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Contents

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Sedimentary Structures and Their Environmental Significance in the Navajo Sandstone, San Rafael Swell, Utah*

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ABSTRACT.—The Navajo Sandstone is interpreted as an extensive dune field in which groundwater played an important role in development of sedimentary structures, which include horizontal-bedded, cross-bedded, contorted-bedded, and indistinct-bedded sandstone. Horizontal stratification is largely the result of subaqueous deposition in ponds or depressions intermittently filled with water, as demonstrated by the presence of thin sandy limestone and limestone conglomerate beds, straight rib-and-furrow ripple marks, and dinosaur tracks associated with these beds. Cross-lamination is the result of eolian deposition, as indicated by large-scale tangential cross-beds, the presence of ripple marks on the cross-bed surfaces similar to those commonly observed on modern dune surfaces, the clean, well-sorted nature of the sand, and the lack of association of these beds with features characteristic of other environments. Units of contorted- and indistinct-bedded sandstone are interpreted as being the result of repetitive flowage of water-saturated sand during deposition of the Navajo Sandstone. This interpretation is based on several lines of evidence including (1) comparison of types of deformational structures with those observed in wet and dry sand by McKee and others (1971), (2) presence of highly deformed relict laminae in the indistinct-bedded sandstone as seen in X-radiographs, (3) gradational nature of the boundary between zones of contorted and indistinct lamination, (4) large size and relative abundance of these features, and (5) stratigraphic relationships of the zones of contorted and indistinct stratification with other types of stratification within the Navajo Sandstone. Frosted grain surfaces in the Navajo Sandstone are the result of chemical solution and deposition, as is seen with the scanning electron microscope, and appear not to be indicative of depositional environment.

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*A thesis submitted to the Geology Department of Brigham Young University in partial fulfillment of the requirements for the degree Master of Science, April 1973. W. Kenneth Hamblin, thesis chairman.

INTRODUCTION

The Navajo Sandstone is a thick sequence of quartz sandstone present over the western part of the Colorado Plateau. It forms striking cliffs many scores of feet high in some areas, and in other areas it crops out as large domal masses or broad, hummocky expanses of bare rock. The sandstone is characteristically light tan to very light gray, although in some areas it may be reddish. This striking light color and the sheer cliffs that it forms have produced some of the most spectacular scenery in the western part of the Colorado Plateau. It is recognized as an important lithologic unit in four national parks in Utah, in which it forms such features as the sheer cliffs of Zion Canyon and many sheer canyon walls along the Colorado River; it is prominently exposed at Capitol Reef and Arches National Parks. Throughout its occurrence in southern Utah it forms what were named the White Cliffs by early explorers and settlers.

The lithology of the Navajo Sandstone is rather uniform throughout its extent, consisting of clean, well-sorted, fine- to medium-grained quartz sandstone. Many workers have described it as being composed of well-rounded grains, but in the San Rafael Swell there are many horizons characterized by subangular to subrounded grains, throughout which are scattered larger, well-rounded grains.

Perhaps the most spectacular characteristic of the Navajo Sandstone is its cross-stratification, which has led many to consider it as a classic eolian deposit. Cross-bed sets vary in thickness from a few inches to many tens of feet, and cross-stratification ranges from predominantly tabular-planar in the lower part of the formation to mostly trough-type in the upper part. The areal extent of the Navajo Sandstone and its equivalents is large. It is exposed extensively in southern and southeastern Utah, in the Navajo Indian Reservation in northeastern Arizona, on the south flank of the Uinta Mountains in northeastern Utah, and occasionally in the mountain ranges of southwestern and central Utah. It crops out in northern Utah and southwestern Wyoming, where it is called the Nugget Sandstone; and in southern Nevada, where it is exposed in the Wilson Cliffs and in the Valley of Fire, it is called the "Aztec Sandstone."

The Navajo Sandstone achieves a maximum thickness of 2,300 feet at Zion National Park in southwestern Utah. It thins gradually eastward from there across southern Utah to a pinch-out just east of the Utah-Colorado border; southward into Arizona its thickness is unknown because of erosional removal—except in the Navajo Reservation, where it ranges 300 to 800 feet. In the San Rafael Swell the thickness is locally variable but ranges between 600 and 700 feet. The Navajo Sandstone thins eastward along the south flank of the Uinta Mountains, ranging from 1,800 feet in the west to 700 feet in the east near Vernal; from Vernal it thins eastward to a pinch-out in western Colorado. The Nugget Sandstone in central Utah is 1,450 feet thick and decreases to 1,300 feet in northern Utah. In Wyoming it thins eastward and pinches out in the central part of the state. In southern Nevada the original thickness of the Aztec Sandstone is unknown because of thrust-faulted relationships.

In the San Rafael Swell the Navajo Sandstone is underlain by the Kayenta Formation, which consists of sandstone with interbedded thin shale and mudstone and is between 40 and 240 feet thick. The Kayenta in turn is underlain by the Wingate Sandstone, a 400-foot-thick sequence similar in appearance and lithology to the Navajo. The Navajo Sandstone is overlain by the Carmel Formation, a sequence of interbedded limestone, gypsum, and red and green shale which ranges in thickness from 150 to 650 feet (after Wright and Dickey, 1963a).

The age of the Navajo Sandstone is uncertain. The overlying Carmel Formation is Middle Jurassic (Bajocian) in the San Rafael Swell (Sohl, 1965). The Chinle Formation, which underlies the Wingate, has been assigned by most workers as Late Triassic. Thus, the largely unfossiliferous Wingate, Kayenta, and Navajo sandstones fall somewhere between Late Triassic and Middle Jurassic. It has become customary to assign the Navajo Sandstone as Early Jurassic, while the Wingate and Kayenta formations have been called Late Triassic by some workers and Early Jurassic by others (Grater, 1948; Stokes, 1963). In either case, assignment of the Navajo Sandstone as Early Jurassic seems reasonable enough.

Acknowledgments

Appreciation is expressed to Dr. W. K. Hamblin, thesis committee chairman, and to Dr. J. K. Rigby, thesis committee member, of the Brigham Young University Geology Department for their untiring interest and enthusiasm in supervising this work. Their guidance and suggestions aided immeasurably in every aspect of the project. Gratitude is expressed to Union Oil Company of California for providing the financial backing without which a project of this magnitude would have been impossible; also to the author's grandfather, Dr. Clarence Cottam, and uncle, H. Dwayne Stevenson, for added financial support. Appreciation is expressed to the author's father, Ivan L. Sanderson, for the loan of a field vehicle, and to the author's wife for much encouragement and understanding. Several others also have contributed time and energy in serving as field assistants or in offering suggestions, for which appreciation is expressed.

Previous Work

Navajo Sandstone was named by Gregory (1917) for extensive outcrops in the Navajo Indian Reservation in Arizona and Utah. No type area is mentioned except for the "Navajo Country." Concerning the environment of deposition, Gregory (1917) says,

> The significant features of the Navajo Sandstone are uniformity of grain size, cross-bedding, and red color. Specimens taken from ledges 200 miles apart are indistinguishable in the laboratory by texture or composition or color; tangential cross-bedding is persistent. The struc-

> ture and composition suggests aridity and the uninterrupted control of the winds, and the "live dunes" now being formed on the floor of Chinle Valley differ only in color from the "frozen dunes" displayed in the bordering rock walls. There is little doubt that desert conditions prevailed in this region during part of Jurassic time, but the boundaries of this ancient Sahara and its relations to highlands and oceans are uncertain.

Gregory further noted the presence of limestone and limestone-conglomerate interbeds within the formation and suggested that they represent ephemeral lakes or playas associated with periodic flooding, not unusual in desert climates.

Gilluly and Reeside (1928) noted the presence of the thin discontinuous limestone bodies mentioned by Gregory but concluded, as did Gregory, that the dominantly cross-bedded Navajo Sandstone is eolian. Early workers considered the Navajo-Carmel boundary to be an unconformity (Gregory, 1917; and others). Gilluly (1929) studied this contact but failed to see any stratigraphic evidence for calling it an unconformity.

Baker, Dane, and Reeside (1936) made further study of the Navajo-Carmel contact and noted the lack of evidence for calling it an unconformity. They also noted ventifacts at two locations in the San Rafael Swell at the top of the Navajo Sandstone.

Intertonguing relationships between the Navajo and Carmel formations have been studied by several workers. Wright and Dickey (1963b) describe the Thousand Pockets Tongue of the Navajo Sandstone, which wedges northwestward into the Carmel Formation in the area north of Glen Canyon Dam.

Thompson and Stokes (1970) described the Temple Cap Member of the Navajo Sandstone in the Zion Park area, a tongue that also wedges northwestward into the Carmel Formation.

Averitt (1962) described the Shurtz Sandstone Tongue of the Navajo in the Cedar Mountain Quadrangle in Iron County, Utah, which wedges into the underlying Kayenta Formation.

Kiersch (1950) studied the Navajo Sandstone at Buckhorn Wash in the northern part of the San Rafael Swell and described a zone of soft-sediment deformation and zones of apparently structureless sandstone. Poole (1962) measured cross-bed dip orientations in the Navajo Sandstone to determine the direction of sediment dispersal. Jordan (1965) made a regional study of the Navajo and Nugget sandstones, noting the extensive occurrence of horizontal and contorted stratification in addition to the cross-stratification.

Marzolf (1969) divided the Navajo Sandstone of the Colorado Plateau into three subdivisions based on differences in internal sedimentary structures. He noted particularly an abundance of horizontal strata in the lower part, the predominance of trough cross-beds and contorted and "structureless" sandstone beds in the middle part, and an abundance of planar cross-bed sets in the upper part. These three divisions he reports as being recognizable in varying proportions throughout the Navajo exposures in the western Colorado Plateau region.

Hallam (1965) proposed a modified paleogeographic interpretation of the Jurassic System in the western United States. Noting thick marine Lower

Jurassic deposits in Nevada and southern Canada, he concluded that there was no significant land mass in that area at that time.

Stanley, Jordan, and Dott (1971) proposed further modifications of Lower Jurassic paleogeographic interpretation and suggested that the Navajo Sandstone is primarily the result of shallow-marine deposition and coastal dunes.

Throughout the literature most workers consider the Navajo Sandstone to be eolian, but there is not complete agreement concerning its environment of deposition. With interpretations ranging from eolian dunes to shallow-marine deposition, it is apparent that more study is needed to provide evidence in helping to resolve this disagreement.

Purpose and Scope

The Navajo Sandstone has many features not readily apparent in a regional study or in a superficial appraisal. The purpose of this study is to observe and describe the characteristics of the Navajo Sandstone on a local basis and to examine in detail the stratigraphy of zones of variously bedded sandstone within the formation. In considering detailed stratigraphy, it is essential to consider sedimentary structures at all scales.

