Stratigraphy of the Uppermost Triassic and the Jurassic Rocks of the Navajo Country

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Prepared in cooperation with the Bureau of Indian Affairs

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By J. W. HARSHBARGER, C. A. REPENNING, *and* J. H. IRWIN

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CONTENTS

ILLUSTRATIONS

[All plates in pocket]

STRATIGRAPHY OF THE UPPERMOST TRIASSIC AND THE JURASSIC ROCKS OF THE NAVAJO COUNTRY

By J. W. HARSHBARGER, C. A. REPENNING, and J. H. IRWIN

ABSTRACT

This study of the Triassic and Jurassic rocks of the Navajo country constitutes a part of a ground-water investigation of the Navajo and Hopi Indian Reservations by the U. S. Geological Survey. Detailed stratigraphic studies and geologic mapping have revealed new data on the stratigraphy of these rocks.

In the Navajo country the boundary between the Chinle formation and the Glen Canyon group has been placed at the top of the "B" division of the Chinle. The "A" division has been reassigned to the Wingate sandstone of the Glen Canyon group and is herein named the Rock Point member of the Wingate. The upper division of the Wingate sandstone is herein named the Lukachukai member. This member is recognized as the lower half of the original type section of the Wingate sandstone at Fort Wingate, New Mexico. The upper half of the original type section has been recognized as the Entrada sandstone since 1947. The Wingate sandstone is herein assigned to the Triassic system, owing to stratal relations and to fossil evidence found in the Rock Point member and in the overlying Moenave formation of the Glen Canyon group.

In the western half of the Navajo country, a rock unit conformably overlying the Wingate sandstone is herein named the Moenave formation. It is of questionable Triassic age and consists of two members previously described as being related to other strata. Their relation to each other is recognized for the first time in this paper. The basal Dinosaur Canyon sandstone member intertongues with the upper part of the Lukachukai member of the Wingate sandstone and with the overlying Springdale sandstone, the upper member of the Moenave formation. The Springdale sandstone member is gradational with the basal part of the overlying Kayenta formation of the Glen Canyon group.

The Kayenta formation, of questionable Jurassic age, unconformably overlies the Wingate sandstone in the eastern half of the Navajo country; however, it does not extend eastward into New Mexico. In the western half of the Navajo country the formation conformably overlies the Moenave formation. A southwestern "silty" facies of the formation is the lateral equivalent of the "typical" facies as exposed at the type locality. The Kayenta formation intertongues with the basal part of the overlying Navajo sandstone of the Glen Canyon group.

The Navajo sandstone, of Jurassic(?) and Jurassic age, overlies the Kayenta throughout most of the Navajo country. It pinches out in the southeastern part of the area and is not present in New Mexico.

The Carmel formation, the lowermost unit of the San Rafael group, unconformably overlies the Navajo standstone in most of the Navajo country. This formation is of Middle and Late Jurassic age and was laid down in a different depositional basin than the Glen Canyon group. Over most of the area the Carmel consists of typical silty strata, but in the southwestern part of the Navajo country it has different lithologic characteristics, owing to the introduction of locally derived sand. This local variation of deposition continued during the deposition of the Entrada sandstone, and thus the Carmel and overlying Entrada are very difficult to differentiate in this area.

The Entrada sandstone of the San Rafael group, except in the southwestern area mentioned above, comprises three members throughout the Navajo country. These units represent two distinct depositional facies. The lower sandy member is a sandy crossbedded facies, in part eolian, and is present only in the northwestern part of the area. The medial silty member more closely approximates the lithology of the type section in the San Rafael Swell in Utah and is present in the central and eastern parts of the Navajo country. The upper sandy member is a crossbedded facies like the lower member and is present in the eastern part of the area. A thin (50-foot) eastward extension of the medial silty member and a thick (253-foot) sequence of the upper sandy member constitute the upper half of the original type section of the Wingate sandstone.

The Todilto limestone of the San Rafael group overlies the Entrada and occurs only in the easternmost part of the Navajo country. It is believed that this limestone was deposited in an isolated basin having a restricted connection with the open sea. It is almost entirely restricted to the New Mexico part of the area and extends into Arizona only at the northern end of the Chuska Mountains.

The Summerville formation of the San Rafael group overlies the Entrada sandstone in the central part of the Navajo country and the Todilto in the eastern part of the area. The Summerville formation comprises two members. The lower silty member represents a quiet-water facies of deposition and is lithologically similar to the type Summerville found in the San Rafael Swell. The upper sandy member shows considerable evidence of sorting and crossbedding by wave action. The upper sandy member occurs near the margins of deposition; the lower silty member is confined to the more central and deeper parts of the Summerville basin. Upon regression of the Summerville sea the upper sandy member was deposited upon the lower silty member and occupies a higher stratigraphic position.

In the eastern, southern, and western parts of the Navajo country, the Summerville formation tongues and grades laterally into the Cow Springs sandstone. The Cow Springs sandstone was deposited under an eolian environment, indicated by studies of crossbedding, degree of sorting, and grain character. A prominent sandstone bed occurs at the top of the Summerville formation in the northern part of the area and is believed to be a tongue of the Cow Springs. This unit is the Bluff sand-

stone of the San Rafael group. The Cow Springs also intertongues with the lower members of the Morrison formation.

Four members of the Morrison formation have been recognized in the Navajo country. In ascending order, these are the Salt Wash, Recapture, Westwater Canyon, and Brushy Basin members. The Morrison is absent in the southwestern part of the area, owing to lateral gradation into the Cow Springs and to removal by pre-Dakota erosion.

In the extreme northeastern part of the area, the Lower Cretaceous Burro Canyon formation conformably overlies the Morrison and is unconformably overlain by the Dakota sandstone.

Terminology used in the description of the physical properties of the sedimentary strata has been standardized in order to eliminate the possibility of misunderstanding the written descriptions. This terminology is explained at the beginning of the presentation of typical stratigraphic sections of all uppermost Triassic and Jurassic rocks in the Navajo country, in the section entitled Stratigraphic Sections.

INTRODUCTION

At the request of the Bureau of Indian Affairs, the United States Geological Survey, in the fall of 1950, began an investigation of the ground-water resources of the Navajo and Hopi Indian Reservations (pl. 1). Intertonguing, lateral gradation, and facies changes within and between the formations considered to be of youngest Triassic and of Jurassic age obscure the regional correlations, so that a study of the regional stratigraphic relationships of these rocks was essential. This report on the results of this work was written with the intention of making these results available prior to the completion of and in greater detail than the overall report on the geology and ground-water resources of the Navajo country.

The Navajo country comprises parts of northeastern Arizona, northwestern New Mexico, and southeastern Utah (fig. 1). It is comparable in size to the State of West Virginia. Jurassic rocks crop out in about two-thirds of this area. The area lies in the southwestern part of the Colorado Plateaus province and includes the Black Mesa basin and the western part of the San Juan Basin. Associated with these basins are the Zuni uplift, the Defiance uplift, and the Monument Valley upwarp.

METHODS OF STUDY

Detailed stratigraphic sections have been measured at critical points throughout the area, and laboratory analyses have been made of samples collected at the time the sections were measured. Laboratory work included both particle-size analyses and heavy-mineral determinations. Analysis of the sedimentary structures has been correlated with data on the properties of the formations and with fossil evidence to deduce paleoenvironments and facies changes. Detailed geologic mapping was done to determine the areal extent of the many aquifers of the Navajo country and has added considerable information regarding intertonguing or gradational relations of the units.

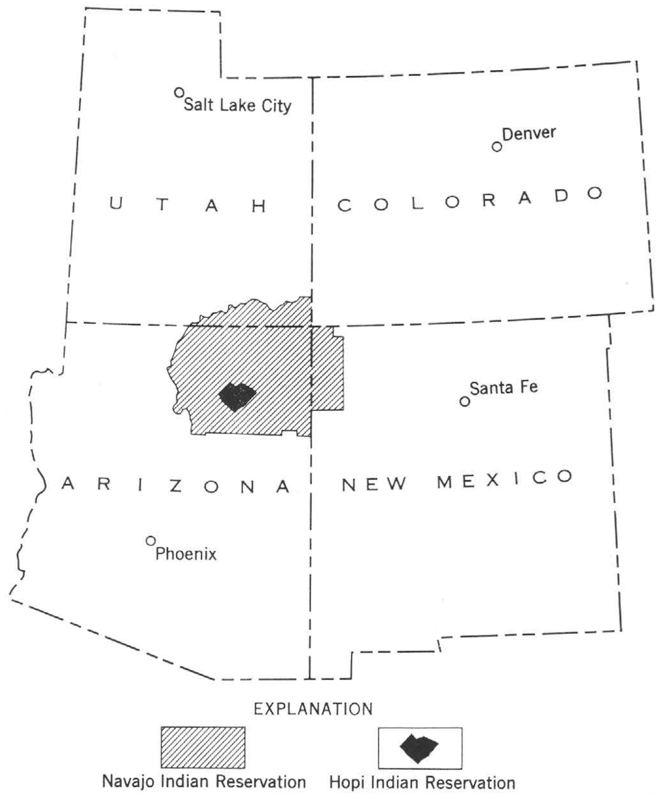

FIGURE 1.—Map showing the location of the Navajo and Hopi Indian Reservations in parts of Arizona, New Mexico, and Utah.

Field description of stratigraphic sections includes megascopic examinations of physical properties of the grains, color, cement, composition, bedding, fossils, surface marks, relations to adjacent units, weathering, and thickness of the strata. Color was determined by comparison with the color chips on the rock-color chart distributed by the National Research Council (Goddard, 1948). Grain size was determined by comparison with prepared samples of standard sizes which were attached to cards or encased in plastic sticks in order to facilitate use in the field. Degree of sorting and roundness were estimated. Composition and accessory-mineral determinations were limited to identifications with a hand lens. Bedding was classified in a manner generally similar to the methods outlined by McKee and Weir (1953). A more complete explanation of the descriptive terminology may be found in the section entitled Stratigraphic Sections.

Laboratory work on the collected samples consisted of particle-size analyses, determination of carbonate-mineral content, and heavy-mineral studies. Median diameter, coefficient of sorting (Trask, 1932), skewness (Trask, 1932), roundness, and sphericity seemed to be the most useful of the properties and ratios established by the particle-size analyses. Because of the time involved, heavy-mineral frequency determinations were generally made only on samples from units of great complexity. Nearly all heavy-mineral work was done on rocks from the lower part of the Glen Canyon group, where stratigraphic problems were most perplexing. Laboratory studies of the Cow Springs sandstone were made as part of a doctoral thesis by the senior author (Harshbarger, 1949) and were not repeated in the laboratory operated by the U. S. Geological Survey for the study of the sedimentary rocks of the Navajo country.

The most positive evidence regarding stratal relations was revealed through the mapping program. Mapping was done with the use of stereophotos at a scale of 2 inches to the mile, making it possible to show in ample detail the general relationships discussed in this paper.

NOMENCLATURE

Stratigraphic nomenclature in this report closely follows that recommended by Baker, Dane, and Reeside (1936, p. 37; 1947). The subdivision of the Morrison formation in this report follows that suggested by Stokes (1944, p. 962–965). Figure 2 shows charts listing the terminology used for the uppermost Triassic and the Jurassic rocks at the following selected areas in the Navajo country: Kachina Point, Navajo Creek, Mex-

