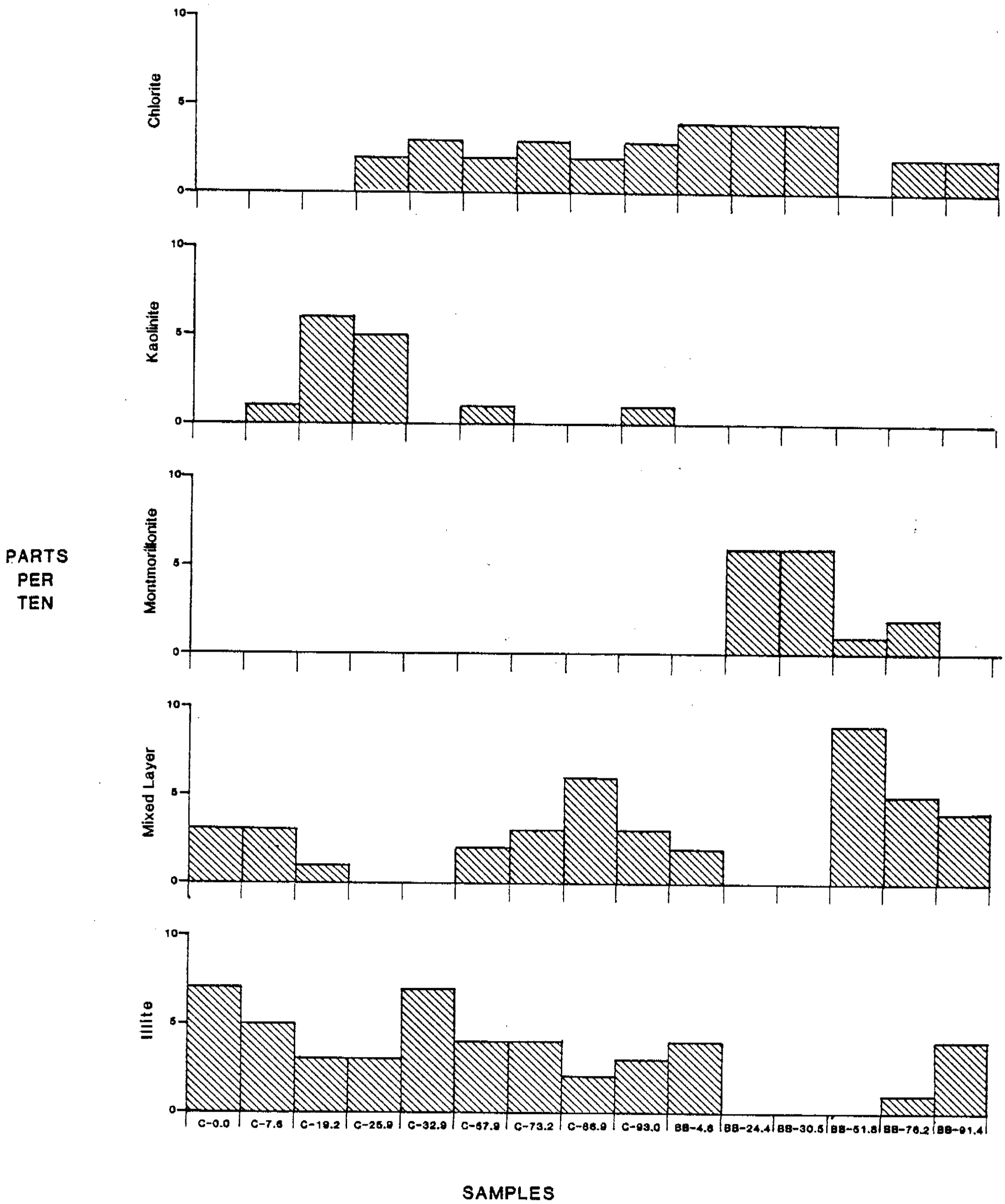


Figure 23. Relative proportions of clay mineral constituents as a function of stratigraphic position. Samples are from the Summerville Formation and the lower member, Salt Wash Member and Brushy Basin Member of the Morrison Formation.

The clay mineral assemblages of samples from the Brushy Basin Member of the Morrison Formation vary stratigraphically. There appears to be an inverse relationship within the Brushy Basin Member between the relative abundance of discrete montmorillonite and the relative abundance of mixed layer clays plus illite. Where discrete montmorillonite is abundant (6 parts in ten) in the lower half of the Brushy Basin Member, illite and mixed layer clays are absent, but as discrete montmorillonite decreases upward, mixed layer clays and illite begin to dominate the clay mineral assemblage.

Clay minerals have been used to a certain degree as aids to interpreting depositional environments. Millot (1952) discusses clay mineral assemblages that are most often associated with particular depositional facies. It is extremely difficult, however, to assign a certain clay mineral assemblage to any particular depositional environment and any attempt to do so should be regarded as tentative. More valid perhaps to interpretations of depositional environments, are the lateral variations of clay mineral assemblages. Parham (1966) and Brown, et al., (1977) discuss the general trends of clay minerals in the transition from marine to nonmarine environments. Both studies indicate general trends of decreasing illite and increasing kaolinite and mixed layer clays inland. Brown and Ingram (1954) studied downstream changes in the dominant clay minerals of modern river sediments. They also noted an increase in kaolinite upstream but found that mixed layer clays decrease upstream (inland).

The results of this analysis are not in agreement with those of

Brown and Ingram (1954), Parham (1966) and Brown, et al., (1977). Illite remains relatively constant throughout the Salt Wash Member but mixed layer clays do tend to increase in abundance from the base to the top of the Salt Wash Member. A decrease in illite upward in the Summerville Formation is associated with an increase in kaolinite, however kaolinite decreases and is present in only trace amounts in the mudstones and claystones of the Salt Wash Member. Smoot (1960) and Millot (1970) describe the presence of moderately-well sorted sandstones and both illite and kaolinite in nearshore marine deposits. Although kaolinite is most stable under acidic, oxidizing conditions such as streams and rivers (Millot, 1952), Smoot (1960) and Millot (1970) conclude that both illite and kaolinite can develop at the interface of nearshore marine and freshwater environments (stream mouths) where mixing by wave and current action preserves kaolinite by rapid burial. This occurrence and the slight increase of kaolinite upward through the Summerville Formation is compatible with the nearshore marine environment postulated for the formation.

Illite can occur in a variety of depositional environments but the physical-chemical conditions postulated by Millot (1970) for stability of illite requires an environment of stagnant water with alkaline pH and an abundance of K^+ ions. Illite is most stable under marine conditions but can also exist in lacustrine environments where pH is alkaline or in semi-arid and arid terrestrial environments where water is alkaline. Although kaolinite is more stable in slightly acidic, well circulated environments, such as streams, perhaps sampling of just mudstone and claystone layers between thicker, cross-stratified sandstones biased the results. The mudstone sequences were probably deposited on floodplains where reduced circulation of water enhanced the stability of illite. Slow-moving or stagnant water allows alkalies to increase in concentration and favors formation of illite rather than kaolinite (Millot, 1970). This may account for the lack of kaolinite in the mudstones and claystones of the Salt Wash Member in this analysis.

In a regional study of the clay mineralogy of the Morrison Formation, Keller (1962) describes the illites of the Salt Wash Member as probably derived from pre-existing sedimentary rocks. The abundance of mixed layer clays is accounted for by partial alteration of illite by moderate leaching and removal of K^+ ions.

The dominance of montmorillonite in the lower half of the Brushy Basin Member is probably a result of alteration of volcanic material in the sediments. This is supported by petrographic observations of relict shards and tuffaceous fragments in the mudstones and claystones of the Brushy Basin Member. Bilbey, et al., (1974) state that if ash falls into a sedimentary basin it will alter to montmorillonite under conditions of arrested drainage and restricted oxidation. These conditions must have existed locally in the Brushy Basin Member in order to preserve montmorillonite. The occurrence and association of illite and montmorillonite in the Brushy Basin Member suggest deposition either under lacustrine conditions, under restricted circulation or in areas of arid to semiarid environments. The presence of many fully preserved shards suggests the volcanic ash fell in place or was not transported far enough to abrade the grain edges.

The above interpretations are based largely on the effects the depositional environment has on the clay mineralogy of the sediments. It is almost impossible to evaluate the combined effects of changes in source material, weathering, climatic changes and diagenesis on clay minerals. Therefore, interpretations of depositional environments cannot be based on clay mineral assemblages alone but the clay analyses must be used in conjunction with other criteria in this study.

DIAGENESIS

Diagenesis is defined in this study to include all physical and chemical changes which occur in the sediment after deposition (Pettijohn, 1957). All the thin sections studied showed evidence of diagenetic changes of some kind, most of which were described earlier. Although minor exceptions exist in individual thin sections, the sequence of diagenetic events for the sandstones and finer-grained rocks is similar. Major events are listed below and numbered in order of their occurrence from older to younger. Lower-case letters indicate events which occurred approximately synchronously or within short intervals of geologic time. The diagenetic sequence based on petrographic evidence is as follows:

1) Compaction caused brittle deformation of detrital grains of quartz and feldspar as well as plastic deformation of less competent lithic fragments, and may also have produced rare interpenetration of detrital quartz grains. Plastic deformation during compaction rearranged the initially open packing of flake-shaped clay minerals into more tightly

packed clays with concomitant expulsion of much pore fluid for the mudstones.

2) a) Formation of secondary quartz and orthoclase overgrowths on detrital quartz and orthoclase grains. b) Devitrification of volcanic fragments to microcrystalline quartz (chert).

3) Precipitation of some pore-filling silica cement (with cherty and/or opaline texture). A possible source of this cement could be from process 2b) above (Pettijohn, Potter and Siever, 1973).

4) a) Precipitation of calcite cement in interstitial spaces. (Neomorphic growth (Folk, 1968) of calcite cement was a progressive event. Initially precipitated microcrystals of calcite formed a micritic texture but progressively crystals enlarged to form continuous, blocky calcite cement). b) Replacement of detrital grains, secondary overgrowths, and matrix material by calcite. Replacement ranges from partial (corroded and embayed grain borders) to complete (isolated remnants and "ghosts" of original grains).

5) Partial replacement of calcite cement by isolated rhombic crystals of dolomite.

6) Partial replacement of calcite cement, authigenic dolomite, some detrital grains and matrix material by microcrystalline quartz.

7) a) Local development of authigenic, lathlike crystals of plagioclase in rocks of the Brushy Basin Member. b) Local development in matrix clays of siltstones of the Salt Wash Member of disseminated microcrystals of pyrite.

Some diagenetic changes could not be placed in the above chronological sequence since their relationships to other events could not be discerned petrographically with any certainty. These events include:

1) Precipitation of hematite (or other iron oxides) - based on petrographic evidence it appears that the precipitation of hematite occurred throughout the diagenetic history of the rocks. This is evidenced by the fact that hematite films coat both detrital grains and their overgrowths and also fills veinlets in later calcite cement. It is not likely that hematite films were transported with the original grains since no red films are observed between detrital grains in contact with each other. It is probable that much of the hematite results from in situ oxidation of detrital magnetite and other iron-bearing minerals (Walker, 1967) since hematite is usually localized and closely associated with opaque grains.

2) Development of phyllosilicate cement - observations of phyllosilicate rims, similar to those described by Carrigy and Mellon (1964) and Dickenson (1970), surrounding detrital grains and their secondary overgrowths indicate that cementation by clays occurred after precipitation of the overgrowths (previously designated 2a)) but before chert replacement (previously designated as 6)). Phyllosilicate rims are embayed by chert that has also replaced matrix material.

3) Partial replacement and alteration of detrital feldspar grains and volcanic lithic fragments by clay minerals - this is probably an early diagenetic event because clay alteration products, along with the original minerals, are replaced by (previously designated as 3) and 4) respectively) microcrystalline silica and calcite. Keller (1962)

suggests that argillation of volcanic material in the Brushy Basin Member occurred near the surface and not long after deposition. This is supported by Schultz (1963) who describes the alteration of volcanic glass to montmorillonite as occurring rapidly under near surface conditions.

4) Replacement of clay-sized material in matrix by aggregates of larger fibrous, micaceous grains - petrographic evidence indicate that this event occurred later in the diagenetic history. Individual micaceous grains frequently extend into and cut across areas that had been replaced by calcite and microcrystalline silica.

5) Silicification of mudstones and finer-grained rocks in the Brushy Basin Member - based on petrographic observations, argillation of tuffaceous material was followed by silicification of some mudstones of the Brushy Basin Member. Patches of microcrystalline quartz are found adjacent to and embaying areas that have altered to montmorillonite and/or chlorite. Keller (1962) discusses the conversion of tuffaceous fragments in the Brushy Basin Member to mobile silica that was later redeposited in the residual clay as secondary silica in the form of cherty microcrystalline quartz.

CHAPTER 5 PALEOCURRENT ANALYSIS

PROCEDURES

A total of 352 paleocurrent measurements are taken from the Salt Wash Member in the study area. Measurements are taken from primary sedimentary structures that include: unidirectional (unique) readings from cross-stratification, and polar (non-unique) readings from current lineations. Tectonic deformation has not affected the original bedding in the study area so that direct measurements of primary structures give true paleocurrent direction.

The paleocurrent data are grouped according to their occurrence in the lower sand, middle silt or upper sand units. This three-part division is done to determine if paleoflow directions are significantly different between the three units. The data for each unit consists of the composite data from all twelve sections so that a statistically valid mean paleocurrent direction is obtained. Each unit is then divided into a lower and upper half to determine if variations in the mean current direction is a function of stratigraphic position and also to maintain a sufficient number of readings in each interval. Appendix 3 presents the paleocurrent data collected for this study.