Methods of Study

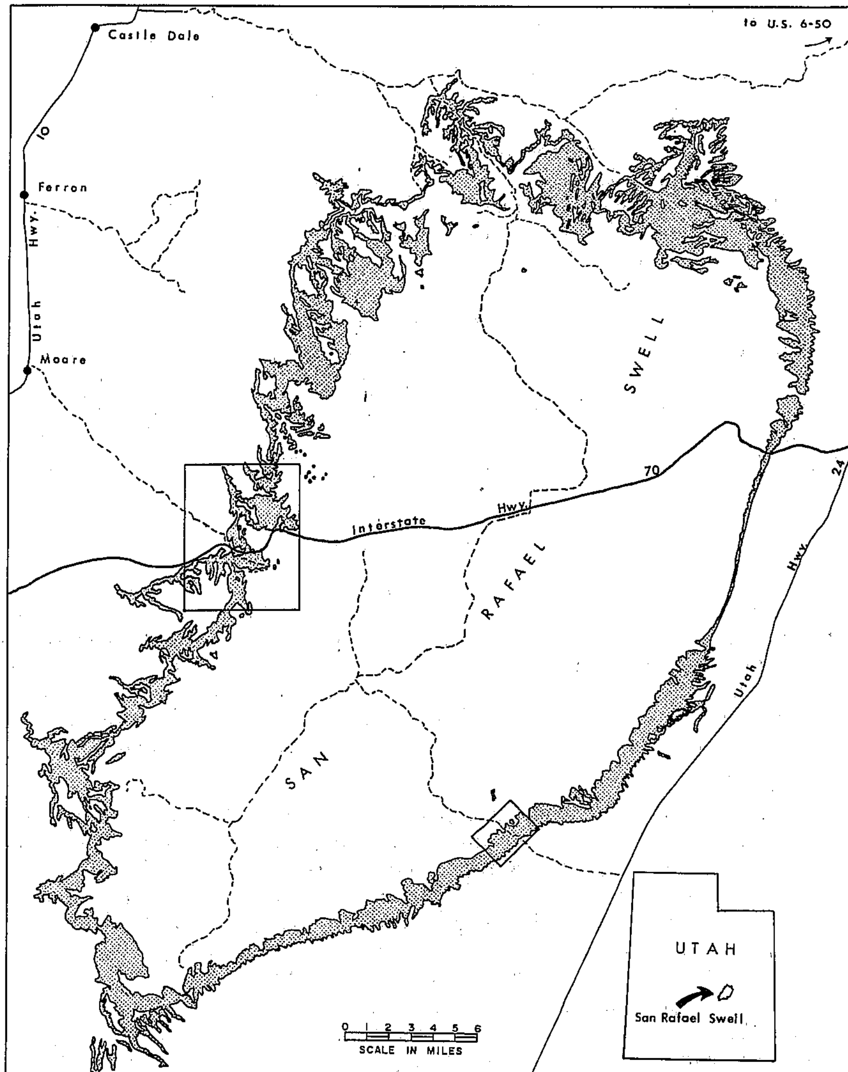
This work comprises a study of sedimentary structures in the Navajo Sandstone ranging in scale from submicroscopic to regional. It involves the use of the scanning electron microscope, petrographic and binocular microscopes, and X-radiographic imagery. It involves the study of outcrops in measured sections, in cross sections constructed from panoramic photographs, in cross-bed dip directions and their variations at different stratigraphic horizons, and in maps constructed from high- and low-altitude aerial photographs.

Field Work

Field work for this study centered in two areas selected for accessibility and quality of exposures. One area is in the vicinity of Temple Mountain on the east flank of the San Rafael Swell and is characterized by broad mappable exposures (Text-fig. 1). Mapping of sedimentary structures in this area was done on low-altitude oblique aerial photographs and on high-altitude aerial photographs procured from the U.S. Geological Survey. Relationships were transferred onto an enlarged topographic base map.

The other area in which field work was centered is on the west flank of the San Rafael Swell where Interstate Highway 70 crosses the Navajo Sandstone outcrop (Text-fig. 1). Stratigraphic sections were measured and cross sections were constructed in Eagle Canyon north of the highway and in Devil's Canyon south of the highway.

Two stratigraphic sections were measured of the Navajo Sandstone for the present study, with emphasis on sedimentary structures, grain size and sorting, porosity, and cross-bed dip directions where applicable. Both sections were measured on the south side of the canyon at the most readily accessible locations. The Devil's Canyon section begins about 50 yards south of the point where Copper Globe Road crosses Devil's Canyon wash. The section traverse continues from that point directly up the slope to the west. The Eagle Canyon section begins at the bottom of the canyon north of the



TEXT-FIGURE 1.—Index map of San Rafael Swell. Two study areas are shown, one on the east flank, at Temple Mountain (see Text-figure 6), and the other on the west flank (see Text-figure 5). Stippled area is Navajo Sandstone outcrop.

extension of Justensen Flat on the north side of Interstate 70. From there it traverses directly up the south side of the canyon to the rim at Justensen Flat, where it is offset to the head of a tributary canyon about a quarter of a mile north of the freeway, and continues from there to the top of the formation directly up the hill westward. Unit numbers of the measured sections have been chiseled deeply into the rock to aid in locating the measured sections.

Both areas are accessible from Interstate 70 by taking Copper Globe Road south from the View Area located at the point of highest elevation along the highway in the San Rafael Swell; Copper Globe Road continues from that point running parallel to the freeway to Justensen Flat. Devil's Canyon is accessible by continuing straight ahead across Justensen Flat on the road that runs parallel to the freeway. The road passes through a wooded area and turns southward across an open area before entering Devil's Canyon. One should not proceed beyond the rim of the canyon without a four-wheel drive vehicle.

Eagle Canyon is accessible by turning north from Copper Globe Road at Justensen Flat and passing through a culvert under the freeway. The road continues northeastward from there and eventually enters Eagle Canyon. This road is not well maintained and should not be attempted without a four-wheel drive vehicle, although with some caution and skill it may be negotiated as far as the northward extension of Justensen Flat. A footpath at this location leads from the road to the rim of the canyon where the measured section traverse emerges.

Variations in grain characteristics were observed in the field with a hand lens; samples were collected at the locations noted on the stratigraphic charts and the grain characteristics were re-evaluated in the laboratory under the binocular microscope.

Panoramic photograph sequences were taken along the north walls of each of the canyons, on which the units of the measured stratigraphic sections were traced laterally and the changes in characteristics noted. Data from these photographs were then transferred to a drafted cross section. Samples were collected throughout the measured sections and in various other locations in both study areas, and these samples were examined in the laboratory using a variety of procedures.

Other observations of the Navajo Sandstone were made in Utah at Thistle Junction, at Arches National Park, and near Kanab.

Laboratory Work

In the laboratory much work was done with the collected samples to determine grain characteristics and bedding features. All of the 35 samples collected were studied under the binocular microscope to determine grain size, rounding, sorting, and porosity. Some samples were photographed using a 35 mm camera attached to one eyepiece of the microscope with an adapter, using a slide projector for a light source. Such photographs present a view of the Navajo Sandstone similar to what may be observed in the field with a hand lens, thus providing for easy comparison.

Thin sections were prepared from several samples selected on the basis of bedding characteristics. Friable sandstones were impregnated with epoxy resin before cutting. "Scotchcast No. 3" electrical resin manufactured by the 3M Company was used because of its low viscosity; when the epoxy resin is heated to 95° C the viscosity is reduced below 100 centipoise. Samples were then submerged in it and placed in a vacuum oven, which maintains the temperature while evacuating the air. Under the vacuum, air in pore spaces came bubbling out, and upon the restoration of atmospheric pressure the epoxy resin was forced into the pore spaces. Curing the samples in an oven heated to 150° C for about 12 hours is necessary to solidify the epoxy resin.

Four samples were studied with the scanning electron microscope. They were disaggregated using a wooden mortar and pestle and were then soaked in dilute (10 percent) acetic acid for 15 minutes to remove calcareous cement and expose grain surfaces. The grains were then mounted with silver cement and coated with gold 150 A thick preparatory to study in the electron microscope. Photographs were taken of the observed grain surfaces using a Polaroid camera built into the microscope.

X-ray work was accomplished using an industrial X-ray device. One-inch-thick slabs of samples representing the various types of stratification were cut using a carpenter's hand saw; use of a liquid-cooled diamond saw would have disaggregated and saturated the samples with water, which adversely affects the X-ray images. Procedures and exposure values used are described by Hamblin (1967). Positive contact prints were made from the X-ray negatives.

RESULTS OF THE STUDY

Measured Stratigraphic Sections

Gross lithology of the sequence as recorded in the measured stratigraphic sections is monotonous. Other features, however, show considerable change. The salient changes in various characteristics follow.

Color

The Navajo Sandstone ranges from dark brown in several thin horizontal-bedded sandstone and sandy limestone beds in the lower part of the section to very light gray in the indistinct-bedded portions. The dominant color, however, is light tan to buff. Occasionally the sandstone is a bright rust red for a few feet immediately above a major bedding plane, where the porosity varies from low below to high above the major bedding plane. For example, see Unit 5, Eagle Canyon section (Text-fig. 2).

Grain Size

Sand grains range in size from very fine to medium (1/16 mm to ½ mm). The lower parts of the sections are more fine grained, while in the upper part the grain size coarsens. In much of the sequence, medium-sized grains are scattered throughout the finer-grained portions. Silt is also present at horizons throughout the Navajo Sandstone, particularly in the lower part. Plate 1 shows that finer grains, which range in size from fine sand to silt, are usually concentrated along stratification planes.

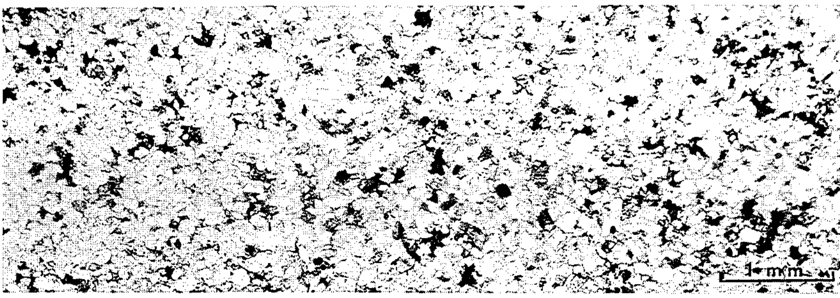
EXPLANATION OF PLATE 1
PHOTOMICROGRAPHS OF NAVAJO SANDSTONE

FIG. 1.—Indistinct-bedded sandstone, fine to very fine grained. Lamination appears absent. From upper part of formation in Temple Mountain area.