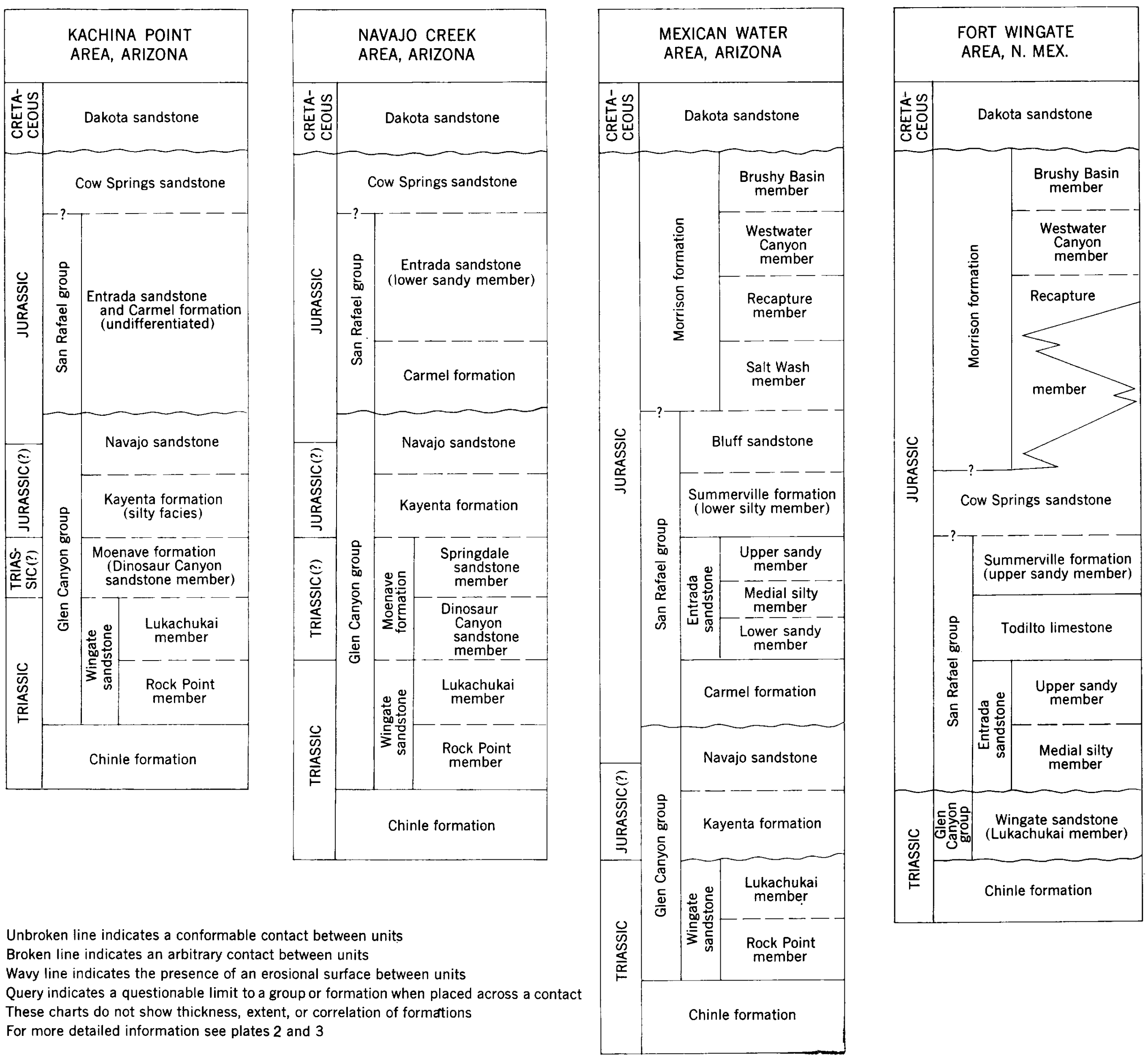

FIGURE 2.—Charts showing nomenclature of the uppermost Triassic and the Jurassic in the Navajo country.

ican Water, and Fort Wingate. The detailed stratigraphic relationships of the units are shown on the fence diagrams (pls. 2 and 3).

The uppermost unit of the Chinle formation, the "A" division as defined by Gregory (1917), has been removed from the Chinle and placed in the Wingate sandstone, the lowermost formation in the Glen Canyon group, because of lithologic and stratal relationships (Harshbarger, Repenning, and Jackson, 1951). This unit is referred to in this paper as the Rock Point member of the Wingate sandstone. The upper unit of the Wingate sandstone is herein referred to as the Lukachukai member. This member constitutes the entire Wingate sandstone at the original type locality at Fort Wingate, N. Mex. A sequence of rocks overlying the Wingate sandstone in the western part of the area is herein referred to as the Moenave formation. Where the Wingate is absent, the Moenave is the basal formation of the Glen Canyon group. The Dinosaur Canyon sandstone, a unit described by Colbert and Mook (1951, p. 151) as equivalent to the "orange-red sandstone" of Ward (1901, p. 413), is recognized in this paper as the lower member of the Moenave formation. The Springdale sandstone member of the Chinle formation (Gregory, 1950) is believed to be a part of the Moenave formation and is treated in this report as the upper member of the Moenave. In the southwestern part of the Navajo country the Kayenta formation of the Glen Canyon group consists of a sequence of intercalated fine-grained sandstone and mudstone beds. Owing to the distinctive lithology of these rocks as compared to those at the type locality of the Kayenta formation, they are discussed separately in this report and are referred to as the silty facies of the Kayenta formation.

The Cow Springs sandstone was defined by Harshbarger, Repenning, and Jackson (1951) as a formation laterally equivalent to parts of both the San Rafael group and the Morrison formation and is so used in this report. The Bluff sandstone is referred to as the uppermost formation of the San Rafael group. In accordance with recommendations of Craig and others (1955), the members of the Morrison formation are used without their original lithologic adjectives.

EXPLANATION OF STRATIGRAPHIC ILLUSTRATIONS

The stratigraphic relations in the Jurassic rocks are shown by fence diagrams (pls. 2 and 3). Plate 2 is a fence diagram showing the stratal relationships of the Glen Canyon group. The top of the "B" member of the Chinle formation (Gregory, 1917) is used as the base datum. For simplicity this surface is shown as a plane, although at the beginning of Glen Canyon deposition the surface was quite irregular. In constructing the fence diagrams no attempt has been made to adjust the thicknesses of the strata for perspective; hence, there is only one vertical scale. Intertonguing relations are shown in a generalized way and indicate only the areas of intertonguing and directions of tonguing along the plane of the fence. In general, the tongues that are shown are diagrammatic and do not necessarily indicate the presence of any specific tongue. Gradational relations are shown by dashed lines, and no attempt has been made to show unconformities. The thicknesses are controlled by measured sections at points indicated on the fences and at intervening points that are not shown.

Plate 3 is a fence diagram of the San Rafael group and the Morrison formation. The unconformity at the base of the Lower(?) and Upper Cretaceous Dakota sandstone is used as the upper datum. Where present, Lower Cretaceous rocks are shown between the Morrison formation and the unconformity at the base of the Dakota sandstone.

PERSONNEL AND ACKNOWLEDGMENTS

The stratigraphic and laboratory studies for this report were made under the immediate supervision of the senior author and under the general direction of Leonard C. Halpenny, former district engineer of the Ground Water Branch of the Geological Survey for Arizona, and A. N. Sayre, chief of the Ground Water Branch. A major part of the fieldwork, including measurement of stratigraphic sections and geologic mapping, was done by the junior authors. During the course of the Navajo ground-water investigation, a number of others made a considerable contribution toward this study, including J. T. Callahan, R. L. Jackson, J. P. Akers, P. R. Stevens, and M. E. Cooley. The laboratory studies were made by S. H. Congdon and H. G. Page.

This work has been a part of the regional groundwater investigation financed by the Bureau of Indian Affairs. Many thanks are given to John B. Reeside, Jr., for review of the stratal relationships in the field and of this manuscript; to Lawrence C. Craig and Jack D. Strobell, Jr., of the U. S. Geological Survey, for their cooperative assistance and critical review of stratigraphic studies during the entire investigation; and to the many other persons of the Geological Survey who have aided in the correlation of the Jurassic rocks. The authors extend appreciation to Edwin D. McKee, former assistant director of the Museum of Northern Arizona, who has given helpful suggestions during the investigation and review of the manuscript. Appreciation is extended also to E. H. Colbert, D. H. Dunkle, R. W. Imlay, Bobb Schaeffer, and S. P. Welles, who have reviewed the manuscript in part or in its entirety.

Special recognition is due Stephen H. Congdon, who operated the sedimentological laboratory for the study of the rocks of the Navajo country and who made the laboratory studies and a large part of their interpretation. A separate report on the results of the laboratory studies of samples from the Glen Canyon group is being prepared by Mr. Congdon.

LOWER BOUNDARY OF THE GLEN CANYON GROUP

The contact between the Chinle formation and Glen Canyon group in the Navajo country lies between Gregory's "A" and "B" divisions (1917, p. 42–43) of the Chinle (Harshbarger, Repenning, and Jackson, 1951). Rocks long assigned to the Chinle formation are therefore included in the Glen Canyon group. This reassignment of the Chinle "A" was based upon intertonguing between the Wingate sandstone and the Chinle "A" in several areas. Subsequent work has further strengthened this reassignment of the Chinle "A" by establishing other depositional relationships between the Chinle "A" and the Wingate sandstone.

DESCRIPTION OF CONTACT

In the western, southwestern, and southeastern parts of the Navajo country, the lower boundary of the Glen Canyon group is marked by an erosional surface showing minor relief and in most places is overlain by a veneer of conglomerate 1–3 inches thick. The conglomerate is composed mainly of pebbles derived from the Chinle formation. In the southern and central parts of the Navajo country, no indication of a break in deposition between the Chinle and the Glen Canyon group has been found, and the boundary is quite arbitrary. There it is based on lithologic differences and is placed at the top of the highest limestone in the "B" division of the Chinle. In the area along the New Mexico-Arizona State line, the contact in most places is marked by a thin granule conglomerate which is particularly persistent to the south. At Thoreau, N. Mex. (pl. 1), the conglomerate is in channels having a relief of 2 or 3 feet, and at Lupton, Ariz., the basal Wingate contains several thick conglomeratic lenses. In the Shiprock area and in the area between the San Juan and Colorado Rivers in Utah, the Chinle formation and the Glen Canyon group appear to represent a continuous sequence of deposition. For the most part, conspicuous breaks in sedimentation between the Chinle and Glen Canyon are in the western and southeastern parts of the Navajo country, whereas in the central part the contact appears to be conformable.

BASIS FOR BOUNDARY ASSIGNMENT

The physical relationships between the Chinle formation and the formations of the Glen Canyon group indicate that their deposition was essentially continuous in the Navajo country. Each of these formations intertongues with superjacent formations in some parts of this area. Above the base of the Chinle formation, the first major break in deposition is marked by the unconformity between the Navajo sandstone and the Carmel formation. Therefore, the boundary between the Chinle and the Glen Canyon group in the Navajo country does not represent a major break in deposition, and the assignment of this boundary is necessarily based upon minor relationships. Throughout the Navajo country the sediments of the Rock Point member appear to have closer relationships to the Wingate than to the Chinle, although the member clearly has some features also common to the Chinle.

The reasons for the assignment of the Rock Point member to the Wingate sandstone are (1) similarity of grain size and composition, (2) similarity of areal distribution, and (3) physical relationships. The above points are discussed in greater detail throughout this report.

Grain size and composition.—Mechanical analyses were made of rock samples from the Rock Point and Lukachukai members of the Wingate sandstone for grain-size comparison. Fifty-five samples from 16 localities were collected from the Rock Point. The median diameter of the grains ranges from 0.051 to 0.150 millimeter. The arithmetical average for all samples is 0.084 millimeter. This size falls about in the middle of the very fine sand range according to the Wentworth classification (1926). Thirty-three samples from 19 localities were collected from the Lukachukai member. The median diameter of the grains ranges from 0.063 to 0.250 millimeter. The arithmetical average for all samples is 0.120 millimeter. This size falls into the upper third of the very fine sand range. Preliminary results of mechanical analyses of samples collected from the upper member of the Chinle formation show that the median diameter of the grains ranges from 0.044 to 0.078 millimeter. The arithmetical average is 0.055 millimeter, which falls into the silt size range. Therefore, on the basis of grain size the Rock Point and Lukachukai members of the Wingate are classified as sandstone, and the Chinle as siltstone.

Composition of the rocks indicates a closer similarity between the Rock Point and the Wingate (Lukachukai member) than between the Rock Point and the Chinle formation. Limestone beds are abundant in the upper part of the Chinle formation, but limestone is essentially absent in the Rock Point. Preliminary determinations of carbonate-mineral concentration show an average of 33 percent for the siltstone of the upper part of the Chinle. The carbonate-mineral content in the

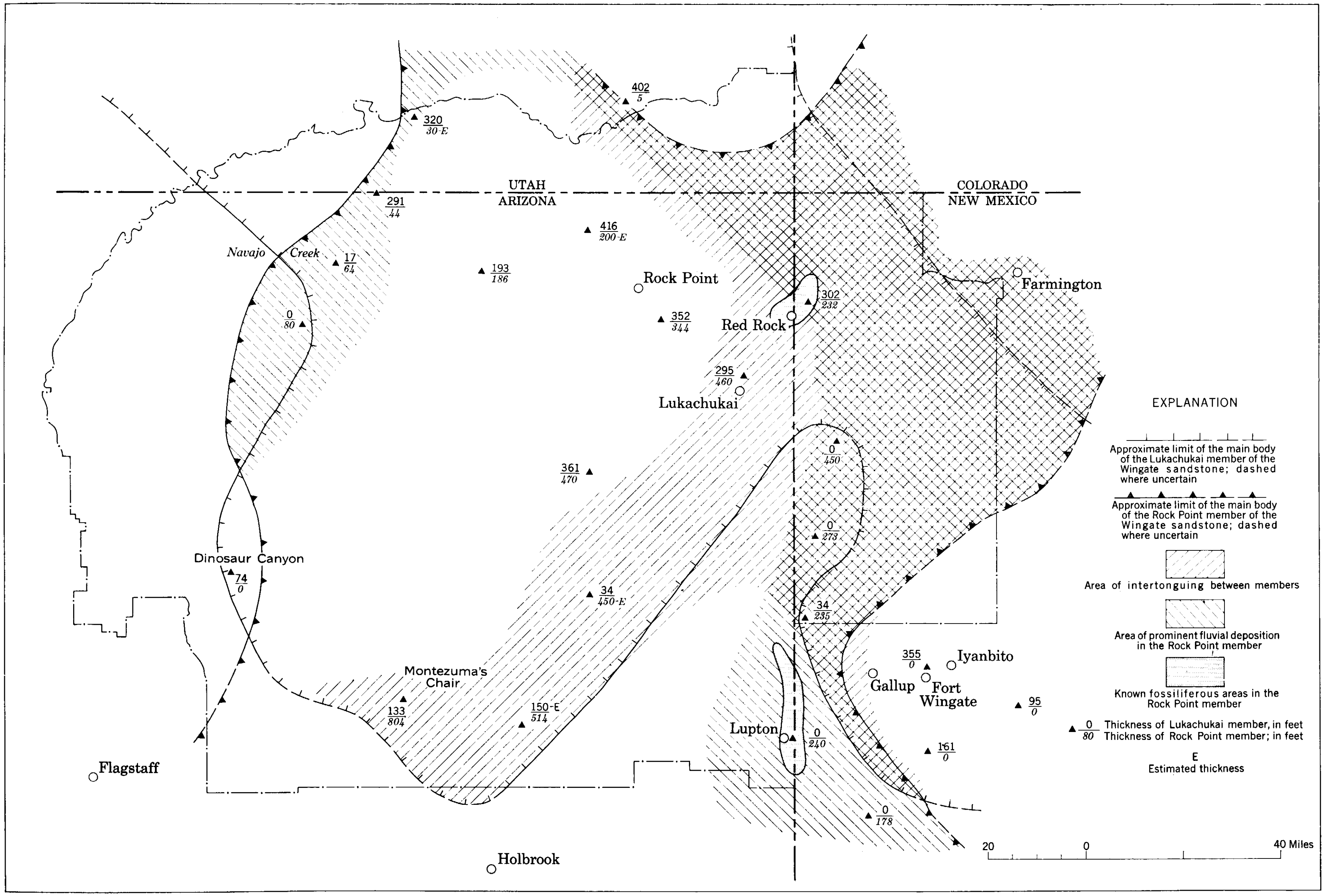

Figure 3.—Map of the Navajo country showing approximate depositional areas of the Rock Point and Lukachukai members of the Winga te sandstone.