The paleocurrent analysis is based on methods discussed by Potter and Pettijohn (1963). Rose diagrams (Figure 24) graphically represent the data from each interval. The data are plotted with a 30° azimuthal grouping and are graphically illustrated according to type of sedimentary structure. For this analysis, current parting lineations are treated as unique directions and are plotted in the 180° segment of the

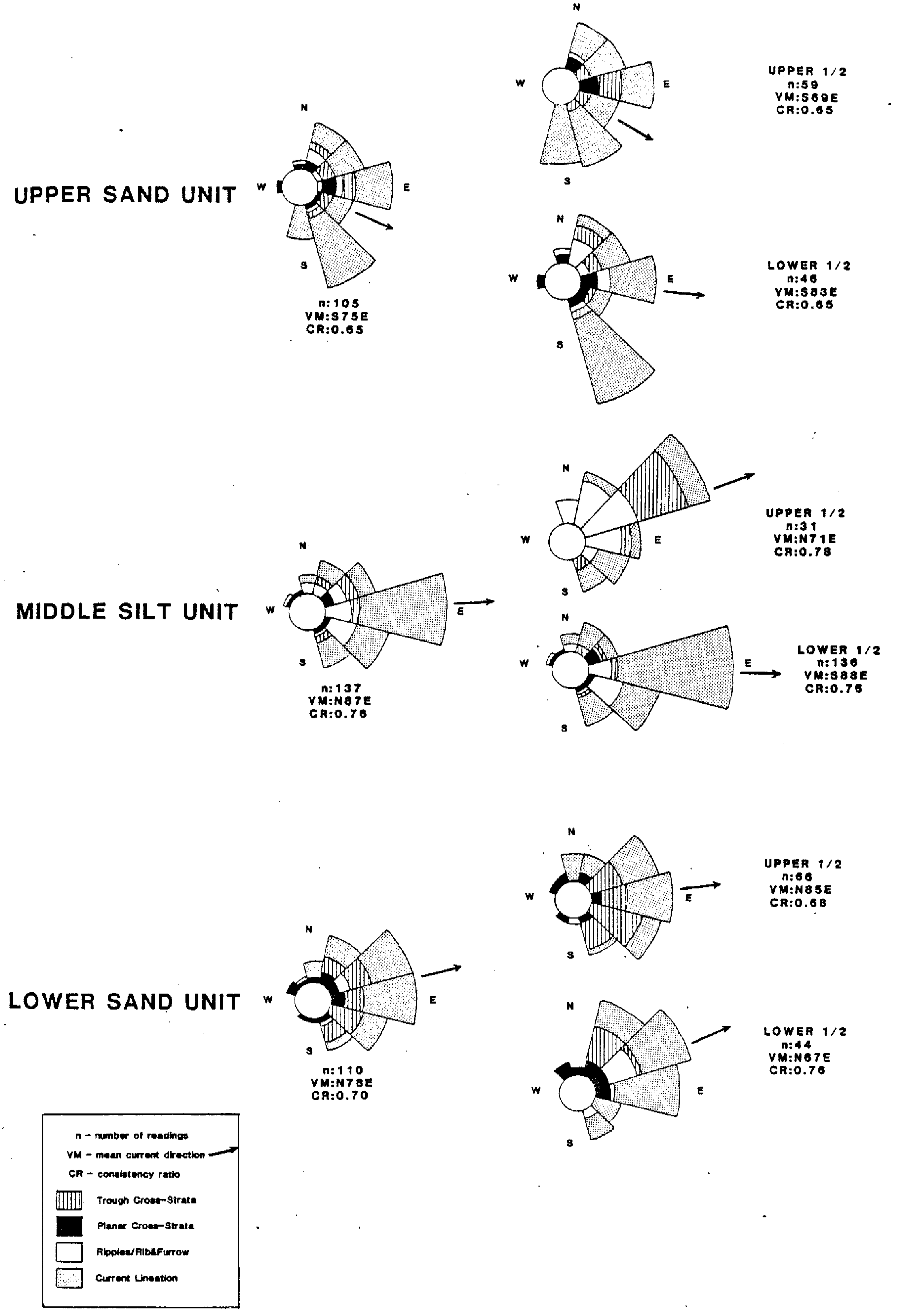


Figure 24. Composite rose diagrams of the three informal units of the Salt Wash Member.

compass that contains the majority of unique readings.

The mean current directions are determined by vector addition and the consistency ratios are determined mathematically.

DISCUSSION

The paleocurrent analysis is made to determine flow direction and to aid in the interpretation of depositional environment. All the rose diagrams show unimodal paleocurrent distributions. Mean current directions for the three units are dominantly eastward. The flow direction, however, changes from northeast in the lower sand unit, to nearly due east in the middle silt unit, and southeast in the upper sand unit, indicating an increasing southerly flow direction as deposition of the Salt Wash Member progressed. Mean current directions of the lower and upper halves of each unit are in agreement with the composite unit diagrams. Consistency ratios range from 0.65 to 0.78, with the lower values belonging to the upper sand unit. The greater amount of dispersion in the upper sand unit may be due to the near bimodal distribution of a stronger southeasterly component and a lesser easterly flow direction.

In all diagrams, readings from planar cross-strata show the widest scatter. It is interpreted that these deposits represent the lateral migration of channel bars (Harms and Fahnestock, 1965; Collinson, 1970; Smith, 1972; and Picard and High, 1973) and that they can be oriented at large angles to the main channel direction. Picard and High (1973) found that planar cross-strata give bi- or polymodal patterns in ancient fluvial deposits. Trough cross-strata and current lineations coincide more closely to the flow direction since they formed by primary currents within the main channel or on bar tops (Harms and Fahnestock, 1965; and Smith, 1972).

CHAPTER 6 INTERPRETATION OF ENVIRONMENT OF DEPOSITION OF THE SALT WASH MEMBER

INTRODUCTION

Based on the regional stratigraphy, sandstone geometry, primary sedimentary structures and fossil evidence, the Salt Wash Member was undoubtedly deposited by a fluvial system. Furthermore, most workers agree that the Salt Wash is a braided river deposit (Craig and others, 1955; Mullens and Freeman, 1957; Stokes, 1961; and Cater, 1970). To determine if this interpretation applies to the Salt Wash Member in the Slick Rock district, comparisons are made to ancient and modern fluvial deposits and models.

FLUVIAL MODELS

Fluvial deposits can be classified into two end-member groups whose characteristics are determined by the geometry of the river channel; high sinuousity or meandering river systems and low sinuousity or braided river systems. For a more thorough discussion of fluvial geomorphology and alluvial sedimentation than what is presented below, the reader is referred to Leopold, *et al*., (1964) and Allen (1965), respectively.

Meandering Fluvial Systems

High sinuousity, meandering river channels typically develop where gradients and discharges are low. Lateral migration of the channel erodes the outer banks of the meander loops and deposits sediment on the inner banks to form point bars. The meandering river model is well established (Harms, *et al*., 1963; and McGowan and Garner, 1970). In general, meandering fluvial deposits are characterized by the following features:

Gross geometry - Meandering systems deposit elongate, shoestring sandstones stratigraphically bounded by shales. In cross section the sandstones are tabular, with edges that are defined by the shape of the channel on the outside of the meander loop. If sediment supply and basin subsidence are steady, a meandering river deposit should consist of laterally discontinuous sandstone lenses interbedded with roughly equal amounts of fine-grained floodplain and overbank shale deposits (Walker and Cant, 1979). A single-sequence sand body should be as thick as the river was deep. A block diagram illustrating the geometry and deposits of a meandering river is shown in Figure 25.

Point bar deposits - Sand deposition is largely the result of point bar development. Point bars build laterally and downstream across the floodplain and are composed of the coarsest sediment available in the river system. Point bar deposits display a characteristic fining-upward sequence of grain size and scale of sedimentary structures. The meandering river fining-upward sequence is shown in Figure 26. In general, point bars overlie channel lag deposits and consist predominantly of trough cross-bedded coarse sands grading upward to small-scale trough cross-laminated fine sands (Visher, 1972). Detailed descriptions of point bar deposits are given by Harms, et al., (1963) and McGowan and Garner (1970).

Abandoned channels - Curved shoestrings of fine-grained deposits, or clay plugs, are frequently set in channel sand bodies. These fine-

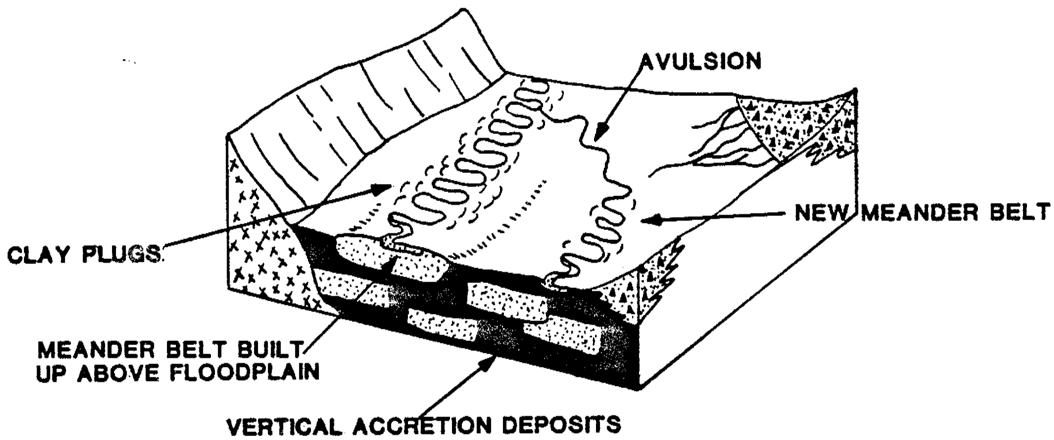


Figure 25. Block diagram of meandering river system showing geometry of deposits. Shoestring sands are preserved and bounded by fine-grained floodplain deposits (modified from Allen, 1965).

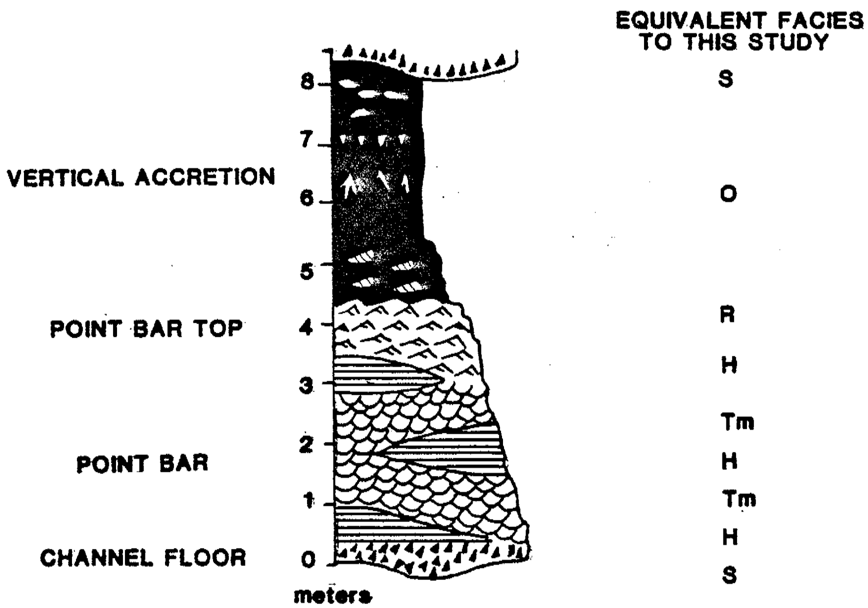


Figure 26. Meandering river model. Vertical scale shows relative distribution of facies (taken from Cant and Walker, 1976).

grained deposits are the result of infilling of abandoned meander loops and tend to have the shape of the original channel in cross section.

Paleocurrent distribution - Due to the meandering nature, current directions vary around the axis of flow and paleocurrents will have an approximate 180^{o} or more spread.

Braided Fluvial Systems

Braided river systems consist of a complex of low sinuousity channels separated by alluvial islands and channel bars. Braided channels are characterized by high width/depth ratios, steep slopes, high sporadic discharges and large amounts of sediment. Unlike meandering rivers, no comprehensive sedimentation model for braided fluvial systems has been developed, and studies of the braided fluvial environment are limited. The following discussion on the characteristics of braided deposits is largely based on studies of ancient and modern examples by Doeglas (1962), Moody-Stuart (1966), Coleman (1969), Smith (1970, 1974), Campbell (1976) and Cant and Walker (1976, 1979).

Gross geometry - When preserved, braided fluvial systems form laterally continuous and extensive sand sheets unconfined by shales (Campbell, 1976). Due to constant channel switching and the formation of coalescing bars, the deposits are dominated by coarse-grained channel sediments to the exclusion of fine-grained overbank silts and clays. Any shales preserved will be thin, sporadic and laterally discontinuous. The arrangement of facies will tend to be haphazard and in marked contrast when compared to meandering rivers with their extensive overbank shales and lateral cyclic sequences. The block diagram in Figure 27 depicts

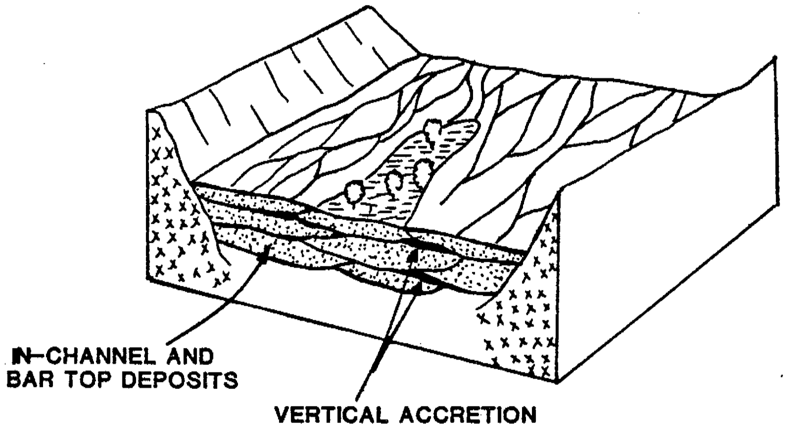


Figure 27. Block diagram of a braided fluvial system. Note development of laterally continuous sand sheet with minimum preservation of mudstone or overbank deposits (modified from Allen, 1965).

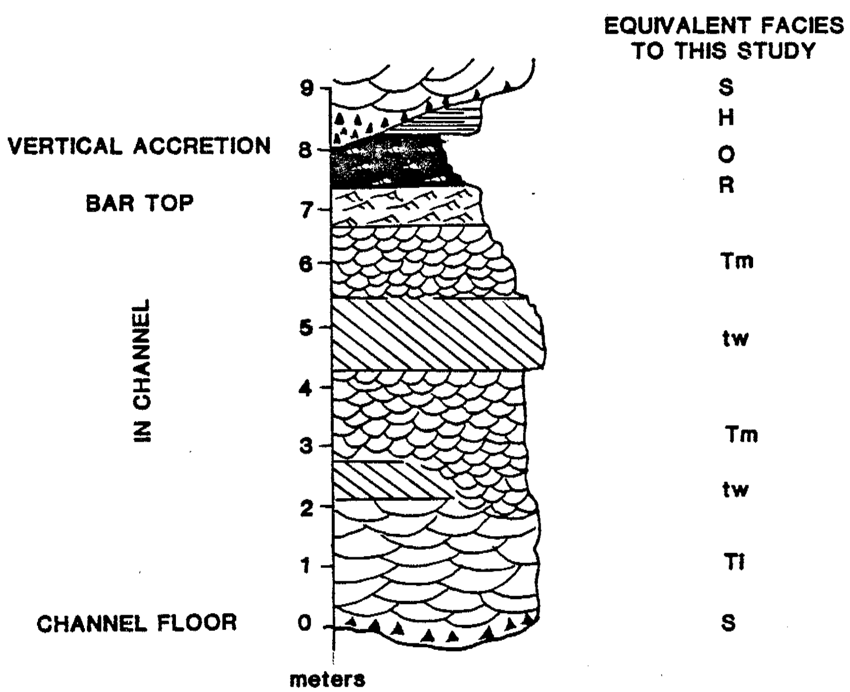


Figure 28. The summary sequence of facies for the Devonian Battery Point Formation, that is interpreted as a braided fluvial deposit (Cant and Walker, 1976).

the geometry and deposits of a braided fluvial system.

Vertical profiles - Although no facies model exists, certain repetitive vertical sequences are recognized in braided fluvial deposits. These vertical sequences are largely a result of four major fluvial processes: bar formation, flooding, channel aggradation and channel abandonment.

Channel bars are characteristic features of braided rivers and are responsible for much of the sediment formation and large scale structures in the system. Two major types of bars occur within braided channels and are termed longitudinal and transverse bars (Smith, 1974). The important differences between these two bar types are the median grain size of the bed material, their internal structures and the development of high angle, downstream foresets (Hein and Walker, 1977). In other words, the type of dominant stratification in braided deposits depends upon the type of bar and on bar migration.