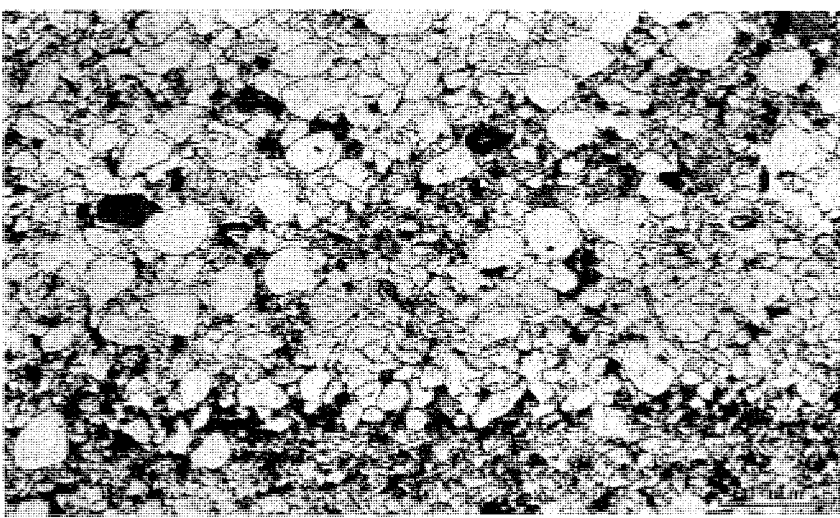
FIG. 2.—Boundary between two sets of cross-strata. Silty laminae are present between beds. Note also well-rounded larger grains scattered throughout smaller subangular to subrounded grains. From 40-foot mark in Unit 8, Devil's Canyon measured section.

FIG. 3.—Horizontal-stratified sandstone. Silty laminae are present between beds. From 35-foot mark of Unit 3, Devil's Canyon measured section.

PLATE 1



1



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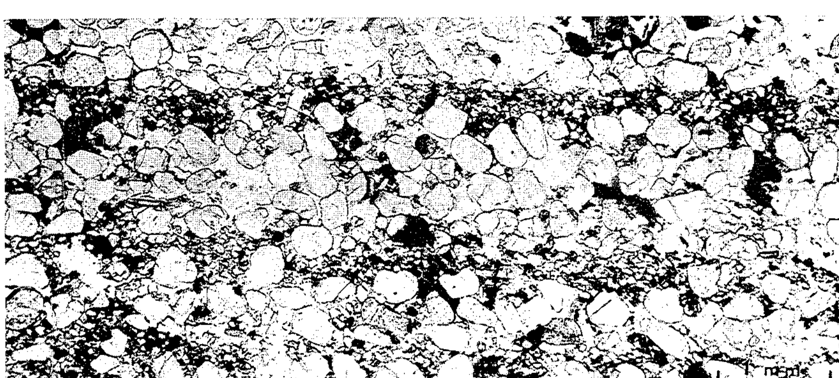
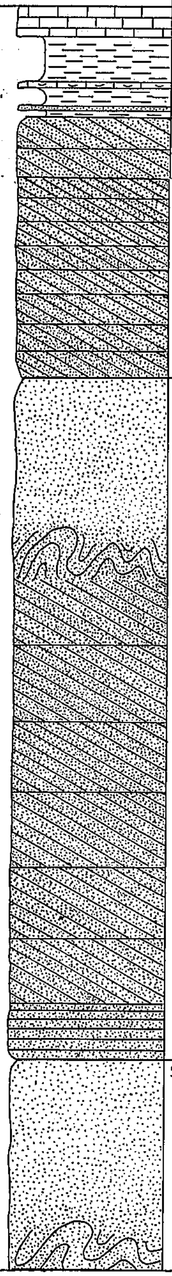


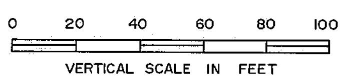
3

UTAH: Emery County, Stinking Spring Creek 2 SW Quadrangle

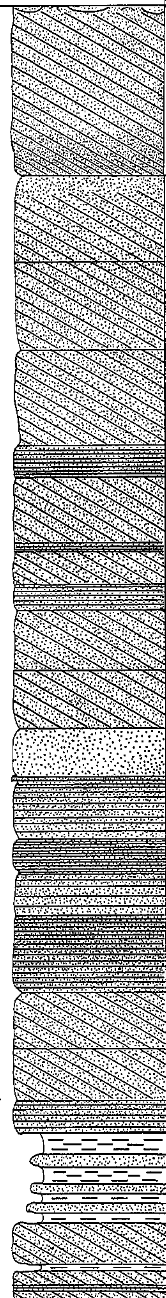
EAGLE CANYON

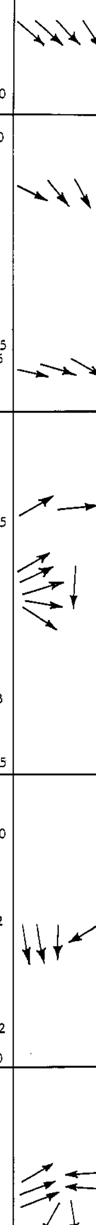


FORMATION	UNIT	FOOTAGE	LITHOLOGY	SAMPLE	POROSITY %	CROSSBED DIP DIRECTIONS
CARMEL	8	34	Interbedded shales, limestones, and sandstone. Sandstone bed 1 foot thick 3 feet from base of unit contains abundant burrows. Limestones tan-brown, medium to platy bedded. Lower limestone contains abundant bivalve shells; upper limestone contains abundant oscillation ripple marks. Average of 6 strike direction measurements on ripple marks is 248°, with measurements between 254° and 239°. Shales gray-brown, ranging in thickness from 2 to 15 feet. Unit ends at top of hill.	X		
NAVAJO	7	83	Sandstone, light tan-gray to tan-orange, fine to medium grained (bimodal); fine grains subangular to subround; medium grains well rounded and frosted; sorting very good to excellent. Porosity 30%; entire unit consists of trough-crossbedded sandstone with most sets of crossbeds about 5 feet thick. Occasional discontinuous zones of brown concretions are observed. Upper 12 feet becomes rust-brown in color immediately underlying Carmel beds of similar color.	X X	30 30	
	6	213	Lower 17 feet: Sandstone, dark tan, very fine to medium grained (bimodal); very fine grains subangular and medium grains spherical and frosted; sorting fair to good, porosity 1%, much silt; bedding horizontal. Upper 196 feet: Sandstone, light tan to buff, fine to medium grained, subangular to well rounded, sorting very good to excellent, porosity 20% to 30%. Upper 63 feet of bedding is indistinct, underlain by 133 feet of crossbedded sandstone; crossbed sets are variable in thickness from 2 to 50 feet and are mostly trough-type with some tabular sets. Transition at 150 feet from crossbedded to indistinct bedding is characterized by some contorted bedding; this contorted bedding becomes more prominent laterally.	X X X	30 20 1	
	5	119	Sandstone, vivid rust-red at base of unit, grading upward within 5 feet to alternating bands of orange and tan; further grades upward to light tan, and to light buff near top of unit; medium grained at base of unit, becoming bimodal upward with very fine and medium grains; grains of medium size are well rounded and frosted, while very fine grains are subangular to subround and not frosted. Sorting excellent at base, decreasing to very good upward with introduction of very fine sand grains; porosity ranges from 30% at base of unit to 15% at top. Lower 50 feet of unit crossbedded, consisting of a single set bounded at base by a major bedding plane; upper part of unit is indistinct-bedded with some contorted beds transitional between crossbedded and indistinct-bedded portions.	X	15	



TEXT-FIGURE 2a.—Measured stratigraphic section, upper part.



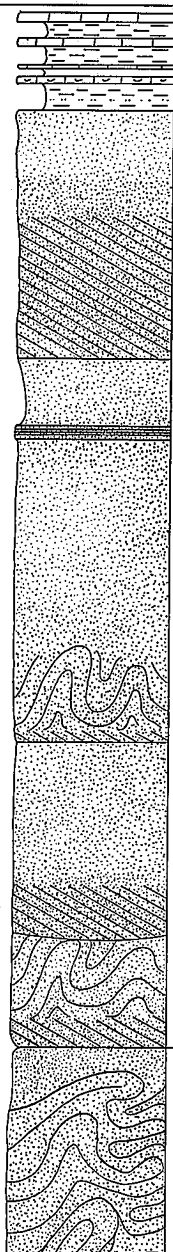


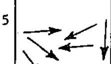
FORMATION	UNIT	FOOTAGE	LITHOLOGY	SAMPLE	POROSITY %	CROSSBED DIP DIRECTIONS
NAVAJO				X	30	
NAVAJO	4	95	Lower 10 feet: Sandstone, brown, medium-grained, subround, sorting good, porosity near zero due to a high proportion of calcareous cement and silt. Horizontally bedded; possible burrowing observed. Calcareous mud clasts forming intraformational conglomerate observed at one location. A significant dip slope which forms Justensen Flats and Secret Mesa in this area is supported by this horizon of relatively resistant rock. Upper 85 feet: Sandstone, very light gray-buff, fine-grained, subangular to subround, sorting excellent; porosity 25% at 10 feet, grading upward to near zero at top of unit. Crossbedded, in planar sets 1 to 4 feet thick near base, grading to thicker sets upward. Bedding becomes indistinct a few feet below top of unit.	X X X X	0 25 5	
NAVAJO	3	113	Sandstone, very light gray to almost white, fine to medium-grained, subround to well-rounded, sorting good (appears bimodal); porosity 3% to 25%. Lower 35 feet horizontally-bedded, sometimes indistinct, with one brown sandstone bed 1 foot thick at 19 feet; overlain by 37 feet of crossbedded sandstone. Upper 41 feet of unit consists of horizontal and occasionally crossbedded sandstones with several interspersed zones of brown concretions.	X	25 3 25	
NAVAJO	2	92	Sandstone, light tan, fine-grained, subround to subangular; sorting excellent; porosity 12%; grains frosted. Lower 10 feet of unit horizontally bedded, intensely burrowed, highly silty; overlain by 35-foot crossbedded sequence, with sets 1 to 3 feet in thickness. Crossbeds appear to be planar. At 45 feet, bedding becomes horizontal; porosity fluctuates in this horizontally-bedded sequence between 20% and near zero, in response to filling of pore space at certain horizons with calcareous cement. Upper 10 feet: sandstone, brown, very fine grained, subangular to subround, sorting good, porosity zero, horizontally-bedded. Some current flow markings observed at base of unit, indicating current direction at 301°.	X X X	0 20 2 12 0	
KAYENTA	1	70	Interbedded sandstones and mudstones. Sandstones light buff, fine grained, subangular to subround; sorting good, porosity 3%, silt content 15%; some burrowing observed. Crossbed sets 6 to 8 inches thick; cosets up to 2 feet thick. Sandstone layers 3 to 13 feet thick; mudstones up to 17 feet thick. Mudstones thin-laminated, light tan-gray, with interbedded thin sandstone layers. Underside of sandstone beds commonly bear mud crack casts.	X	3	

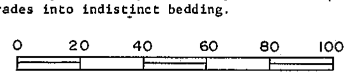
TEXT-FIGURE 2b.—Measured stratigraphic section, lower part.

UTAH: Emery County, Stinking Spring Creek 2 SW Quadrangle.