Rock Point member averages 16 percent. These differences in limestone content and carbonate-mineral concentration indicate a difference of depositional environment between the Chinle and the Rock Point.

The desirability of including the Rock Point member (Chinle "A") in the Wingate sandstone first became apparent from subsurface stratigraphic correlations. Because of the similarity of composition, it is impossible to determine the contact between the Wingate (Lukachukai member) and the Chinle "A" (Rock Point member) with any confidence from drill samples. The Chinle "A"-Chinle "B" contact is easily determined from drill cuttings because of the limestone in "B". The similarity of composition of the Lukachukai and Rock Point members also makes the contact difficult to determine, and map, where surface exposures are poor. Even in many areas of excellent exposures the contact can be accurately chosen only by close examination of the outcrop, whereas the Chinle "A"-Chinle "B" contact is always easily determined.

Areal distribution.—The Chinle formation and its equivalents have been recognized across the northern parts of the States of Arizona, New Mexico, and Texas and northward into northeastern Utah, western Colorado, and southern Nevada. The Lukachukai member of the Wingate sandstone is recognized only in northwestern New Mexico, northeastern Arizona, eastern Utah, and southwestern Colorado. The Rock Point member is even more restricted in distribution than the Lukachukai member, as it is confined almost entirely to northeastern Arizona, although it extends a short distance into northwestern New Mexico, southeastern Utah, and southwestern Colorado. Because the distributions of the Lukachukai and Rock Point members are more similar to each other than they are to the distribution of the Chinle, it would seem that they are more closely related.

Physical relationships.—In the Navajo country intertonguing between the Rock Point and the Lukachukai members has been established over an area of about 6,000 square miles. This area extends about 120 miles in a southwest direction and is about 80 miles wide (fig. 3). These intertonguing relationships occur on a large and conspicuous scale (fig. 4). Intertonguing between the Rock Point and the Chinle in the Navajo country was observed in an area of only about 24 square miles, insignificant in comparison to the area of the Rock Point-Lukachukai intertonguing. The Chinle-Rock Point contact appears to be gradational in most of the Navajo country, but this does not necessarily show an interrelation. Channeled surfaces occur locally at the contact even in areas where gradation seems most obvious. Thus a greater depositional break may occur between the Chinle and Rock Point than can be detected where a similarity of composition masks the contact. The intertonguing relations between the Rock Point and the Wingate (Lukachukai) seem more significant than the gradational contact between the Rock Point and the Chinle.

FIGURE 4.—Intertonguing between the Rock Point (Ꞧwr) and Lukachukai (Ꞧwl) members of the Wingate sandstone, 3 miles east of Lukachukai, Ariz.

The physical relationships between sedimentary rocks of the Rock Point and the Lukachukai members, in addition to the relationships suggested by the distribution, grain size, and composition of the Rock Point, seem to justify the assignment of the boundary between the Chinle formation and the Glen Canyon group that is adopted in this report.

GLEN CANYON GROUP

The name Glen Canyon was first applied by Gilluly, Reeside, Gregory, and Moore to a group of rocks having a similar lithologic character and areal extent. The group was named after Glen Canyon of the Colorado River in southeastern Utah, where it is typically exposed. The first published reference to the name is by Baker, Dobbin, McKnight, and Reeside (1927). In the original description, the Glen Canyon group included the Wingate sandstone (Dutton, 1885), the Todilto formation (Gregory, 1917), and the Navajo sandstone (Gregory, 1917). The Kayenta formation (Baker, Dane, and McKnight, 1931) was later introduced to replace what was at first considered to be a sandstone facies of the Todilto formation. The type Todilto limestone was recognized as being much younger than the Kayenta formation. The type localities of all the formations in the Glen Canyon group lie within the Navajo country.

The Glen Canyon group overlies the Triassic Chinle formation and underlies the Carmel formation, which is of Middle and Late Jurassic age (Imlay, 1952, p. 963). The interpretation of faunal and stratigraphic evidence presented in the present paper indicates that the Glen Canyon group should be assigned to both the Triassic and Jurassic systems.

WINGATE SANDSTONE

The Wingate sandstone of Late Triassic age was originally described by Dutton (1885, p. 136–137) from exposures in the cliffs north of Fort Wingate, N. Mex. (fig. 5). In the description he refers to the limestone unit in the Chinle formation, since referred to as Chinle "B" by Gregory (1917), mentioning that it contains no fossils. He further states, in subchapter 3, that "Next in order comes the most conspicuous stratigraphic member of the whole region. It is a massive bright red sandstone . . ." This unit he describes and names the Wingate sandstone after Fort Wingate. Dutton states that "In the immediate vicinity of the Zuni Plateau its thickness averages about 450 feet." The units Chinle "B" and Wingate stand out clearly in the sketch included in his report. At the point shown in this sketch, the unit described as the Wingate sandstone is 658 feet thick. Of this total thickness, the basal 355 feet is composed of sedimentary rocks now considered to be the Wingate sandstone, as recognized throughout northeastern Arizona, southeastern Utah, and parts of western Colorado. The upper 303 feet of Dutton's type Wingate sandstone is now recognized (Baker, Dane, and Reeside, 1947, p. 1667) as the Entrada sandstone of the San Rafael group, a unit much younger than the lower half of Dutton's type Wingate sandstone. Owing to these stratigraphic relationships, the authors restrict the Wingate sandstone to the lower half of Dutton's type section (fig. 5).

In the Navajo country the Wingate sandstone comprises two mappable units. The lower unit consists of reddish-orange parallel-bedded, thin-bedded siltstone and sandstone. This unit is described as the Rock Point member from typical exposures near Rock Point School, Apache County, Ariz. (fig. 6). The upper unit consists of reddish-brown fine-grained sandstone which is crossbedded on a large scale and commonly forms vertical massive cliffs. This unit is herein referred to as the Lukachukai member, from typical exposures along the escarpment north of Lukachukai, Apache County, Ariz. (fig. 4). The Lukachukai is the only member of the Wingate sandstone that is present at the type locality near Fort Wingate. The Rock Point and Lukachukai members are closely related, as indicated by their lithologic character and stratal relations. Descriptions of measured sections of these units are given in the section on stratigraphic sections and their locations are shown on the index map (pl. 1).

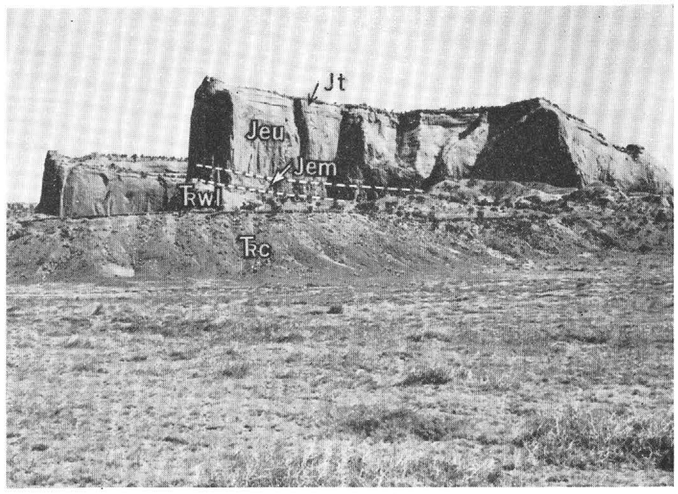

FIGURE 5.—The Wingate sandstone at the type locality and the overlying Entrada sandstone near Fort Wingate, N. Mex. The unit in the foreground and middle ground constitutes the upper part of the Chinle formation (c); the overlying rounded outcrop constitutes the Lukachukai member of the Wingate sandstone (Ꞧwl); the flat-bedded unit at the base of the vertical cliff is the medial silty member (Jem), and the main part of the cliff is the upper sandy member (Jeu), of the Entrada sandstone. The cliff is capped by the Todilto limestone (Jt).

ROCK POINT MEMBER

The name Rock Point member of the Wingate sandstone is proposed for the lower, slope-forming unit exposed in Little Round Rock, a prominent butte, 15 miles south of the Rock Point School, that is chosen for the type locality (fig. 6). The rocks that are included in this member were formerly designated as the "A" division of the Chinle formation (Gregory, 1917, p. 42).

The Chinle "A" unit has been correlated over wide areas. In general, any reddish silty sandstone unit, underlying the vertical cliffs of the Lukachukai member of the Wingate, has been called Chinle "A." Unfortunately, this has led to considerable confusion, especially to the north of the Navajo country where underlying units of the Chinle have a high percentage

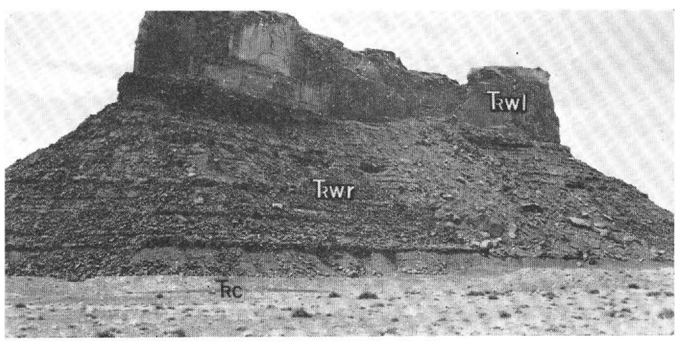

FIGURE 6.—Rock Point member of the Wingate sandstone at the type locality, Little Round Rock, 15 miles south of Rock Point, Ariz. Upper part of the Chinle formation (Ꞧc); and Rock Point (Ꞧwr) and Lukachukai (Ꞧwl) members of the Wingate sandstone.

of sand and are quite reddish. Also, to the west of the Navajo country, the Moenave formation is lithologically similar to the Chinle "A" and overlies the shale and limestone of the Chinle. The Chinle "A," the Rock Point member of the Wingate sandstone as used in this report, has a much more limited distribution than has been previously supposed (fig. 3). It extends beyond the limits of the Navajo country to the northeast, and probably its equivalent is present along the Dolores River above Dolores, Colo. It is present to the north of the Navajo country as far as Monticello, Utah, although west of Monticello it is not believed to extend very far north of the confluence of the San Juan and Colorado Rivers. The Rock Point member of the Wingate sandstone does not extend beyond the limits of the Navajo Indian Reservation to the west and northwest (pl. 2).

General description and field relations.—At the type locality the Rock Point member of the Wingate sandstone consists of a sequence of beds 344 feet thick forming ledges of silty sandstone and slopes of siltstone. It is pale reddish brown, about 10*R*5/4 as compared with the rock-color chart distributed by the National Research Council (Goddard, 1948). The sandstone is composed primarily of subrounded to subangular quartz grains. The member weathers into a fairly uniform ledgy slope beneath vertical cliffs of the Lukachukai member of the Wingate and rises above a plain formed on the uppermost limestone of the "B" division of the Chinle formation (fig. 6). Most of the bedding is very thin to thin (1–60 cm) and flat. Crossbedding is not present in the type area; however, it is in other areas, especially near the margins of deposition of the member. It is common also in places where the Rock Point intertongues with the Lukachukai member of the Wingate sandstone.

At the type locality the Rock Point member conformably overlies the Chinle formation with no apparent break in deposition. The only suggestion of a break is a conglomeratic zone consisting of reworked pebbles of limestone at the top of the highest limestone of the Chinle. As similar conglomeratic limestones are common throughout the "B" division of the Chinle, this one is thought to be of no significance.