Longitudinal bars are elongate, symmetrical forms with slightly convex upward surfaces and form parallel to current flow. They consist of structureless to crudely-bedded gravel and sand and are characteristic of proximal, or near source, braided rivers. If preserved, longitudinal bars would be structureless or show crude horizontal stratification. Longitudinal bars are described in Horse Creek (Leopold and Wolman, 1957), the Durance and Ardeche Rivers (Doeglas, 1962), the Donjek River (Williams and Rust, 1969) and the Kicking Horse River (Smith, 1974).

Transverse bars are characterized as relatively broad, flat-topped tabular bodies with downstream foreset slopes. They dominate in distal ends of braided rivers where sediment load and water discharge are lower and where better-sorted, finer size sediments favor their formation (Smith, 1970). Transverse bars are internally composed of tabular-shaped sets of planar cross-strata that represent foreset progradation. Transverse bars have been described in the lower Horse Creek (Leopold and Wolman, 1957), Platte River (Smith, 1970), and lower Kicking Horse River (Smith, 1974).

A vertical profile of a bar deposit begins with a lower erosional basal contact overlain by structureless beds or large-scale cross-stratification formed by lateral and downstream migration of the bar. The entire vertical sequence fines upward in grain size and scale of sedimentary structures. Trough-shaped sets of cross-stratified sand overlie the basal unit due to dune migration across the bar top, and are followed by a unit of ripple-laminated sand and silt. Deposition of a thin horizontally laminated mud layer completes the bar profile.

Waning floods are represented by deposits that also fine upward in grain size and in scale of sedimentary structures. These deposits always have erosional bases overlain by trough-shaped sets of cross-stratified and/or horizontally bedded gravel-sand cycles, and capped by ripple-laminated sands of low water stages. Each flood cycle will be bounded by a lower erosional surface. Cycle thicknesses will approximate channel depths present during flood discharge.

Channel aggradation and abandonment show gross upward fining sequences that are similar to flood cycles. This type of depositional profile is characterized by cyclic sedimentation as a result of successive events of vertical aggradation followed by channel switching. The profile is dominated by channel floor lag deposits, trough and planar cross-stratified sand, ripple-laminated fine sand, silt and mud. The last sediments deposited are as a fine-grained drape that covers the entire upper surface of the coarser channel deposits (Moody-Stuart, 1966). Major cycles are those involving complete channel sequences. Minor cycles involve those that occur within channels, in particular, dune migration and bar formation. Figure 28 shows a vertical sequence of the Battery Point Formation that is also interpreted as a braided river deposit by Cant and Walker (1976). The diagram is a good example of the characteristic facies of a braided stream deposit.

Proximal-distal relationships - A model for interpreting ancient proximal and distal portions of braided stream deposits has been postulated by Smith (1970). The model cannot determine actual distance from the source in ancient deposits, but can provide relative measures of proximity.

In a downstream direction there is a general tendency for sediment and water discharge to decrease and bed load material to fine. Since the type of dominant bars in a braided reach depends on rates of discharge and grain size, the ratio of transverse bars to longitudinal bars should increase in a downstream direction. This trend is accompanied by simultaneous changes in the distribution of internal stratification. As longitudinal bars are gradually replaced by transverse bars downstream, there is a downstream increase in planar cross-stratification relative to horizontal stratification. The proportion of trough cross-strata remains unchanged since migrating dunes and ripples occur throughout the channel and bar surfaces (Smith, 1970).

To determine relative proximity in ancient deposits, Smith (1970) uses bedding ratios. Smith (1970) divides the abundance of planar cross-strata (representing transverse bars) by the abundance of planar cross-strata plus the abundance of horizontal strata (representing longitudinal bars).

Peterson (personal communication, 1979) utilizes the method of Smith (1970) and also the bedding ratio of Travena (1977) to determine the proximity of the Salt Wash Member in the Henry Basin. The bedding ratio as determined by Travena (1977) divides the abundance of both horizontal strata plus planar cross-strata by the abundance of trough cross-strata. Travena (1977) states that trough cross-stratification increases in a downstream direction.

Paleocurrent distribution - Braided channels commonly show a variability of 90° to 120° in paleocurrent directions, while meandering rivers vary up to 180° or more. Consistency ratios are greatest for braided streams and tend to be the lowest for meandering rivers, however, no absolute values have been determined (Potter and Pettijohn, 1963).

INTERPRETATION OF THE SALT WASH MEMBER

Based on the observations and the data presented in this study, the Salt Wash Member in the Slick Rock district is interpreted as a braided fluvial deposit. This interpretation is substantiated by the following discussions.

Gross geometry - The Salt Wash Member in the study area consists dominantly of multilateral and multistory sandstone layers that in turn are composed of smaller coalescing individual channels. These individual channels cross-cut each other vertically and laterally and show fining upward sequences in grain size and scale of sedimentary structures. Mudstone layers, or overbank deposits, compose a lesser part of the entire member and are predominantly thin and laterally discontinuous.

The gross appearance of the Salt Wash Member in the Slick Rock district closely resembles that described by Campbell (1976) for the Westwater Canyon Member of the Morrison Formation, which he also attributes to a braided river system.

Vertical profile - Vertical sequences of textures and sedimentary structures in the Salt Wash Member are similar to modern day examples of cycles described in the Donjek River (Williams and Rust, 1969) and the lower Platte River (Smith, 1970). In addition, the local model developed for the Salt Wash Member in this study compares very closely to the local model developed by Cant and Walker (1976) for the ancient Battery Point Formation (compare Figures 21 and 28).

Like the Battery Point Formation, the Salt Wash Member is characterized by the preservation of thick sandstone sequences dominated by trough cross-stratification. The formation and migration of transverse bars within the Salt Wash Member channels are based on the presence of thick, isolated and grouped sets of planar cross-strata which have anomalous paleocurrent readings. Planar cross-strata overlie trough cross-stratification implying channel aggradation before bar formation. Planar cross-stratification is again overlain by trough-shaped sets indicating channel filling above the level of bars. These features indicate that channel aggradation was an important depositional process in the Salt Wash Member. Mudstone intervals that occur between the major channel sandstones represent overbank flooding and/or areas that were covered by fine-grained sediment as the channel was abandoned. The thinner, lenticular sandstone layers within the mudstone intervals probably represent second order distributary channels. The smaller scale structures of these sandstone lenses indicate deposition under lower flow regime (Harms and Fahnestock, 1965).

The abundance of trough cross-stratification, evidence of transverse bars with lateral growth of planar cross-strata, and the meager preservation of overbank or floodplain deposits, all suggest a braided or low sinuousity fluvial system for the Salt Wash Member.

Paleocurrent distribution - The distribution of paleocurrent readings for each unit of the Salt Wash Member indicates a low sinuousity channel system. The upward increase in variance, i.e., consistency ratio, and the increase in a southeasterly flow component from the lower sand unit to the upper sand unit, may indicate local tectonic influences. Along with changes in the paleocurrent pattern, the upper sand unit is also distinguished by its coarser grain size, its abundance of cut and fill structures, and by its greater abundance of carbonaceous material, primary gray mudstone and uranium-vanadium deposits. Considering this evidence it may be possible that local tectonics in southwest Colorado and southeast Utah influenced deposition of the Salt Wash Member through time.

Shawe (1962) suggested that the pattern of the Uravan mineral belt resulted from deposition along the toe of a subsidiary fan locally superposed on the larger alluvial apron that formed the entire Salt Wash Member. This smaller fan formed in an area of shallow subsidence that developed during deposition of the Salt Wash Member. The local subsidence is defined by a thicker section of the Salt Wash Member, coinciding with the position of the Uravan mineral belt, than in surrounding areas (Shawe, 1962). Subsidence of this local basin could have caused the development of a lake or smaller alluvial fan which permitted deflection or capture of a part of the distributary streams during deposition of the Salt Wash Member. This may explain the upward vertical change in paleocurrent readings from northeast to southeast in the Salt Wash Member of the Slick Rock district.

The preservation of carbonaceous material and the occurrence of primary gray mudstone is restricted to the upper sand unit of the Salt Wash Member. Conditions allowing for these features apparently did not exist previously during deposition of the lower sand unit and the middle silt unit. Shawe (1962) attributes the abundance of carbonaceous material in the upper sand unit to its preservation below the water table at time of deposition as at the foot of an aggrading slope at the edge of a water body. The increase in cut and fill structures and the coarser grain size of the upper sand unit may have been a response to the increase in slope during subsidence.

Stratification ratios - Stratification ratios were calculated using Smiths' (1970) equation for the lower sand, middle silt and upper sand units (Table 8). Smith (1970) determined that a predominance of longitudinal bars was indicated by a low stratification ratio of 0.3 or less and that a predominance of transverse bars was indicated by a high stratification ratio of 0.6 or greater. The stratification ratios for all three units varies from 0.48 to 0.63 and indicates a more distal braided stream system.

Stratification Ratio (Smith, 1970)	
Upper Sand Unit	0.53
Middle Silt Unit	0.48
Lower Sand Unit	0.63

Table 8. Stratification ratio for the three informal units of the Salt Wash Member.

APPENDIX I

I. Nomenclature used in field descriptions.

II. Description of measured stratigraphic sections.

I. Nomenclature used in field descriptions of lithology and sedimentary structures.

A. Lithology

1. Rock color - determined from the GSA Rock Color Chart (1963).

2. Grain size - determined from the Udden-Wentworth scale (1922).

3. Sorting - determined visually from sorting images and sorting classes of Folk (1968).

B. Stratification

1. Thickness - terminology is taken from Ingram (1954).

2. Shape of individual strata - Wavy, undulatory 

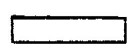
Horizontal 

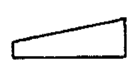
3. Cross-stratification - classification of cross-stratified units is modified from McKee and Weir (1953) and Allen (1963).

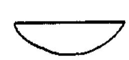
a. Scale based on length of cross-strata:

small-scale $<$ 0.3 m
medium-scale 0.3 m to 6.0 m
large-scale $>$ 6.0 m

b. Shape of set:

tabular-shaped 

wedge-shaped 

trough-shaped 

c. Arching:

planar 

tangential 

concordant 

II. Description of measured stratigraphic sections.

A. Locations of measured stratigraphic sections

Section	Location
A	N½ of NW¼, Sec. 18, R18W, T44N
B	N½ of SE¼, Sec. 13, R19W, T44N
C	S½ of NE¼, Sec. 25, R19W, T44N and N½ of NW¼, Sec. 30, R18W, T44N
D	S½ of NE¼, Sec. 6, R18W, T43N and S½ of NW¼, Sec. 5, R18W, T43N
E	SE¼, Sec. 23, R19W, T44N and NW¼, Sec. 24, R19W, T44N
F	S½ of NW¼, Sec. 27, R19W, T44N
G	N½ of NE¼, Sec. 32, R19W, T44N
H	S½ of SE¼, Sec. 24, R19W, T44N and S½ of SE¼, Sec. 19, R18W, T44N
I	N½ of SE¼, Sec. 24, R19W, T44N
J	N½ of NE¼, Sec. 24, R19W, T44N
K	N½ of NW¼, Sec. 5, R18W, T43N
L	S½ of NE¼, Sec. 27, R19W, T44N

B. Field descriptions

Abbreviations

C - chert

cont - continuous

dia - diameter

F - feldspar

HM - heavy minerals

ht - height

le - length, wavelength

LF - lithic fragments

Q - quartz

SECTION A

Unit 1 0 to 18.6 m: Interbedded sandstone, siltstone and mudstone. Erosional base. Sandstone - pinkish gray, fine-grained, moderately-sorted, subangular, (Q 97%, F 2%, C tr%, HM 1%), well-indurated. Siltstone - grayish red, poorly-sorted with very fine-grained sand, poorly-indurated.

a - 2.4 m: Horizontally-laminated and ripple cross-laminated; small-scale, wedge-shaped sets (15.0 cm thick) of planar cross-laminae. Local symmetrical ripple marks.

b - 1.8 m: Small-scale, wedge-shaped sets of planar cross-laminae (low angle); small-scale, trough-shaped sets of concordant cross-laminae.

c - 14.4 m: Lenticular layers of sandstone, siltstone and mudstone range from 5.0 cm to 1.4 m thick; ripple cross-laminated sets (1.0 to 5.0 cm thick); horizontally-laminated. Asymmetrical ripple marks (ht - 3 mm, le - 15 mm). Includes 3.7 m thick covered interval.

Unit 2 18.6 to 43.9 m: Sandstone. Pronounced scour base. Sandstone - grayish orange pink, medium-grained, moderately- to poorly-sorted, subrounded, (Q 90%, F 5%, C 2%, HM 3%), well-indurated. Grayish red claystone clasts and clay seams at base of trough- and wedge-shaped sets.

a - 4.3 m: Horizontal strata (laterally cont up to 7.6 m); large- and medium-scale, wedge-shaped sets (1.0 to 1.5 m thick, laterally cont up to 6.1 m) of planar cross-strata.

b - 1.2 m: Medium-scale, trough-shaped sets (laterally cont up to 4.6 m) of concordant cross-strata.

c - 16.8 m: Horizontal strata (laterally cont up to 6.1 m); medium-scale, wedge-shaped sets (up to 1.8 m thick, laterally cont up to 6.1 m) of planar cross-strata.

d - 3.0 m: Medium-scale, trough-shaped sets (laterally cont up to 3.0 m) of concordant cross-strata.

Unit 3 43.9 to 53.0 m: Interbedded mudstone and sandstone. Gradational base. Lenticular layers of grayish red sandstone and mudstone.

a - 9.1 m: Ripple cross-laminated and horizontally-laminated. Includes 7.3 m thick covered interval.

Unit 4 53.0 to 59.4 m: Sandstone. Pronounced scour base. Sandstone - grayish orange pink, medium-grained, poorly-sorted, subangular, (Q 91%, F 4%, C 3%, HM 2%), moderately-indurated.

a - 4.3 m: Medium-scale, trough-shaped sets (0.6 m thick) of concordant cross-strata. Mudstone clasts at base of lower sets.

SECTION A (cont'd)

b - 2.1 m: Medium-scale, tabular-shaped sets (15.0 cm thick) of tangential cross-strata.

Unit 5 59.4 to 64.9 m: Covered interval. Sparse outcrops show unit to be similar to Unit 4 below.

Unit 6 64.9 to 72.8: Sandstone. Pronounced scour base. Sandstone - grayish orange pink, fine- to medium-grained, moderately- to poorly-sorted, subangular, (Q 94%, F 3%, C 2%, HM 1%), well-indurated. Granules of C, F, LF concentrated along lower trough bases.

a - 7.9 m: Medium-scale, trough-shaped sets (0.9 to 1.2 m thick, laterally cont up to 6.1 m) of concordant cross-strata.

Unit 7 72.8 to 74.7 m: Interbedded siltstone, mudstone and sandstone. Gradational base. Grayish red and greenish gray sandstone, siltstone and mudstone.

a - 1.8 m: Ripple cross-laminated sets.

Unit 8 74.7 to 82.6 m: Sandstone. Pronounced scour base. Sandstone - light gray, fine- to medium-grained, moderately-sorted, subangular, (Q 95%, F 3%, C 1%, HM 1%), well-indurated.

a - 7.9 m: Horizontal strata; tabular- and wedge-shaped sets of planar cross-strata (low angle); medium-scale, trough-shaped sets of concordant cross-strata.