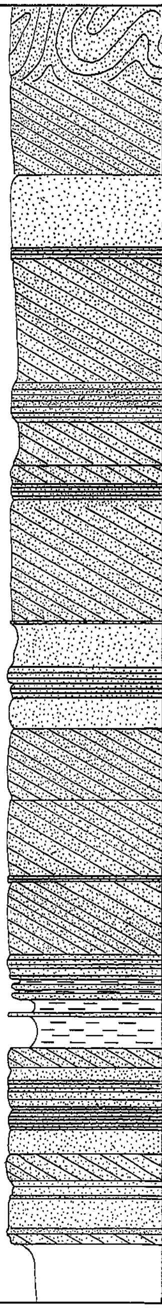
DEVIL'S CANYON



FORMATION	UNIT	FOOTAGE	LITHOLOGY	SAMPLE	POROSITY %	CROSSBED DIP DIRECTIONS
CARMEL	9	29	Interbedded sandy limestones and shales. Limestones brown, contain abundant bivalve shells, and range in thickness from 1 to 3 feet; shales up to 7 feet thick. Abundant ripple marks observed in limestone layers. Unit ends at top of hill.			
NAVAJO	8	294	Sandstone, light tan to buff, medium-grained, subround to well-rounded, sorting excellent, porosity 25% at maximum. Bedding varied throughout: lower 10 feet trough-crossbedded, overlain by 25 feet of contorted bedding. At 35 feet, a 15-foot layer of trough cross-beds is observed, which appears incised into contorted bedding below; at 50 feet, a 45-foot sequence of indistinct bedding is observed; at 95 feet, this is overlain by 25 feet of trough crossbeds which grade upward to contorted bedding; this is overlain at 120 feet by indistinct bedding 70 feet thick. At 190 feet a 5-foot brown sandstone bed, horizontally laminated, occurs; this grades upward into trough crossbeds. This crossbedded layer is 45 feet thick, and grades upward to indistinct bedding at 260 feet; indistinct bedding continues to top of unit. Porosity varies from a maximum of 25% in crossbedded sandstone to 10-15% in contorted bedding and approaches zero in indistinct bedding.	X	25	
				X	25	
				X	28	
	7	123	Sandstone, tan, fine-to-medium grained, subround to well-rounded, sorting good to excellent, porosity at base 25%, decreasing upward to near zero. Sand grains frosted; lower 25 feet of unit crossbedded, consisting of trough crossbeds in sets 10 - 20 feet thick; grades upward to large-scale contorted bedding, which continues upward nearly to the top of the unit, where it grades into indistinct bedding.			

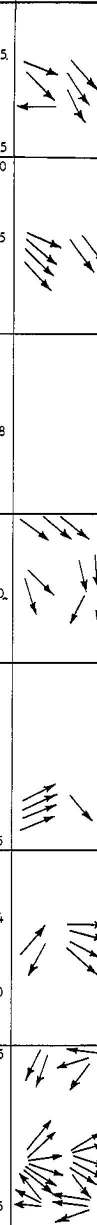


TEXT-FIGURE 3a.—Measured stratigraphic section, upper part.



FORMATION	UNIT	FOOTAGE	LITHOLOGY	SAMPLE	POROSITY %
NAVAJO				X	15, 25
NAVAJO	6	65	Sandstone, light buff, fine to very fine grained, subangular to subround, with occasional well-rounded medium-sized frosted grains; sorting excellent, porosity 15%, slightly silty; contains zones of numerous pea-sized spherical concretions. Lower part crossbedded; single set of crossbeds 38 feet thick, overlain by 3-foot horizontally-bedded layer with occasional zones of very low-angle crossbedding. Upper 24 feet of unit appears massive. This unit thins abruptly northwestward.	X, X	10, 15
NAVAJO	5	26	Lower 12 feet: Sandstone, light gray-buff, fine to very fine grained, subangular to subround, sorting excellent, porosity 28%, crossbedded, somewhat indistinctly. Upper part horizontally-bedded light brown sandstone with abundant irregularly shaped brown concretions in alternating layers. The horizontally-bedded slope-forming upper part forms Justensen Flats, an extensive dip slope in this area. Abundant 3-toed dinosaur tracks observed in this upper part in the bottom of Devil's Canyon.	X	28
NAVAJO	4	49	Sandstone, very light gray, fine to very fine grained, subround to well-rounded, sorting excellent, porosity 20%, crossbedded; crossbed sets up to 5 feet thick, trough-type. At 35 feet, a 6-foot sequence of alternating brown sandstone beds and horizontal and massive bedded layers; occasional low-angle crossbeds present. Overlain by crossbedded sandstone, as below, to top of unit.		20
NAVAJO	3	56	Sandstone, light tan, fine-to-medium grained, subangular to subround, sorting good to excellent, porosity 15%, some larger grains frosted. Lower 21 feet crossbedded; upper part horizontally-bedded or massive, with a 4-foot brown sandstone bed at 35 feet and a 1-foot brown sandy limestone bed at top of unit. This bed forms a splintery ledge. Some probable 3-toed dinosaur tracks about 6 inches long and some possible worm or crawling insect trails observed at 35 feet on top of brown sandstone bed.	X, X	1, 15
NAVAJO	2	78	Lower 25 feet: mostly covered; inferred siltstone or shale with a few thin sandstone beds. Lower contact of Navajo Sandstone at 25 feet. Upper Part: Sandstone, very light gray, fine-grained, subround to subangular, sorting good, porosity 3%, crossbedded, with occasional thin horizontal-bedded layers between major bedding planes. Crossbed sets up to 10 feet thick. Bedding planes delineated by thin clayey zones within sand. Some sand grains appear frosted. Occasional cusp-type ripple marks observed.	X, X, X, X	24, 3, 5, 10
KAYENTA	1	62	Sandstone in beds 3 to 20 feet thick with abundant layers of brown calcareous-cemented sandstone ranging in thickness from a few inches to 3 feet, with a few interbedded thin siltstones and shales. Sandstones light buff, fine grained, subangular to subround, sorting excellent, porosity 25%; crossbedded in upper 5 feet of unit. Brown calcareous-cemented sandstones dark to light brown, fine-grained, subangular to subround, sorting good to excellent, porosity 0 to 15%, horizontally bedded. Below Unit 1: Covered.	X, X, X	25, 25, 0-15

CROSSBED DIP DIRECTIONS



TEXT-FIGURE 3b.—Measured stratigraphic section, lower part.

Grain Rounding

Roundness of a grain appears to be closely related to its size. In the sandstones with two sizes of grains the larger grains are well rounded to subrounded while the smaller grains are typically subangular to subrounded (Plate 1). In the medium-grained sandstone near the top of the sequence the grains are generally well rounded. Frosted surfaces also appear more conspicuously on the well rounded, medium-sized grains, although frosting is probably as common on the smaller, more angular grains.

Grain Sorting

The Navajo Sandstone is well sorted throughout. However, the presence of two distinct sizes of sand grain at some horizons influences the degree of sorting, as does the presence of, silt. Samples of sandstone that contain essentially one size of grains are classified as having excellent sorting; those with two grain sizes or with abundant silt are classified as having very good sorting. In general, sorting increases upward in the Navajo Sandstone.

Porosity

Porosity in the Navajo Sandstone ranges from a maximum of 30 percent to near zero. Cross-bedded and contorted-bedded sandstone are of higher porosity, generally, than are horizontal and indistinct-bedded sandstone. Calcareous cement, conspicuous at particular horizons throughout the section and particularly significant in most of the indistinct-bedded sequences, seems to account for most of the low porosity; silt, which is more abundant in the horizontal-bedded sandstone, is responsible for additional reduction. Cement in zones of high porosity is often iron oxide that has affected the color of the rock. Some highly porous sandstones, however, are almost white and show little evidence of loss of pore space through cementing.

Stratification

Although the Navajo Sandstone is predominantly cross-stratified, there are some significant variations. Strata in the Navajo Sandstone are delineated by differences in texture. Thin laminae of silt are often present at bedding planes, both in cross-bedded and horizontal-bedded sandstone, and smaller but distinct differences in grain size between strata are common in cross-bedded sandstone (Pl. 1, figs. 2, 3). Silty laminae seem to have more iron cement than do the surrounding coarser-grained laminae, producing a somewhat darker horizon readily visible in the outcrop. These differences in grain size and cement have a pronounced effect on the resistance to erosion of the rock, such that the laminations are often carved into bold relief by erosion.

Bedding is of four types: cross-stratification, horizontal stratification, contorted strata, and indistinct stratification. Although a discussion of the proportions of the different types of stratification might seem appropriate in considering the measured stratigraphic sections, bedding types change rapidly laterally and are more easily treated in a discussion of cross sections.

Cross-stratification.—Long considered the dominant characteristic of the Navajo Sandstone, cross-stratification is of two types in the stratigraphic sections. In the lower part of the formation, tabular-planar cross-bed sets alternate with horizontal-bedded sandstone. In the upper part of the formation trough-type cross-stratification dominates and is often associated with contorted and indistinct stratification. Sets of cross-beds range in thickness from a few inches to

50 feet. Tabular-planar sets range from 10 to 30 feet thick, while trough sets are characteristically a few inches to 20 feet thick. Occasional thicker sets are observed in both styles.

Horizontal stratification.—Horizontal strata, present in two lithologies, are concentrated in the lower part of the Navajo Sandstone. Sandstone similar in grain size and sorting to the typical cross-bedded portions of the Navajo occurs in horizontal-bedded layers that range from a few inches to 20 feet thick. The other lithology, called "brown beds" in the present study, has abundant silt and iron oxide and is medium to dark brown. Often the brown beds show a high proportion of calcite, sufficient to justify classifying the rock as sandy limestone. These beds range from a few inches to 6 feet thick, with most such beds about 2 feet thick. The brown color is from iron oxide that appears to have been carried into the sandstone by groundwater and preferentially deposited in these zones of high silt proportion. These brown beds often contain ripple marks, dinosaur tracks, intraformational limestone conglomerates, and burrows. The geomorphological significance of the brown beds is subtle but significant. Because they are relatively resistant to erosion, these beds often form the caprock of mesas, beehive-shaped domes, and monuments. A significant brown-bed horizon forms Justensen Flat and Secret Mesa and has no doubt caused some confusion regarding the location of the base of the Navajo Sandstone in this area.

Contorted strata.—Zones of contorted beds are a significant feature of the Navajo Sandstone. Far from being restricted to the small-scale disturbances characteristic of lee-side laminae of eolian dunes as described by McKee, Douglass, and Rittenhouse (1971), these features are often over 100 feet in amplitude. These features are generally compressional and consist of elaborate convolutions, high-angle asymmetrical folds, "drag" folds, and flame structures. They occur in irregular zones that often extend laterally for thousands of feet, with upper and lower boundaries forming irregular surfaces that rise and fall abruptly in stratigraphic position but without interfering with major bedding planes. The lower boundary of a contorted zone is generally above cross-bedded sandstone. The boundary is transitional, with strata in the cross-bedded portion becoming folded and warped upon extension into the contorted zone. Beds do not lose their integrity when distorted but remain as discrete traceable features for some distance into the contorted zone. There is seldom any evidence of truncation or displacement at the lower boundary of contorted zones. Although the boundary is transitional, it can usually be located to within an inch or two in the outcrop. By their nature, cross-bedded sands readily show distortion, no matter how slight, because where the extremely regular smooth curves of the crossbeds are deflected, they describe a surface where the distortion loses effect.

