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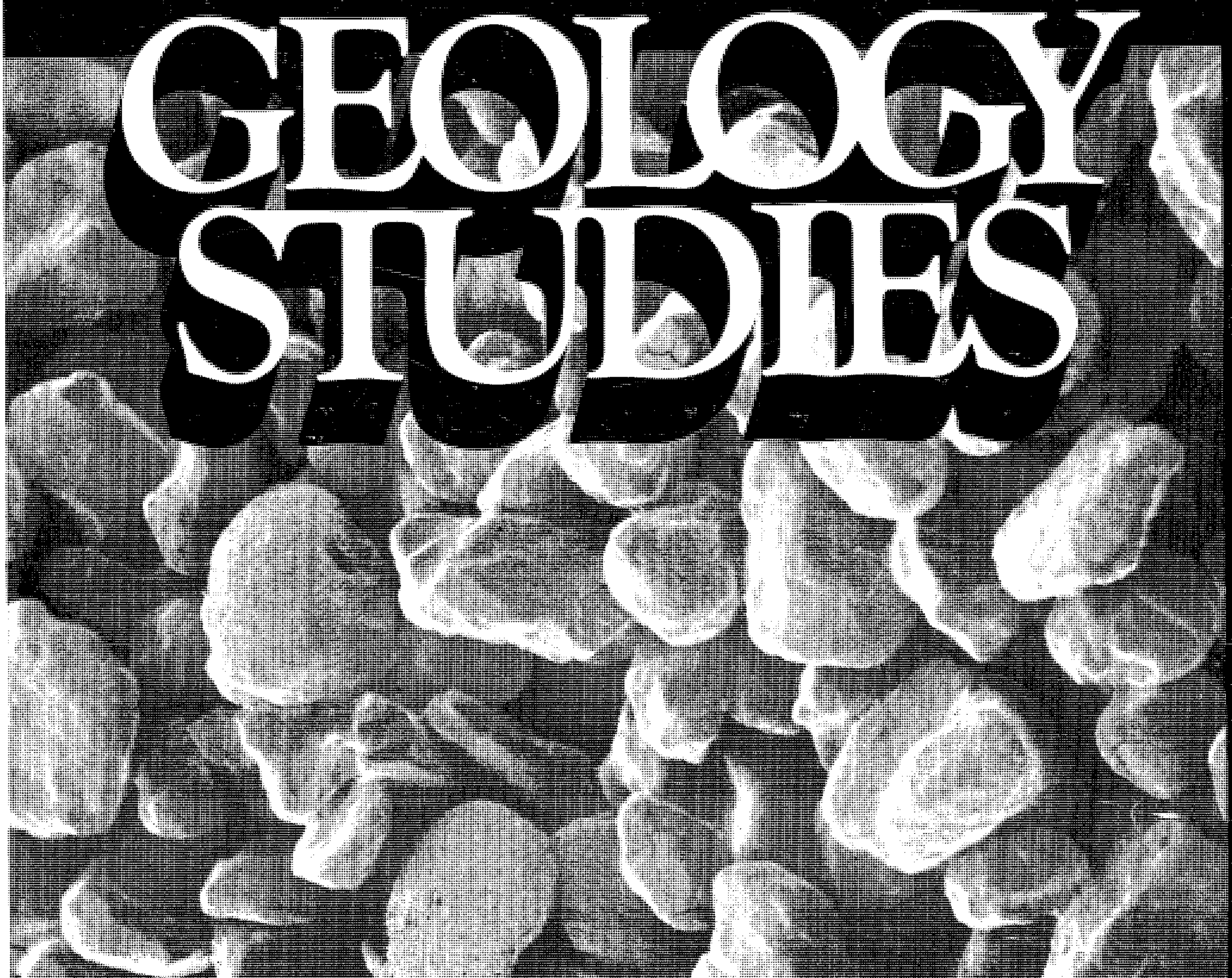

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THE GLORY OF GOD IS INTELLIGENCE

Cover: Sahara dune sand, X130. Photo courtesy Amoco Production Research, Tulsa, Oklahoma, contributed by Paul E. Potter, Department of Geology, University of Cincinnati, Cincinnati, Ohio 45221.

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Paleoenvironments of the Moenave Formation, St. George, Utah*

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ABSTRACT.—Geometry of sandstone bodies, sedimentary structures, and paleocurrent trends obtained from channel pods and numerous ribbon sandstone lenses in the Moenave Formation in St. George, Utah, were studied to determine the Moenave environment of deposition.

A north-south trending roadcut leading to St. George Municipal Airport exposes two major channels filled with homogeneous very fine sandstone and siltstone which fine upward. The south channel consists of four major undulations, each of which appears to represent a different segment of a single sinuous channel. Sixty-five oriented hand samples taken from all the channel undulations reveal environmentally diagnostic sedimentary structures (flaser and wavy bedding) and bimodal paleocurrent trends. The hand samples, cut in three dimensions, indicated strong primary north and northeast current trends, but also revealed weak secondary trends to the west and southwest. Anticipated characteristics of subaerial fluvial processes in these channels were lacking.

East of the airport location 2 km, the vertical sequence is composed of bundles of sandstone and siltstone ribbonlike lenses whose average width-to-depth ratios exceed 40:1. Sixty paleocurrent measurements taken in this roadcut show north-south bimodal current trends with central tendencies of 1.0 calculated from vector analysis of the current measurements. Three hundred additional current measurements taken in the erosional cliffs north of the city of St. George, indicate bimodal trends toward the northeast and southwest. Only ichnofaunal fossil types resembling *Skolithos, Arenicolites,* and *Diplocraterian* were found in the sandstone lenses of the erosional cliffs and eastern roadcut.

Bimodality of paleocurrent trends in the Moenave sediments is interpreted to be related to depositional processes in a tidal flat system. The large channel undulations and surrounding deposits are interpreted to have formed in the subaqueous subtidal zone. Paleocurrent results from the erosional cliffs help define a north-south trend of the paleoshoreline, and ribbon sandstone bodies at the eastern roadcut locations suggest deposition in the sandy intertidal zone. Regional paleocurrent trends indicate that the Moenave tidal flat extended from Ivins, Utah, to Zion Canyon, Utah, and may have occupied a peripheral position on a large delta forming on the eastern margin of a shallow sea which existed in the present site of southeast Nevada.

INTRODUCTION

The Upper (?) Triassic Moenave Formation of northern Arizona and southwestern and south central Utah forms the basal section of the familiar reddish-brown Vermillion Cliffs which tend in a sinuous pattern from the Moenave type section near Moenave, Arizona, westward to the Beaver Dam Mountains, Nevada, and northward to Cedar City, Utah. Excellent exposures of two unusually well-preserved channel deposits within the Moenave Formation are revealed in a roadcut on the highway leading to the municipal airport in the city of St. George, Utah. The two northeast trending channels are cut obliquely by the roadcut so that five large channel undulations are exposed. The first channel consists of a single, large concave upward undulation and is found at the north end of the roadcut. The second channel is located 40 m south of the first, and consists of four major undulations, each of which appears to represent a different segment of a single channel meander. Overall length of the two channels in this roadcut is 195 m.

A second roadcut, located at the intersection of Middleton Black Ridge and Interstate 15, exposes a vertical sequence of bundles of ribbonlike or lenticular sandstone and siltstone bodies. Seen in vertical section, this exposure cuts diagonally across the long axis of the lenses. The rocks of these cliffs consist of thick lenses of sandstone and siltstone, and massive, tabular layers of mudstone.

Sediments exposed in the two roadcuts and the cliffs north of St. George Boulevard are part of the slope-forming Dinosaur Canyon Member of the Upper (?) Triassic Moenave Formation. This member consists of siltstone, silty mudstone, and very fine sandstone, with minor amounts of intraformational mud-pebble conglomerate. Sandstone and siltstone lithologies of the study area are confined to the thick channel undulations or to thin ribbonlike lenses within the Dinosaur Canyon Member of the Moenave Formation. Intraformational conglomerates are found sandwiched between lenses of sandstone.

Sedimentary structures commonly found in the sediments of the study area are flaser and wavy bedding, planar and trough cross-bedding, current ripple marks, burrows, feeding trails, and mud cracks. Bimodal current directions and overall slight upward fining also characterize the Moenave sediments. Massive layers of mudstone enclose the channel undulations and ribbon sandstone lenses and have very few sedimentary structures, but are mildly bioturbated. Moenave sediments in the St. George study area are but little deformed except for slight regional tilting to the north, and are accessible by several major roads: Interstate 15, Utah Highway 18, U.S. Highway 91, and residential streets within the city of St. George, Utah.

The main objective of this research is to determine the paleodepositional environment which was responsible for the stratigraphic and sedimentary characteristics of these rocks as seen in vertical sequences of selected outcrops. This objective was accomplished by analyzing the geometry, internal structures, current flow measurements, and depositional fabric of the sediments in the roadcuts and cliffs of the study area and synthesizing this information into a reconstruction of a paleodepositional model.

Previous Work

Regional stratigraphic studies of the Chinle, Moenave, Wingate, Kayenta, and Navajo formations began in the early 1900s, and their classification and subdivision have been revised several times (Harshbarger, Repenning, and Irwin 1957). The first attempt to discriminate the Moenave Formation was made by L. F. Ward (1901) in his studies of the basal unit of the "orange red sandstone" of the "Painted Desert beds." Ward's use of the term *Painted Desert beds* subsequently led to considerable confusion owing to the widespread occurrence of painted deserts in the Chinle Formation. What is now referred to as the Chinle Formation constituted Ward's "Le Roux beds." Ward's "Painted Desert beds" rep-

*A thesis presented to the Department of Geology, Brigham Young University, in partial fulfillment of the requirements for the degree Master of Science, December 1976: W. Kenneth Hamblin, thesis chairman.

resent the Glen Canyon Group and include the Dinosaur Canyon siltstone member (Ward's "orange red sandstone"), the silty facies of the Kayenta Formation (Ward's "variegated sandstones," the well-known "Painted Cliffs"), and the Navajo Sandstone (Ward's "brown and white sandstone").

In 1917, Gregory described Ward's "Painted Desert beds" as "undifferentiated La Plata and McElmo" of the Moenkopi Plateau. He also correlated Ward's "brown and white sandstone" with the Navajo Sandstone to the north. Gregory and Williams (1947), and Gregory (1948, 1950a, b) made a detailed study of the geology and geography of southwestern Utah which included the Moenave strata. In his 1950 publication Gregory revised the preexisting Mesozoic stratigraphic correlations of the region and named and defined the Springdale Member as one of the four subdivisions of the Chinle Formation.