Unit 9 82.6 to 85.3 m: Covered interval. Sparse outcrops of interbedded lenticular layers of grayish red siltstone and fine-grained, greenish gray sandstone. Sandstone layers up to 0.6 m thick. Locally horizontally-laminated.

Unit 10 85.3 to 99.4 m: Sandstone. Pronounced scour base. Sandstone - light gray, fine- to medium-grained, moderately-sorted, subangular, (Q 93%, F 5%, C 1%, HM 1%), well-indurated.

a - 11.0 m: Medium-scale, wedge-shaped sets of planar cross-strata (low angle); medium-scale, trough-shaped sets of concordant cross-strata.

b - 3.0 m: Horizontal strata.

Unit 11 99.4 to 116.4 m: Covered interval. Sparse outcrops of interbedded grayish red siltstone and sandstone. Sandstone - light gray, fine-grained, moderately-sorted, subangular, (Q 97%, F 2%, C tr%, HM 1%), moderately-indurated.

Unit 12 116.4 to 131.1 m: Sandstone. Pronounced scour base. Sandstone - greenish gray, coarse-grained (granules and pebbles of C, F and LF concentrated in base of trough sets), poorly-sorted, subangular, (Q 83%, F 7%, C 4%, HM 1%), very well-indurated.

SECTION A (cont'd)

a - 14.6 m: Medium- to large-scale, trough-shaped sets of concordant cross-strata; medium- to large-scale, wedge-shaped sets of planar cross-strata (low angle).

SECTION B

Unit 1 0 to 12.3 m: Interbedded siltstone, mudstone and sandstone. Gradational base. Sandstone and siltstone layers vary from 0.6 m to several cm thick. Sandstone - pinkish gray, very fine- to fine-grained, moderately-sorted, subangular, (Q 92%, F 3%, C 3%, HM 2%), moderately-indurated. Siltstone - grayish red, poorly-sorted with very fine-grained sand, poorly indurated.

a - 12.3 m: Internally structureless; locally ripple cross-laminated sets (15.0 cm thick).

Unit 2 12.3 to 25.9 m: Interbedded sandstone and siltstone. Erosional base. Sandstone - pinkish gray, very fine- to fine-grained, moderately-sorted, subrounded, (Q 95%, F 2%, C tr%, HM 2%), well-indurated. Siltstone - grayish red, poorly-sorted with very fine-grained sand, poorly-indurated.

a - 1.1 m: Internally structureless; local horizontal laminae.

b - 2.4 m: Ripple cross-laminated sets. Asymmetrical ripple marks.

c - 1.5 m: Horizontally-laminated.

d - 1.2 m: Ripple cross-laminated sets (10.0 cm thick). Asymmetrical ripple marks.

e - 7.0 m: Lenticular layers of sandstone and siltstone range from several cm to 0.5 m thick, laterally cont up to 1.5 m. Ripple cross-laminated sets (7.5 cm thick). Locally bioturbated.

Unit 3 25.9 to 30.9 m: Sandstone. Pronounced scour base. Sandstone - grayish orange pink, fine- to medium-grained, poorly-sorted, subangular, (Q 91%, F 3%, C 1%, HM 5%), well-indurated. Grayish red claystone clasts (dia 1 mm to 1.5 cm) in base of trough sets.

a - 4.1 m: Medium- to large-scale trough-shaped sets (decrease upward from 0.6 to 0.3 m thick, laterally cont up to 7.6 m) of concordant cross-laminae. (Appears to be two overlapping channels, lower channel 0.8 m thick and 7.5 m wide, upper channel 3.4 m thick).

b - 0.9 m: Horizontally-laminated.

Unit 4 30.9 m to 32.0 m: Siltstone and mudstone. Gradational base. Lenticular layers of greenish gray siltstone and mudstone.

SECTION B (cont'd)

Unit 5 32.0 to 50.3 m: Sandstone. Pronounced scour base. Sandstone - grayish orange pink, medium-grained, (coarse sand in base of trough sets), poorly-sorted, subangular, (Q 91%, F 4%, C 2%, HM 3%), well-indurated.

a - 10.7 m: Medium- to large-scale, wedge-shaped sets (0.3 to 0.6 m thick, laterally cont up to 7.6 m) of planar cross-strata (low angle); trough-shaped sets of concordant cross-strata. Grayish red mudstone seams between sets of cross-strata.

b - 7.6 m: Medium-scale, trough-shaped sets (0.3 to 0.6 m thick, laterally cont up to 3.7 m) of concordant cross-strata; horizontal strata (1.2 m thick, laterally cont up to 3.0 m). Grayish red mudstone seams and clasts between sets of cross-strata.

Unit 6 50.3 to 51.8 m: Covered interval.

Unit 7 51.8 to 64.6 m: Sandstone. Pronounced scour base. Sandstone - grayish orange pink, fine- to medium-grained, moderately sorted, subangular (Q 92%, F 5%, C 2%, HM 1%), well-indurated.

a - 12.8 m: Medium-scale, trough-shaped sets (0.5 m thick, laterally cont up to 6.1 m) of concordant cross-laminae; horizontally-laminated (1.2 to 1.5 m thick).

Unit 8 64.6 to 68.4 m: Interbedded sandstone and siltstone. Gradational base. Sandstone - greenish gray, very fine- to fine-grained, poorly-sorted, subangular, moderately-indurated.

a - 2.3 m: Ripple cross-laminated sets (2.5 cm thick); horizontally-laminated.

b - 1.1 m: Medium-scale, wedge-shaped sets (2.5 to 7.5 cm thick) of planar cross-laminae (low angle).

c - 0.5 m: Horizontally-laminated.

Unit 9 68.4 to 78.9 m: Sandstone. Pronounced scour base. Sandstone - grayish orange pink, medium-grained, moderately-sorted, subangular, well-indurated.

a - 5.3 m: Medium-scale, trough-shaped sets (0.3 to 0.6 m thick, laterally cont up to 6.1 m) of concordant cross-strata.

b - 5.2 m: Medium-scale, wedge-shaped sets (0.3 to 0.6 m thick) of planar cross-strata (low angle); medium-scale, trough-shaped sets of concordant cross-strata.

Unit 10 78.9 to 80.3 m: Covered interval.

SECTION B (cont'd)

Unit 11 80.3 to 85.3 m: Sandstone. Pronounced scour base. Sandstone - grayish orange pink, fine- to medium-grained, poorly-sorted, subangular, well indurated.
a - 5.0 m: Medium-scale, wedge-shaped sets (0.3 to 0.6 m thick) of planar cross-strata (low angle).

Unit 12 85.3 to 92.0 m: Covered interval. Sparse outcrops of interbedded grayish red and greenish gray mudstone and sandstone. Lenticular layers of sandstone and mudstone range from 2.0 cm to several cm thick. Carbonized plant fragments in mudstone layers.

Unit 13 92.0 to 103.3 m: Sandstone. Pronounced scour base. Sandstone - grayish orange pink, fine- to medium-grained, poorly-sorted, subangular, poorly-indurated.
a - 1.7 m: Internally structureless. Contains numerous greenish gray claystone clasts and carbonized plant fragments.

b - 7.8 m: Horizontally-laminated. Includes 1.0 m thick grayish red claystone and siltstone layer.

c - 2.1 m: Medium-scale, wedge-shaped sets of planar cross-strata; trough-shaped sets of concordant cross-strata. Upper 1.0 m burrowed (dia - 0.5 cm).

Unit 14 103.3 to 111.6 m: Covered interval. Sparse outcrops of interbedded siltstone and sandstone. Small- to medium-scale, trough-shaped sets (0.5 m thick) of concordant cross-laminae.

Unit 15 111.6 to 116.4 m: Sandstone. Pronounced scour base. Sandstone - grayish orange pink, medium-grained, poorly-sorted, subangular, (Q 90%, F 5%, C 3%, HM 2%), well-indurated.
a - 4.9 m: Medium-scale, trough-shaped sets of concordant cross-strata.

Unit 16 116.4 to 118.4 m: Covered interval. Sparse outcrops of grayish red and greenish gray siltstone.

Unit 17 118.4 to 119.8 m: Sandstone. Erosional base. Sandstone - grayish orange pink, medium-grained, poorly-sorted, subangular, (Q 91%, F 4%, C 3%, HM 2%), well-indurated.
a - 1.4 m: Small- to medium-scale, wedge-shaped sets of planar cross-strata.

SECTION C

Unit 1 0 to 19.2 m: Interbedded siltstone and sandstone. Gradational base. Sandstone and siltstone layers average 0.2 to 0.3 m thick. Sandstone pinkish gray, fine- to medium-grained, subangular, (Q 93%, F 4%, C 1%, HM 2%), poorly-indurated.

SECTION C (cont'd)

Siltstone - grayish red, poorly-sorted with very fine-grained sand, poorly-indurated.
a - 19.2 m: Internally structureless.

Unit 2 19.2 to 32.9 m: Interbedded sandstone and siltstone. Erosional base. Sandstone - pinkish gray, very fine- to fine-grained, moderately-sorted, subangular, (Q 95%, F 3%, C 1%, HM 1%), well-indurated. Siltstone - grayish red, poorly-sorted with very fine-grained sand, poorly-indurated.
a - 0.9 m: Lower 0.6 m internally structureless and bioturbated. Horizontally-laminated (laterally cont up to 2.7 m); medium-scale, trough-shaped sets (18.0 cm thick, laterally cont up to 1.8 m) of concordant cross-laminae. Local symmetrical ripple marks (ht - 4 mm, le - 3 cm).

b - 0.5 m: Wavy, undulatory laminae.

c - 1.1 m: Horizontally laminated (laterally cont up to 4.6 m); medium-scale, trough-shaped sets (3.0 cm thick, laterally cont up to 0.8 m) of tangential cross-laminae. Burrowed - curved and oblique to strata (dia - 7 mm, le - up to 40 cm).

d - 0.2 m: Wavy, undulatory laminae.

e - 0.5 m: Horizontally-laminated (laterally cont up to 6.1 m); ripple cross-laminated sets (6.3 cm thick). Symmetrical and asymmetrical ripple marks (ht - 2 to 3 mm, le - 1.5 to 2.0 cm).

f - 10.7 m: Lenticular layers of greenish gray sandstone and siltstone range from 5.0 to 20.0 cm thick. Horizontally-laminated (laterally cont up to 4.5 m); ripple cross-laminated sets (2.5 cm thick). Abundant plant fragments and greenish gray claystone clasts along strata in siltstone.

Unit 3 32.9 to 35.4 m: Sandstone. Pronounced scour base. Sandstone - pinkish gray, fine- to medium-grained, poorly-sorted, subangular (Q 95%, F 2%, C 2%, HM 1%), well-indurated.
a - 0.3 m: Horizontally-laminated (laterally cont up to 15.2 m).

b - 0.5 m: Medium-scale, trough-shaped sets (13.0 to 15.0 cm thick, laterally cont up to 2.1 m) of tangential cross-laminae.

c - 0.9 m: Large-scale, tabular-shaped sets (0.2 to 0.4 cm thick, laterally cont up to 9.1 m) of planar cross-laminae (low angle). Burrowed.

d - 0.8 m: Horizontally-laminated (laterally cont up to 15.2 m). Extensively burrowed - at all angles to strata (dia - 0.5 to 1.0 cm, le - up to 0.6 m).

SECTION C (cont'd)

Unit 4 35.4 to 36.9 m: Interbedded mudstone and sandstone. Gradational base. Sandstone and mudstone layers range from 8.0 cm to 0.3 m thick. Sandstone - light gray, very fine-grained sand to silt, poorly-sorted, subangular, (Q 90%, F 7%, C 2%, HM 1%), moderately-indurated.

a - 1.5 m: Ripple cross-laminated sets (2.5 cm thick).

Unit 5 36.9 to 52.0 m: Sandstone. Pronounced scour base. Sandstone - pinkish gray, fine- to medium-grained, poorly-sorted, subangular, (Q 91%, F 5%, C 2%, HM 2%), well-indurated.

a - 0.3 m: Internally structureless. Strong scour base with claystone clasts.

b - 3.4 m: Horizontal very thin beds to laminae (laterally cont for more than 30 m); large-scale, tabular-shaped sets (8.0 to 20.0 cm thick, laterally cont for more than 30.0 m) of planar cross-laminae (low angle).

c - 1.5 m: Medium-scale, trough-shaped sets (15.0 to 18.0 cm thick, laterally cont up to 3.0 m). Pronounced scour bases.

d - 1.1 m: Horizontally-laminated (laterally cont up to 13.7 m). Burrowed - normal to strata (dia - 0.5 to 1.0 cm).

e - 2.4 m: Medium-scale, trough-shaped sets (decrease upward from 0.5 m to 8.0 cm thick, laterally cont up to 4.6 m) of tangential and concordant cross-laminae; medium-scale, tabular- and wedge-shaped sets of planar cross-laminae (low angle).

f - 1.0 m: Horizontally-laminated (laterally cont up to 9.0 m).

g - 3.0 m: Medium-scale, trough-shaped sets (0.2 to 0.3 m thick, laterally cont up to 6.1 m) of concordant cross-laminae.

h - 1.8 m: Medium-scale, trough-shaped sets (10.0 to 20.0 cm thick, laterally cont up to 1.8 m) of concordant cross-laminae; ripple cross-laminated sets (8.0 to 10.0 cm thick). Thin intercalated mudstone layers. Locally burrowed.

i - 0.6 m: Large scale, tabular-shaped sets (13.0 cm thick, laterally cont up to 7.5 m) of planar cross-laminae (low angle).

Unit 6 52.0 to 54.4 m: Interbedded mudstone and sandstone. Gradational base. Sandstone and mudstone layers range from 10.0 cm to 0.3 m thick. Sandstone - light gray, very fine-grained, moderately-sorted, subangular (Q 93%, F 3%, C 3%, HM 1%), moderately-indurated.

a - 2.4 m: Ripple cross-laminated sets (2.5 to 10.0 cm thick, laterally cont up to 2.1 m). Burrowed - (dia - 0.5 cm, le - up to 6.0 cm).

SECTION C (cont'd)

Unit 7 54.4 to 56.4 m: Sandstone. Pronounced scour base. Sandstone - pinkish gray, fine- to medium-grained, poorly-sorted, subangular, (Q 93%, F 4%, C 2%, HM 1%), well-indurated.
a - 1.2 m: Medium-scale, trough-shaped sets (decrease upward from 0.3 m to 5.0 cm, and from 4.3 m to 1.5 m in lateral extent) of concordant and tangential cross-laminae.

b - 0.8 m: Ripple cross-laminated sets (8.0 cm thick).

Unit 8 56.4 to 58.2 m: Interbedded mudstone and sandstone. Gradational base. Lenticular layers of sandstone and grayish red mudstone range from 2.5 cm to 0.3 m thick, laterally cont up to 3.0 m. Sandstone - greenish gray, very fine- to fine-grained, moderately-sorted, subangular, (Q 90%, F 4%, C 2%, HM 2%), moderately-indurated.
a - 1.8 m: Ripple cross-laminated sets (2.5 cm thick); horizontally-laminated (laterally cont up to 3.0 m).