Upper boundaries of contorted zones are usually gradational from contorted to indistinct stratification. Where there is no overlying indistinct stratification, convolutions are truncated abruptly by a major horizontal bedding plane. This upper boundary was never seen to be a transition from contorted-bedded to cross-bedded sandstone. Occasionally, contorted zones have disturbed brown beds. When this has happened, brown beds have been broken into blocks and carried upward by the intruding sand to form flame structures and other features. In Plate 2, figure 2, flame structures formed from a distorted brown bed are observed on the wall of Devil's Canyon. In some

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EXPLANATION OF PLATE 2

CONTORTED STRATA IN THE NAVAJO SANDSTONE

FIG. 1.—Rippled cross-bed surface overturned in asymmetrical fold.

FIG. 2.—Flame structures formed of disturbed brown bed. Contorted zone grades upward to indistinct stratification and is bounded below by undisturbed cross-strata.

notable cases, blocks of brown sandstone from 2 to 15 feet long are carried upward as much as 100 feet from their original position in the brown bed to form roughly outlined domes that define the extent of the upward displacement of the sand.

In the study of these contorted features, considerable effort was devoted to determining that they really are bedding and not liesegang banding. Samples were collected from various localities within the study areas; thin sections were prepared; and X-radiographic images were prepared from slabs cut from the sandstone. Samples of known liesegang banding were collected from the Shinarump Member of the Chinle Formation (Triassic) at the Virgin Anticline, Washington County, Utah; similar X-ray work was done on them, and the results were compared with those from the Navajo Sandstone. Contorted beds have the same characteristics of bedding as do the horizontal and cross-bedded portions of the Navajo Sandstone. Thin-section studies show the contorted beds do have variations in grain size between laminae identical to the other types of beds. X-ray work details the contorted strata such that microcross-lamination can be recognized. Shear planes can be seen in some samples that offset the beds, demonstrating that movement has taken place. In Plate 3, contorted and indistinct stratifications are seen in great detail and can be recognized as true bedding that has been deformed. Rippled surfaces on cross-bed planes such as are seen in Plate 2, figure 1 become overturned upon extension into a zone of contortion, demonstrating that it is true bedding.

Comparison of X-radiographs of contorted Navajo Sandstone with samples displaying liesegang banding gives further proof that it is true contorted stratification. The appearance of liesegang banding in X-radiographs is fundamentally different from that of true stratification. Banding is characteristically diffuse, wavy, discontinuous laterally, and quite blotchy, showing great variation in X-ray penetration at different areas on the slab. Stratification, by contrast, is sharply defined, permitting easy recognition of small-scale cross-lamination and other common features, and is more uniformly penetrated by X-rays. In the X-radiographs showing banding, the original stratification is readily observed, often occurring at widely divergent angles from the banding. Strata, though, are somewhat obscured by the banding. The contorted Navajo Sandstone samples show easily recognizable bedding characteristics and lack features diagnostic of liesegang banding. Previous workers have observed these deformational structures, including Marzolf (1969), Jordan (1965), and Kiersch (1950).

Indistinct stratification.—In surface exposures, indistinct-bedded sandstone appears to lack bedding of any kind, although grain characteristics are not different from those of the cross-bedded sandstones. Kiersch (1950) recognized the indistinct stratification and thought that it represented case hardening under the effect of weathering. Marzolf (1969) recognized it, considering it to be a primary sedimentary structure whose interpretation is environmentally significant, but he made no attempt to explain its origin. As can be seen in Plate 3, figure 3, relict stratification that has been highly deformed and dislocated is readily visible in X-ray images of the indistinct stratification. This suggests that the sands at one time were cross-bedded or horizontal-bedded and subsequently were subjected to flowage that virtually destroyed identifiable bedding. Thus, contorted laminae are gradational between undisturbed and indistinct stratification, the difference between the contorted and indistinct beds being one simply of degree of deformation. Marzolf (1969) referred to these rocks as "structureless sandstone"; but because they are not really structureless, they are here described as having "indistinct" stratification.

Zones of indistinct stratification are usually transitionally bounded below by zones of contorted laminae. Occasionally there is little or no contorted stratification beneath the indistinct-bedded zones, and then they are underlain by cross-bedded sandstone. When this occurs, the contact is invariably sharp and bears parallel laminations not related to bedding, suggesting that flowage has occurred. The upper boundary of the zones of indistinct stratification is usually a major bedding plane, which in turn is overlain by undisturbed cross-bedded sandstone.

Indistinct stratification is similar to contorted stratification, the main difference being only the degree of flowage. Thus, when the environmental significance of these beds is considered, they must be treated together.

The style of contorted laminae compares very closely with deformational structures produced in wetted and water-saturated sand in the laboratory by McKee, Douglass, and Rittenhouse (1971). Although there is a great difference in scale between the laboratory models and the features in the Navajo Sandstone, the similarity is great enough to warrant the interpretation that these features in the Navajo Sandstone were formed in water-saturated sand. The features observed most commonly in the Navajo Sandstone and produced by McKee and his associates in wetted and water-saturated sand are high-angle asymmetrical folds, warps, "drag" folds, flames, fade-out laminae, and occasional rotated plates and blocks. Other features more common in dry sand are seldom observed in the Navajo Sandstone.

Cross-bed Dip Directions

Cross-bed dip directions were measured wherever present in the stratigraphic sections, were corrected for regional tilt by applying the method described by Fisher (1938), and were plotted onto the stratigraphic charts (Text-figs. 2, 3) in separate columns to allow for easy comparison. Each arrow on the charts represents a separate reading taken in the field. Minor variations in dip directions, noted at practically every horizon, are significant enough to facilitate stratigraphic correlation on this basis. Thus, it can be noted that Unit 7 at the top of the Navajo Sandsone in Eagle Canyon (Text-fig. 2) is not present in Devil's Canyon (Text-fig. 3). This absence accounts for the difference in overall thickness between the two sections.

The prevalent cross-bed dip direction is to the south-southeast, as can be observed in the measured stratigraphic sections and as is described by Poole

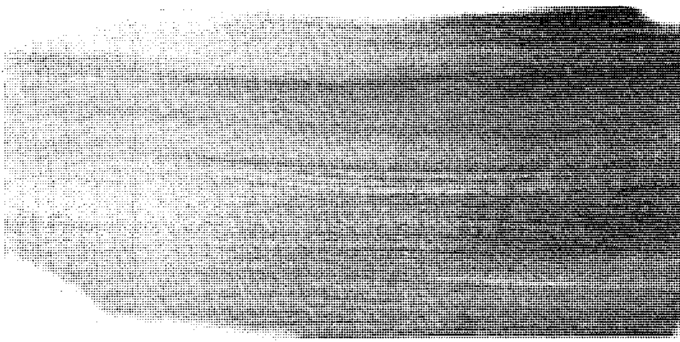
EXPLANATION OF PLATE 3
POSITIVE PRINTS OF X-RADIOGRAPHS OF STRATIFICATION IN THE NAVAJO SANDSTONE

FIG. 1.—Cross-bedded sandstone. Microcross-laminations are easily recognized. Sample collected from limb of large-scale contorted bedding fold.

FIG. 2.—Contorted-bedded sandstone. Overthrusts displace laminae in several places. Note incipient zones of indistinct-bedded sandstone associated with overthrusts.

FIG. 3.—Indistinct-bedded sandstone. Numerous shear zones offset relict stratification. Black spots are calcite-rich nodules, relatively opaque to X-rays.

PLATE 3



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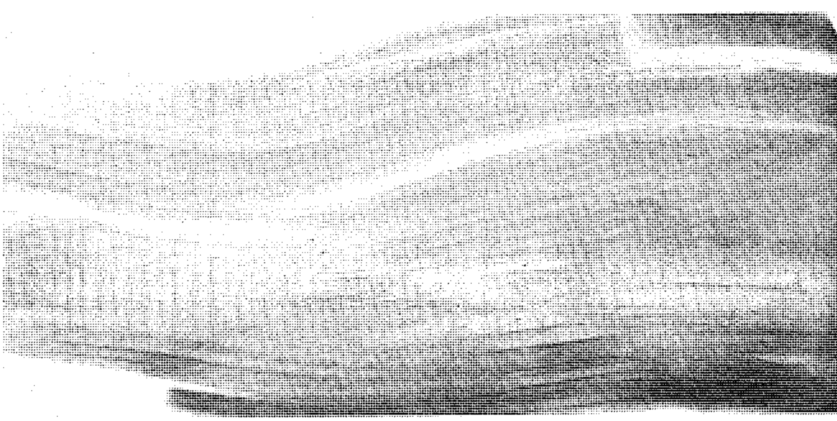

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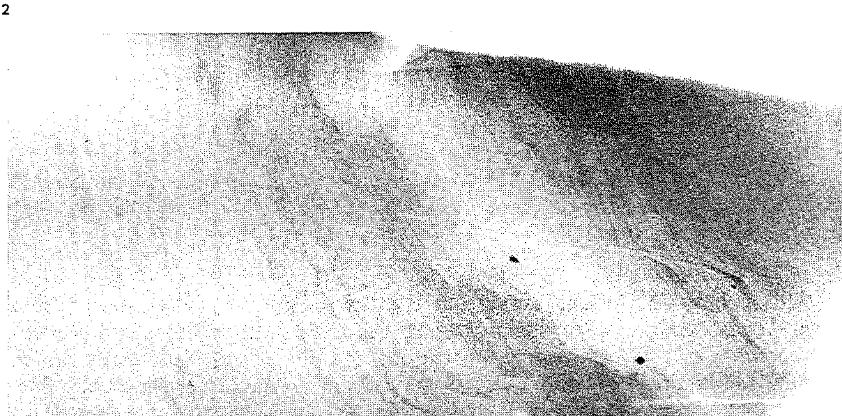

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(1962). Cross-bed dips in the underlying Kayenta Formation are bimodal, suggesting a difference in depositional environment between the two formations. (It is generally accepted that the Kayenta Formation is fluvial.) There appears, however, to be some overlapping of environments in the upper part of the Kayenta.

Other Features

Ripple marks of two types are found in the Navajo Sandstone. Cusp-type ripples, characteristic of a sand-laden stream, are found at a few locations near the base of the formation. Asymmetry of the ripples indicates a westward-moving current.

Straight rib-and-furrow ripples are observed in two lithologies, one in horizontally bedded brown beds, and the other on cross-bed surfaces suggestive of rippling commonly observed on the surfaces of modern dunes. The ripples in horizontal beds are of small wavelength (about one inch), are symmetrical, and are apparently produced in shallow standing water by wave action; these ripple marks are generally oriented with crests perpendicular to the average direction of sediment transport (Pl. 4, fig. 4). The ripples on cross-bed surfaces are of larger amplitude (about 2 inches) and are asymmetrical (Pl. 2, fig. 1).