In all directions from the type locality, except to the south, the Rock Point member increases in sand content and tends to weather into flaggy outcrops. Because of this weathering feature, the term "board-bedded Wingate" has been used for many years as a field term for the unit by some workers. Lenticularity and crossbedding accompany the increase in sand. Locally in the eastern part of the Navajo country, deposits believed to be fluvial are found in the member. Ripple marks and clay slicks, containing worm trails and borings, are also found in this area. Most crossbedding is at low angle (dips less than 20° from horizontal), of small to medium scale (crossbeds less than 20 feet long), and of the trough type (individual sets bounded by curved surfaces of erosion); these are descriptive terms outlined by McKee and Weir (1953).

South of the type locality the Rock Point member increases in silt content and, as a result, weathers into a smooth slope (fig. 7). The bedding is not lenticular, but the member is very thin bedded to laminated (1–5 cm); also, the thickness of the member increases.

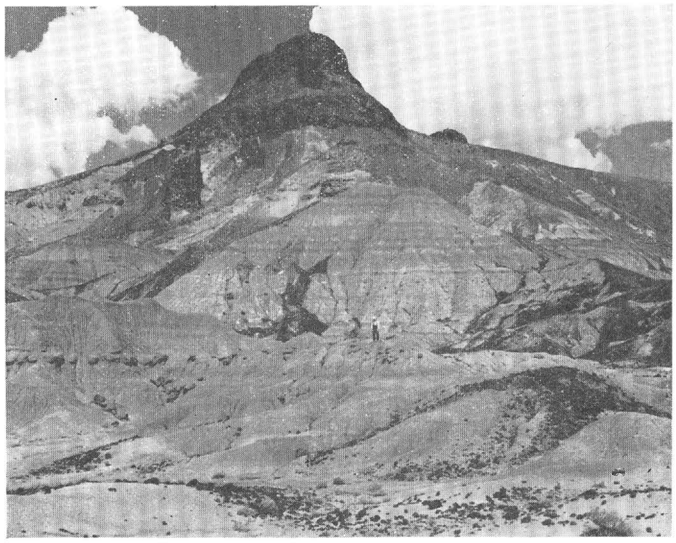

FIGURE 7.—Rock Point member of the Wingate sandstone, 8 miles south of Indian Wells, Ariz. In this area the unit weathers into a smooth slope because it contains a high percentage of silt. Tertiary basalt forms the cap rock.

The Rock Point was deposited in a shallow basin that plunged to the south. Its maximum observable thickness is 804 feet, in the Hopi Buttes area (pl. 2). From this point it thins abruptly to the west and is absent above Ward Terrace, east of Cameron, Ariz. Eastward also the unit thins, having a thickness of 203 feet at Lupton, Ariz., and it is absent at Fort Wingate, N. Mex. To the north the unit thins along the axis of the basin and is 344 feet thick at the type locality. The unit is 250 feet thick at Todilto Park, N. Mex., 263 feet at Lukachukai, Ariz., 130 feet thick on Tyende Mesa north of Kayenta, and is absent at Lees Ferry, Ariz. The unit is still thinner northward in Utah beyond the limits of the Navajo Indian Reservation. South of the Hopi Buttes area it was removed by erosion.

Laboratory studies.—Representative rock samples were collected from the Rock Point member of the Wingate for evaluation of its petrologic characteristics. In the area of the type locality the member is composed of grains that have an average median diameter of 0.067 millimeter; the coefficient of sorting of these sediments averages 1.14. Roundness studies show that subrounded grains constitute about 25 percent of the average sample and subangular grains about 75 percent; sphericity averages 0.78. Zircon, tourmaline, garnet, and rutile are the most common heavy minerals in the type area. Although not noted in samples from the type area, epidote is common elsewhere.

In the Rock Point member, grains of maximum sphericity occur at Cheechilgeetho, N. Mex., and Twin Buttes and Indian Wells, Ariz. However, maximum average sphericity was observed at Betatakin and Kayenta. The most angular grains are in the Hopi Buttes area, where the unit is thickest and contains the greatest percentage of silt. The sediments of this member have least skewness in the southwestern and eastern parts of the Navajo country. Determinations of the coefficient of sorting show results that are somewhat erratic. Rocks exhibiting the best sorting have a wide distribution throughout the area. However, good sorting (Payne, 1942) occurs in a north-south belt along the center of the Rock Point depositional basin, and poor sorting occurs in marginal areas. In general, the median diameter of grains within the member decreases toward the south. The percentage of carbonate minerals appears to be highest in the northwest part of the area. In general, the results of particle-size analyses appear to substantiate field evidence that the Rock Point is a quiet-water deposit.

The Rock Point member has a lower content of garnet than has any other unit of the Glen Canyon group, which suggests that an oxidizing environment prevailed in the areas from which its sediments were derived (see Heinz-Sindowski, 1949) and also, probably, in the area of deposition (see Goldstein, 1950; Dryden and Dryden, 1946). Ilmenite progressively increases, in relation to leucoxene, upward in the section. This suggests that new material was continuously introduced to the basin during Rock Point deposition, thus restricting opportunities for the reworking of old material. A large percentage of zircon, tourmaline, and garnet suggest that most of the sediments of the Rock Point were derived from older sedimentary terranes (see Milner, 1952; Pettijohn, 1941). The interstitial hematite, causing the red color, is believed to have been derived from older deposits. However, some "new" material was brought in which indicates source areas including metamorphic and acidic, ultrabasic, and pegmatitic igneous terranes (see Krumbein and Pettijohn, 1938).

Fossil occurrences.—Locally the Rock Point member of the Wingate sandstone contains fossils which are usually associated with conglomeratic fluvial deposits and consequently are very fragmentary. Reptilian teeth are the most common. These are found in conglomeratic lenses in the deposits of the Rock Point in the vicinity of Lupton, Ariz. Teeth and bone fragments also have been found in the conglomerate of the Rock Point near Red Rock, Ariz., and were tentatively identified by D. H. Dunkle (written communication, 1952) as of the phytosaur *Machaeroprosopus*. The crocodilelike phytosaurs are characteristic reptiles of the Late Triassic and apparently lived under ecological and climatic conditions similar to those under which the modern crocodile lives. Unidentifiable plant remains, including some petrified wood, are associated with the vertebrate remains found in the vicinity of Red Rock.

LUKACHUKAI MEMBER

The Lukachukai member of the Wingate sandstone is the only member that occurs at the type locality of the Wingate sandstone near Fort Wingate, N. Mex. As mentioned previously, the Lukachukai member constitutes the lower half of the original Wingate sandstone, as defined by Dutton, whereas the upper half is now recognized as the Entrada sandstone (fig. 5). The name Lukachukai member of the Wingate sandstone is proposed for the sandstone that forms the vertical cliff on the escarpment northeast of Lukachukai, Apache County, Ariz. (fig. 4). This exposure has been chosen as the type locality of the Lukachukai member because the lithology there is typical of the Wingate sandstone over wide areas in parts of Utah, Colorado, New Mexico, and Arizona. This member has a larger areal distribution than the Rock Point member.

General description and field relations.—The Lukachukai member of the Wingate sandstone at the type locality is a pale-reddish-brown (10*R*5/4) fine-to very fine-grained quartz sandstone. It is a massive sandstone that weathers into sheer cliffs above the slope-forming Rock Point member. At the type locality, as

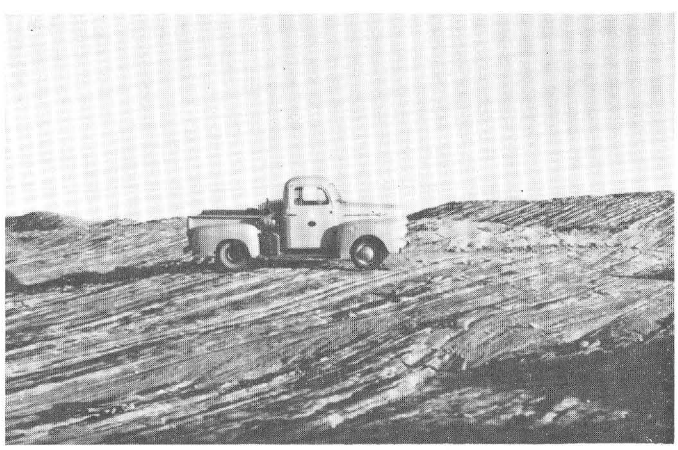

FIGURE 8.—Crossbedding in the Lukachukai member of the Wingate sandstone, 2 miles east of Rock Point, Ariz.

elsewhere, the Lukachukai member is predominantly crossbedded, although in this area it intertongues with the flat-bedded Rock Point member (figs. 3 and 4, pl. 2). The crossbedding is usually of the trough type, and the crossbeds are high angle (dips greater than 20° from horizontal) and large scale (fig. 8). This type of crossbedding commonly occurs in modern sand dunes. The lithology of the Lukachukai member is homogenous throughout the Navajo country. In the area between Chinle, Ariz., and the Four Corners (where Arizona, Colorado, New Mexico, and Utah have a common corner), limestone lenses are locally common and flat-bedded sandstone is associated with them.

At Fort Wingate the Lukachukai member overlies the "B" division of the Chinle formation, as the Rock Point member of the Wingate is not present. The basal boundary is a channeled surface overlain by a 6-inch granule conglomerate. In this locality the upper contact of the member is much more difficult to ascertain than the lower contact, as the basal part of the Entrada sandstone consists mainly of material reworked from the Wingate sandstone. In other areas, where the member is overlain by the Kayenta formation (pl. 2), the upper boundary of the Wingate sandstone is marked by an erosional unconformity. At Piute Mesa the channeled upper surface of the Wingate has as much as 15 feet of relief. However, toward the southwest, where the basal Dinosaur Canyon sandstone member of the Moenave formation is present, the unconformity is absent; and in the extreme southwestern part of the Navajo country, the Lukachukai member of the Wingate intertongues with the Dinosaur Canyon sandstone member of the Moenave.

The Lukachukai member of the Wingate sandstone is present throughout most of the Navajo Indian Reservation (fig. 3). However, it does not seem to have been deposited very far south of the Navajo country. In that direction its southern limit cannot be determined because pre-Cretaceous and more recent erosion has removed all Jurassic rocks. The Lukachukai as well as the Rock Point member does not occur in the extreme western part of the Navajo country. The Lukachukai member is present throughout eastern Utah and is well known as the basal unit of the Glen Canyon group. It is present also in the western part of Colorado, although absent in the extreme southwestern part, near Cortez. In New Mexico it is absent in the eastern part of the San Juan Basin but is present along the southern side.

Throughout the Navajo country the Lukachukai member of the Wingate sandstone is about 300 feet thick. From Fort Wingate eastward it is progressively thinner, being 75 feet thick at Staple, N. Mex., and 27 feet at Laguna; and it pinches out within 30 miles south of Laguna, N. Mex. (Silver, 1948, p. 68–81), and 15 miles east of Laguna (Rapaport, Hadfield, and Olson, 1952, p. 18). However, the member thins and pinches out to the west and south as well as to the east of the Navajo country. It is 127 feet thick at Piute Canyon, 17 feet at Navajo Creek, 74 feet at the southeastern end of Ward Terrace, about 25 feet at Tovar Mesa, 133 feet at Montezuma's Chair, and 113 feet at Steamboat Canyon, Ariz. Proceeding to the northwest along Ward Terrace, the Lukachukai member disappears between the Chinle and the basal member of the Moenave formation (pl. 2).

Along the southern limits of the Lukachukai (fig. 3), from the vicinity of Montezuma's Chair through Indian Wells, Steamboat Canyon, Chinle, and Lukachukai, Ariz., and through Toadlena, Todilto Park, Gallup, and Cheechilgeetho, N. Mex., the member intertongues with the Rock Point. The approximate limits of the eolian deposition of the Lukachukai member and the subaqueous deposition of the Rock Point member within the Navajo country are shown in figure 3.

Laboratory studies.—At the type locality of the Wingate sandstone, near Fort Wingate, sand in the Lukachukai member has a median diameter of 0.15 millimeter, which is about the average for the unit throughout the Navajo country. Median diameters as small as 0.063 millimeter (Ward Terrace) and as large as 0.250 millimeter (Thoreau) have been noted. The average coefficient of sorting at Fort Wingate is 1.34, which indicates poorer sorting than the average (1.23) for the member throughout the Navajo country. Subrounded grains constitute 60 percent of the member, subangular 35 percent, and angular 5 percent. The sphericity of grains in the Lukachukai member at Fort Wingate averages 0.79, which is about average for the unit elsewhere in the Navajo country. The skewness of 0.80 is slightly higher than the regional average.

In general, the Lukachukai member of the Wingate sandstone shows little or no regional trend in the range of sphericity and roundness. The sediments exhibit the greatest degree of skewness in the marginal areas of deposition, where the member was contaminated by sediments derived from bounding units. The sorting is generally very good except in the fringe areas where sorting is poor, owing to intermixture with the sediments of the Rock Point. The largest median diameter of grains occurs in the northern and eastern parts of the Navajo country.