Unit 9 58.2 to 62.5 m: Sandstone. Pronounced scour base. Sandstone - yellowish gray, medium- to fine-grained (coarse sand concentrated in base of lower trough sets), poorly-sorted, subangular, (Q 91%, F 4%, C 3%, HM 2%), well-indurated.
a - 0.5 m: Large-scale, trough-shaped set (laterally cont up to 15.2 m) of concordant cross-laminae.

b - 3.8 m: Horizontally-laminated; large-scale, tabular- and wedge-shaped sets (decrease upward from 0.5 m to 13.0 cm, and from 11.0 to 4.6 m in lateral extent) of tangential and planar (low angle) cross-laminae.

Unit 10 62.5 to 71.3 m: Interbedded mudstone, claystone and sandstone. Gradational base. Lenticular layers of sandstone and grayish red and greenish gray mudstone range from 0.3 to 1.8 m thick. Sandstone - greenish gray, fine-grained to silt, moderately-sorted, subangular, (Q 91%, F 4%, C 4%, HM 1%), moderately-indurated.
a - 8.8 m: Ripple cross-laminated sets (1.0 to 2.5 cm thick); horizontally-laminated.

Unit 11 71.3 to 79.7 m: Sandstone. Pronounced scour base. Sandstone - light gray, medium- to fine-grained (coarse sand in base of lower trough sets), moderately-sorted, subangular, (Q 91%, F 5%, C 3%, HM 1%), moderately-indurated.
a - 6.4 m: Large- and medium-scale, trough-shaped sets (decrease upward from 1.2 m to 10.0 cm thick, and from 18.3 to 1.8 m in lateral extent) of concordant cross-laminae; large- and medium-scale, wedge-shaped sets of tangential cross-laminae. Intercalated greenish gray claystone layers between trough sets.

b - 0.6 m: Ripple cross-laminated sets (2.5 cm thick).

SECTION C (cont'd)

c - 1.4 m: Horizontally-laminated. Extensively burrowed - normal and oblique to strata (dia - 3 to 6 mm, le - 2.0 to 13.0 cm).

Unit 12 79.7 to 91.4 m: Covered interval. Sparse outcrops show unit to be similar to Unit 10 below.

Unit 13 91.4 to 101.3 m: Sandstone. Pronounced scour base. Sandstone - pinkish gray, medium-grained (coarse sand, granules and pebbles concentrated in base of lower trough sets), moderately-sorted, subangular, (Q 92%, F 6%, C 2%, HM tr%), well-indurated.

a - 1.4 m: Horizontally-laminated (laterally cont up to 54.9 m).

b - 3.7 m: Large- and medium-scale, trough-shaped sets (decrease upward from 0.6 m to 13.0 cm thick, and from 15.2 to 3.0 m in lateral extent).

c - 1.2 m: Medium-scale, wedge-shaped sets (13.0 cm, thick, laterally cont up to 3.0 m) of planar (low angle) cross-laminae.

d - 3.7 m: Horizontally-laminated; large-scale, wedge-shaped sets (20.0 cm thick, laterally cont up to 45.7 m) of planar (low angle) cross-laminae. Lower 0.9 m burrowed - normal to strata (dia - 5 mm).

Unit 14 101.3 to 105.6 m: Partially covered interval. Sparse outcrops of grayish red siltstone.

Unit 15 105.6 to 113.2 m: Sandstone. Pronounced scour base. Sandstone - grayish orange pink, medium-grained, well-sorted, subangular, (Q 88%, F 8%, C 3%, HM 1%), well-indurated. (Isolated layers of granules of F and LF.)

a - 7.6 m: Medium-scale, trough-shaped sets (12.0 cm thick, laterally cont up to 2.1 m).

SECTION D

Unit 1 0 to 18.0 m: Interbedded siltstone and sandstone. Gradational base. Sandstone and siltstone layers range from 5.0 cm to 0.5 m thick. Sandstone - light gray, fine-grained, moderately-sorted, subangular, (Q 93%, F 5%, C 1%, HM 1%), moderately-indurated. Siltstone - grayish red, poorly-sorted with very fine-grained sand, poorly-indurated.

a - 5.2 m: Internally structureless.

b - 0.6 m: Ripple cross-laminated sets. Symmetrical ripple marks.

SECTION D (cont'd)

Unit 2 18.0 to 22.9 m: Interbedded sandstone and siltstone. Erosional base. Sandstone - pinkish gray, fine-grained, moderately-sorted, subangular, (Q 96%, F 3%, C tr%, HM 1%), moderately-indurated. Siltstone - grayish red, poorly-sorted with very fine-grained sand, poorly-indurated.

a - 4.1 m: Horizontally-laminated (local undulatory, wavy laminae); some layers internally structureless. Interbedded siltstone layers range from 5.0 to 10.0 cm thick.

b - 2.0 m: Ripple cross-laminated sets (5.0 cm thick); horizontally-laminated. Asymmetrical and symmetrical ripple marks.

Unit 3 22.9 to 31.7 m: Partially covered interval. Gradational base. Outcrops of interbedded grayish red siltstone and sandstone. Sandstone - pinkish gray, fine-grained, well-sorted, subangular (Q 92%, F 3%, C 1%, HM 4%), well-indurated.

a - 7.6 m: Ripple cross-laminated sets; horizontally-laminated.

Unit 4 31.7 to 38.1 m: Sandstone. Pronounced scour base. Sandstone - grayish orange pink, fine-grained, moderately-sorted, subangular (Q 95%, F 3%, C 1%, HM 1%), moderately-indurated.

a - 0.6 m: Horizontally-laminated.

b - 3.0 m: Large-scale, wedge-shaped sets (laterally cont up to 10.0 m) of planar cross-laminae (low angle).

c - 2.7 m: Horizontally-laminated; medium-scale, trough-shaped sets (15.2 cm to 20.0 cm thick) of concordant cross-laminae. Upper 0.6 m burrowed.

Unit 5 38.1 to 42.7 m: Partially covered interval. Gradational base. Outcrops of interbedded grayish red siltstone and grayish red sandstone. Sandstone and siltstone layers range from 15.0 to 20.0 cm thick.

a - 4.6 m: Ripple cross-laminated sets; horizontally-laminated.

Unit 6 42.7 to 48.8 m: Sandstone. Pronounced scour base. Sandstone - grayish orange pink, medium-grained, poorly-sorted, subangular, (Q 94%, F 3%, C 2%, HM 1%), moderately-indurated.

a - 4.3 m: Large-scale, wedge-shaped sets (0.3 m to 0.6 m thick) of planar cross-strata; medium- to large-scale, trough-shaped sets (0.3 m to 0.6 m thick) of concordant cross-strata.

b - 0.9 m: Horizontally-laminated siltstone.

c - 0.9 m: Medium- to large-scale, trough-shaped sets (0.3 m to 0.6 m thick) of concordant cross-strata.

SECTION D (cont'd)

Unit 7 48.8 to 53.6 m: Covered interval. Sparse outcrops of interbedded grayish red and greenish gray mudstone and very fine-grained sandstone. Ripple cross-laminated and horizontally-laminated.

Unit 8 53.6 to 57.8 m: Sandstone. Pronounced scour base. Sandstone - grayish orange pink, fine-grained, moderately-sorted, subangular, (Q 89%, F 8%, C 1%, HM 2%), well-indurated.
a - 4.1 m: Large-scale, trough-shaped sets (0.3 to 0.6 m thick, laterally cont up to 9.1 m) of concordant cross-laminae. Numerous claystone clasts in lower trough sets.

Unit 9 57.8 to 64.0 m: Covered interval. Outcrops of interbedded grayish red siltstone and mudstone. Horizontally-laminated.

Unit 10 64.0 to 68.4 m: Sandstone. Pronounced scour base. Sandstone - grayish orange pink, fine-grained, moderately-sorted, subangular, (Q 90%, F 7%, C 1%, HM 2%), well-indurated.
a - 2.7 m: Large-scale, wedge-shaped sets (0.5 to 0.6 m thick, laterally cont up to 12.2 m) of planar cross-laminae (low angle); large-scale, trough-shaped sets (0.5 to 0.6 m thick, laterally cont up to 12.2 m) of concordant cross-laminae. Channels appear to be 5.0 m thick and greater than 30.0 m in lateral extent.

b - 1.7 m: Horizontally-laminated.

Unit 11 68.4 to 74.7 m: Covered interval. Sparse outcrops of interbedded grayish red mudstone and sandstone. Ripple cross-laminated sets.

Unit 12 74.7 to 86.6 m: Sandstone. Pronounced scour base. Sandstone - grayish orange pink, fine-grained, moderately-sorted, subangular, (Q 89%, F 7%, C 2%, HM 2%), well-indurated.
a - 11.9 m: Large-scale, trough-shaped sets (0.9 to 1.8 m thick, laterally cont up to 30.5 m) of concordant cross-strata. Numerous claystone clasts in base of trough sets. Upper 2.5 m burrowed.

Unit 13 86.6 to 87.8 m: Mudstone. Gradational base. Mudstone - grayish red and greenish gray.
a - 1.2 m: Horizontally-laminated.

Unit 14 87.8 to 101.8 m: Sandstone. Pronounced scour base. Sandstone - light gray, medium- to coarse-grained, poorly-sorted, subangular, (Q 89%, F 8%, C 1%, HM 2%), well-indurated.
a - 5.5 m: Medium-scale, trough-shaped sets (0.3 to 0.6 m thick) of concordant cross-laminae, horizontally-laminated. Claystone clasts in bases of trough sets. Lower 1.5 m burrowed. Abundant carbonized plant fragments along bedding planes.

SECTION D (cont'd)

b - 8.5 m: Large-scale, trough-shaped sets (0.6 to 0.9 m thick) of concordant cross-strata. Upper 1.2 m burrowed.

Unit 15 101.8 to 108.5 m: Partially covered interval. Outcrops of interbedded grayish red and greenish gray mudstone and siltstone.

Unit 16 108.5 to 113.7 m: Sandstone. Pronounced scour base. Sandstone - light gray, fine- to medium-grained, (granules of LF), poorly-sorted, subangular (Q 86%, F 6%, C 1%, HM 2%, LF 5%), well-indurated.
a - 5.2 m: Medium-scale, trough-shaped sets (0.3 m thick) of concordant cross-strata.

Unit 17 113.7 to 116.7 m: Siltstone. Gradational base. Siltstone - grayish red and pale blue, poorly-sorted with very fine-grained sand, poorly-indurated.

Unit 18 116.7 to 121.6 m: Sandstone. Pronounced scour base. Sandstone - moderate yellowish brown, coarse-grained (numerous granules and pebbles of C, F and LF), poorly-sorted, subangular (Q 83%, F 7%, C 5%, HM 1%, LF 4%), moderately-indurated.
a - 4.9 m: Medium- to large-scale, trough-shaped sets of concordant and tangential cross-strata.

SECTION E

Unit 1 0 to 24.7 m: Interbedded siltstone and sandstone. Gradational base. Sandstone and siltstone layers range from 20.0 cm to 0.9 m thick. Sandstone - pinkish gray, fine-grained, poorly-sorted, subangular, (Q 90%, F 8%, C 1%, HM 1%), moderately-indurated. Siltstone - grayish red, poorly-sorted with very fine-grained sand, poorly-indurated.
a - 24.7 m: Internally structureless.

Unit 2 24.7 to 30.5 m: Sandstone. Gradational base. Sandstone - pinkish gray, fine-grained, moderately-sorted, subangular, (Q 96%, F 3%, C tr%, HM 1%), well indurated.
a - 1.5 m: Horizontal strata; local wavy, undulatory strata. Overlain by 10.0 cm thick siltstone layer.

b - 0.9 m: Small-scale, trough-shaped sets (10.2 to 20.3 cm thick) of concordant cross-laminae. Overlain by thin siltstone layer.

c - 3.4 m: Ripple cross-laminated sets; horizontal strata. Asymmetrical ripple marks.

Unit 3 30.5 to 35.7 m: Partially covered interval. Outcrops of interbedded grayish red siltstone and light gray sandstone. Sandstone

SECTION E (cont'd)

and siltstone layers range from 15.0 cm to 0.8 m thick. Ripple cross-laminated sets, horizontally-laminated. Symmetrical ripple marks.

Unit 4 35.7 to 38.4 m: Sandstone. Scour base. Sandstone - pinkish gray, fine-grained, poorly-sorted, subangular, (Q 91%, F 6%, C 2%, HM 1%), well-indurated.
a - 2.7 m: Medium-scale, trough-shaped sets (0.3 to 0.6 m thick) of concordant cross-strata. Claystone clasts in bases of trough sets.

Unit 5 38.4 to 44.5 m: Interbedded siltstone and sandstone. Gradational base. Sandstone and siltstone layers average 12.0 cm thick. Sandstone - pinkish gray, fine-grained, moderately-sorted, subangular, (Q 94%, F 4%, C 2%, HM tr%), moderately-indurated.
a - 6.1 m: Internally structureless; locally ripple cross-laminated.

Unit 6 44.5 to 57.5 m: Sandstone. Pronounced scour base. Sandstone - grayish orange pink, fine- to medium-grained (coarse sand and granules in bases of trough sets), poorly-sorted, subangular, (Q 91%, F 6%, C 2%, HM 1%), well-indurated.
a - 5.2 m: Large-scale, trough-shaped sets (0.3 to 0.6 m thick) of concordant cross-strata; medium-scale, wedge-shaped sets (0.2 to 0.5 m thick) of planar cross-strata (low angle). Claystone clasts in lower sets.

b - 1.7 m: Medium-scale, trough-shaped sets (15.0 cm thick, laterally cont up to 4.6 m) of concordant cross-strata.

c - 2.4 m: Horizontally-laminated.

d - 3.7 m: Medium-scale, trough-shaped sets (0.5 to 0.6 m thick) of concordant cross-strata.

Unit 7 57.5 to 66.8 m: Interbedded siltstone and sandstone. Gradational base. Sandstone layers average 0.9 m thick. Sandstone - pinkish gray, fine-grained, moderately-sorted, subangular, (Q 90%, F 5%, C 3%, HM 2%), moderately-indurated.
a - 3.7 m: Medium-scale, trough-shaped sets (15.0 to 20.0 cm thick, laterally cont up to 1.8 m).

b - 5.6 m: Ripple cross-laminated sets. Includes 4.0 m thick covered interval.

Unit 8 66.8 to 72.2 m: Sandstone. Erosional base. Sandstone - grayish orange pink, fine-grained, well-sorted, subangular, (Q 94%, F 5%, C 1%, HM tr%), well-indurated.
a - 5.5 m: Medium-scale, trough-shaped sets (0.2 to 0.5 m thick) of concordant cross-strata. Upper 0.6 m of

SECTION E (cont'd)

interbedded lenticular layers of siltstone and sandstone, 15.0 to 20.0 cm thick.

Unit 9 72.2 to 79.6 m: Sandstone. Erosional base. Sandstone - grayish orange pink, medium-grained, poorly-sorted, subangular, (Q 92%, F 4%, C 2%, HM 2%), well-indurated.
a - 7.3 m: Horizontal strata. Lower 0.3 m basal trough-shaped set.

Unit 10 79.6 to 95.1 m: Covered interval. Outcrops of interbedded grayish red and greenish gray siltstone and sandstone. Ripple cross-laminated sets.

Unit 11 95.1 to 100.1 m: Sandstone. Scour base. Sandstone - grayish orange pink.
a - Medium scale, trough-shaped sets (15.0 cm to 0.6 m thick) of concordant cross-strata.