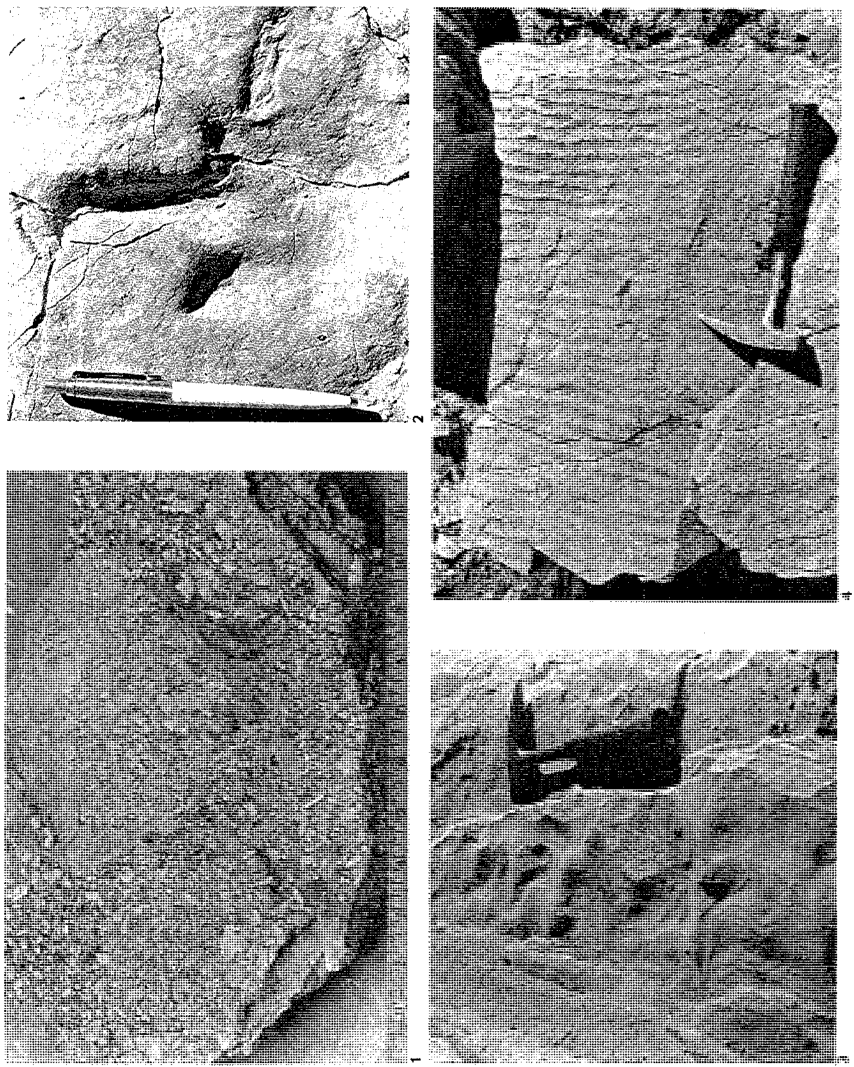
Dinosaur tracks are observed at several horizons in the Navajo Sandstone, predominantly on the surfaces of brown beds. As seen in Plate 4, figure 2, these tracks are generally 5 or 6 inches long and are three-toed with the middle toe longer than the other two, which is characteristic of carnivorous dinosaurs. Jordan (1965) reports similar tracks on cross-bed surfaces; none were observed on cross-beds in this area, however.

Intraformational limestone conglomerate has been reported in the Navajo Sandstone by Gregory (1917) and others. One such occurrence is in the Eagle Canyon stratigraphic section at the Justensen Flat horizon. The conglomerate is composed of rip-up clasts of limestone, as can be seen on Plate 4, figure 1. The limestone conglomerate is indicative of shallow-water deposition followed by dessication, formation of rolled-up mud cracks, rewetting, and reworking before final burial.

Burrows have been noted at several horizons in the lower part of the formation and in thin sandstone beds in the basal Carmel Formation. The most common type consists of apparent irregularly oriented straight or slightly curved tubules that are abundant where present. The tubules are 2 to 4 mm in diameter and are usually about 5 cm long. Burrows vaguely similar to *Ophiomorpha* occur in the basal Navajo Sandstone in the Eagle Canyon section. These consist of horizontal, crescent-shaped tubules 1 cm in diameter and up to 15 cm long and are tapered at both ends. The walls of the burrows resemble those of *Ophiomorpha* in having their outer surface ornamented with wartlike protuberances, but differ in being thinner and having inner surfaces that are not smooth.

Overall Thickness

Although most workers agree that the thickness of the Navajo Sandstone is far from constant even locally, there are complications that deserve consideration. On the east flank of the San Rafael Swell, especially in the Temple Mountain area, the Navajo Sandstone is extensively jointed. Some of the joints are offset only a few inches, but others have developed into faults that can be recognized when the type of bedding on either side is



EXPLANATION OF PLATE 4
FEATURES ASSOCIATED WITH HORIZONTAL STRATA

FIG. 1.—Limestone conglomerate. From lower 10 feet of Unit 4, Eagle Canyon measured section.

FIG. 2.—Three-toed dinosaur footprint. From upper 5 feet of unit 5, Devil's Canyon measured section.

FIG. 3.—Cusp-type current ripple marks. From basal Navajo Sandstone, lower 5 feet of Unit 2, Devil's Canyon measured section. Point of pick shows current direction.

FIG. 4.—Oscillation ripple marks with 1-inch wavelength. From upper 5 feet of Unit 5, Devil's Canyon measured section.

considered. Displacement of each fault is difficult to determine; a section measured across these faults without correcting for their displacement might be up to 100 feet short of the true thickness.

The lower boundary of the Navajo Sandstone has been picked at different horizons by different workers. The Geologic Map of Utah (Stokes and Hintze, 1964) locates the basal Navajo Sandstone contact above the Justensen Flat horizon in the western part of the San Rafael Swell. Horizontal beds assigned to the Navajo Sandstone in the present study were assigned to the Kayenta Formation on the Geologic Map of Utah in this part of the San Rafael Swell, and Wright and Dickey (1963a) evidently picked the contact at this point also, assigning the Navajo Sandstone a thickness ranging from 440 to 540 feet in this area.

There are several reasons for picking the lower Navajo contact considerably lower in the present study. Marzolf (1969) divided the Navajo Sandstone into three units based on the predominance of various types of stratification recognizable in varying proportions throughout the region. The lowermost is horizontal and cross-bedded, the middle is contorted and indistinct-bedded, and the uppermost is largely planar cross-bedded sandstone. These three divisions are readily recognizable on the west flank of the San Rafael Swell and in the Temple Mountain area. Picking the contact at the Justensen Flat horizon excludes Marzolf's lower subdivision. This lower subdivision has been included in the Navajo Sandstone as shown on the state map in the Temple Mountain area. In the two measured stratigraphic sections and in nearby outcrops, the major significant lithologic change occurs where the shales are no longer present in the sequence, considerably below the Justensen Flat horizon. This occurrence is more easily recognizable in the field and in well logging and is thus designated as the base of the Navajo Sandstone. Further, this shaly horizon is noted as a significant change in cross-bed dip direction values, suggesting a change in depositional environment.

The Navajo Sandstone is thus 715 feet thick in Eagle Canyon and 666 feet thick in Devil's Canyon where the top unit is absent.

Cross Sections

Two cross sections were constructed, one of Eagle Canyon and the other of Devil's Canyon (Pl. 6). Lithologic units of the stratigraphic sections were traced laterally on the north walls of the canyons and plotted on enlarged panoramic photographs. Cross sections were then constructed from the data plotted on the photographs, with lateral control being established by reference to points on the topographic quadrangle maps of the area. Vertical control was established by the measured stratigraphic sections and was carried laterally at constant values along major bedding planes unless physical observations indicated otherwise.

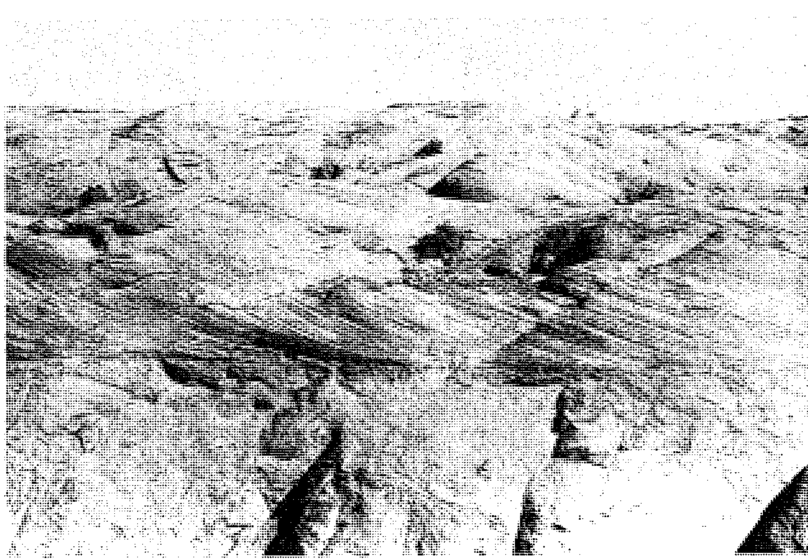
As has been mentioned previously, the lateral changes in bedding type are sudden and varied between major bedding planes; thus, a stratigraphic section is of limited value in describing the Navajo Sandstone. A cross section, however, shows lateral changes in detail and has the advantage that proportions of stratification types can be determined by point-counting the drafted cross section. Each intersection of a superimposed grid was considered a point to be counted, and the number of such points falling within zones of each type of bedding was tallied and calculated on a percentage basis.

TABLE 1
PERCENTAGE OF TYPES OF BEDDING
IN THE EAGLE CANYON AND DEVIL'S CANYON CROSS SECTIONS

Bedding Type	Eagle Canyon	Devil's Canyon	Average
Cross-stratified	57	59	58
Horizontal	15	7	11
Contorted	12	23	17
Indistinct	16	11	14
Total	100	100	100

A total of 572 points was counted on the Eagle Canyon cross section and 428 points on the Devil's Canyon cross section. The results are shown in Table 1.

The relationship between cross-stratification, contorted laminae, and indistinct stratification shows on the cross sections. A typical sequence consists of a basal cross-bedded zone overlain by a contorted zone, which in turn grades upward into indistinct stratification. The sequence is bounded above and below by major bedding planes, which are parallel despite the extreme variability in thickness of the three types of bedding within the sequence. The sequence is usually repeated two or three times within the thickness of the Navajo Sandstone. In Text-figure 4, an indistinct-stratified zone is seen in the lower part of the photograph. This zone is bounded above by a major bedding plane, above which lies a single set of tangential cross-beds.