Colbert and Mook (1951) named and defined the Dinosaur Canyon Sandstone after Dinosaur Canyon, 16 km east of Cameron, Coconino County, Arizona. Harshbarger, Repenning, and Irwin (1957) redefined the stratigraphic relationships of the Chinle, Moenave, Wingate, Kayenta, and Navajo formations and proposed that they be placed in the Glen Canyon Group. Wilson (1959) made a regional stratigraphic study of the Moenave and Kayenta formations of northwestern Arizona and southwestern Utah. He mapped the boundary relationships of these two formations and suggested that fluvial and eolian environments, respectively, were responsible for the deposition of them. He also mapped, defined, and named a third member of the Moenave Formation, called the Whitmore Point Member. Day (1967) mapped the Moenave Formation in the western portion of Zion Canyon and Washington areas and also proposed that fluvial processes were responsible for deposition of Moenave sediments in his study area. These earlier papers provide adequate lithologic descriptions and set a regional framework for the present study.

Location

The principle study area is confined to selected outcrops to the west, north, and northeast of St. George, Utah (fig. 1). The westernmost outcrop studied is located at the base of the access road leading to the St. George Municipal Airport where it intersects Utah Highway 18. This outcrop will be referred to as the "airport roadcut" in this study. The northern outcrops are the east-west trending natural slopes and cliffs which lie north of the city and parallel the length of St. George Boulevard. The northeast outcrop is the Interstate 15 roadcut which passes through the north-south trending lava-capped Middleton Black Ridge. This outcrop will be referred to as the "Interstate 15 roadcut" in this study. Paleocurrent measurements were collected at selected locations near the Leeds offramp along Interstate 15, above the Visitors' Center in Zion Canyon, in Kanab Canyon along U.S.Highway 89, and north of the community of Ivins, Utah.

The principle study area is located in sections 24 and 25 of T. 42 S, R. 16 W, and sections 19, 20 and 21, of T. 42 S, R. 15 W.

Methods of Study

This study concentrated on the character of the channel deposits near the airport and the lenticular sandstone bodies in the Interstate 15 roadcut. Initial field work commenced with construction of a detailed photomosaic cross section of each roadcut. This task was accomplished by photographing in sequence small segments of roadcut, each segment measuring 4 m in width. A 4-m stadia rod was especially helpful for thickness measurements of inaccessible beds in both roadcuts. Each bed was then plotted on the cross section so that geometry and bedding relationships between each lithic layer could be determined.

Hand samples were collected at the airport roadcut in vertical sections at every change in lithology and at horizontal intervals of approximately 15 m. Sampling and study of the outcrop face at precarious and inaccessible heights of this roadcut were accomplished by the use of a utility telephone truck equipped with a hydraulic extensional arm and personnel bucket. Hand samples were also collected in some of the large sandstone lenses in the Interstate 15 roadcut. Proper orientation control of the samples was maintained by marking a reference azimuth on the samples in situ. All collected samples were sawed in the laboratory into approximately rectangular shapes (about 9 cm on a side) so that internal structures and current directional properties could be analyzed in a true three-dimensional perspective.

A few thin sections of channel sandstones/siltstones and mudstones were made so that lithology, sorting, microstructures, and fabric relationships could be studied. Some samples were etched for model composition of alkali feldspar and X-rayed for identification of the presence of iron minerals.

A total of 300 measurements of current directions was made at various locations within the St. George study area and plotted on low-altitude, oblique aerial photographs in order to provide control of the locations of current flow measurements. An additional 165 paleocurrent measurements were collected at Ivins, Leeds, Zion Canyon, and Kanab, Utah, to provide a regional concept flow direction at the time of deposition of the Dinosaur Canyon Member of the Moenave Formation in the St. George, Utah, study area.

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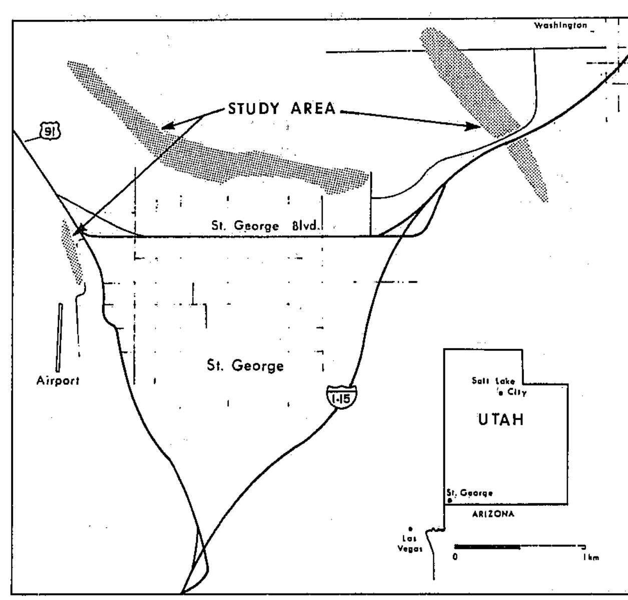

FIGURE 1.–Index map.

the Department of Geology for their advice and assistance in field research, illustration techniques, and writing of the thesis. Financial assistance was provided through the Jake L. Berge Exploration Grant. Rudger MacArthur of the city of St. George, Utah, provided a utility telephone truck for sampling roadcuts at inaccessible positions. Appreciation is also extended to all the graduate students in the Geology Department who freely gave their advice, counsel, and consolation.

GEOLOGIC SETTING

Regional paleotectonic history of the southwestern United States during Triassic and Jurassic time has been summarized by McKee et al. (1959). During Early Triassic time the Colorado Plateau area of the Four Corners region and southern Utah was relatively quiescent tectonically, and the highlands of western Colorado were eroded to low or moderate relief. Regularity of bedding, fineness of grain sizes, and related features suggest tectonic stability.

In contrast to the Early Triassic period, the Late Triassic was tectonically unstable because of uplift of the Colorado Plateau in the east and subduction along the North American plate margin to the west (Burchfiel and Davis 1975). Wide dispersal of conglomerate beds and lenses in the western Colorado Plateau attest to the irregularities of sedimentational processes resulting from episodic orogenic pulsations. Uplift in the Colorado Plateau, however, was probably more influential upon the sedimentary systems involved in the deposition of the Moenave Formation than were the orogenic influences to the west in west central Nevada. Grain-size distribution (size increase toward the east) and increases in mud/clay content in the sediments westward to the St. George area from the Colorado Plateau suggest an eastern provenance (Harshbarger et al. 1957).

As subduction processes evolved and persisted at the western plate margin in western Nevada, miogeosynclinal sequences were being deposited in southeastern Nevada and southwestern Utah (McKee et al. 1959). Fluvial processes in the Four Corners region contemporaneously carried sediments from the uplifted Colorado Plateau to the southwestern Utah area during Moenave time. Wide flood plains, with well-developed meandering channel systems and isolated lacustrine environments, evolved during this period (Harshbarger et al. 1957; Wilson 1959).

The overall depositional system of the Moenave Formation in western Utah appears to be fluvial-deltaic (Wilson 1959) as inferred from interpretation of the overall upward coarsening of its members: Dinosaur Canyon Member–very fine sandstone, siltstone, and mudstone; Whitmore Point Member–siltstone, mudstone; and Springdale Sandstone Member–fine to medium sandstone. The Dinosaur Canyon Member of the study area is not typically fluvial as it lacks the characteristic point bar sequences of upward fining sediments in sandstone lenses. The Moenave sediments of the study area may represent a marginal tidal flat within the larger deltaic system which bordered the shallow marine shelf environment southwest and west of the study area in southeastern Nevada.

GENERAL SEDIMENTARY FEATURES

Stratigraphically, the Moenave Formation is included in the Glen Canyon Group and lies above the uppermost member of the Chinle Formation (Petrified Forest Member) and below the Kayenta Formation, with minor unconformities at both upper and lower contacts. In some locations the Moenave/Kayenta contact is gradational. The intertonguing facies relationships of the Springdale Sandstone with the Whitmore Point and Dinosaur Canyon members are complex but are not included as part of the objective of this research. Overall geometry of the Moenave Formation on a regional scale is somewhat wedge shaped, thickening toward the west and northwest from the Four Corners region. Thicknesses vary from 103 m in the type locality to 165 m at Cedar City, Utah. Locally, the geometry of the Moenave sediments is pod and lenticular shaped. Grain size of the Moenave sediments generally decreases from the Four Corners area toward the St. George and Cedar City areas.

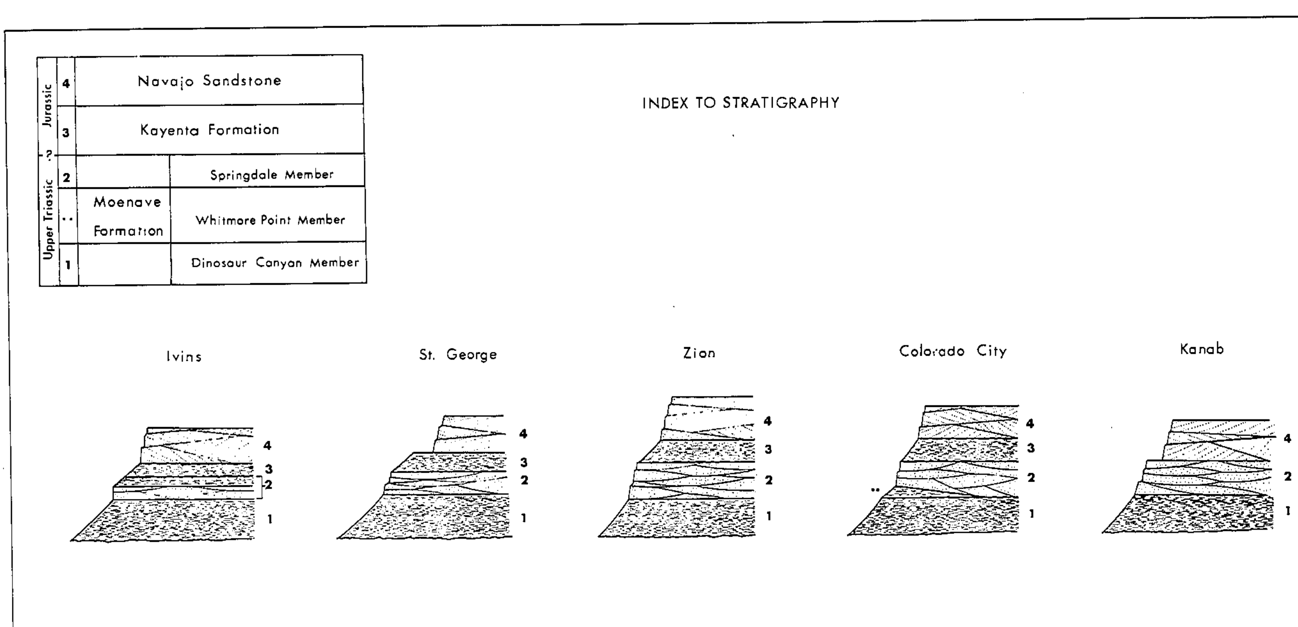

FIGURE 2.–Moenave Formation stratigraphy from Ivins to Kanab, Utah.