SECTION F

Unit 1 0 to 17.4 m: Interbedded siltstone, mudstone and sandstone. Gradational base. Sandstone and siltstone layers range from 15.0 cm to 0.9 m thick. Sandstone - pinkish gray, fine-grained, poorly-sorted, subangular, (Q 95%, F 3%, C tr%, HM 2%), moderately-indurated. Siltstone - grayish red, poorly-sorted with very fine-grained sand, poorly-indurated.
a - 17.4 m: Internally structureless.

Unit 2 17.4 to 29.3 m: Interbedded siltstone and sandstone. Gradational base. Sandstone - very fine- to fine-grained, moderately-sorted, subangular, (Q 95%, F 3%, C tr%, HM 2%), well-indurated. Siltstone - grayish red, moderately-sorted, poorly-indurated.
a - 1.5 m: Horizontally-laminated; undulatory, wavy laminae.

b - 10.4 m: Ripple cross-laminated.

Unit 3 29.3 to 33.4 m: Sandstone. Scour base. Sandstone - pale red, fine-grained, moderately-sorted, subangular, (Q 94%, F 2%, C 1%, HM 3%), well-indurated.
a - 0.6 m: Small- to medium-scale, trough-shaped sets of concordant cross-laminae.

b - 1.8 m: Horizontally-laminated; ripple cross-laminated.

c - 1.7 m: Ripple cross-laminated. Contains interbedded grayish red siltstone layers that range from 20.0 cm to 0.3 m thick.

Unit 4 33.4 to 51.8 m: Sandstone. Pronounced scour base. Sandstone - pinkish gray, medium-grained (coarse sand, granules and pebbles of C in base of trough sets), poorly sorted, subangular, (Q 94%, SECTION F (cont'd)

F 2%, C 3%, HM 1%), well-indurated.

a - 6.6 m: Medium-scale, trough-shaped sets (0.3 m to 0.6 m thick) of concordant cross-laminae; medium-scale, wedge-shaped sets of planar cross-laminae. Thin mudstone seams and claystone clasts between trough sets. (Channels appear to be 0.6 m to 1.2 m thick, and from 3.0 m to 12.5 m in lateral extent).

b - 3.0 m: Horizontally-laminated.

c - 0.9 m: Medium-scale, trough-shaped sets (15.2 cm thick) of concordant cross-laminae.

d - 0.9 m: Medium-scale, tabular-shaped sets (12.5 cm thick) of planar cross-laminae.

e - 4.3 m: Medium- to large-scale, trough-shaped sets of concordant cross-laminae; wedge-shaped sets of planar cross-laminae (low angle).

f - 2.7 m: Small- to medium-scale, trough-shaped sets (20.3 cm to 0.3 m thick) of concordant cross-laminae.

Unit 5 51.8 to 56.8 m: Interbedded siltstone, mudstone, claystone, and sandstone. Gradational base. Sandstone - pinkish gray, (fine-grained, moderately-sorted, subangular, (Q 90%, F 5%, C 3%, HM 2%), moderately-indurated. Siltstone - grayish red.

a - 5.0 m: Horizontally-laminated.

Unit 6 56.8 to 63.6 m: Sandstone. Scour base. Sandstone - pinkish gray, fine-grained, poorly-sorted, subangular, (Q 92%, F 5%, C 2%, HM 1%), well-indurated.

a - 0.9 m: Medium-scale, wedge-shaped sets (15.2 cm thick) of planar cross-strata (low angle).

b - 5.8 m: Horizontal strata; medium-scale, wedge-shaped sets (15.2 cm thick) of planar cross-strata (high angle). Burrowed. Upper 1.5 m contains interbedded grayish red siltstone layers less than 15.0 cm thick.

Unit 7 63.6 to 78.8 m: Interbedded siltstone, mudstone, claystone, and sandstone. Gradational base. Sandstone - pinkish gray, very fine-grained, poorly-sorted, subangular (Q 90%, F 5%, C 4%, HM 1%), well-indurated. Siltstone, mudstone and claystone - grayish red and greenish gray.

a - 14.0 m: Ripple cross-laminated; horizontally-laminated.

b - 1.2 m: Horizontally-laminated. Carbonaceous plant fragments along stratification planes.

Unit 8 78.8 to 97.7 m: Sandstone. Pronounced scour base. Sandstone - pinkish gray, medium-grained, poorly-sorted, subangular, (Q 93%, SECTION F (cont'd)

F 5%, C 1%, HM 1%), well-indurated.
a - 9.8 m: Large- to medium scale, trough-shaped sets of concordant and tangential cross-strata. Greenish gray claystone clasts and carbonaceous plant fragments along stratification planes.

b - 0.9 m: Horizontal strata.

c - 2.7 m: Medium-scale, trough-shaped sets of concordant cross-strata. Overlain by 0.3 m thick section of grayish red mudstone and claystone.

d - 5.5 m: Horizontal strata; small-scale, trough-shaped sets.

Unit 9 97.7 to 105.3 m: Covered interval. Sparse outcrops of interbedded grayish red siltstone and pinkish gray sandstone.

Unit 10 105.3 to 112.5 m: Sandstone. Pronounced scour base. Sandstone - light gray, fine- to medium-grained, moderately-sorted, subangular, (Q 91%, F 7%, C 2%, HM tr%), well-indurated.
a - 7.2 m: Medium-scale, trough-shaped sets of concordant cross-strata; horizontal strata.

Unit 11 112.5 to 116.1 m: Covered interval. Same as Unit 9 below.

Unit 12 116.1 to 119.5 m: Sandstone. Pronounced scour base. Sandstone - pinkish gray, fine-grained, poorly-sorted, subangular, (Q 90%, F 6%, C 2%, HM 2%), well indurated.
a - 3.4 m: Medium-scale wedge-shaped sets of planar cross-strata (low angle). This unit is scoured by conglomeratic sandstone with small- to medium-scale trough-shaped sets.

SECTION G

Unit 1 0 to 20.7 m: Interbedded siltstone and sandstone. Gradational base. Layers of sandstone and siltstone range from 13.0 cm to 0.9 m thick. Sandstone - pinkish gray, fine-grained, poorly-sorted, subangular, (Q 92%, F 3%, C 3%, HM 2%), moderately-indurated. Siltstone - grayish red, poorly-sorted with very fine-grained sand, poorly-indurated.
a - 20.7 m: Internally structureless. Includes 11.9 m thick covered interval.

Unit 2 20.7 to 28.9 m: Interbedded siltstone, mudstone and sandstone. Gradational base. Lenticular layers of sandstone and grayish red siltstone range from 20.0 cm to 0.6 m thick. Sandstone - light gray, fine-grained, moderately-sorted, subangular, (Q 93%, F 4%, C 2%, HM 1%), moderately-indurated.
a - 8.2 m: Ripple cross-laminated sets. Asymmetrical ripple marks. (Clay drapes between ripple cross-laminations.)

SECTION G (cont'd)

Unit 3 — 28.9 to 38.7 m: Sandstone. Pronounced scour base. Sandstone - grayish orange pink, fine-grained, poorly-sorted, subangular, (Q 90%, F 5%, C 2%, HM 3%), well-indurated.

a - 1.2 m: Medium-scale, trough-shaped sets (0.5 m thick) of concordant cross-strata. Abundant claystone clasts in bases of trough sets.

b - 3.7 m: Horizontal strata (laterally cont up to 15.2 m). Overlain by 0.3 m thick layer of grayish red mudstone.

c - 4.6 m: Medium- to large-scale, trough-shaped sets (0.3 m to 0.6 m thick) of concordant cross-strata. (Channels appear to be 1.2 m to 1.5 m thick).

d - 0.3 m: Horizontal strata.

Unit 4 — 38.7 to 39.9 m: Interbedded mudstone, siltstone and sandstone. Gradational base. Sandstone - pinkish gray. Siltstone - grayish red.

a - 1.2 m: Ripple cross-laminated sets.

Unit 5 — 39.9 to 59.4 m: Sandstone. Pronounced scour base. Sandstone - grayish orange pink, fine-grained, poorly-sorted, subangular, (Q 90%, F 5%, C 2%, HM 3%), well-indurated.

a - 18.9 m: Large- and medium-scale, trough-shaped sets (sets increase upward from 10.0 cm to 0.5 m thick); medium-scale, wedge-shaped sets of planar cross-strata. Numerous claystone clasts in bases of sets.

b - 0.6 m: Horizontal strata.

Unit 6 — 59.4 to 63.2 m: Covered interval. Sparse outcrops of interbedded grayish red siltstone and pinkish gray, fine-grained sandstone.

Unit 7 — 63.2 to 70.6 m: Sandstone. Pronounced scour base. Sandstone - grayish orange pink, fine- to medium-grained (coarse sand at base of trough sets), moderately-sorted, subangular, (Q 91%, F 5%, C 3%, HM 1%), well-indurated.

a - 1.5 m: Horizontally-laminated.

b - 5.8 m: Medium-scale, trough-shaped sets (0.5 m thick) of concordant cross-laminae.

Unit 8 — 70.6 to 77.7 m: Covered interval.

Unit 9 — 77.7 to 86.4 m: Interbedded siltstone and sandstone. Gradational base. Sandstone - pinkish gray, fine-grained, moderately-sorted, subangular. Siltstone - grayish red.

a - 8.7 m: Ripple cross-laminated.

SECTION G (cont'd)

Unit 10 86.4 to 89.8 m: Sandstone. Scour base. Sandstone - light gray, medium-grained, moderately-sorted, subangular, (Q 95%, F 4%, C 1%, HM 1%), well-indurated.
a - 3.4 m: Medium-scale, trough-shaped sets (0.5 m to 0.6 m thick) of concordant cross-strata; horizontal strata.

Unit 11 89.8 to 94.9 m: Interbedded siltstone and mudstone. Gradational base. Siltstone and mudstone - greenish gray and grayish red.

Unit 12 94.9 to 104.7 m: Sandstone. Pronounced scour base. Sandstone - light gray, medium-grained (coarse sand in base of trough sets), moderately-sorted, subangular, (Q 93%, F 3%, C 1%, HM 2%), well-indurated.
a - 9.8 m: Large-scale, trough-shaped sets (up to greenish gray claystone clasts in bases of lower trough sets.

SECTION H

Unit 1 0 to 1.2 m: Interbedded mudstone and sandstone. Lenticular layers of sandstone and grayish red mudstone range from several cm to 0.3 m thick. Sandstone - grayish red, very fine-grained, poorly-sorted, subangular, moderately-sorted.
a - 1.2 m: Internally structureless.

Unit 2 1.2 to 3.7 m: Sandstone. Scour base. Sandstone - light gray, fine- to medium-grained, poorly-sorted, subangular, (Q 89%, F 5%, C 3%, HM 3%), moderately-indurated.
a - 1.8 m: Medium-scale, wedge-shaped sets (0.3 m thick) of planar cross-strata (low angle). Carbonaceous plant fragments along stratification planes.

b - 0.7 m: Horizontally-laminated; ripple cross-laminated.

Unit 3 3.7 to 7.5 m: Interbedded siltstone, mudstone and sandstone. Gradational base. Lenticular layers of sandstone and grayish red siltstone range from 15.0 cm to 0.6 m thick, laterally cont up to 3.7 m. Sandstone - light gray, very fine- to fine-grained, moderately-sorted, subangular, (Q 90%, F 4%, C 4%, HM 2%), moderately-indurated.
a - 3.8 m: Ripple cross-laminated sets; small-scale, wedge-shaped sets of planar cross-laminae.

Unit 4 7.5 to 17.4 m: Sandstone. Pronounced scour base. Sandstone - grayish orange pink, fine- to medium-grained, poorly-sorted, subangular, (Q 93%, F 3%, HM 1%, C 3%), well-indurated.
a - 7.9 m: Large- and medium-scale, trough-shaped sets of concordant cross-strata; large- and medium-scale, wedge-shaped sets (0.6 m thick) of planar cross-strata (low

SECTION H (cont'd)

angle). Numerous mudstone clasts in bases of lower trough sets.

b - 1.1 m: Horizontally-laminated.

c - 0.9 m: Ripple cross-laminated.

Unit 5 17.4 to 18.3 m: Claystone. Gradational base. Claystone - grayish red.

Unit 6 18.3 to 19.7 m: Sandstone. Scour base. Sandstone - pinkish gray, fine-grained, moderately-sorted, subangular, (Q 90%, F 4%, C 4%, HM 2%), moderately-indurated.
a - 1.4 m: Small- to medium-scale, trough-shaped sets of concordant cross-strata. Claystone clasts in bases of lower trough sets.

Unit 7 19.7 to 27.3 m: Interbedded mudstone, claystone and sandstone. Gradational base. Lenticular layers of grayish red and greenish gray mudstone and siltstone and sandstone range from 0.3 m to 0.9 m thick. Sandstone - light gray, very fine-grained, poorly-sorted, subangular, poorly-indurated.
a - 7.6 m: Internally structureless. Carbonaceous plant fragments.

Unit 8 27.3 to 31.5 m: Sandstone. Pronounced scour base. Sandstone - grayish orange pink, fine- to medium-grained, poorly-sorted, subangular, (Q 94%, F 4%, C 1%, HM 1%), well-indurated.
a - 2.7 m: Medium-scale, wedge-shaped sets of planar cross-strata (low angle). Numerous claystone clasts in bases of wedge sets.

b - 1.5 m: Medium-scale, trough-shaped sets of concordant cross-strata.

Unit 9 31.5 to 32.2 m: Siltstone: Gradational base. Siltstone - grayish red.

Unit 10 32.2 to 41.3 m: Sandstone: Scour base. Sandstone - grayish orange pink, fine- to medium-grained, poorly-sorted, subangular, well-indurated.
a - 8.2 m: Medium- to large-scale, wedge-shaped sets of planar cross-strata (low angle); horizontal strata.

b - 0.9 m: Ripple cross-laminated. Overlain by greenish gray claystone layer (10.5 cm thick).

Unit 11 41.3 to 46.3 m: Sandstone. Scour base. Sandstone - light gray, fine-grained, poorly-sorted, subrounded, (Q 96%, F 4%, C tr%, HM tr%), well-indurated.
a - 2.6 m: Large-scale, wedge-shaped sets of planar cross-strata (low angle). Greenish gray claystone layers (15.5 cm

SECTION H (cont'd)

thick), containing carbonaceous plant fragments, between lower wedge sets.

b - 2.4 m: Medium-scale, wedge-shaped sets of planar cross-strata (low angle); medium-scale, trough-shaped sets of concordant cross-strata. (Channels appear to be 2.5 m thick and 12.2 m wide.)

Unit 12 46.3 to 46.9 m: Interbedded siltstone and claystone. Gradational base. Siltstone and claystone - greenish gray. Abundant carbonaceous plant fragments within claystone.

Unit 13 46.9 to 49.7 m: Sandstone. Scour base. Sandstone - grayish orange pink, fine- to medium-grained, poorly-sorted, subrounded, (Q 94%, F 4%, C 2%, HM tr%), well-indurated.
a - 2.8 m: Medium-scale, trough-shaped sets of concordant cross-strata.

Unit 14 49.7 to 57.3 m: Covered interval. Sparse outcrops of interbedded grayish red siltstone and pinkish gray sandstone.

Unit 15 57.3 to 62.1 m: Sandstone. Pronounced scour base. Sandstone - grayish orange pink, medium-grained, moderately-sorted, subangular, (Q 87%, F 7%, C 4%, HM 2%), well-indurated.
a - 4.8 m: Medium-scale, trough-shaped sets of concordant cross-strata.