The simplicity of the heavy-mineral suite in the Lukachukai member of the Wingate, the absence of platy and micaceous minerals, and the low carbonate-mineral content seem to substantiate an interpretation of eolian origin indicated by the sedimentary structures and the particle-size analyses. An eolian origin is further indicated by the presence of anatase, epidote, and titanite in areas where there is intertonguing with the Rock Point. These minerals are common in the Rock Point, and their general absence away from areas of intertonguing is what normally would be expected in an eolian deposit. A few miles north of Lukachukai (see unit 6, section 2, in Stratigraphic Sections p. 61) small vertebrate tracks were found which traverse a foreset slope in the Lukachukai member and cross a smaller trail, apparently made by a fairly large invertebrate. The presence of these trails and their relation to the depositional structures in the Lukachukai member, coupled with the mineral composition of the unit and its physical features, including its crossbedding, its areal distribution, and the nature of intertonguing with the Rock Point member, seem to establish conclusively that the member is primarily an eolian deposit.

The presence of heavy minerals such as zircon, tourmaline, and garnet suggests, as it does for the Rock Point member, that a large part of the material in the Lukachukai member was derived from older sediments. The "new" material seems to indicate acidic and ultrabasic terranes as a source of part of the sediments. The heavy-mineral suite is a reflection of the sources supplying the same minerals to the Rock Point member. In the later stages of the deposition of the Wingate, they reflect also the sources of the Dinosaur Canyon sandstone member of the Moenave formation.

MOENAVE FORMATION

Overlying the Wingate sandstone in most of the western part of the Navajo country is a sequence of rocks whose relationships have not been clearly recognized heretofore. This unit was included in the basal part of Ward's "Painted Desert beds" (1901). It was assigned by Gregory (1917) to the "Undifferentiated La Plata and McElmo of the Moenkopi Plateau." Because of its stratigraphic position, where the Wingate is absent, the unit has usually been assigned to the Wingate sandstone by subsequent workers, as was done by Wanek and Stephens (1953). However, lateral tracing has revealed that the unit overlies the Wingate sandstone in some areas and that in composition, depositional history, and stratigraphic position it is related more closely to the type Kayenta formation than it is to the Wingate. As it is a distinct mappable unit extending over large areas, it is herein defined as a separate formation in the Glen Canyon group, the Moenave formation of Triassic(?) age.

At the type locality, near Moenave, 6 miles west of Tuba City, Coconino County, Ariz., the Moenave formation is composed almost entirely of sandstone. Here, as in many areas to the west of the Navajo country, the formation consists of an upper cliff-forming sandstone and a lower slope-forming silty sandstone (fig. 9). These two units are herein recognized as members of the formation. Although the Moenave formation is introduced in this paper, these two members have been recognized by other workers in widely separated areas. The names previously established for these two units are used in this paper.

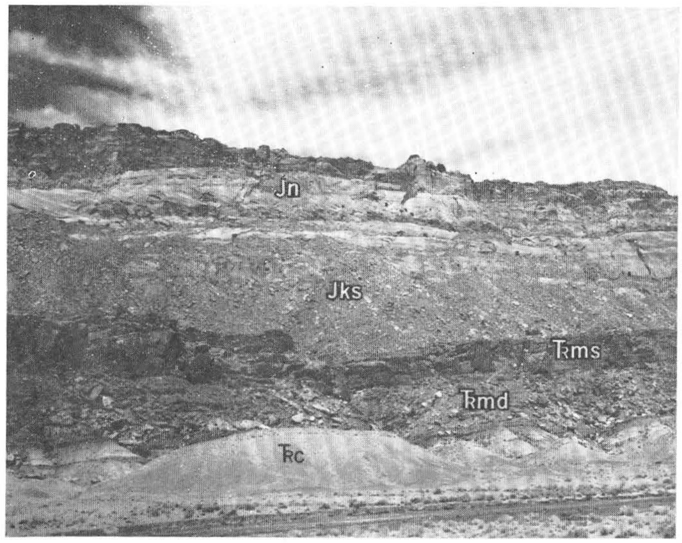

FIGURE 9.—Glen Canyon group along Echo Cliffs, 6 miles north of Moenave, Ariz. The upper part of the Chinle formation (Ŧc); Dinosaur Canyon sandstone member (Ŧmd) and Springdale sandstone member (Ŧms) of the Moenave formation; silty facies of the Kayenta formation (Jks); overlain by the Navajo sandstone (Jn).

The basal member of the Moenave formation, as herein defined, is the Dinosaur Canyon sandstone member (Colbert and Mook, 1951) and, at its type locality 19 miles south of the type locality of the Moenave formation, it is immediately overlain by a thick sequence of brownish-gray siltstone herein referred to as the silty facies of the Kayenta formation. At Kachina Point, 20 miles north of Leupp, Ariz., the Dinosaur Canyon sandstone member of the Moenave conformably overlies the Lukachukai member of the Wingate and conformably underlies the Kayenta formation.

To the northwest of Kachina Point, near Moenave, a prominent wedge of sandstone appears at the very top of the Dinosaur Canyon sandstone member, lying between the Dinasaur Canyon member and the Kayenta formation. This sandstone unit is traceable, along nearly continuous outcrops, to Kanab, Utah, where it has been described by Gregory as the Springdale sandstone member of the Chinle formation (Gregory, 1950, p. 67). Accordingly, the Springdale sandstone is herein reassigned, as a member, to the Moenave formation owing to the spatial relations in the Navajo country. Descriptive sections of the Moenave formation and its members are given in that part of this report entitled Stratigraphic Sections.

DINOSAUR CANYON SANDSTONE MEMBER

The Dinosaur Canyon sandstone member of the Moenave formation was named after Dinosaur Canyon, 10 miles east of Cameron, Coconino County, Ariz., by Colbert and Mook (1951, p. 151); it is exposed at the head of the canyon. In view of the fairly inaccessible nature of the type locality, it seems advisable to mention that the Dinosaur Canyon member is completely and excellently exposed in the cliffs of Kachina Point, 40 miles northwest of Winslow, Navajo County, Ariz. Distribution, lithology, sedimentary structures, and depositional sequence have demonstrated a relationship of the Dinosaur Canyon sandstone member of the Kayenta formation. However, the character of the Dinosaur Canyon and Springdale sandstone members in outcrops is sufficiently distinctive to warrant their recognition as members of a separate formation.

The Dinosaur Canyon sandstone member of the Moenave has, for many years, been referred to as the "Orange-red sandstone," originally described by Ward (1901, p. 413) as the basal unit in the "Painted Desert beds." Ward's use of the term "Painted Desert beds" has 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" represent the Glen Canyon group and include the Dinosaur Canyon sandstone 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 sandstones").

Gregory (1917, p. 66) described Ward's "Painted Desert beds" as "Undifferentiated La Plata and McElmo of the Moenkopi Plateau," and, although he did not differentiate them on his map or in his descriptive sections, he recognized the units described by Ward. Also, he correlated Ward's "Brown and white sandstones" with the Navajo sandstone to the north. Colbert and Mook recognized the Kayenta and, erroneously, the Wingate sandstone between the Dinosaur Canyon and the Navajo, thus suggesting a correlation of the Dinosaur Canyon with the "A" division of the Chinle herein referred to as the Rock Point member of the Wingate. Regional studies have since demonstrated that both the Rock Point member and the Lukachukai member of the Wingate pinch out to the east of Dinosaur Canyon, along the southeastern end of Ward Terrace.

The Dinosaur Canyon sandstone member of the Moenave is confined mostly to the southwestern part of the Navajo country (fig. 10). However, the unit can be traced beyond the borders of the Navajo country and is believed to be represented by 145 feet of red sediments lying between the marls of the Petrified Forest member of the Chinle and the Springdale sandstone member of the Moenave at Kanab, Utah. It is believed to be present also, at the same horizon but with a range in thickness, along most of the Vermilion Cliffs of southern Utah.

General description and field relations.—At the type locality the Dinosaur Canyon sandstone member of the Moenave consists of a sequence of lenticular units which are predominantly of fluvial origin but include an appreciable amount of eolian sandstone which is most conspicuous near the base. The overall color is about moderate reddish orange (10*R*6/6); however, closer inspection shows a surprising amount of light-brown to brownish-gray rocks in many of the units. The member crops out either as a vertical blocky cliff, as at Kachina Point (fig. 11), or as an extremely rough and irregular terrain marked by countless pillars and knobby red hills, as at the head of Dinosaur Canyon.

At the type locality the Dinosaur Canyon sandstone member comprises coarse- to very fine-grained quartz sand and a large amount of silt, which is concentrated in the finer grained units. In general, the silt content increases from east to west. Granule stringers are locally present in the channels at the base of individual fluvial units. Grains are mainly subrounded to subangular quartz. Most of the sandstone is poorly sorted and has a firm calcareous cement. Accessory minerals are rare. Argillaceous material is fairly common in the fluvial units, both as interstitial material and as flakes of mudstone.

The beds of the member are extremely lenticular, and individual beds range in thickness from 1 foot to 20 feet. These beds include two major rock types, one considered to be of eolian origin and the other, fluvial. Crossbedding is mostly of the trough type in both the fluvial and eolian deposits; however, the bedding in the eolian units is on a markedly larger scale and is at steeper angles than that in the fluvial units. In general, fluvial lenses are more drab in color, coarse in grain, and poor in sorting. Where the fluvial units rest upon the eolian deposits, the contact between them is marked by an irregular erosion surface. These relationships appear to indicate that the eolian beds originally had a greater extent but subsequently were partially removed by the streams that deposited the succeeding fluvial unit.

At its type locality the Dinosaur Canyon sandstone member unconformably overlies the Chinle formation (fig. 12). The unconformity is marked by an erosion surface showing minor channeling. A thin, 2- to 5-

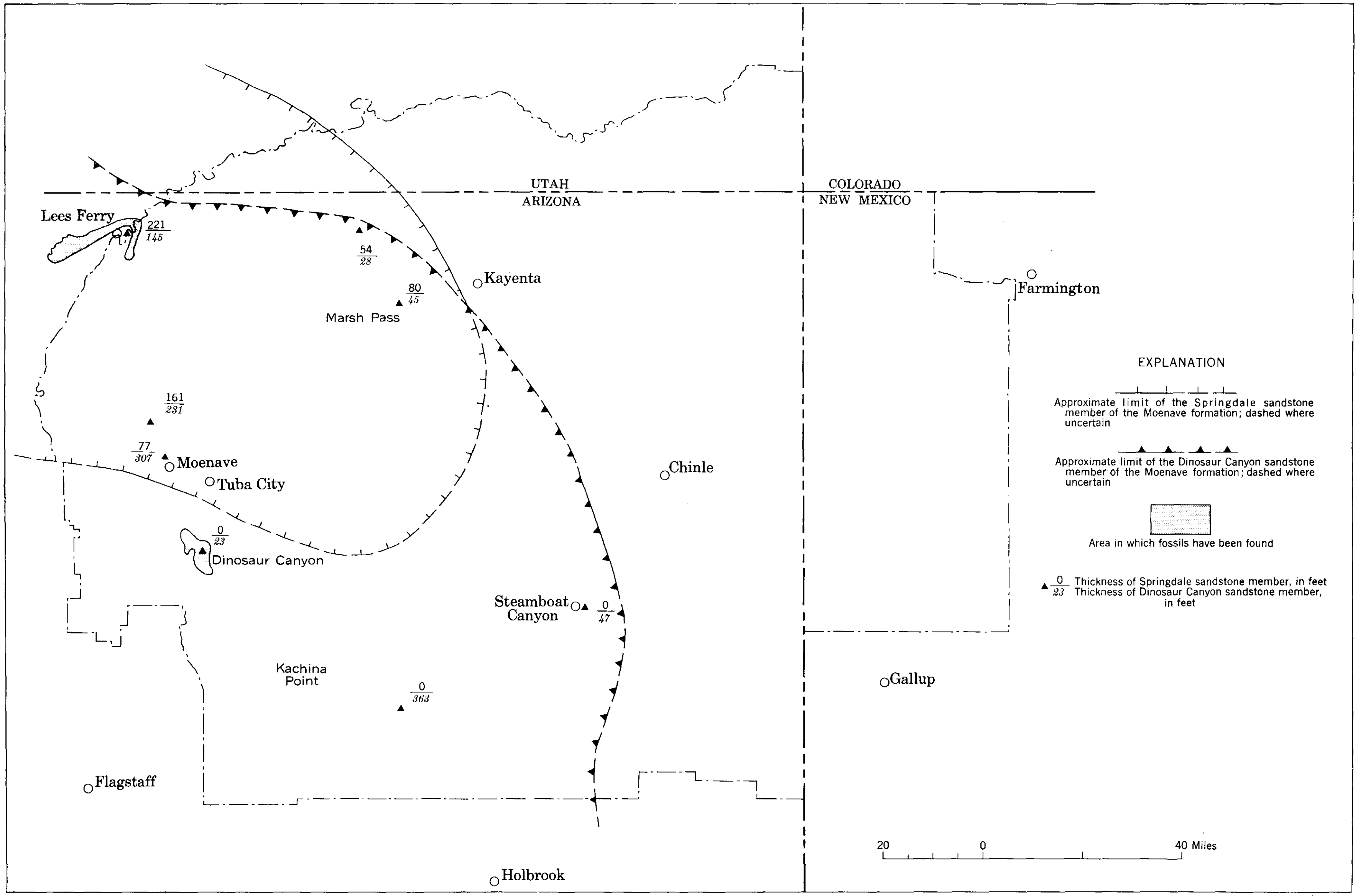

FIGURE 10.—Map of the Navajo country showing approximate depositional areas of the Dinosaur Canyon sandstone and Springdale sandstone members of the Moenave formation.