FIGURE 3.—North channel in airport roadcut. Stadia rod is 4 m.

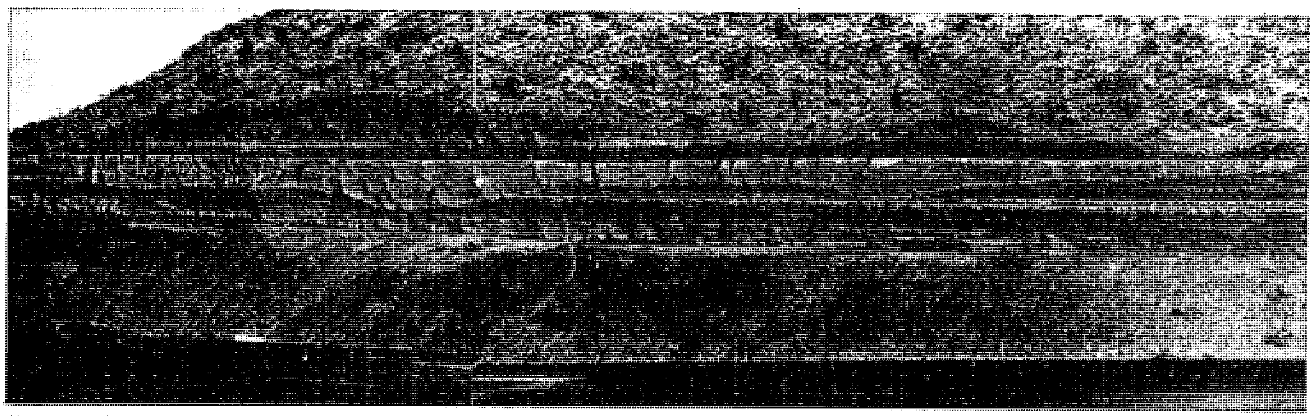

FIGURE 4.—South channel in airport roadcut, located 40 m south of the north channel.

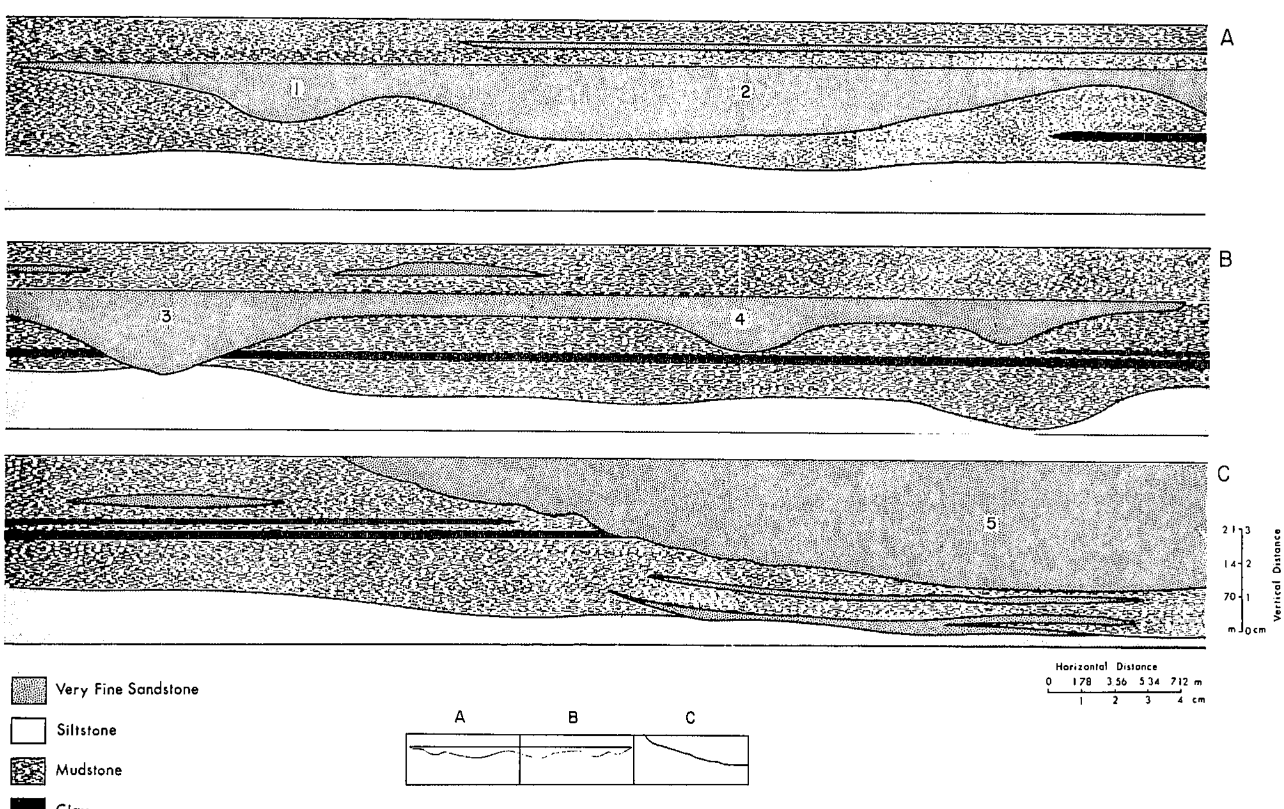

FIGURE 5.—Schematic drawing of tabular appearance of massive mudstone layers which enclose the channel deposits. Letters A, B, and C are in sequence from south to north.

Three members comprise the Moenave Formation: (1) a basal slope-forming Dinosaur Canyon Member, consisting of dull reddish brown siltstone and silty mudstone, which varies in thickness from 60 m at the type locality to 135 m at Cedar City; (2) a middle slope-forming Whitmore Point Member found between Pipe Springs National Monument, Arizona, and the Silver Reef mining district, Washington, Utah, consisting of greyish colored siltstone and mudstone; and (3) the uppermost light brown prominent cliff-forming unit, the Springdale Sandstone, consisting of fine- to medium-size sandstone conspicuously cross stratified by medium-to-large-scale planar and trough type cross-bedding. Roadcuts of the study area and the natural cliffs north of St. George Boulevard are part of the Dinosaur Canyon Member. Comparative profiles of stratigraphic sequences of the Moenave Formation and units above and below it, from Ivins to Kanab, Utah, appear in figure 2.

Geometry

Sandbodies of the Moenave Formation in the study area have three different shapes: (1) thick, pod-shaped channel deposits composed of siltstone and very fine sandstone found in the airport roadcut; (2) thin, lenticular ribbon bodies composed of siltstone and very fine sandstone located in the Interstate 15 roadcut; and (3) massive tabular layers of mudstone which surround the channel pods and ribbonlike lenses and are found at both roadcuts.

The north-south trending airport roadcut exposes two major channels (figs. 3 and 4). Approximately one-half of the northern channel (fig. 3) has been eroded; the remaining half is 45 m wide and 5 m deep. Its upper boundary is flat and horizontal whereas the lower surface is concave upward. The width-to-depth ratio is 9:1. Contacts of the channel boundaries with the enclosing mudstone deposits are sharp and well defined (fig. 5).

The southern channel, located 40 m south of the north channel (figs. 4 and 5), consists of four major undulations, each of which appears to represent a different segment of a single sinuous channel. Its overall exposed width measures 115 m. The upper surface of this large channel is flat and horizontal, with lower boundaries of all undulations concave upward. Width-to-depth ratios of the undulations average 6:1. Upper and lower contacts of all channel undulations with the surrounding mudstone sediments are sharp and well defined.

The geometry of the channel pods, expressed as a ratio of its length-to-width or width-to-depth dimensions, is significant in that width/depth ratios may be indicators of the nature of sediment load (Schumm 1968). Width/depth ratios are used in this study because only a single plane or surface of the channels is expressed in the roadcuts. Streams carrying sand by bed-load processes have width/depth ratios which commonly exceed 40 (Schumm 1968), whereas in dominantly suspended load streams, w/d ratios are less than 10 (Pettijohn et al. 1973).

W/d ratios in the Moenave channel deposits in the airport roadcut average 6:1 and may suggest that the sediments which filled the channels were carried by suspension.

Channels are produced either by streams in a partially subaerial position or by submerged or submarine currents (McKee 1957). Decreases in velocity result in proportionate rates of deposition and eventual complete infilling of the channel. Sediments of the channel fill are commonly different from sediments which may surround the channel deposits. In general, at the base of fluvial channels, coarse sediment–mud pebbles, gravel, shells, plant debris, etc.—accumulates as channel lag. The remainder of the overlying sediments of a fluvial channel fill may be composed of graded sandy material. It is not uncommon to find channels completely filled with muddy and/or silty sediments, as in gullies and channels in tidal flat environments.

Sediments which fill the Moenave channels at the airport roadcut are fairly homogeneous siltstone and very fine sandstone. It is particularly significant that no coarse debris, rock particles, or graded bedding are present. Homogeneity of the sediments in these channels may indicate that they were deposited in submerged channels produced by submarine currents rather than by subaerial fluvial processes.

Channel-Filling Mechanisms

Channels may be filled in three ways as suggested by McKee (1957):

1. By horizontal layers (fig. 6a). Channels filled by this method are not submerged, and the water level remains within the channel. This method of channel fill may represent rapid deposition because of rapid increase of sediment load or decrease in stream velocity. Sediment sizes are somewhat coarse.
2. By layers conforming approximately to the channel shape with upward concavity (fig. 6b). Channels filled in this manner are usually submerged, and, in cross section, the channel fill may show uniform thickness of layers, or layers may thin laterally toward the sides.
3. By asymmetrical filling with steeply inclined layers (fig. 6c). Asymmetrical channel fills are produced by diagonally passing currents as in submerged intertidal zones where flow of tidal water is controlled more by

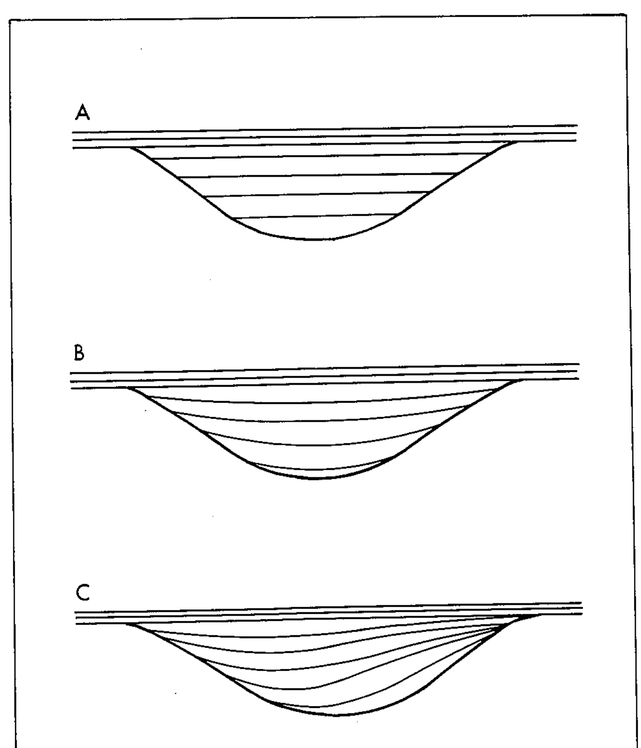

FIGURE 6.—Bedding plane inclinations in channels indicate types of channel filling processes.

differences in tidal levels than by surface morphology or by laterally migrating, meandering streams.