SECTION I

Unit 1 0 to 8.8 m: Sandstone. Scour base. Sandstone - pinkish gray, medium- to fine-grained, poorly-sorted, subrounded, (Q 94%, F 4%, C 2%, HM tr%), well-indurated.
a - 8.8 m: Medium-scale, trough-shaped sets (15.2 cm to 0.3 m thick) of concordant cross-strata. Upper 0.6 m burrowed.

Unit 2 8.8 to 10.0 m: Covered interval. Sparse outcrops of interbedded siltstone and mudstone.

Unit 3 10.0 to 13.7 m: Sandstone. Scour base. Sandstone - pinkish gray, medium-grained, poorly-sorted, subangular, (Q 95%, F 3%, C 1%, HM 1%), well-indurated.
a - 3.7 m: Medium-scale, wedge-shaped sets of planar cross-strata; medium-scale, trough-shaped sets.

Unit 4 13.7 to 26.7 m: Partially covered interval. Outcrops of interbedded grayish red siltstone and sandstone. Sandstone - grayish red, very fine-grained, poorly-sorted, subangular, (Q 88%, F 5%, C 5%, HM 2%), moderately-indurated.
a - 13.0 m: Ripple cross-laminated.

SECTION I (cont'd)

Unit 5 26.7 to 31.7 m: Sandstone. Scour base. Sandstone - grayish orange pink, fine-grained, poorly-sorted, subangular, (Q 97%, F 2%, C 1%, HM tr%), well-indurated.
a - 2.3 m: Horizontally-laminated.

b - 2.7 m: Medium-scale, wedge-shaped sets of planar cross-strata (low angle). Numerous claystone clasts in lower wedge sets.

Unit 6 31.7 to 32.9 m: Interbedded siltstone and sandstone. Gradational base. Lenticular layers of grayish red siltstone and sandstone average 8.0 cm thick.
a - 1.2 m: Ripple cross-laminated; horizontally-laminated.

Unit 7 32.9 to 39.0 m: Sandstone. Scour base. Sandstone - grayish orange pink.
a - 1.8 m: Medium- to large-scale, wedge-shaped sets (20.0 cm to 0.5 m thick) of planar cross-strata (low angle).

b - 4.3 m: Large-scale, trough-shaped sets (0.5 m thick) of concordant cross-strata.

Unit 8 39.0 to 40.8 m: Siltstone. Gradational base. Siltstone - grayish red.

Unit 9 40.8 to 45.4 m: Sandstone. Pronounced scour base. Sandstone - grayish orange pink, fine- to medium-grained, moderately-sorted, subrounded, (Q 95%, F 5%, C tr%, HM tr%), well-indurated.
a - 1.2 m: Horizontally-laminated. Claystone clasts along lower stratification planes.

b - 1.4 m: Medium-scale, trough-shaped sets of concordant cross-strata.

c - 2.0 m: Medium-scale, wedge-shaped sets of planar cross-strata (low angle); horizontally-laminated.

Unit 10 45.4 to 46.6 m: Interbedded siltstone, mudstone, claystone, and sandstone. Gradational base. Lenticular layers of sandstone and grayish red siltstone average 0.3 m thick.
a - 1.2 m: Ripple cross-laminated; horizontally-laminated.

Unit 11 46.6 to 49.4 m: Sandstone. Scour base. Sandstone - grayish orange pink, fine-grained, moderately-sorted, subangular, well-indurated.
a - 2.8 m: Medium-scale, trough-shaped sets (15.0 cm thick) of concordant cross-strata; horizontal strata. Burrowed. Abundant carbonaceous plant fragments along stratification planes.

SECTION I (cont'd)

Unit 12 49.4 to 61.6 m: Interbedded siltstone, mudstone and sandstone. Gradational base. Sandstone - grayish red, very fine-grained, moderately-sorted, subangular, (Q 90%, F 5%, C 5%, HM tr%), poorly-indurated.

a - 12.2 m: Internally structureless. Locally ripple cross-laminated; small-scale, trough-shaped sets (10.0 cm to 15.0 cm thick, laterally cont up to 0.3 m).

Unit 13 61.6 to 63.4 m: Sandstone. Scour base. Sandstone - light gray, fine-grained, well-sorted, subangular, (Q 81%, F 6%, C 7%, HM 6%), moderately-indurated.

a - 1.8 m: Medium-scale, tabular-shaped sets of planar cross-laminae.

SECTION J

Unit 1 0 to 5.6 m: Sandstone. Scour base. Sandstone - pinkish gray, medium-grained, moderately-sorted, subangular, (Q 92%, F 5%, C 3%, HM tr%), well-indurated.

a - 5.6 m: Medium-scale, trough-shaped sets (increase upward from 15.0 cm to 0.6 m thick) of concordant cross-laminae; horizontally-laminated. Burrowed.

Unit 2 5.6 to 12.5 m: Interbedded siltstone, mudstone, claystone, and sandstone. Gradational base. Lenticular layers of sandstone, siltstone and mudstone range from 15.0 cm to 0.9 m thick, laterally cont from 3.5 m to 5.0 m. Sandstone - grayish red, very fine-grained, moderately-sorted, subangular, poorly-indurated. Siltstone - greenish gray and grayish red, poorly-sorted with very fine-grained sand, poorly-indurated.

a - 6.9 m: Ripple cross-laminated sets (12.5 cm thick).

Unit 3 12.5 to 17.0 m: Sandstone. Pronounced scour base. Sandstone - a pinkish gray, medium- to fine-grained, poorly-sorted, subrounded, (Q 91%, F 5%, C 4%, HM tr%), well-indurated.

a - 3.0 m: Medium-scale, trough-shaped sets (15.0 cm thick) of concordant cross-strata. Numerous claystone clasts in bases of trough sets.

b - 0.6 m: Horizontally-laminated. Burrowed.

c - 0.9 m: Medium-scale, trough-shaped sets (0.6 m thick) of concordant cross-strata.

Unit 4 17.0 to 27.0 m: Covered interval. Sparse outcrops of interbedded siltstone, claystone, and sandstone.

SECTION J (cont'd)

Unit 5 27.0 to 37.0 m: Sandstone. Pronounced scour base. Sandstone - pinkish gray, grain size variable (see below), poorly-sorted, subrounded, (Q 90%, F 4%, C 3%, HM 3%), well-indurated.

a - 3.2 m: Medium-scale, wedge-shaped sets of planar cross-strata (low angle). Thin claystone seams between wedge sets. (Fine-grained sandstone).

b - 2.0 m: Medium-scale, trough-shaped sets (12.7 cm to 0.3 m thick). Thin claystone seams between trough sets. (Medium-grained sandstone).

c - 0.5 m: Ripple cross-laminated sets. (Very fine-grained sandstone and siltstone).

d - 4.3 m: Medium-scale, trough-shaped sets (0.3 m to 0.6 m thick); horizontal strata. Thin lenticular greenish gray claystone layers and claystone clasts in base of trough sets. (Medium- to coarse-grained sandstone).

Unit 6 37.0 to 42.8 m: Interbedded siltstone and sandstone. Gradational base. Lenticular layers of sandstone and grayish red siltstone range from 0.3 m to 0.6 m thick. Sandstone - greenish gray, very fine-grained, poorly-sorted, subangular, (Q 90%, F 4%, C 5%, HM 1%), moderately-indurated.

a - 5.8 m: Medium-scale, wedge-shaped sets (0.3 m thick) of planar cross-laminae (low angle). Burrowed. Includes 3.0 m thick covered interval.

Unit 7 42.8 to 48.0 m: Sandstone. Pronounced scour base. Sandstone - grayish orange pink, coarse-grained, poorly-sorted, subangular, well-indurated.

a - 5.2 m: Medium-scale, trough-shaped sets (15.0 cm to 20.0 cm thick) of concordant cross-strata. Numerous claystone clasts and carbonaceous plant fragments along stratification planes.

Unit 8 48.0 to 52.6 m: Interbedded siltstone and mudstone. Gradational base. Siltstone and mudstone - grayish red.

a - 4.6 m: Ripple cross-laminated.

Unit 9 52.6 to 58.7 m: Sandstone. Pronounced scour base. Lenticular sandstone, laterally discontinuous. Sandstone - grayish orange pink, medium-grained, moderately-sorted, subangular, (Q 87%, F 8%, C 4%, HM 1%), well-indurated.

a - 6.1 m: Medium-scale, trough-shaped sets.

SECTION K

Unit 1 0 to 5.6 m: Interbedded siltstone, mudstone and sandstone.

SECTION K (cont'd)

Gradational base. Lenticular layers of sandstone and grayish red siltstone range from several cm to 0.6 m thick. Sandstone - pinkish gray, very fine-grained, moderately-sorted, subangular, (Q 88%, F 4%, C 8%, HM tr%), poorly-indurated.
a - 5.6 m: Ripple cross-laminated.

Unit 2 5.6 to 9.3 m: Sandstone. Gradational base. Sandstone - light gray, very fine- to fine-grained, moderately-sorted, subangular, (Q 92%, F 4%, C 2%, HM 2%), moderately-indurated.
a - 1.7 m: Ripple cross-laminated sets (15.2 cm thick).

b - 2.0 m: Small- to medium-scale, trough-shaped sets (20.3 cm thick) of concordant cross-strata; horizontally-laminated.

Unit 3 9.3 to 25.0 m: Interbedded siltstone and sandstone. Gradational base. Sandstone - greenish gray, fine-grained, moderately-sorted, subangular, (Q 89%, F 4%, C 4%, HM 3%), poorly-indurated. Siltstone - grayish red.
a - 15.7 m: Ripple cross-laminated sets.

Unit 4 25.0 to 28.3 m: Sandstone. Gradational base. Sandstone - grayish orange pink, fine- to medium-grained, poorly-sorted, subrounded, (Q 90%, F 5%, C 2%, HM 3%), well-indurated.
a - 1.8 m: Horizontally-laminated.

b - 1.5 m: Ripple cross-laminated sets. Abundant carbonaceous plant fragments along bedding planes.

Unit 5 28.3 to 37.5 m: Interbedded siltstone, mudstone, claystone, and sandstone. Gradational base. Sandstone - greenish gray, fine-grained, moderately-sorted, subangular, (Q 90%, F 3%, C 4%, HM 3%), poorly-indurated. Siltstone, mudstone and claystone - grayish red.
a - 9.2 m: Ripple cross-laminated sets.

Unit 6 37.5 to 52.8 m: Sandstone. Pronounced scour base. Sandstone - grayish orange pink, grain size variable (see below), moderately-sorted, subangular (Q 93%, F 5%, C 2%, HM tr%), well-indurated.
a - 3.7 m: Medium- to large-scale, trough-shaped sets of concordant cross-strata. Numerous claystone clasts between trough sets. (Fine- to medium-grained sandstone).

b - 7.6 m: Large-scale, trough shaped sets (0.6 m thick, laterally cont up to 18.0 m) of concordant cross-strata. Numerous claystone clasts between trough sets. (Medium- to coarse-grained sandstone).

c - 4.0 m: Medium-scale, trough-shaped sets (15.0 cm to 0.3 m thick, 1.5 m to 5.0 m in lateral extent) of concordant cross-strata; medium-scale, tabular-shaped sets of planar cross-strata. Granules of F and LF along bases of trough

SECTION K (cont'd)

sets. (Medium-grained sandstone).

Unit 7 52.8 to 58.9 m: Covered interval.

Unit 8 58.9 to 66.2 m: Sandstone. Scour base. Sandstone - greenish gray, medium-grained, poorly-sorted, subangular, (Q 82%, F 8%, C 8%, HM 2%).

a - 7.3 m: Small- to medium-scale, trough-shaped sets; small- to medium-scale, wedge- and tabular-shaped sets of planar cross-strata. Granules and pebbles of C, F and LF within scour bases of trough sets. Lower 3.0 m burrowed.

SECTION L

Unit 1 0 to 6.6 m: Interbedded siltstone and sandstone. Gradational base. Sandstone - pale red, fine- to medium-grained, moderately-sorted, subangular (Q 92%, F 4%, C 3%, HM 1%), moderately-indurated. Siltstone - grayish red.

a - 3.4 m: Partially covered interval.

b - 1.4 m: Medium-scale, wedge-shaped sets of planar cross-laminae; horizontally-laminated.

c - 1.8 m: Internally structureless.

Unit 2 6.6 to 15.8 m: Sandstone. Pronounced scour base. Sandstone - grayish orange pink, grain size variable (see below), poorly-sorted, subangular, (Q 90%, F 5%, C 3%, HM 2%), well-indurated.

a - 1.7 m: Ripple cross-laminated sets; small-scale, trough-shaped sets of concordant cross-laminae. (Very fine-grained sandstone).

b - 3.0 m: Medium-scale, trough-shaped sets (0.5 m thick, laterally cont up to 3.0 m) of concordant cross-laminae. (Medium- to coarse-grained sandstone with granules in bases of lower trough sets).

c - 1.0 m: Ripple cross-laminated sets (2.5 cm thick). (Very fine-grained sandstone with thin layers of grayish red siltstone and mudstone).

d - 3.5 m: Medium-scale, trough-shaped sets (0.3 m to 0.6 m thick, laterally cont up to 2.4 m) of concordant cross-laminae. (Fine- to medium-grained sandstone).

Unit 3 15.8 to 19.5 m: Covered interval. Sparse outcrops of interbedded siltstone and very fine-grained, ripple cross-laminated sandstone.

SECTION L (cont'd)

Unit 4 — 19.5 to 26.7 m: Sandstone. Scour base. Sandstone - grayish orange pink, fine-grained, moderately-sorted, subangular, (Q 95%, F 4%, C 1%, HM tr%), well-indurated.
a - 7.2 m: Small-scale, trough-shaped sets (20.0 to 25.0 cm thick, laterally cont up to 0.3 m) of concordant cross-laminae; ripple cross-laminated.

Unit 5 — 26.7 to 27.6 m: Covered interval.

Unit 6 — 27.6 to 30.5 m: Interbedded siltstone, mudstone and sandstone. Gradational base. Lenticular layers of siltstone and sandstone average 0.8 m thick. Sandstone - grayish red, very fine- to fine-grained, moderately-sorted, subangular, (Q 91%, F 4%, C 2%, HM 3%), moderately-indurated.
a - 2.9 m: Small-scale, trough-shaped sets (15.0 cm thick) of concordant cross-laminae; ripple cross-laminated sets; horizontal laminae overlie trough sets and ripple cross-laminated sets.

Unit 7 — 30.5 to 35.5 m: Covered interval.

Unit 8 — 35.5 to 41.8 m: Sandstone. Scour base. Sandstone - grayish orange pink, fine- to medium-grained, moderately-sorted, subrounded, (Q 87%, F 6%, C 4%, HM 3%), moderately-indurated.
a - 1.1 m: Small-scale, trough-shaped sets (15.0 cm to 20.0 cm thick) of concordant cross-laminae; ripple cross-laminated sets.

b - 0.3 m: Horizontally-laminated.

c - 4.9 m: Medium- to large-scale, trough-shaped sets (up to 0.6 m thick) of concordant cross-strata.

Unit 9 — 41.8 to 42.7 m: Interbedded mudstone, siltstone and sandstone. Gradational base. Lenticular layers of grayish red siltstone, mudstone and sandstone.