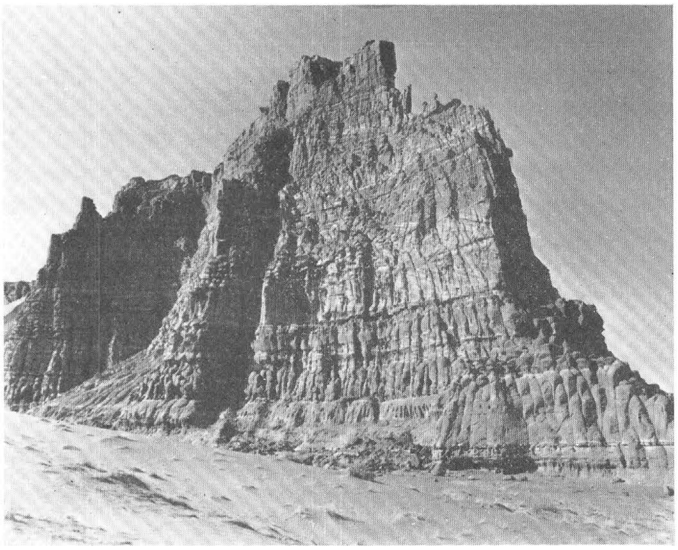

FIGURE 11.—Dinosaur Canyon sandstone member of the Moenave formation at Kachina Point, 20 miles north of Leupp, Ariz., showing upper part of Lukachukai member of the Wingate sandstone, Dinosaur Canyon sandstone, and cliff capped by the lower part of the silty facies of the Kayenta formation.

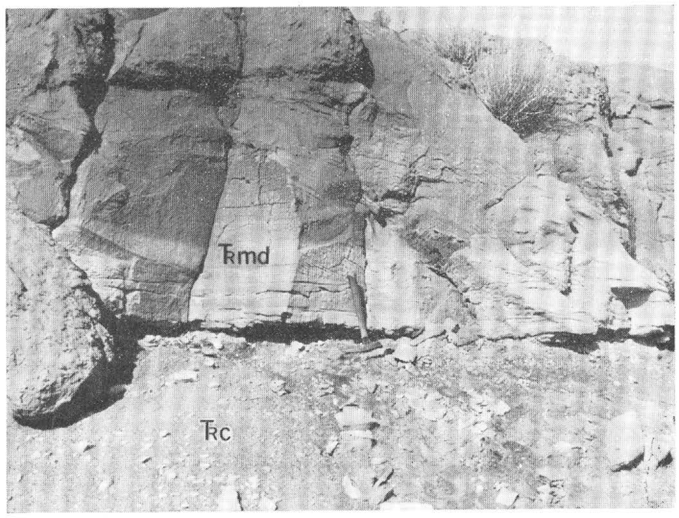

FIGURE 12.—Contact between the Chinle formation (T̄Rc) and the Dinosaur Canyon sandstone member of the Moenave formation (T̄Rmd) near Dinosaur Canyon, Ariz.

inch basal conglomerate is present in many places and is composed mainly of material derived from the underlying Chinle (Callahan, 1951, p. 51). At Kachina Point the upper boundary of the Dinosaur Canyon sandstone member is placed at the base of a conspicuous cherty limestone which can be traced about 30 miles to the east into the Hopi Buttes area. To the west, along the cliffs above Ward Terrace, the limestone can be traced for a few miles to where it pinches out. Beyond the point of disappearance of the limestone, this horizon can be traced as a conspicuous bedding plane to about 15 miles west of Kachina Point. Beyond this locality, the boundary between the Dinosaur Canyon sandstone member and the silty facies of the Kayenta is gradational, and, at Dinosaur Canyon, the contact is arbitrarily located on the basis of gross lithologic differences between the sandstone of the Dinosaur Canyon member and the siltstone of the Kayenta.

East of the type locality the Dinosaur Canyon sandstone member contains more lenses of eolian sandstone than it does to the west, and the basal part intertongues with the upper part of the Lukachukai member of the Wingate sandstone. West of the type area the eolian deposits are fewer, and they are absent along the Echo Cliffs. Likewise, the extremely lenticular character of the member is more conspicuous at the type locality than to the west, and in the Echo Cliffs area the unit consists of thin flat-bedded strata.

The Dinosaur Canyon sandstone member of the Moenave formation is 202 feet thick at its type locality. However, the thickness differs locally and is 307 feet at Moenave and 321 feet to the southeast at Kachina Point (pl. 2). From the type locality the member thins toward the northeast and is 110 feet thick at Navajo Creek, 28 feet at Piute Canyon, and 47 feet at Steamboat Canyon. It is not present in the northeastern half of the Navajo country (fig. 10). The available data on the thickness of the Dinosaur Canyon sandstone member indicate that the center of the depositional basin was west of that of the Wingate sandstone. The basin of deposition occupied by the Kayenta formation appears to coincide approximately with that of the Dinosaur Canyon sandstone member in the Navajo country.

Laboratory studies.—At the type locality of the Dinosaur Canyon sandstone member of the Moenave formation, the median diameter of all samples from the unit averages 0.256 millimeter, which is about average for the entire unit within the Navajo country. The average coefficient of sorting is 1.40 at the type locality. This is one of the areas having the most poorly sorted sediments of the member, as the average coefficient of sorting in all samples studied from the member is 1.27. Roundness studies indicate that subrounded grains constitute about 26 percent of the samples, subangular grains, 66 percent, and angular grains, 8 percent. The average sphericity is 0.82 in the type area, but this is considerably higher than the average for the member in the Navajo country, which is 0.77. This higher sphericity may be attributed to the relatively great amount of eolian deposits at the type locality. Skewness at the type locality averages 1.00, about average for the unit within the Navajo country.

The greatest sphericity of the sediments in the Dinosaur Canyon sandstone member is at Betatakin Ruin. This area is near the northeastern limit of the member, and here the unit consists mainly of windblown sand probably reworked from the Lukachukai member of the Wingate sandstone. The roundness of the grains generally decreases toward the south, and angular grains are most prevalent in the extreme southern part of the area. The greatest skewness is found in samples from the Kachina Point and Montezuma's Chair areas. The sediments of this member generally have a more narrow range of skewness than do those of the Kayenta. Sorting is the poorest at Montezuma's Chair, but the degree of sorting improves to the west and northwest of this area, with an exception at the type locality. No trends were observed in laboratory examinations of median diameter or percentage of carbonate minerals. The carbonate-mineral content of the Dinosaur Canyon sandstone member is considerably lower than that of the Rock Point member of the Wingate, although somewhat higher than that of the Lukachukai member of the Wingate, and is about the same as in the Kayenta. The results of the particle-size analyses seem to indicate that the source area of the deposits was to the southeast of the Navajo country, because of increased angularity and poorer sorting in the southern part of the area. The sorting in the Dinosaur Canyon is erratic and generally slightly poorer than that in the Wingate, suggesting a large percentage of fluvial sediments.

The Dinosaur Canyon sandstone member contains a greater variety of heavy minerals than does the underlying Wingate sandstone. Minerals in the Dinosaur Canyon that are not present in the underlying Lukachukai member of the Wingate are as follows: Glaucophane, andalusite, hypersthene, augite, enstatite, and kyanite. The additional minerals indicate that sediment was brought into the basin from new sources. The garnet content is higher than in the Wingate. Amphibole, staurolite, sillimanite, and andalusite are common at the type locality. The occurrence of these metamorphic minerals suggest a local source. Anatase, augite, and diopside seem concentrated in the southeastern part of the area. Epidote is scarce in the northern part of the area, and titanite is absent in the northeastern border areas, but both are common elsewhere.

The Dinosaur Canyon sandstone member also contains several minerals not observed in the Kayenta formation, including actinolite, tremolite, glaucophane, corundum, kyanite, sillimanite, staurolite, and titanite. Topaz and fluorite, which are present throughout most of the Kayenta formation, are not observed in the Dinosaur Canyon sandstone member. The general increase in mica suggests a subaqueous environment. In general, the heavy-mineral suite of the Dinosaur Canyon sandstone member suggests a mixture of minerals from the source areas of both the Kayenta and the Wingate.

Fossil occurrences.—A few fossils have been found in the Dinosaur Canyon sandstone member of the Moenave formation. Between 1931 and 1934, Barnum Brown collected six specimens of the primitive crocodile *Protosuchus* from the unit near the head of Dinosaur Canyon. Samuel P. Welles visited the area in 1941 and collected a partial skeleton of this animal. Colbert and Mook (1951) give a complete description of *Protosuchus* and define the unit from which the fossil was taken as the Dinosaur Canyon sandstone. They state that the relationship of *Protosuchus* to other known primitive crocodilians is suggestive of a Triassic age (1951, p. 180), although they state that such a suggestion of age should be substantiated by other evidence.

Along the Vermilion Cliffs in Arizona, fish remains are locally common in the upper part of the Dinosaur Canyon sandstone member, beneath the Springdale sandstone member. These remains are considered by Schaeffer and Dunkle (1950) to be of Triassic age. (See Fossil Occurrences, Springdale sandstone member.)

SPRINGDALE SANDSTONE MEMBER

The Springdale sandstone was named by Gregory (1950, p. 67) after the village of Springdale, Washington County, Utah, where the unit forms a prominent cliff. He assigned this sandstone unit to the Chinle formation. Recent work, however, has shown that the Springdale sandstone is traceable, by nearly continuous outcrops, from Kanab, Utah, along the Vermilion Cliffs to Lees Ferry, Ariz., and thence southward along the Echo Cliffs. In the Echo Cliffs area this sandstone unit had previously been referred to as the Wingate sandstone (Callahan, 1951, and Wanek and Stephens, 1953). Geologic studies in the Navajo country have established that the Springdale is stratigraphically higher than the Wingate sandstone, and these stratal relations are clearly recognizable along Ward Terrace (pl. 2). The Springdale member has been recognized as a mappable unit, beneath the base of the Kayenta formation, as far east as Marsh Pass, 12 miles west of Kayenta, Ariz. (fig. 10). Consequently, the authors believe that the Springdale should be removed from the Chinle formation, and herein it is defined as a member of the Moenave formation.

General description and field relations.—Gregory (1950, p. 67) reports that in the type area the Springdale sandstone appears from a distance as a single massive bed "which retains its form and thickness as far as the eye can reach. Near views show it to be a series of laminated, in places ripple-marked and cross-bedded ledges and lenses, most of them less than 300 feet long and 30 feet thick." He reports that shale lenses and mud pockets are common in this unit.

He refers also to the existence of an unconformity at the base of the unit marked by "angular gravel, sun-baked surfaces and cracks, and balls and slabs of blue-green shale." Without exception, his description can be applied to the exposures of this member throughout the Navajo country.

Within the area of this report, the Springdale is a pale-red (10*R*6/2) to pale-reddish-brown (10*R*5/4) fine- to medium-grained sandstone. The grains are subangular to angular. It has a firm calcareous cement and therefore weathers into a prominent ledge. The member contains many claystone lenses and conglomeratic zones. Crossbedding is common and is mostly of the trough type. Crossbeds are usually medium scale and were formed at low angles. The member is extremely lenticular, showing a marked similarity to ledges in the Kayenta formation. A channeled erosion surface in most places underlies the unit. In the vicinity of Moenave the member grades into the uppermost part of the Dinosaur Canyon sandstone member. Northeast of the Echo Cliffs the unit is thinner, and east of Marsh Pass it is inseparable from the Kayenta formation, owing to an increase in sand content in the Kayenta. Because of this, the unit is not recognizable northeast of Kayenta, Ariz., or Paria, Utah (Gregory, 1950, p. 67).

In most parts of the Navajo country the Springdale sandstone member of the Moenave formation is 100 to 150 feet thick. The thickness differs locally, owing to the lenticular nature of the sandstone units that form the member. Along the Echo Cliffs the member is progressively thinner to the southeast, ranging from 221 feet at Lees Ferry to 161 feet at Gap and to 77 feet at Moenave, just west of Tuba City. Farther southeast the member grades into the upper part of the Dinosaur Canyon sandstone member. The Springdale sandstone member is 127 feet thick in Navajo Creek, 168 feet on Piute Mesa at the Utah-Arizona State boundary, and 80 feet at Betatakin Ruin, just west of Marsh Pass. Northeast of Marsh Pass it cannot be distinguished from the ledges of the Kayenta formation.