Sediments filling the channels in the airport roadcut are mostly parallel bedded at the tops of the channels, but become more inclined near the sides of the deepest portions of the channels (fig. 3). This slight inclination of the bedding may suggest that the channels were filled by methods 2 or 3.

The vertical sequence in the Interstate 15 roadcut is made up of bundles of thin ribbonlike lenses composed of siltstone, very fine sandstone, and mudstone (fig. 7). These lenses are both asymmetrical and symmetrical and appear in a vertical cut as ribbons. The asymmetrical ribbon sandstone lenses have flat tops and concave upward lower surfaces (fig. 8). Symmetrically shaped lenses are biconvex on upper and lower surfaces. Contacts of all sandstone and siltstone lenses in this roadcut are sharp and well defined. There are 21 identifiable sandstone and siltstone lenses in this roadcut whose widths range from 12 to 80 m, and whose average maximum depth is 1.2 m. Width-to-depth ratios range from 12:1 to 67:1 (fig. 8).

The geometry of the sediments of this roadcut is indicative of rather unstable conditions of sedimentation where periods of deposition and erosion are relatively short and somewhat cyclic (Weller 1960). The high w/d ratios may indicate that very fine sand- and silt-size particles were carried by bed-load mechanisms in shallow water having relatively strong currents (Schumm 1968). Some of the sandstone lenses may have been small channels or runnels.

Quantitatively, the dominant lithology of the airport roadcut area consists of massive layers of mudstone deposits which surround thick sandstone channel pods (undulations). Mudstone layers are laterally persistent and fairly horizontal and appear to be somewhat tabular (fig. 5). Thicknesses of the individual mudstone layers are reasonably consistent, ranging from 18 cm to 1.5 m, although their consistency is periodically interrupted by some minor irregular pinching and swelling of their upper and lower contacts. Lateral continuity is also interrupted by deep excavations of the channel undulations (fig. 5). Channel undulations 3 and 5 of figure 5 both cut through the green clay marker bed (the narrow stippled pattern in fig. 5), but channel undulation 3 scoured even deeper into the underlying massive very fine sandstone layer at the base of the outcrop. All contacts of the mudstone units with the sandstone and siltstone bodies are sharp and well defined.

Shapes of mudstone layers found in Interstate 15 roadcut are not so easily determined because of the complex stratigraphic appearance imparted to the vertical cut from the bundles of sandstone and siltstone lenses (fig. 8). Mudstone layers located in the basal one-third of this roadcut are massive and average 0.9 to 1.5 m in thickness. Upper surfaces are fairly flat and horizontal, while lower surfaces are covered by talus and are not observed. Mudstone layers in the middle portion of this roadcut are not so thick as those in the basal section and average 0.5 m in thickness. Upper and lower surfaces of the mudstone layers in the middle section are mostly flat but show moderate pinching and swelling where they are in contact with the sandstone and siltstone lenses. Layers of mudstone located in the upper third of this roadcut have flat and horizontal upper and lower boundaries, but slight pinch-

FIGURE 7.–Bundles of ribbon sand bodies at Interstate 15 roadcut.

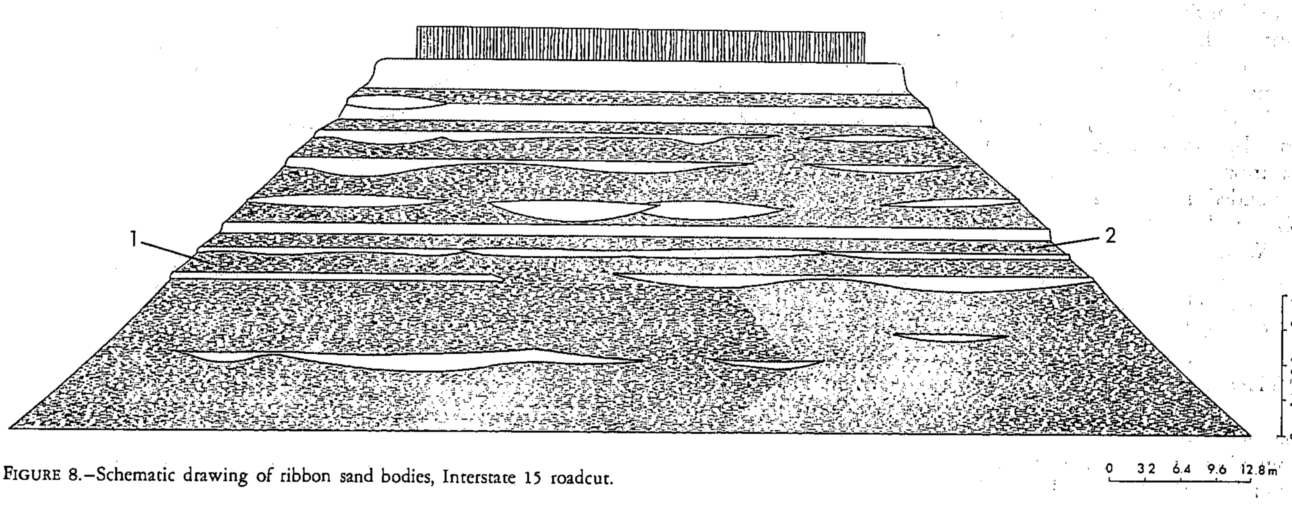

FIGURE 8.–Schematic drawing of ribbon sand bodies, Interstate 15 roadcut.

ing and swelling are observed. Average thickness of the lenses in the upper section is 40 cm.

The geometry of the vertical sequence of the Moenave sediments in erosional cliffs north of St. George Boulevard is composed of thick lenses of sandstone and siltstone and thick tabular mudstone layers. In some locations, lenses of intraformational conglomerate consisting of rounded mud/clay balls, 1.3 cm to 5.0 cm in diameter, are found sandwiched between the layers of mudstone and lenses of siltstone or sandstone (fig. 9). Exact measurements of the thicknesses of the sandstone lenses and tabular mudstone layers were not made, but in general, they thicken toward the western extremity of the cliffs.

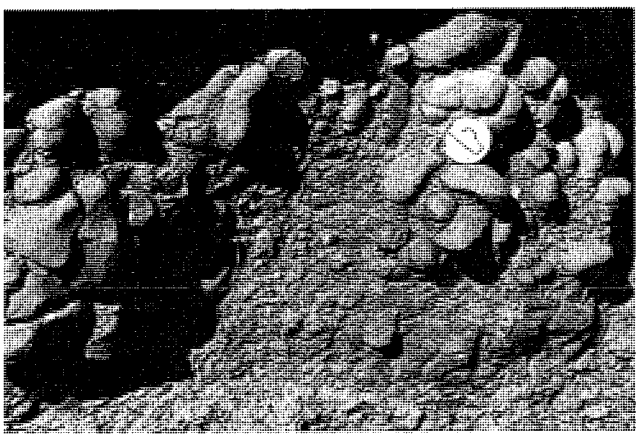

FIGURE 9.–Intraformational conglomerate lens.

Composition

Moenave channel deposits and lenticular or ribbon sandstone bodies all consist of rather homogeneous siltstone and very fine sandstone and show slight upward fining. Grains in both rock types are well rounded and cemented. They are set in a matrix of calcite and iron oxide cement. Mineralogically, 95 percent of the grains is quartz, the remaining 5 percent is alkali feldspar, with minor amounts of biotite, muscovite, and iron silicate minerals (amphibole). Sorting is poor to moderate as the mud, silt, and sand fractions are commonly intermixed to some degree. Bedding planes in the channel deposits are somewhat parallel at the tops of the channels but appear to conform to the concave upward shape of the channel bottoms or undulations (fig. 3).

Most Moenave sediments are characteristically a reddish brown color due to pigmentation by the iron oxide coating on quartz grains of the siltstone and sandstone.

Mudstone units of the Moenave roadcut study areas are composed of poorly sorted, subrounded grains of quartz and minor amounts of alkaline feldspar cemented with calcite and iron oxicide. They are highly effervescent in dilute hydrochloric acid. Coloration of these units varies from light brown or tan to greyish green. Characteristically, the mudstones are highly mottled with spherical inclusions of clay. For example, a mudstone unit which appears to have an overall greenish color can be mottled with brown clasts, or the unit will have a brownish color and be modified by the presence of greenish-colored clasts. The light brown coloration is from pigmentation of iron oxide coatings on the quartz grains. The greyish green coloration is suggestive of reducing conditions. Burrows and trails, also suggestive of rich organic domains, were the only forms of bioturbation preserved and were found in the mudstone layers. Weathered surfaces of the mudstone are typically bulbous or semispherical owing to the presence of clay in minor quantities in the mudstone.

Very few sedimentary structures are seen in the mudstone bodies other than parallel colorations (alternating cream color, brown or light green), or traces of microsize flaser beds or wavy laminations.

Sedimentary Structures

Sedimentary structures found in the channel deposits and ribbon sandstone bodies are mostly flaser and wavy bedding and small- to medium-scale planar and trough type cross bedding (figs. 10–13). Details of bedding are commonly poorly expressed and obscured in natural outcrop and the roadcuts of the study area. Major lithologies, especially in the airport roadcut, appear to be massive and homogeneous, with only local faint expressions of small-scale sedimentary structures. Clean hand samples reveal that most, if not all, of the siltstone within the channel undulations and ribbon sandstone bodies contain flaser and wavy bedding, ripple laminations, or microscale cross stratification ranging from a millimeter to a centimeter or two in thickness. Flaser and wavy bedding structures are distributed throughout all portions of the channels. Small-scale planar cross-beds are found predominantly at the tops of the channels and nearest the boundary edges of the channel undulations. Planar and trough type cross-beds of medium scale are distributed throughout the central and basal portions of the channels.