Unit 10 — 42.7 to 60.8 m: Sandstone. Pronounced scour base. Sandstone - grayish orange pink, fine- to medium-grained, moderately-sorted, subrounded, (Q 92%, F 5%, C 3%, HM tr%), well-indurated.
a - 4.0 m: Large-scale, trough-shaped sets (20.0 cm to 0.3 m thick) of concordant cross-laminae. Lower 0.6 m contain numerous interbedded claystone seams.

b - 9.0 m: Horizontal strata. Upper 0.6 m burrowed.

c - 1.5 m: Medium- to large-scale, wedge-shaped sets (0.5 m thick) of planar cross-strata (low angle).

d - 3.6 m: Medium- to large-scale, trough-shaped sets (20.0 cm to 0.4 m thick) of concordant cross-strata.

SECTION L (cont'd)

Unit 11 60.8 to 67.5 m: Interbedded siltstone, mudstone and sandstone. Gradational base. Sandstone- pinkish gray, very fine- to fine-grained, well-sorted, moderately-indurated. Siltstone and mudstone - grayish red.

a - 6.7 m: Ripple cross-laminated sets; locally internally structureless.

Unit 12 67.5 to 73.6 m: Sandstone. Scour base. Sandstone - light gray, fine- to medium-grained, moderately-sorted, subangular, (Q 91%, F 7%, C 2%, HM tr%).

a - 6.1 m: Medium-scale, trough-shaped sets of concordant cross-strata.

SECTION BB

Unit 1 0 to 9.8 m: Interbedded siltstone, mudstone, claystone and sandstone. Gradational base. Sandstone - pinkish gray, very fine- to fine-grained, moderately-sorted, subrounded, (Q 81%, F 5%, C 8%, HM 6%), moderately-indurated. Siltstone, mudstone and claystone - grayish red.

a - 7.9 m: Ripple cross-laminated sets (1.0 cm to 3.0 cm thick, laterally cont up to 5.0 cm); small-scale, tabular-shaped sets (11.0 cm thick, laterally cont up to 25.0 cm) of planar cross-laminae (low angle). Burrowed normal and oblique to stratification (dia - 0.6 cm, le - up to 20.0 cm). Soft sediment deformation prevalent.

b - 1.9 m: Medium scale, trough-shaped sets (23.0 cm to 0.4 m thick, laterally cont up to 5.0 m) of concordant cross-laminae. Burrowed normal to strata (dia - 0.8 cm, le - 23.0 cm). Soft sediment deformation in upper 0.6 m.

Unit 2 9.8 to 14.0 m: Covered interval. Outcrops of interbedded siltstone and fine-grained, ripple cross-laminated sandstone.

Unit 3 14.0 to 16.2 m: Interbedded sandstone and claystone. Slight scour base. Lenticular layers of sandstone average 0.8 m thick, interbedded with claystone layers that average 15.0 cm thick. Sandstone - pinkish gray, fine-grained, moderately-sorted, subrounded, (Q 82%, F 5%, C 7%, HM 6%), moderately-indurated.

a - 2.2 m: Medium-scale, tabular-shaped sets of planar cross-laminae.

Unit 4 16.2 to 31.2 m: Interbedded sandstone, siltstone, mudstone and claystone. Gradational base. Lenticular layers of sandstone range from 10.0 cm to 1.2 m thick. Sandstone - light gray, very fine- to fine-grained.

a - 8.4 m: Internally structureless. Burrowed (dia - 0.7 cm, le - up to 25 cm); ripple cross-laminated sets.

SECTION BB (cont'd)

b - 6.6 m: Covered interval.

Unit 5 31.2 to 57.2 m: Interbedded siltstone, mudstone, claystone and sandstone. Gradational base. Alternating lenticular layers of greenish gray siltstone, mudstone, claystone and sandstone that average 0.3 m thick and are laterally cont up to 3.0 m.
a - 26.0 m: Internally structureless.

Unit 6 57.2 to 62.0 m: Interbedded siltstone, mudstone, claystone and sandstone. Gradational base. Lenticular layers of greenish gray, fine-grained sandstone range from 0.6 m to 0.9 m thick and are laterally cont up to 30.0 m.
a - 4.8 m: Internally structureless.

Unit 7 62.0 to 77.6 m: Interbedded siltstone, mudstone, claystone, and sandstone. Same as Unit 5 below.

Unit 8 77.6 to 82.4 m: Sandstone. Pronounced scour base. Sandstone - medium yellowish brown, medium- to coarse-grained (granules concentrated in lower sets), poorly-sorted subangular, (Q 77%, F 5%, C 2%, HM 1%, LF 15%), well-indurated.
a - 4.8 m: Medium-scale, trough-shaped sets (0.5 m thick, laterally cont up to 2.1 m) of concordant cross-strata; medium-scale, tabular-shaped sets of planar cross-strata (low angle).

APPENDIX 2

Data and matrices used in Markov chain analysis.

SALT WASH MEMBER

COUNT MATRIX

	S	T_L	T_M	tw	H	R	O
S		14	29	16	10	4	
T_L			14	2	4	2	2
T_M		2		22	25	21	15
tw		5	22		18	3	1
H		4	20	14		18	6
R	11		6		3		29
O	54					1	

RANDOM PROBABILITY MATRIX

	S	T_L	T_M	tw	H	R	O
S		.075	.274	.163	.181	.148	.160
T_L	.175		.245	.145	.161	.132	.142
T_M	.212	.082		.176	.196	.160	.173
tw	.190	.073	.265		.175	.143	.155
H	.193	.074	.270	.160		.145	.157
R	.187	.072	.261	.155	.172		.152
O	.189	.073	.265	.157	.174	.142	

TRANSITION PROBABILITY MATRIX

	S	T_L	T_M	tw	H	R	O
S		.192	.397	.219	.137	.055	
T_L			.583	.083	.167	.083	.083
T_M		.024		.259	.294	.247	.176
tw		.102	.449		.367	.061	.020
H		.065	.323	.226		.290	.097
R	.224		.122		.061		.592
O	.982					.018	

DIFFERENCE MATRIX

	S	T_L	T_M	tw	H	R	O
S		+.117	+.123	+.056	-.044	-.093	
T_L			+.338	-.062	+.006	-.049	-.059
T_M		-.058		+.083	+.098	+.087	+.003
tw		+.029	+.184		+.192	-.082	-.135
H		-.009	+.053	+.066		+.145	-.060
R	+.037		-.139		-.111		+.440
O	+.793					-.124	

LOWER SAND UNIT

COUNT MATRIX

	S	T_L	T_M	tw	H	R	O
S		3	4	2	3		
T_L			6	1			
T_M				10	12	2	
tw		2	7		6		
H		2	12	4		5	1
R	3		1		1		2
O	3						

RANDOM PROBABILITY MATRIX

	S	T_L	T_M	tw	H	R	O
S		.081	.349	.198	.256	.081	.035
T_L	.071		.353	.200	.259	.082	.035
T_M	.097	.113		.274	.355	.113	.048
tw	.080	.093	.400		.293	.093	.040
H	.086	.100	.428	.243		.100	.043
R	.071	.082	.353	.200	.259		.035
O	.067	.079	.337	.191	.247	.079	

TRANSITION PROBABILITY MATRIX

	S	T_L	T_M	tw	H	R	O
S		.250	.333	.167	.250		
T_L			.857	.143			
T_M				.417	.500	.083	
tw		.133	.467		.400		
H		.083	.500	.167		.208	.042
R	.429		.143		.143		.286
O	1.000						

DIFFERENCE MATRIX

	S	T_L	T_M	tw	H	R	O
S		+.169	−.016	−.031	−.006		
T_L			+.504	−.507			
T_M				+.143	+.145	−.030	
tw		+.040	+.067		+.107		
H		−.017	+.072	−.076		+.108	−.001
R	+.358		−.210		−.116		+.251
O	+.933						

MIDDLE SILT UNIT

COUNT MATRIX

	S	T_L	T_M	tw	H	R	O
S		6	11	5	2	2	
T_L			2	1	2	1	
T_M				5	5	9	6
tw			5		6	1	1
H			3	2		10	1
R	3		4		1		19
O	21					1	

RANDOM PROBABILITY MATRIX

	S	T_L	T_M	tw	H	R	O
S		.054	.225	.117	.144	.216	.243
T_L	.186		.194	.101	.124	.186	.209
T_M	.218	.055		.118	.145	.218	.245
tw	.197	.049	.205		.131	.197	.221
H	.202	.050	.210	.109		.202	.227
R	.216	.054	.225	.117	.144		.243
O	.222	.056	.231	.120	.148	.222	

TRANSITION PROBABILITY MATRIX

	S	T_L	T_M	tw	H	R	O
S		.231	.423	.192	.077	.077	
T_L			.333	.167	.333	.167	
T_M				.200	.200	.360	.240
tw			.385		.462	.077	.077
H			.188	.125		.625	.063
R	.111		.148		.037		.704
O	.955					.045	

DIFFERENCE MATRIX

	S	T_L	T_M	tw	H	R	O
S		+.177	+.198	+.075	−.063	−.139	
T_L			+.139	+.066	+.209	−.019	
T_M				+.082	+.055	+.142	−.005
tw			+.180		+.331	−.120	−.144
H			−.022	+.016		+.423	−.164
R	−.105		−.077		−.107		+.461
O	+.733					−.177	

UPPER SAND UNIT

COUNT MATRIX

	S	T_L	T_M	tw	H	R	O
S		5	14	9	5	1	
T_L			6		2	1	2
T_M		2		7	8	6	8
tw		3	10		6	1	
H		2	5	8		3	3
R	2		1		1		8
O	21						

RANDOM PROBABILITY MATRIX

	S	T_L	T_M	tw	H	R	O
S		.095	.284	.189	.173	.094	.165
T_L	.167		.261	.174	.159	.087	.152
T_M	.202	.105		.211	.193	.105	.184
tw	.183	.095	.286		.175	.095	.167
H	.180	.094	.281	.188		.094	.164
R	.167	.087	.261	.174	.159		.152
O	.178	.093	.279	.186	.171	.093	

TRANSITION PROBABILITY MATRIX

	S	T_L	T_M	tw	H	R	O
S		.147	.412	.265	.147	.029	
T_L			.545		.182	.091	.182
T_M		.065		.226	.258	.194	.258
tw		.150	.500		.300	.050	
H		.095	.238	.381		.143	.143
R	.167		.083		.083		.667
O	1.000						

DIFFERENCE MATRIX

	S	T_L	T_M	tw	H	R	O
S		+.052	+.128	+.076	-.026	-.065	
T_L			+.284		+.023	+.004	+.030
T_M		-.040		+.015	+.065	+.089	+.074
tw		+.055	+.214		+.125	-.045	
H		+.001	-.043	+.193		+.049	-.021
R	.000		-.178		-.076		+.515
O	+.822						

APPENDIX 3

Paleocurrent measurements.

Unit	Parting Lineation	Planar Cross-Strata	Trough Cross-Strata	Ripple Marks/ Rib & Furrow Marks
		Section A		
2	N30°E	N80°E	S60°E	S10°E
	N80°E (2)*	N52°W		
	N60°E (3)	N42°E		
	N40°W			
	N0°E			
3	N80°E	N70°E	S85°E	S80°E
	N88°W		N85°E	S85°E
4				N10°W
				S30°E
5	N30°E			
6	N40°W			
7				N50°E
				N52°E
8	N55°E		N50°E	
	N65°E			
9	N85°E (3)		N80°E	S38°E
10	N75°E (2)	N85°E		
	N85°W (2)			
	N65°W (2)			
		Section B		
5	N0°E		S60°E (3)	
	N90°E		S30°E	
	N70°W		S20°E	
	N85°W (2)		S80°E	
	N80°E (2)		S55°E	
	N10°E		S70°E (3)	
	N5°W		S90°E	
	N45°W (2)		S40°E (2)	

*Number of readings.

Unit	Parting Lineation	Planar Cross-Strata	Trough Cross-Strata	Ripple Marks/ Rib & Furrow Marks
		Section B		
			S45°E (2)	
			N70°E (2)	
			N75°E (2)	
			N65°E	
7	N55°W			
8	N25°W (3)			
	N35°W (2)			
	N30°W (2)			
	N50°W			
9			S35°E	
		Section C		
5	N20°W		S20°E	
	N35°W		S60°E (2)	
	N25°W		S40°E	
	N55°W (2)		S85°E (2)	
	N50°W		S70°E (2)	
	N48°E			
	N50°E (2)			
	N85°W (2)			
9	N30°W			
10	N70°W (3)			
	N80°W (6)			
	N90°E (10)			
	N80°E			
	N75°E			
	N85°W (2)			
	N75°W (4)			

Unit	Parting Lineation	Planar Cross-Strata	Trough Cross-Strata	Ripple Marks Rib & Furrow Marks
		Section C		
10	N85°E			
	N65°W (2)			
11			N70°E	
13	N40°W (3)			
	N30°W (3)			
	N25°W (2)			
	N15°W			
	N20°W (2)			
	N35°W (3)			
		Section D		
6	N65°E (2)			
	N65°W			
9	N70°W			
	N90°E			
	N85°E			
14	N35°E			
	N30°E			
	N45°W (2)			
	N15°W (2)			
	N50°W			
	N30°W (3)			
	N40°W (2)			
	N35°W (2)			
		Section E		
6	N85°E (3)	N38°E		
	N80°W (2)	N8°E		

Unit	Parting Lineation	Planar Cross-Strata	Trough Cross-Strata	Ripple Marks/ Rib & Furrow Marks
		Section E		
6	N85°W (2)			
	N35°E			
	N45°E (2)			
13	N70°E (3)			
	N85°E (3)			
	N0°E (4)			
	N60°W (2)			
	N75°W (2)			
		Section F		
3	N65°E (3)	N48°E		N90°E (2)
	N50°E			N53°E
				N65°E
				N55°E
4	N57°E	N80°E		
	N65°E (2)	S40°W		
	N70°E (2)	N75°E		
5	N5°W	S18°E	N63°E	
	N35°E	S65°E	N30°E	
	N5°E		N35°E	
	N40°W			
	N45°W			
	N85°E (2)			
	N70°E			
6	N90°E			
	N85°E (2)			
	N75°W			
	N80°W			

Unit	Parting Lineation	Planar Cross-Strata	Trough Cross-Strata	Ripple Marks/ Rib & Furrow Marks
		Section F		
8	N90°E (2) N80°W (3) N70°E (2) N75°W (2) N78°W (2) N70°W (2)			
10	N10°W (4)			
		Section G		
3	N85°W (2)	N60°W N90°E N65°W		
5		N20°W	N80°E	
6				S85°E N60°E
7		N65°E		N80°E
9	N50°W N48°W N27°W		N60°E N80°E N75°E (2)	N10°W N20°E N10°E N40°E
10	N90°E N85°E		S50°E (2) S20°E	
12	N20°E		S75°E	N30°E

Unit	Parting Lineation	Planar Cross-Strata	Trough Cross-Strata	Ripple Marks/ Rib & Furrow Marks
		Section I		
9	N60°E			
	N80°W (2)			
	N15°E			
	N10°E			
	N40°W (3)			
	N35°W (2)			
	N45°W			
		Section L		
1		N62°W		
		N50°E		
		N20°W		
10	N35°W	N80°E (2)	S75°E (2)	
	N40°W	N36°E		

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