Laboratory studies.—Within the Navajo country the carbonate-mineral content of all samples from the Springdale averages about 8 percent. The median diameter of the sediments averages 0.91 millimeter. The coefficient of sorting averages 1.36; the sphericity averages 0.77; and the skewness averages 1.00. Subrounded grains average 17 percent; subangular, 41 percent; and angular, 42 percent in samples studied. The median diameter decreases consistently, and the sphericity increases toward the southwestern part of the area. Angular grains are more common in the northeastern part, and angularity seems to decrease consistently toward the southwest. No regional trends are notable in the range of skewness or sorting. The heavy-mineral determinations show a metamorphic-mineral suite similar to that in the Dinosaur Canyon sandstone member.

Fossil occurrences.—Within the Navajo country no fossils have been found in the Springdale sandstone member of the Moenave formation. However, Eastman (1911, 1917), Hesse (1935), and Schaeffer and Dunkle (1950) have reported on fossil fish which were collected from either the Springdale or from beds immediately below in the Dinosaur Canyon sandstone member northwest of the Navajo country at Kanab, Utah. Eastman at first (1911) concluded that these fish were of Early Jurassic age; however, later (1917) he assigned the fish a Late Triassic age, as have subsequent workers. At the time these fish were described, it was believed that they came from the Chinle formation.

KAYENTA FORMATION

The sequence of rocks now referred to as the Kayenta formation of Jurassic(?) age was originally described by Gregory (1917, p. 56) as a sandy facies of the Todilto formation. The lithology of this sequence was so different from that of the type Todilto that he regarded its correlation with the Todilto only as a working field hypothesis. Subsequent work substantiated his doubts and in 1931 Baker, Dane, and McKnight introduced the term "Kayenta formation" to replace Todilto(?) where applied to the red sandy unit overlying the Wingate sandstone in the Glen Canyon of the Colorado River. A characteristic exposure of this unit occurs at the type locality near Kayenta, Ariz. (fig. 13), although differences in lithology are quite pronounced in different parts of the Colorado Plateau. The formation has been mapped over wide areas in southeastern Utah, western Colorado, and northeastern Arizona.

Two facies of the Kayenta formation are recognized in the Navajo country. At its type locality the Kayenta is represented by a sandstone facies typical of the formation throughout most of the Colorado Plateau. To the southwest of the type locality, the Kayenta increases rapidly in thickness and silt content. About 75 miles southwest of Kayenta, in the vicinity of Tuba City, the formation is represented by a silty facies (fig. 14) which is markedly different in outcrop character from the sandstone facies. Because of the lithologic difference between these two facies of the Kayenta, they are discussed as the typical facies and as the silty facies in this report. The typical and silty facies of the Kayenta formation represent a lateral variation of deposition within a single basin (pl. 2). Descriptions of measured sections of these two facies are given in this report under the heading of Stratigraphic Sections.

General description and field relations.—The Kayenta formation, at its type locality (fig. 13) about a mile northeast of Kayenta, is 144 feet thick (Baker, Dane, and Reeside, 1936, p. 5). At the type locality it rests on an eroded surface on the Wingate sandstone. The upper boundary of the formation is arbitrary, as the Kayenta intertongues with the basal part of the Navajo sandstone. Consequently, tongues of the Navajo sandstone are common in the upper part of the Kayenta, and their extent and thickness differ.

At the type locality the formation consists of the typical facies. This facies of the Kayenta weathers into an irregular series of ledges between the massive cliffs of the Navajo and Wingate sandstones. In general, this facies consists of a pale-red-purple (5*RP* 6/2) to pale-reddish-brown (10*R* 5/4) fine-grained quartz sandstone interbedded with grayish-red mudstone. The grains are subrounded to subangular and bonded with calcareous cement. All the units are lenticular, and the sandstone exhibits trough-type small- to medium-scale low-angle crossbedding. Clay flakes are common in the sandstone, and most of the units have a channeled surface at their base.

The typical facies of the Kayenta formation grades into an intercalated siltstone, mudstone, and sandstone sequence in the southwestern part of the Navajo country. This gradation is well shown along the Echo Cliffs. In the vicinity of Tuba City the Kayenta formation is completely dissimilar in appearance to the formation as exposed at the type locality; therefore, the rocks of the formation in this area are herein called

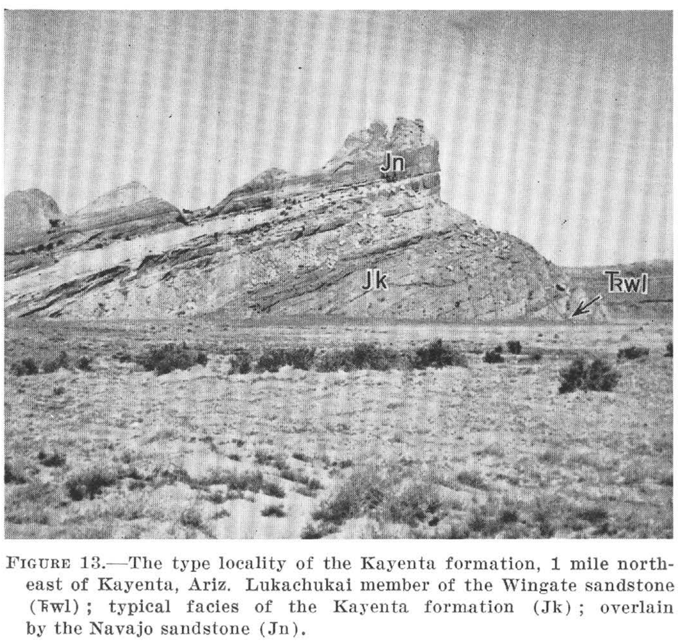

FIGURE 13.—The type locality of the Kayenta formation, 1 mile northeast of Kayenta, Ariz. Lukachukai member of the Wingate sandstone (Ꞧwl); typical facies of the Kayenta formation (Jk); overlain by the Navajo sandstone (Jn).

FIGURE 14.—The silty facies of the Kayenta formation, 3 miles southwest of Tuba City, Ariz.

the silty facies (fig. 14) of the Kayenta. In the Tuba City area the Kayenta formation conformably overlies the Moenave formation. It intertongues with the basal part of the Navajo sandstone throughout its area of occurrence in the Navajo country. Because of the presence of sandstone tongues in the silty facies, its upper part appears similar to the typical facies. However, lateral tracing has established the equivalence of the entire formation in the two localities.

The strata of the silty facies of the Kayenta formation were referred to by Ward (1901, p. 413) who described them as the "Variegated sandstones, regularly stratified and brilliantly colored; the well-known Painted Cliffs." At Moenave the silty facies of the Kayenta formation consists of 495 feet of fine-grained sandstone and mudstone. Most of the sand grains are subrounded to subangular. The bedding is lenticular, and crossbedding is common in the sandy units. Much of the mudstone occurs as flat thin- to very thin-bedded units. Locally, thin limestone ledges occur in the upper part of the member. The entire unit is banded pale red (10*R* 6/2) and grayish red (10*R* 4/2), but the overall color more nearly approximates pale red (section 3, Stratigraphic Sections).

The silty facies weathers into irregular badlands. The outcrop area is marked by rounded hills and earth pillars (demoiselles) having resistant caprocks. The silty facies has outcrops that are strikingly similar to those of the Petrified Forest member of the Chinle formation, except for their color (fig. 14).

The Kayenta formation is 55 feet thick at Rock Point, near its eastern limit, and is 144 feet thick at Kayenta. Westward from Kayenta the formation has essentially the same thickness, as it is 121 feet near Marsh Pass and 153 feet at Navajo Creek. At Gap it has a thickness of 466 feet because it includes many silty units that are tongues of the silty facies. To the south of Gap the Kayenta is 495 feet thick at Moenave and is 678 feet thick along Ward Terrace, the greatest measured thickness of the formation in the Navajo country. The Kayenta pinches out to the east and southeast of Black Mesa and is absent in the southeastern part of the Navajo country (fig. 15). Because of the relationships between the silty and typical facies of the Kayenta, it is difficult to designate the place where the one term is to be abandoned and the other used. In the vicinity of Gap (pl. 2) the formation consists of an alternation of strata of both the facies. This alternation is characteristic of the Kayenta over wide areas to the northwest of the Navajo country. In mapping the geology of the Navajo country, the practice has been to apply the term "silty facies" to the rocks of the Kayenta formation beyond the point where essentially all the ledges characteristic of the typical facies are absent. According to this usage, the unit that crops out along most of the Vermilion Cliffs, between the Navajo sandstone above and the Springdale sandstone member of the Moenave formation below, would be considered the typical facies of the Kayenta formation. The Kayenta formation of southeastern Utah and western Colorado would also be considered the typical facies.

Laboratory studies.—Although the laboratory studies of sediments of the Kayenta formation are perhaps insufficient for conclusive interpretation, the results are worth recording. The sediments at the type locality have an average median diameter of 0.12 millimeter. Rounded grains make up about 2 percent; subrounded grains, 37 percent; and subangular grains, 61 percent of the formation. The sphericity averages 0.75. The best sorting of the sediments within the formation occurs in the area near the formational pinchout where the sandstone facies is present. The poorly sorted sediments are present in the areas where alternation of strata of both facies are conspicuous. In the Tuba City area the silty facies has an average median diameter of 0.06 millimeter. The poorest sorting of the sediments in the formation is near its southern limit, where it is represented by the silty facies. For example, the coefficient of sorting of the rocks of the Kayenta averages 2.24 at Montezuma's Chair. The average coefficient of sorting of the formation throughout the Navajo country is 1.29. The poor sorting at Montezuma's Chair is due to the local presence of medium-grained sand in the silty facies. It is believed that this sand was derived from nearby areas of nondeposition.

Fossil occurrences.—Baker (1933, p. 46) reports the occurrence of the fresh-water mussel *Unio* in the Kayenta formation near Moab, Utah, and Gregory (1917, p. 68) reports the occurrence of two new species of fresh-water gastropods. Gregory (1917, p. 56) also reports dinosaur tracks in the Kayenta in the Navajo Creek area. Dinosaur tracks are fairly common in the silty facies of the Kayenta.

One complete and one partial skeleton of a new species of dinosaur have been removed from the basal part of the Kayenta near Moenave by S. P. Welles. He states (1954, p. 597) that these dinosaurs appear to be of Early to Middle Jurassic age. Remains of two other reptiles have been found in the Kayenta; the most complete of these was discovered in 1952 by Benjamin C. Hoy about 10 feet below the base of the Navajo sandstone and about 7 miles northeast of Kayenta, Ariz. Preliminary study of these fossils by G. E. Lewis (written communication, 1954) indicates that they belong to the superfamily Tritylodontoidea, which represent the evolutionary position between Reptilia and Mammalia. This is the first discovery of these rare animals in the Western Hemisphere, and, indeed, they are little known throughout the world. All known tritylodonts occur in rocks considered to be of Late Triassic and Early and Middle Jurassic age. Although preparation and study of the fossils are incomplete, the Kayenta Tritylodontoids seem to be closest to Old World forms generally referred to the Upper Triassic.

NAVAJO SANDSTONE

The uppermost formation of the Glen Canyon group is the Navajo sandstone of Jurassic age, named by Gregory (1917, p. 57–59). The type locality as given by Gregory is the Navajo country in general. This sandstone is one of the most conspicuous formations in the region and is widely recognized over most of the Colorado Plateau. It has been correlated with the Aztec sandstone (Baker, Dane, and Reeside, 1936, pl. 3) of southern Nevada and with the Nugget sandstone in the Wasatch Mountains, Utah (fig. 2, idem, and Imlay, 1952, chart 8–C). The Navajo sandstone is absent in the southeastern part of the Navajo country (fig. 16).

General description and field relations.—The Navajo sandstone ranges from very pale orange (10*YR* 8/2) to pale reddish brown (10*R* 5/4). It is composed of medium- to fine-grained subrounded quartz grains and in most places is bonded with a weak calcareous cement. The formation has a remarkably consistent lithology throughout the Navajo country. It contains many lenticular beds of cherty limestone. These beds form conspicuous ledges in the southern part of the area, between Tuba City and the Hopi Buttes.