Distribution of the various types of sedimentary structures within the channels may be useful in defining locations of relative current strengths within each channel. Strongest currents (thalweg) in the Moenave channels are defined by

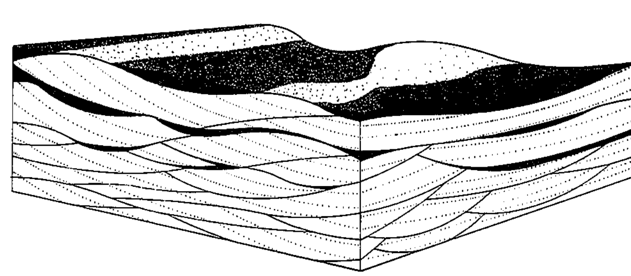

FIGURE 10.–Flaser bedding.

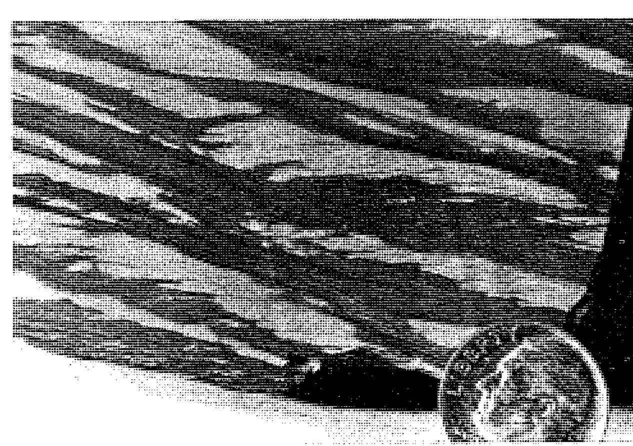

FIGURE 11.–Wavy bedding.

the distribution of the small- to medium-scale cross-beds located in the central and basal portions of the channels. Generally, sedimentary structures diminish in size outwardly from the central portions of the channels, suggesting decreasing current strength toward the sides of the channels.

Flaser and wavy bedding are the most common sedimentary structures found in all the sediments of the study areas. They suggest the availability of both sand and mud during alternating periods of current-flow and slack-water conditions (Reineck 1973). During periods of current activity, sand is transported and deposited as ripples, and mud is held in suspension. As the current ceases, mud and fecal pellets settle out and accumulate in ripple troughs, or completely cover the ripple crests (fig. 10). The relative thicknesses of sand or mud between the successive flaser or mud ribbons indicate the availability of relative amounts of sand or mud and which conditions were more conductive to deposition of one sediment over the other. For example, if more mud was available than sand, and periods of slack water were longer than periods of tidal flow, wavy bedding structures would be more common than flaser bedding.

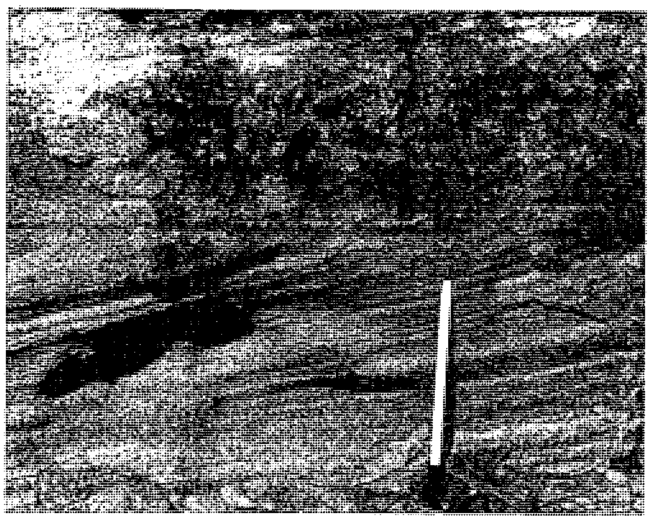

FIGURE 12.–Planar cross-bedding.

FIGURE 13.–Small-scale trough type cross-bedding.

Sedimentary bedding of this type is common in the tidal-flat environment. Sand deposition results from bed-load transport, from movements of incoming tidal currents, and from the back-flow currents of ebb tides. The relative periods of quiescence between the two currents result in deposition of mud or fecal matter held in suspension (Reineck 1973).

PALEOCURRENT DATA

The most significant information revealed by the sedimentary structures of the Moenave sediments was the directions of paleocurrent flow trends derived from the cross-bedding.

Paleocurrent directions in the channel deposits of the airport roadcut were determined by measuring micro-cross-laminae in 65 hand samples collected at relatively close intervals within the channels. Approximately 15 samples were collected in each channel undulation. Large oriented specimens were collected and sawed into rectangular blocks in the laboratory so that true current directions could be measured. Each sample was sawed into blocks, and horizontal sections cut through the cuspate cross-laminae revealed the true current directions of several sets of strata. The points or narrow rounded noses of the cusps pointed in the direction of current flow, as well as the intersection of two planes of dipping stratification. Ten additional measurements of cross-bedding directions were collected on the outcrop face of the north channel, designated as channel 5 in figure 14. Channel undulations in the south channel are indicated by the numbers 1-4. Current flow measurements in all locations of the study area are represented individually as vectors (fig. 15) having equal length (8 mm) or magnitude. They were plotted in vector groups or trains for each location. The mean current direction of each group of vectors is calculated by drawing a heavy arrow from the origin of each train of vectors trending in one direction toward the end vector. Letters A-J of the vector diagrams in figure 15 designate the locations of each group of measurements and correspond to the locations indicated by the same letters in figure 18. The

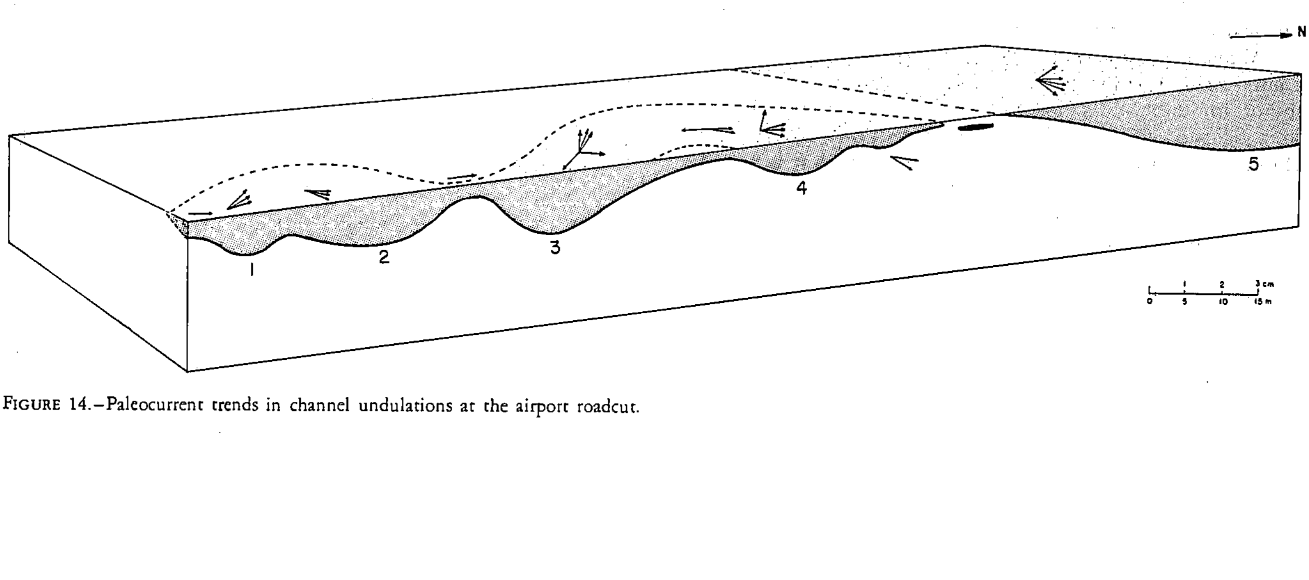

FIGURE 14.–Paleocurrent trends in channel undulations at the airport roadcut.

north and south channels of the airport roadcut are designated I and J, respectively. A measure of central tendency, or consistency ratio, in each direction was calculated by comparing the ratio of the total length of the vector mean with the cumulative magnitude of the individual vectors.

The general trend of the channels is northeast and is summarized in table 1. However, second order trends in channel undulations numbered 1, 3, and 4 indicate current flow in the opposite direction of the vectoral sum. Using the data from table 1 and figure 14, which show the location of current measurements and current directions of each channel, it appears that the four interconnected channel undulations are parts of the same channel meander and may have intersected the large, single channel immediately to the north in this roadcut. The overall large size, depth, and paleocurrent direction of the largest channel suggest that it was not part of the same channel meanders as the other four connected channel undulations (fig. 14).

Interstate 15 cuts through the Middleton Black Ridge roadcut study area approximately normal to the regional north-south trend of the lenticular sandstone and siltstone bodies. Paleocurrent flow directions of these lenses were determined from 60 in situ measurements of micro-cross-laminae found within various sandstone and siltstone lenses located near positions 1 and 2 of figure 8 and from hand samples collected from some of the sandstone and siltstone lenses. The uppermost portions of the roadcut were inaccessible for current measurements. At location 1, current flow data from 30 measurements indicated bidirectional trends of equal significance having vectoral sums of 001° and 189° (fig. 15A). Central tendencies in each direction were 1.00. Vector mean directions and central tendencies were calculated in the same manner as the paleocurrent data calculated for the sediments of the airport roadcut. Measurements at location 2 are similar to those at location 1, i.e., 000° and 192° (fig. 15A), with central tendencies of 1.00 in each direction.

An additional 300 measurements of cross-bedding structures were taken in sandstone and siltstone lenses exposed along the basal and middle sections of the cliffs north of St. George Boulevard. An aerial photograph (fig. 16) indicates the locations where measurements were made. Each general location of measurements is designated on the aerial photographs by a large white letter b–f, and the exact position of each group of measurements is indicated by a small white numbers. Positions G and H shown in the summary vector diagram (fig. 15, G and H) are located in figure 17. Current flow data at each location is shown by vector diagrams figure 15, B–H. Vector means and central tendencies are calculated in the manner cited earlier.

Figure 18 summarizes the general bimodal current flow tendencies measured along these cliffs. The number of measurements at each location (fig. 18) is indicated near the letter designating each location, and the lengths of the arrows in this diagram indicate relative significance of current flow in each direction. There is a stronger tendency of current flow towards the northeast and east at positions D, G, F, and H than towards the southwest or west (vector diagrams of figure 15, D, F, G, and H). At locations B, C, and E (fig. 18), a stronger trend of current flow is indicated toward the northwest than toward the northeast. Position F also has a strong second order tendency to the northwest.