TEXT-FIGURE 4.—Relation of cross-bedded, contorted, and indistinct strata. Indistinct stratification occurs in lower part of view and is bounded above by major bedding plane. A single set of cross-bedded sandstone overlies, and grades upward successively into contorted and indistinct-bedded sandstone.

The cross-bedded zone gives way upward to contorted beds, which in turn grade upward into indistinct stratification.

A detailed description of the types of stratification represented in the cross sections is found in the discussion of the measured stratigraphic sections and need not be repeated. Some features are more easily related to the cross sections, however, and will be discussed here.

Zones of contorted and indistinct stratification extend laterally thousands of feet and are almost invariably bounded above by major bedding planes. It can be seen that deformation of the sediment which produced zones of contorted and indistinct stratification occurred at repetitive intervals during deposition of the Navajo Sandstone rather than in a single episode after the entire thickness of sand was deposited; otherwise, the zones of contorted and indistinct stratification would transect major bedding planes indiscriminately.

The thickest zones of contortion seem to occur in roughly north-south-trending troughs, based on correlation of similar structures in both cross sections. Coincidence of a similarly oriented fault with one of these troughs suggests the possibility of movement along the fault as a triggering mechanism for the sediment deformation; however, this relationship may be purely fortuitous.

Horizontal beds, as seen on the cross sections, are discontinuous laterally and represent ponds in which shallow water was intermittently standing; this interpretation is based on the presence of limestones, limestone conglomerates, ripple marks, burrows, and dinosaur tracks.

Gregory (1938) correlated horizontal beds that he observed in the San Juan Country in the upper part of the Navajo Sandstone with similar beds that he reported in the upper Navajo Sandstone in the San Rafael Swell. Horizontal strata, however, are observed principally in the lower part of the Navajo Sandstone in the San Rafael Swell, with only occasional brown beds higher in the section. The discontinuous nature of these horizontal beds in the cross sections further indicates that correlation of these beds over such a distance is not valid.

Map of Bedding Types

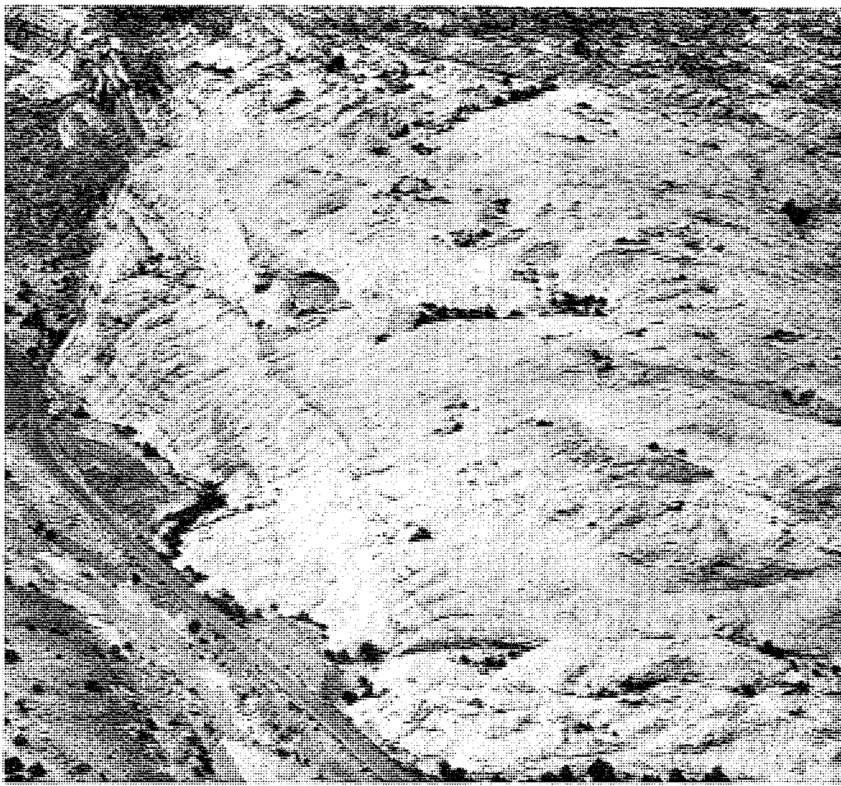
An exposure of Navajo Sandstone that lends itself well to a study of variations in bedding type in a mappable plane over a fairly wide area occurs in the Temple Mountain area of the San Rafael Swell (Pl. 5). A detailed map was constructed from bedding relationships recorded on a series of low-altitude oblique aerial photographs (Text-fig. 6). Data on the photographs were transferred to a topographic base map modified and enlarged from a portion of the 7.5-minute topographic quadrangle map of the area. Field

EXPLANATION OF PLATE 5
FIELD VIEWS

FIG. 1.—Low-altitude oblique aerial photograph of cuesta north of Temple Mountain Road. Upper part of cuesta is indistinct-bedded Navajo Sandstone.

FIG. 2.—Trough cross-beds in upper part of Navajo Sandstone in Temple Mountain area. Zones of contorted and indistinct stratification can be seen underlying the trough sets.

PLATE 5



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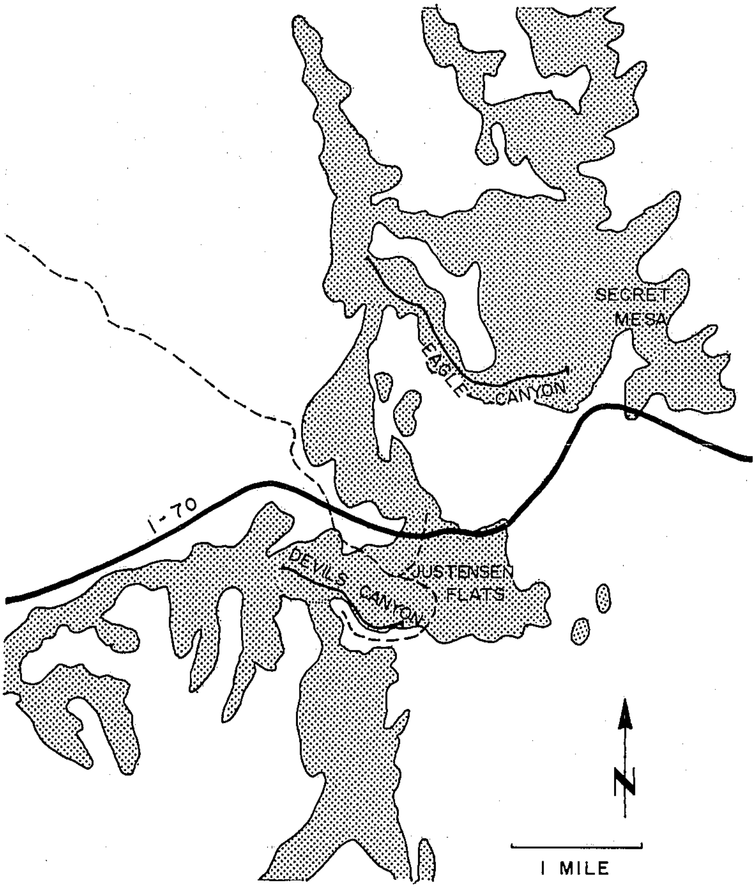


TEXT-FIGURE 5.—Index map of cross section locations. Stippled area is Navajo Sandstone outcrop from state geologic map.

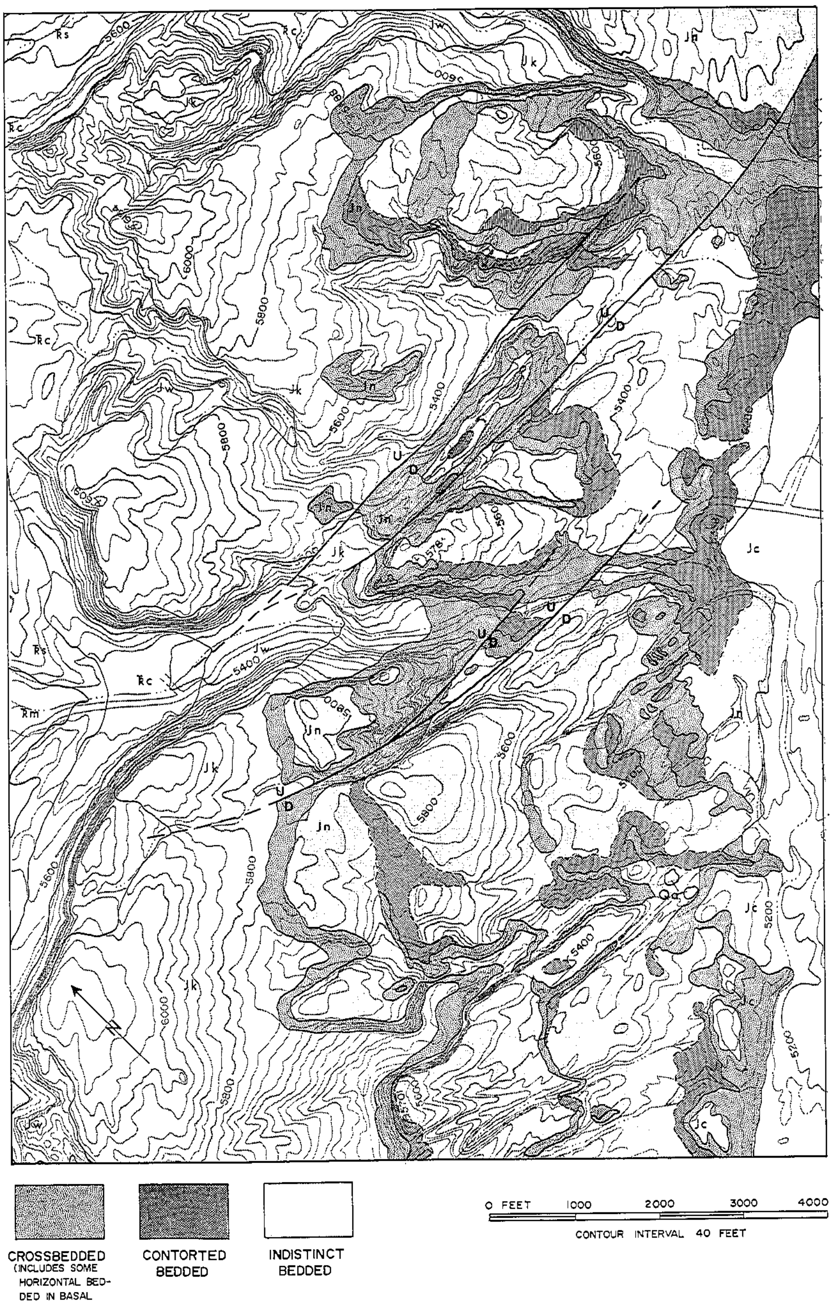
work associated with compilation of the map consisted of tracing bedding relationships in the field, plotting them on aerial photographs, and then field-checking the relationships after they were transferred from the photographs to the base map.