Bimodal current flow in opposite directions, as indicated along these cliffs, is interpreted to be related to ancient tidal flat-current conditions. Using the directional data from figure

TABLE 1

SUMMARY OF CURRENT FLOW DATA IN THE CHANNELS OF THE AIRPORT ROADCUT

Channel no.	No. Meas.	Vector sum	Consistency ratio	General trend
1	5	318°	.95	310°
	1	138°	1.00	
2	7	008°	.96	008°
3	7	018°	.89	018°
	4	291°	.94	
	1	134°	1.00	291°
4	11	013°	.91	013°
	3	303°	.92	
	1	174°	1.00	303°
5	14	025°	.96	025°
	5	303°	.80	

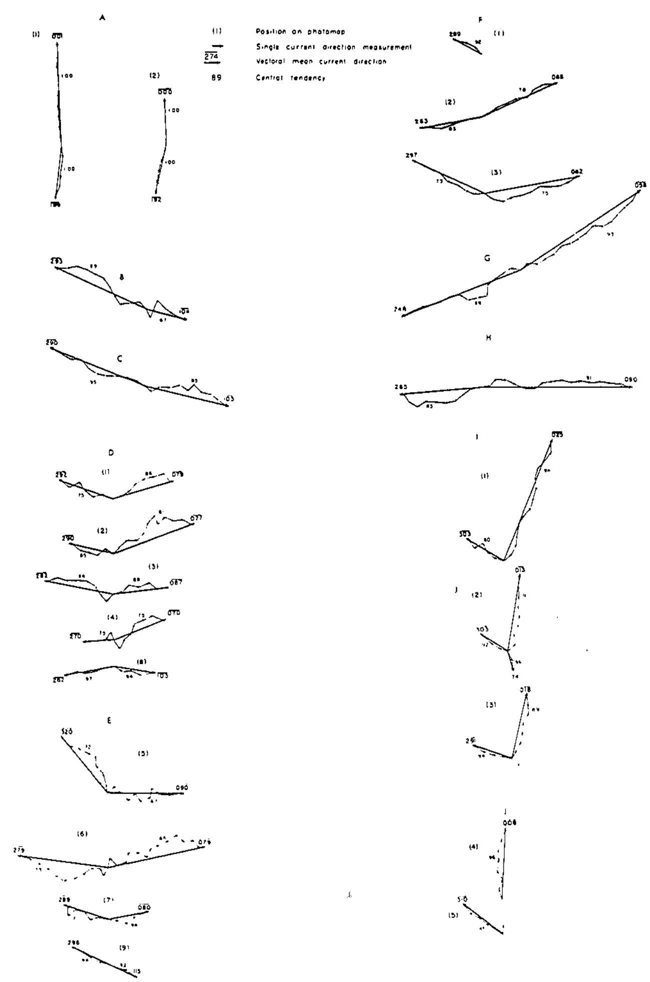

FIGURE 15.—Vector diagrams of paleocurrent trends in all locations of study area in St. George.

18, the trend of a paleoshoreline can be inferred by drawing a dotted line approximately normal to the locations of bidirectional current flow. The approximation of the shoreline trend may help to establish a depositional relationship between the channel deposits of the airport roadcut and the sandstone lenses of the Interstate 15 roadcut within the inferred tidal environment.

FOSSILS

Fossils are rare and poorly preserved in the Moenave sediments of the study area, and they include trace fossils, burrows, and trails found mostly in mudstone layers just below surfaces of contact with siltstone and sandstone lenses. Very few burrows or trails were found at the airport location, but those observed were somewhat U– or J–shaped. Average burrow length measures 9 cm and .9 cm in diameter. Burrows were abundant in both siltstone lenses and mudstone layers in the natural cliffs north of St. George Boulevard and in the Interstate 15 roadcut but did not occur in any predictable pattern of distribution. Most burrows were straight, oriented in an upright vertical position (fig. 19) or horizontally (fig. 20). Average lengths and diameters are 14 cm and .9 cm respectively. Modes of preservation are of two types: (1) as cavities (fig. 21) or (2) as solid casts (figs. 19 and 20).

These burrows may be representative of three categories of ichnofaunal, or trace-fossil, burrowing structures: (1) feeding structures, or Fondinichnia, (2) dwelling structures, or Domichnia, and (3) escape structures, or Fugichnia. Feeding structures consist of temporary burrows of deposit feeders ex-

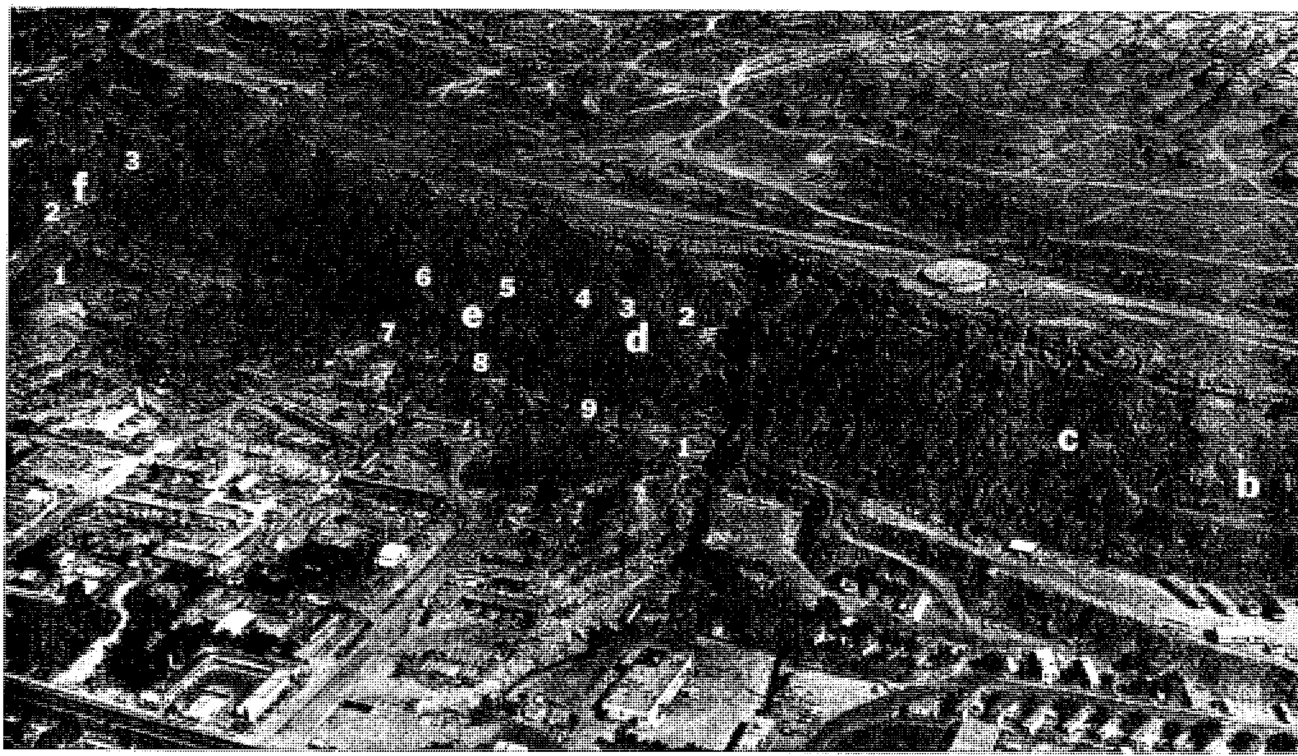

FIGURE 16.–Location map of paleocurrent measurements along the erosional cliffs north of St. George Blvd.

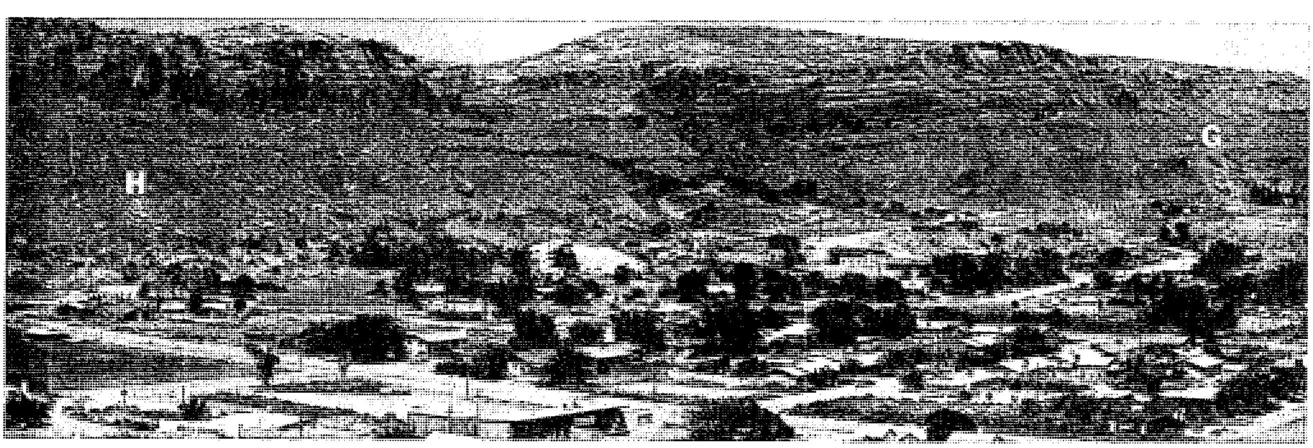

FIGURE 17.–Location map of paleocurrent measurements for positions G and H.

cavated while in search of food within the sediment or at the sediment surface. Burrow patterns typical of Fondinichnia are radial and U-shaped, i.e., *Diplocraterion* and *Phycodes.* Dwelling structures (Domichnia) include those burrow types which are more or less permanently inhabited by suspension feeders. These structures are cylindrical, having agglutinated or strengthened walls. They are also U-shaped and include *Ophimorpha, Skolithos,* and *Arenicolites.*

Escape structures, or Fugichnia, are produced by bivalves and suspension feeders which uncover themselves after having been buried by influx of sediment, or burrow deeper into the sediment to offset erosion at the substrate surface. Fugichnia are not well understood but are considered to be a transition classification to feeding structures and Cubichnia, or resting traces. Examples may be *Diplocraterion* and *Asteriacites.*

Ichnofaunas are environmentally significant because variations in this faunal group can be used to infer both vertical and lateral facies changes in ancient sediments and hence may provide clues to viable paleogeographic reconstructions (Frey 1975). Ichnofossils found in the study area resemble species of the three groups Fugichnia, Fondinichnia, and Domichnia, which are normally associated with the sandy shore of the littoral zone. This niche is somewhat exacting in that animals living in this zone must be able to tolerate strong current and wave action, desiccation, and rapid fluctuations in salinity and temperature. Toleration of such conditions is accomplished by escaping from the surface into permanent or semipermanent burrows. This response is reflected in the corresponding trace fossils showing a preponderance of vertical burrows such as Skolithos, or "pipe rock", or U-shaped burrows as *Arenicolites* and *Diplocraterion.* The intertidal zone is characterized by abundant U-shaped burrows and burrows with protective linings.

INTERPRETATION AND RECONSTRUCTION OF THE MOENAVE ENVIRONMENT OF DEPOSITION

Interpretation I

Collectively, the major Moenave characteristics of paleocurrent trends, geometry, sedimentary structures, and, to a lesser degree, ichnofaunal types suggest that the deposition of the Moenave sediments in the St. George area was related to a tidal-flat system located peripherally on a larger delta.

The major characteristics of the Moenave sediments found at the airport roadcut indicate that these deposits were formed in the subtidal zone where subaqueous conditions predominated over subaerial conditions (fig. 22). This zone occupies the area which extended landward about 1 m above mean sea level and seaward to a depth of several meters below sea level. The subtidal zone was submerged for at least one-half of the tidal cycle and thus was exposed subaerially

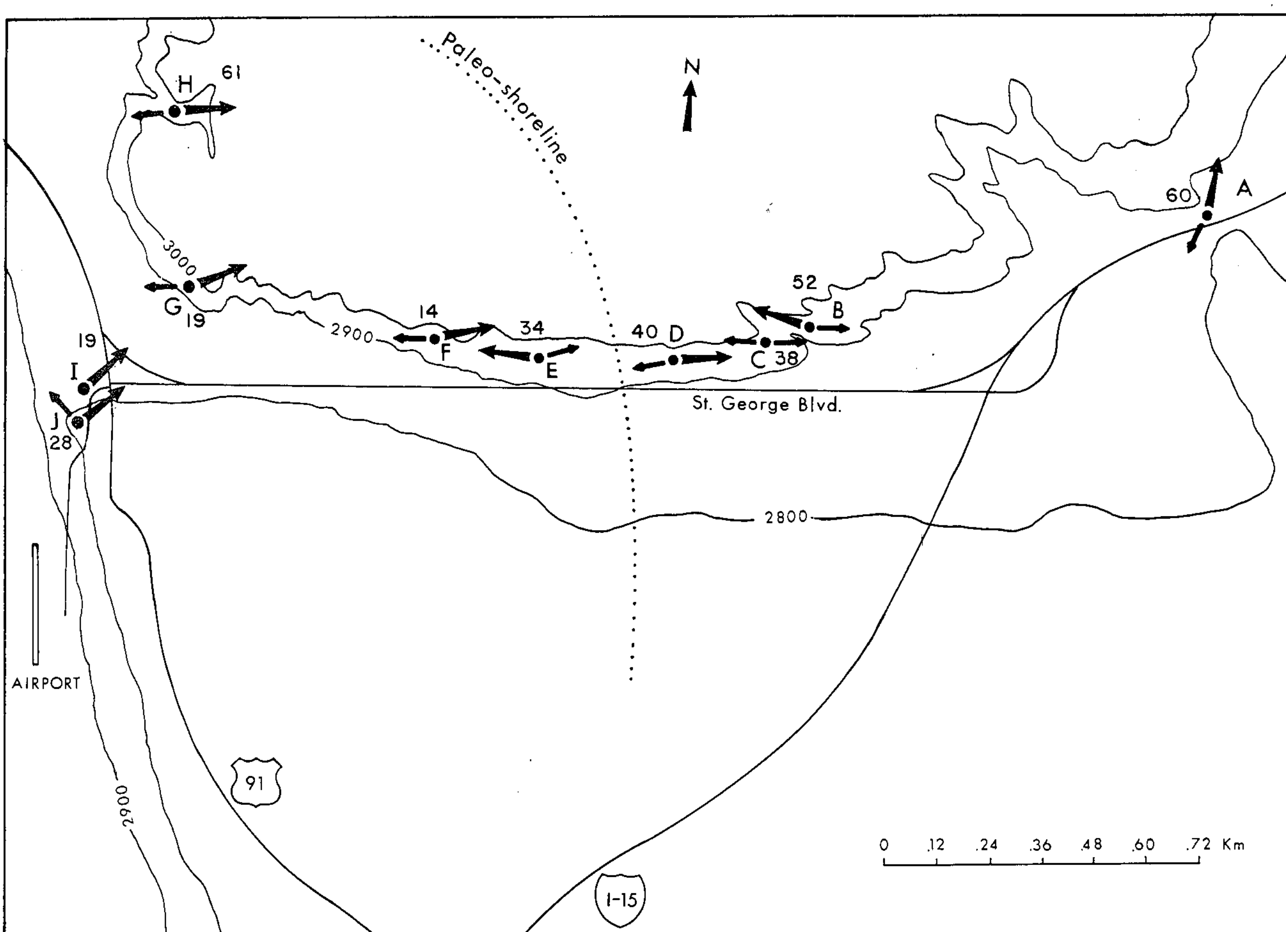

FIGURE 18.—Paleocurrent summary diagram of positions A–J. Sizes of arrows indicate relative strengths of current tendencies. Dotted line is inferred trend of paleoshoreline.

the lesser amount of time. The main features of this zone are channels and sandbars characterized by megaripples, small-scale cross-bedding, and flaser, wavy, and lenticular bedding in the channel walls. Bipolar current flow produced herring-bone cross-bedding. Bioturbation is sparse. Alternating sand and mud layers are common and are caused by tidal phases of current and slack-water conditions (Reineck 1973).

The thickness of the airport channel deposits and their size indicate that they were formed by strong incoming tidal currents flowing landward to the northeast. The large single channel (channel 5, fig. 14) may have been a major sub-aqueous channel in the subtidal zone while the smaller channel undulations were parts of a tributary meander within the same location. Weak bimodal current flow measurements, indicating current flow in the opposite direction, suggest depositional influences from ancient ebb currents flowing seaward toward the southwest. The low w/d ratios (less than 10:1) of the channels indicate that the channel fill material and the surrounding mudstone sediments were carried and deposited mostly by suspension, as in slack-water conditions where currents are weak in the interim of tidal influx and ebb flow.

The sandstone and siltstone lenses of the Interstate 15 roadcut may have been produced by incoming tidal and regressive ebb currents in the intertidal zone of the tidal flat environment.

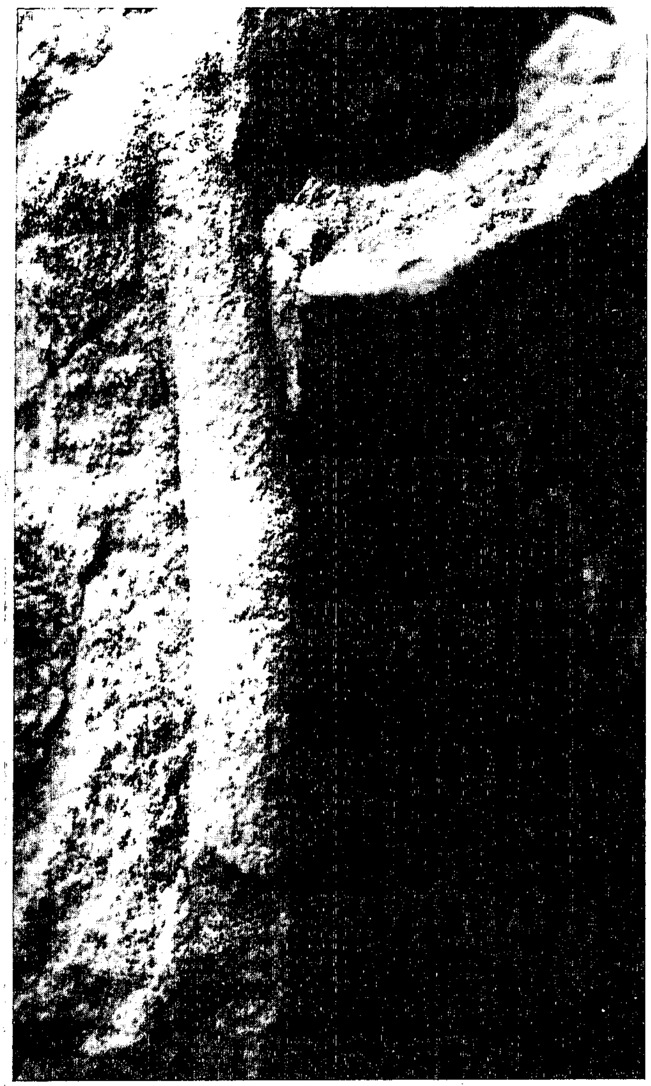

FIGURE 19.—Vertical burrows.

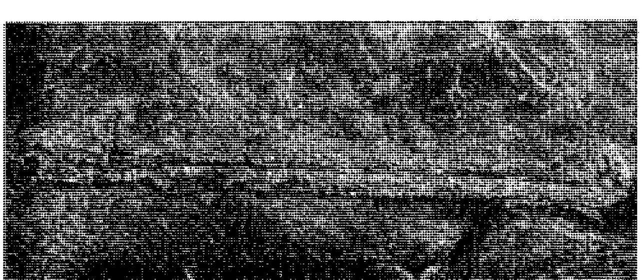

FIGURE 20.—Horizontal burrows.

Interpretation II

The intertidal zone occupies the area covered by high tide and low neap tides, and the tidal range may represent a vertical difference in water depth of 2 to 5 m (Reineck 1973). The upper portion of the intertidal flat (high tidal zone) is subaerially exposed for the greatest periods of time during neap tidal stages. The lower portion is subject to daily flooding and is drained by numerous dendritic, linear, and meandering channels. These channels distribute water across the flats during flood tide and then collect and funnel it back in the opposite direction (seaward) during ebb tide. It is the tidal fluctuations of water level which produce the channels, runnels, and gullies on the intertidal flat. Currents of high tidal range excavate deeper channels than currents of low tidal range (Thompson 1968).

Sediments of the intertidal flats are mostly fine-grained mud and silt and very fine sand. Gravels are rare, but mud clasts and shells may be abundant in tidal channel deposits. Most of the sediments of the intertidal zone have a characteristic distribution pattern: sediments of the high water level of this zone are muddy, but become more sandy in the lower level. This distribution pattern of sediment is due largely to the available energy and transportation mechanisms. Near the low water line the wave activity is strongest and active for

FIGURE 21.—Burrows preserved as cavities.

the longest time as compared to the higher parts of the intertidal zone. For this reason sand is concentrated in the lower intertidal zone.

The sand flats of the intertidal zone are characterized by well developed small-scale current and wave ripple cross-bedding. Flaser and wavy bedding are also present but less common. Megaripples are common in intertidal channels, and some climbing ripple laminations may be found in the mouths of small channels and gullies.

The most common bedding forms found in the mixed flat (sand and mud) environments are flaser, wavy, and lenticular bedding (Reineck 1973), and all variations of thinly and thickly interlayered sand-mud beds. Point bar deposits, if present, may also have well-developed interlayered sand-mud bedding. Horizons of shells in their living positions are also common. Intraformational conglomerates composed of mudstone balls, shells, and gravel, as shown in figure 9, are also commonly found in the intertidal zone (Thompson 1968).