A cross-sectional view of the map area would show interbedded horizontal and cross-bedded layers in the lower part of the formation, overlain by three repetitions of the cross-bedded—contorted—indistinct sequence

EXPLANATION OF TEXT-FIGURE 6

TEXT-FIGURE 6.—Variations in bedding type in the Navajo Sandstone in the Temple Mountain area. Geologic formations in the map area are the Triassic Moenkopi (T_{Rm}), Shinarump (T_{Rs}), and Chinle (T_{Rc}); Jurassic (?) Wingate (Jw) and Kayenta (Jk); and Jurassic Navajo (Jn) and Carmel (Jc) formations.

TEXT-FIGURE 6



of strata described earlier. Because the indistinct-bedded parts of the formation are less porous and more resistant to erosion than the rest of the formation, these massive units characteristically cap the broad cuesta surfaces. Contorted, horizontal, and cross-bedded portions of the sequence that are less resistant to erosion are exposed typically in the steep sides of canyons and in escarpments. Since the lower part of the Navajo Sandstone crops out as cliffs and steep escarpments, no attempt was made to separate horizontal and cross-stratification on the map.

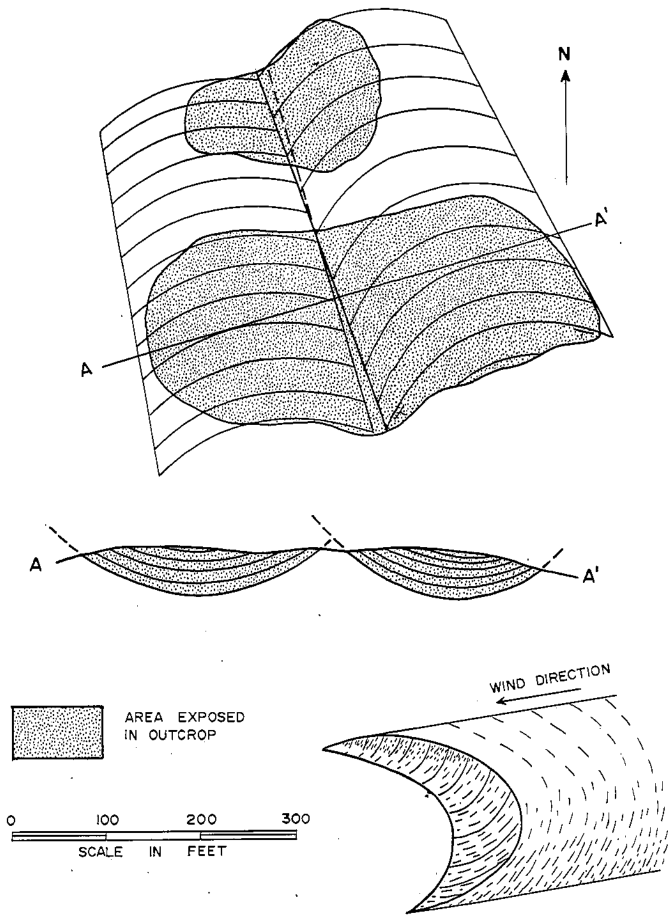
A point-count analysis of the map similar to that applied to the cross sections reveals that 57 percent of the map area of the Navajo Sandstone exposure is indistinct-bedded sandstone, 15 percent of the map area is contorted-bedded sandstone, and the remaining 28 percent of the area is made up of cross-bedded and horizontal-bedded sandstone, in which the horizontal stratification is probably less significant than the cross-stratification. These figures do not represent actual stratigraphic proportions of the types of strata, as do the cross sections; rather, they show that a particular bedding type dominates the exposure in response to variations in resistance to erosion. Indistinct-bedded zones are typified by tighter cementing, lower porosity, and greater resistance to erosion than are zones with other types of stratification.

Zones of stratification are variable laterally, with zones of cross-stratification and contorted laminae pinching out and grading into zones of indistinct stratification. It is difficult to determine the shape of indistinct-bedded bodies of sandstone on the map (Text-fig. 6) because of the extent of dissection in the exposure. There are several faults in the area that are easily traced through the Navajo Sandstone by comparing bedding variations on opposite sides of the faults. These faults appear to be *en echelon* step faults which were probably displaced in response to increasing steepness of folding to the northeast along the east flank of the San Rafael Swell.

Geometry of Cross-bed Planes

A study of cross-bed sets exposed on a projected plane was conducted in a part of the Temple Mountain map area just south of the road along the San Rafael Reef in the upper part of the Navajo Sandstone (Text-fig. 7). Two adjacent sets of trough cross-beds were traced laterally as far as possible, and variations in cross-bed dip directions at different localities within the sets were noted. The dune faces are concave, as determined by comparing dip values near the bottom with those near the top of the sets. Values at the bottom are about 18°, while near the top the dips are about 30°. The dune faces appear to have been crescent shaped, barchan dune style, based on differences in dip direction measured on either side of the sets. The dunes may not have been barchans, however, because they appear to be incised into underlying sets. Barchan and longitudinal dunes, according to Hack (1941), occur in areas of limited sand supply. It seems unlikely that there was a limited sand supply in the Navajo environment, although it seems possible that the abundance of sand was reduced or that the sand was immobilized by vegetation in the waning stages of Navajo deposition. Thus, it seems more likely that these cross-bed sets were deposited as transverse dunes with crescentic reentrants along the leading edges.

The few horizontal exposures of cross-bedded sandstones in the San Rafael Swell do not permit an adequate study of horizontally exposed cross-beds,

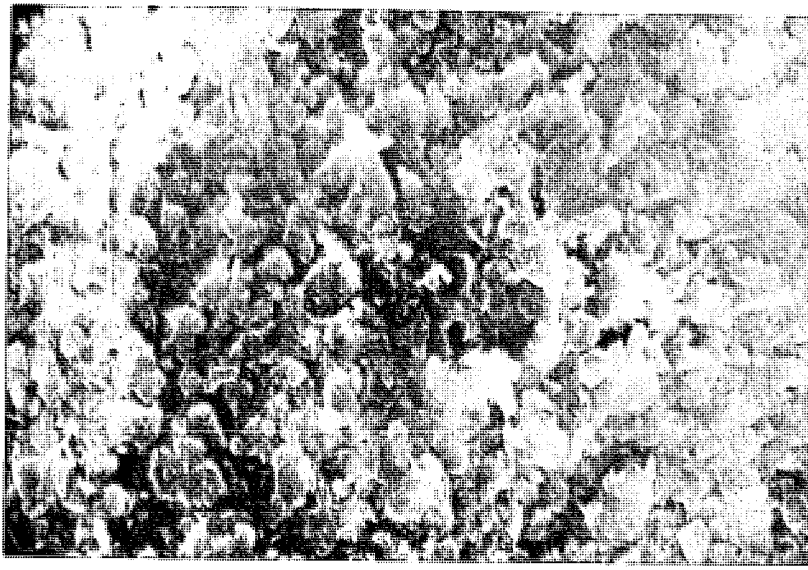


TEXT-FIGURE 7.—Geometry of cross-bed planes. Top, map view; middle, cross section along line A-A; bottom, interpreted geometry of dune slip face.

and such a study in another area would provide much information regarding the dune structures and the Navajo environment.

Grain Surface Textures

The scanning electron microscope permits observation of the nature of grain surface frosting. Kuenen and Perdok (1962) provide criteria for recognizing three types of frosting. Percussion frosting is characterized by crescent-shaped depressions that, on a slightly irregular grain, are present on the protruding parts and absent from the better protected parts of the grain. Frosted surfaces produced by chemical precipitation are characterized by euhedral growths of recognizable crystal habit on the grain surface; for example, quartz growths result in the development of hexagonal tabulae. Frosted surfaces



TEXT-FIGURE 8.—Electron photomicrograph of frosted grain surface. Surface features are hexagonal tabulae formed by chemical precipitation of quartz. Magnification is 1450X.

produced by chemical solution are characterized by a pitted texture with occasional deep cavities.

Examination of the surfaces of sand grains from the Navajo Sandstone reveals that the frosting is caused, not by percussion, but by chemical action. Characteristics of both chemical precipitation and solution can be seen on the grains. In Text-figure 8, hexagonal quartz growths can be seen on the surface of a quartz sand grain; this grain has been frosted by chemical precipitation.

Marzolf (1973) notes similar features on the surfaces of grains in the Navajo Sandstone and attributes them to chemical action rather than percussion; he states that "the 'frosted' sand grains in the Navajo Sandstone bear no relationship to original depositional environments."

CONCLUSIONS

The Navajo Sandstone is eolian except for horizontally bedded portions. Dune structures as observed in the upper part of the formation are similar to barchan sand dunes in the shape of the cross-bed surfaces, but they are more likely transverse dunes with crescentic reentrants along the leading edges. Ripple marks on these surfaces are like those observed on modern dunes. Ventifacts in the upper part of the Navajo Sandstone indicate that those beds in which they were found are eolian.

Consistency of sediment-dispersal directions throughout the Navajo Sandstone thickness as evidenced by cross-bed dip orientations is a strong indication that the cross-bedded units were all deposited in the same environment. The style of cross-beds changes somewhat between the lower and upper portions of the sequence, but this is probably in response to fluctuations in sand supply or wind velocity.

The large scale and the tangential nature of cross-beds; the presence of wind ripple marks on dune surfaces; the clean, well-sorted nature of the sand; and the lack of association of these beds with features diagnostic of other environments lends further credence to an eolian interpretation.

Contorted and indistinct-bedded portions within the Navajo Sandstone are interpreted as zones of flowage in the sand. This occurred at repetitive intervals throughout the deposition of the sand, intervals followed by planation and resumed deposition of cross-bedded sand. Major bedding planes that truncate contorted and indistinct zones but that are not disturbed by them indicate that the flowage did not take place in a single event after the entire sequence of sand was deposited; were this so, major bedding planes would be disturbed by flowage.

The style of contorted features, such as high-angle asymmetrical folds, flame structures, and "drag" folds, indicates that the sand was water-saturated or wetted when flowage took place. Major bedding planes are the result of wind erosion effective down to a relatively high water table. Were these major bedding planes the result of hydraulic action in subaqueous or neritic environments as has been suggested by Jordan (1965), these surfaces would be replete with horizontal laminae and ripple marks.

The abundance, in the lower Navajo Sandstone, of horizontal-bedded strata that bear ripple marks, limestone, limestone conglomerate, and burrows is further evidence that water was a significant part of the Navajo environment; while the presence of dinosaur tracks and limestone conglomerates formed from rolled-up mud cracks shows that the water involved in the deposition of these beds was intermittent. These horizontal beds are interpreted as being deposits in ponds that formed in depressions where the water table intersected the surface. Further, it seems unlikely that standing water would have been present in pools in the Navajo sands long enough to form limestone or horizontal beds unless the water table was high enough to intersect the surface in these low spots.

Based on these conclusions, the Navajo Sandstone is interpreted as being an extensive dune field in which water was abundant and played an important role in the development of sedimentary structures.

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