Slightly stronger landward tidal currents flowing northward excavated relatively shallow channels (less than 1.5 m), resulting in some of the thicker lenses in the central portion of the Interstate 15 roadcut. Regressive ebb flow funneled water seaward toward the southwest, modifying the tidal influx channels and scouring out narrow gullies and runnels which became filled with silt and sand carried by tidal currents. The relatively thin layers or lenses of mudstone may have resulted from the accumulation of mud and fecal matter during the interim slack-water period. Sandstone and siltstone predominate over mudstone in this roadcut because this area probably was the sandy, lower intertidal flat where strong paleocurrent tidal activity prevented the accumulation of mud.

Reconstruction of the Moenave Tidal Flat Environment

During the late Middle to Late Triassic Period, westward flowing fluvial systems drained the Colorado Plateau region and deposited the sediments which comprise the Glen Canyon Group of the Four Corners region and southwestern Utah (Harshbarger et al. 1957). The Moenave Formation may have been deposited in a tidal flat system in the St. George area as suggested from evidences presented in this study. At some locations in southwestern Utah, the Moenave and Kayenta formations have sedimentological characteristics related to lacustrine, or fluvial-deltaic environments (Wilson 1959; Harshbarger et al. 1957). McKee et al. (1959) show that miogeosynclinal deposits typical of a continental shelf were deposited in southeastern Nevada and the extreme southwest border of Utah. The Dinosaur Canyon Member of the Moenave Formation in the St. George area, then, may have occupied a peripheral position on a tide-dominated delta which bordered on a shallow sea to the southwest and west much the same, by analogy, as the tidal flat situated on the northwestern flank of the delta formed by the Colorado River in the Gulf of California (Meckel 1975). Within this regional framework, and from the position of the shoreline inferred from figure 18, aspects of the Moenave tidal environment in the St. George area can be defined.

Figure 22 reconstructs the ancient tidal flat in the St. George study area. Numbers 1-4 are locations in the study

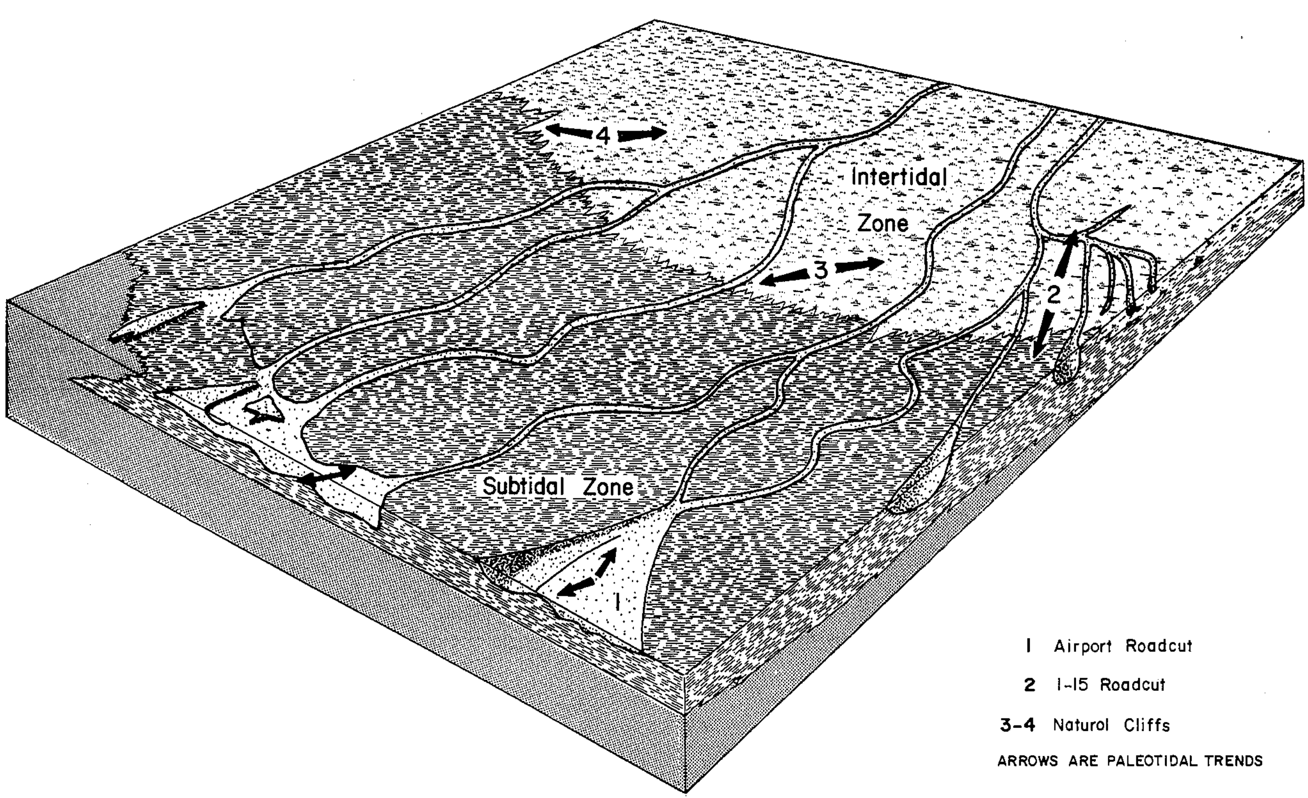

FIGURE 22.–Reconstructed model diagram of the Moenave tidal flat in the St. George area.

area and indicate their relative position in the reconstructed model. A seaward transition to deeper portions of the tidal flat west of Middleton Black Ridge roadcut is suggested by the increasing thicknesses of sandstone lenses and mudstone layers in the natural cliffs. The position of the subtidal zone is indicated by the thick channel pods and thick mudstone layers which enclose the channel sandstone deposits in the airport roadcut. The channels in the airport roadcut may represent remnants of major subtidal channels through which strong incoming northeast-flowing tidal currents were funneled. Some ebb flow through these channels toward the southwest is indicated from paleocurrent data (figs. 14 and 15, I and J, and table 1).

Regional bidirectional current flow data collected at Ivins, Utah, and above the Visitors' Center in Zion Canyon suggest that this tidal system occupied an area at least 100 km wide (fig. 23).

SUMMARY

Spectacular channels and bundles of lenticular sandstone sequences in the Dinosaur Canyon Member of the Moenave Formation in St. George, Utah, are exposed by roadcuts near the municipal airport and in Middleton Black Ridge along Interstate 15. Orientation and geometry of the channels and lenticular sandstone and siltstone bodies, fining upward of all vertical sequences, and bidirectional current flow measurements indicate that these deposits were formed in a tidal flat system.

The bundlelike appearance of the sandstone and siltstone lenses of the Interstate 15 roadcut and their high w/d ratios (greater than 40) suggest relatively unstable or fluctuating depositional conditions in which sediments were carried by bed-load processes in shallow water. Consistent bidirectional current flow measurements in this roadcut indicate deposition occurred in the intertidal zone of the tidal flat.

Low w/d ratios (less than 10) and type of channel filling mechanisms inferred from the nature of bedding within the thick channel deposits of the airport roadcut indicate that transportation and deposition of these sediments was mostly by suspension processes in relatively deeper water than is represented by the sediments of the vertical sequences at the Interstate 15 roadcut. The channel deposits and thick mudstone layers which surround these channels may represent deposition in the subtidal zone.

Current flow data indicate a possible meander pattern of the four interconnected channel undulations and intersection with the large single channel undulation exposed at the north end of this roadcut. Regional bidirectional current flow data collected at Ivins, Utah, and by the Visitors' Center, Zion Canyon National Park, suggest that the Moenave tidal system extended a distance 100 km in width and may have occupied a peripheral position within a large prograding fluvial-deltaic system which drained the Colorado Plateau to the east and dumped its sediment load into the shallow back arc sea of eastern Nevada.

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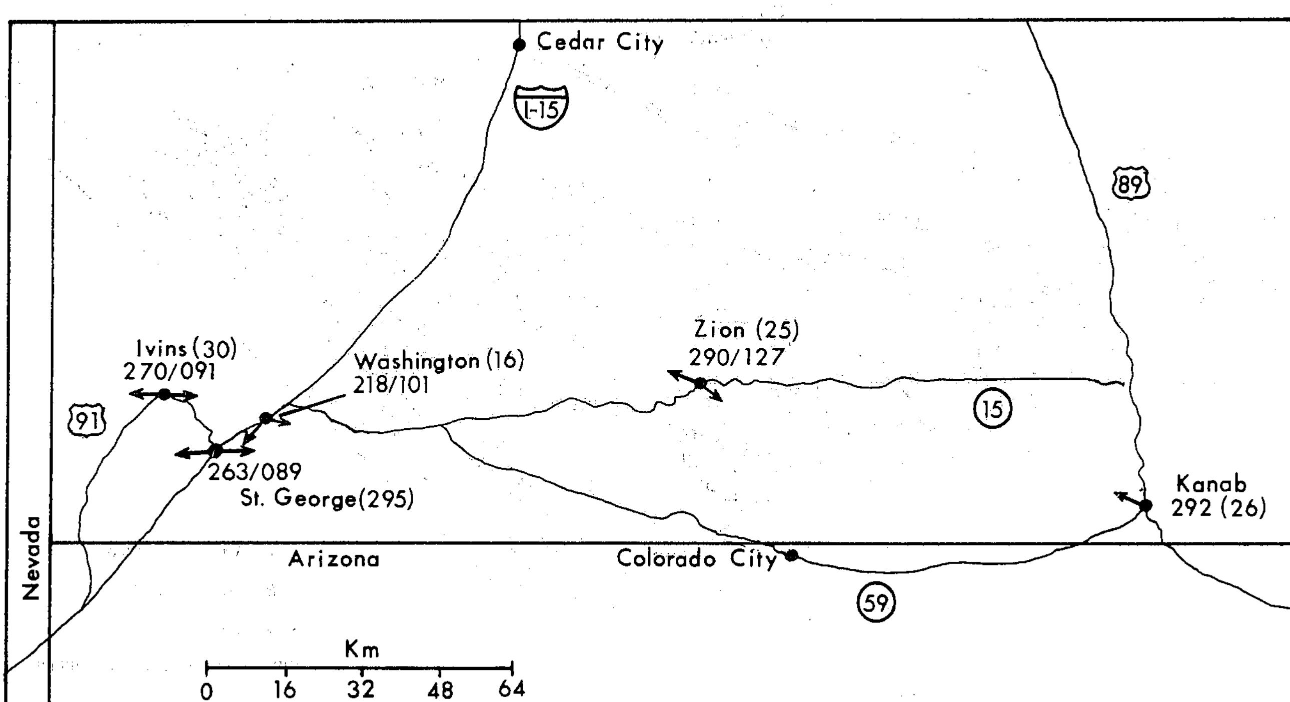

FIGURE 23.–Regional paleocurrent trends.

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