The crossbedding in the Navajo sandstone is one of its most conspicuous features. It is typically large

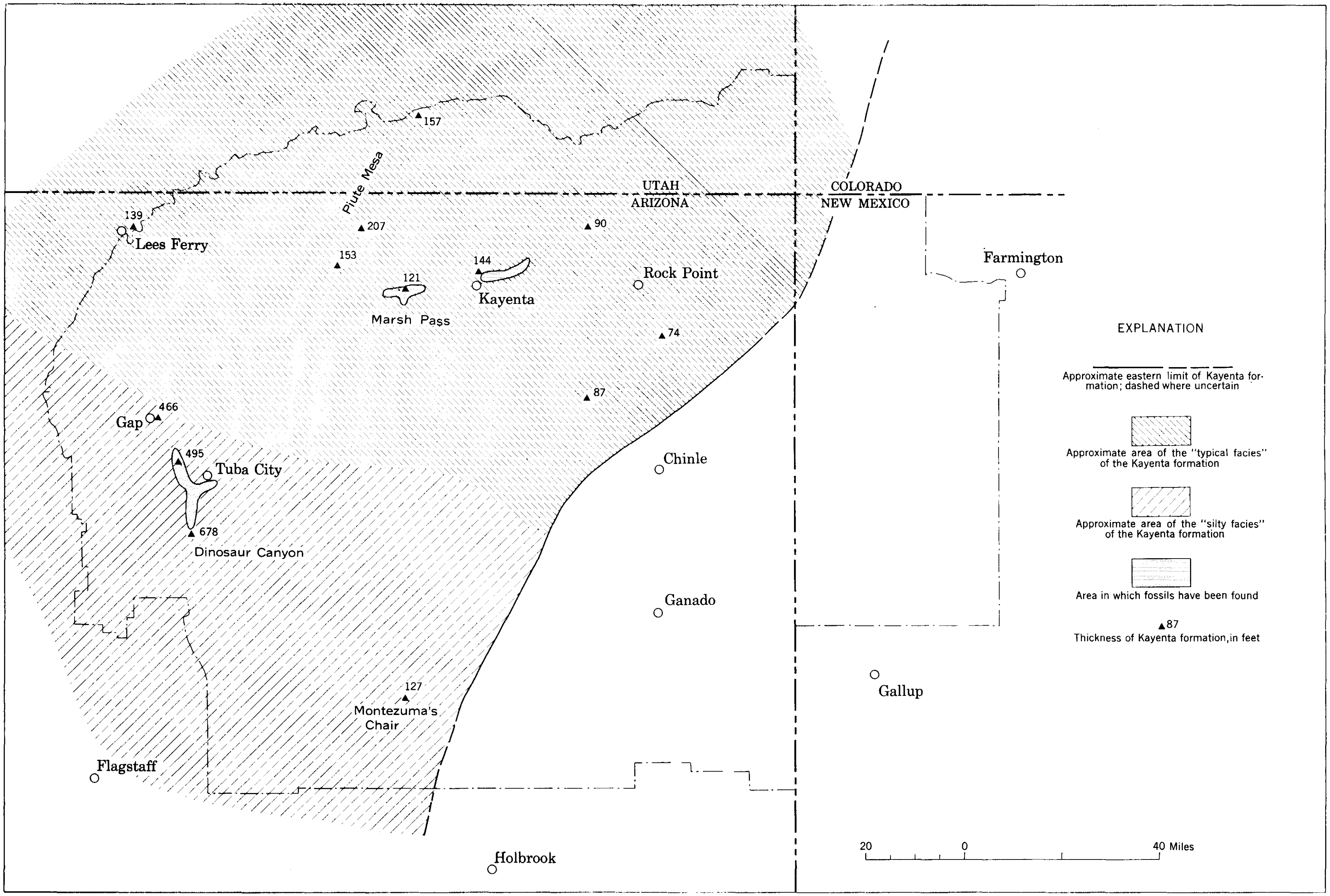

FIGURE 15.—Map of the Navajo country showing approximate depositional area of the Kayenta formation.

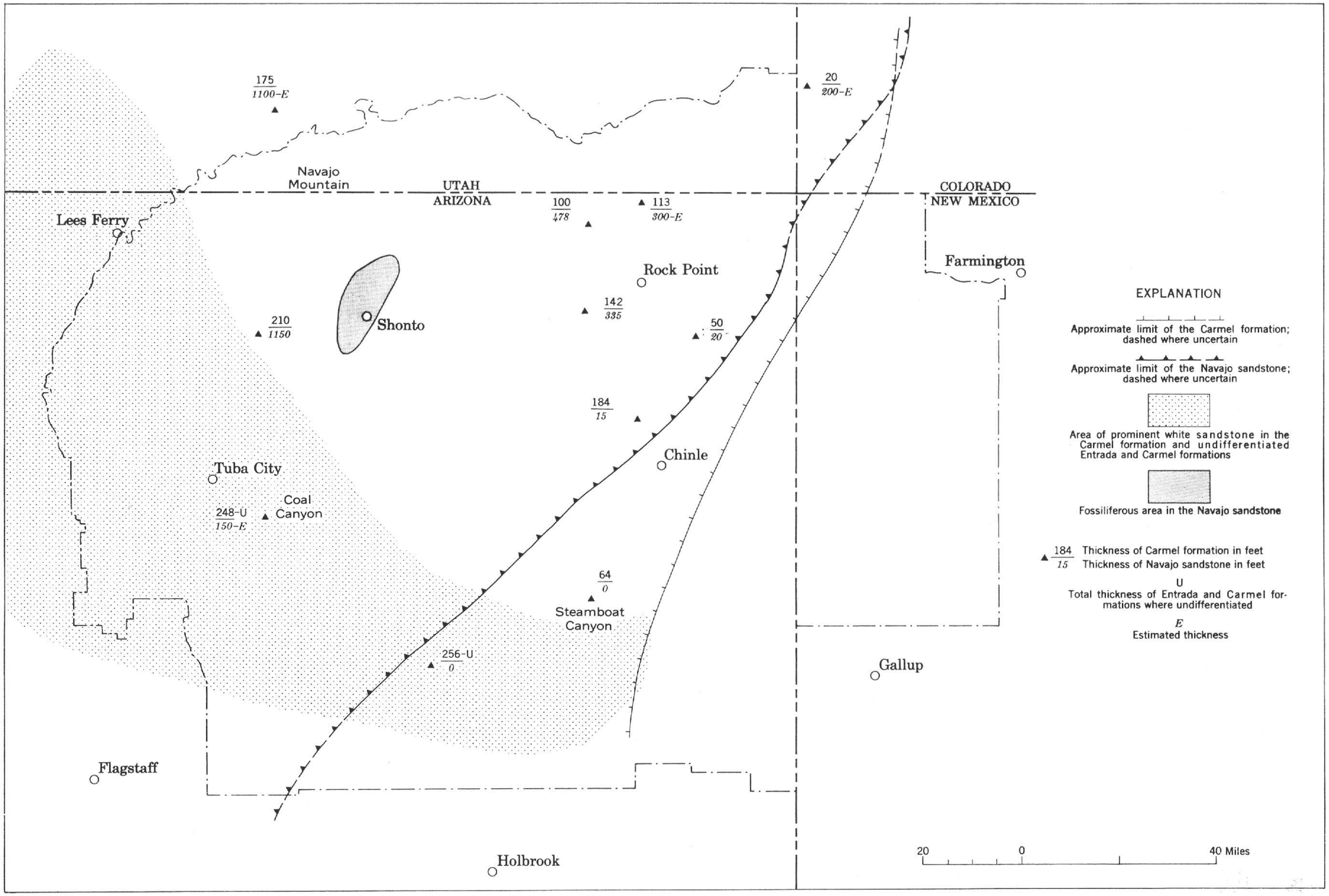

FIGURE 16.—Map of the Navajo country showing approximate depositional areas of the Navajo sandstone and the Carmel formation.

scale and high angle and of the trough type (fig. 17). These bedding features are identical to those in modern dunes of the transverse and barchan types. Therefore, the interpretation of an eolian origin for the Navajo sandstone is supported by its crossbedding. The many criteria cited by Baker, Dane, and Reeside (1936, p. 52–53) and also the unique position of burial of the small dinosaur described by Camp substantiate the concept of eolian origin. According to V. L. Vanderhoff (*in* Camp, 1936, p. 39–40) the dinosaur "lay on a tilted plane parallel to the planes of crossbedding of the Navajo sandstone at that point. The axis of the body was horizontal and the right hind foot was pressed into the sand above the level of the left." Camp later states (1936, p. 41) that "Apparently the animal had been covered by shifting sand before death, or soon after. It lay in a squatting posture with the body extended and the hind feet drawn up tightly beneath the pelvis." The crossbedding in the Navajo sandstone is modified in many places by peculiar slumpage pattern which appear to be due to a combination og oversteepening of the dune profile and seepage of ground water (Kiersch, 1950, p. 923–942).

The Navajo sandstone is perhaps the most conspicuous formation seen in the area of this study. It has a larger outcrop area than any of the other Jurassic formations in the Navajo country. Characteristically it weathers into rounded hills and domes in which the conspicuous crossbedding is etched out by erosion. Across vast areas of the Navajo country it weathers into a very rough surface and is dissected by deep, sheer-walled canyons. Much of the outcrop area is completely devoid of soil and vegetation. The uniformity of the lithology is favorable for the development of natural bridges and arches by weathering, and the Navajo sandstone is famous for these features. The Navajo sandstone is unequaled in the Colorado Plateau for impressiveness of topographic expression.

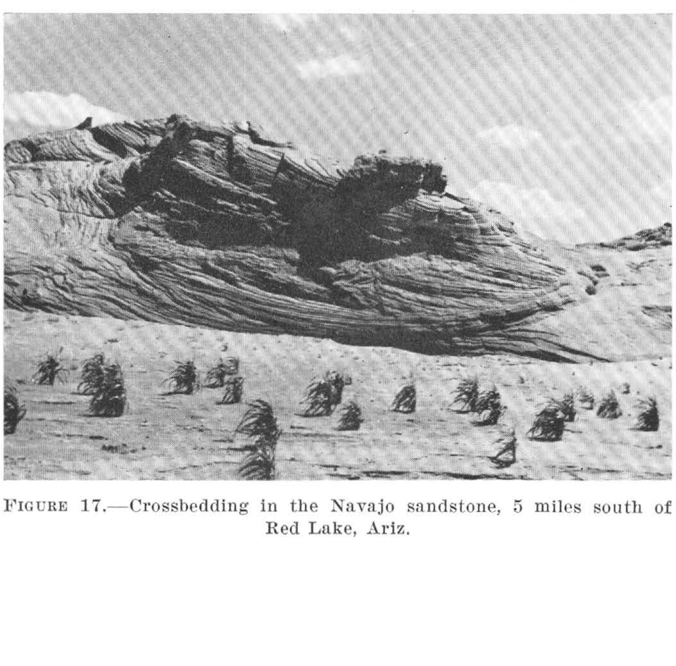

FIGURE 17.—Crossbedding in the Navajo sandstone, 5 miles south of Red Lake, Ariz.

Within the Navajo country the Navajo sandstone attains its greatest thickness in the northwestern part, where it is about 1,400 feet thick. It is thinner to the southeast of this area, having a thickness of 1,150 feet at Kaibito, 950 feet near Shonto, 478 feet near Dinnehotso, 335 feet at Rock Point, and 15 feet northwest of Chinle. This sandstone does not occur along the southern flanks of the Definance uplift, and it is absent in most of New Mexico (fig. 16). The eastern limit has a southwest alinement extending from the Carrizo Mountains to the Hopi Buttes area.

In the Navajo country the Navajo sandstone intertongues with the underlying fluvial deposits of the Kayenta formation. The general alinement of tongues of the Navajo is southeastward. This sandstone is unconformably overlain by the Middle and Upper Jurassic (Imlay, 1952, p. 963–964) Carmel formation. A detailed description of this boundary is given in the discussion of the San Rafael group.

Laboratory studies.—The Navajo sandstone is bonded chiefly with calcareous cement but contains also minor amounts of siliceous cement. The average median diameter of the sandstone grains is 0.21 millimeter. The average coefficient of sorting is 1.18. Most of the grains are subrounded to subangular, although some samples contain as much as 25 percent of rounded grains. The average sphericity is 0.85, which indicates that the grains are nearly equant. The average coefficient of skewness is 0.94, indicating that the coarser grains are better sorted than the finer.

The Navajo sandstone consists chiefly of quartz grains, which make up about 98 percent of the total sample. Feldspar is present in most samples but not in amounts greater than 2 percent. Plagioclase is the predominant feldspar; orthoclase is present in minor amounts. The heavy-mineral fraction invariably makes up less than 0.5 percent of a sample. The heavy minerals in order of their abundance are as follows: Magnetite (making up more than half the total fraction), ilmenite, leucoxene, tourmaline, zircon, garnet, and staurolite. No attempt was made to determine regional trends of mineral occurrence or of the physical character of grains because of the small number of samples studied.

Fossil occurrences.—Brady (1935) and Camp (1936) have described small primitive bipedal dinosaurs from the upper part of the Navajo sandstone; both occurrences are near Shonto, Ariz. More recently, organic remains have been found in two limestone lenses in the upper part of the Navajo sandstone, also near Shonto. From this collection a small bivalved crustacean was identified by J. B. Reeside, Jr., as *Cyzicus* ("*Estheria*") aff. *C. ovata* (Lea); abundant but nondescript smooth-shelled ostracodes similar to *Candona* sp. were examined by I. G. Sohn and R. E. Peck, and *Equisetum* sp. and fragmentary ferns have been identified by R. W. Brown. In several areas within the Navajo country, dinosaur tracks have been noted in limestone lenses of the Navajo sandstone, but beyond the limits of this region very little additional fossil material has been reported. The fossils provide additional information on the environment of deposition of the Navajo sandstone. Unfortunately, the material is not diagnostic of age.

SEDIMENTATIONAL HISTORY OF THE GLEN CANYON GROUP

The termination of Chinle deposition is sharply recorded only in the eastern and western parts of the Navajo country. Deposition of the lowermost Glen Canyon strata originated in a small area, about at the center of the area of Chinle deposition. The lowermost strata of this group constitute the Rock Point member of the Wingate sandstone. For the most part they apparently were deposited in a body of quiet water. The presence of a few lenses of fluviatile sandstone at the base of the Rock Point suggests that streams flowed into the basin during the initial stages of deposition. However, initial deposition of this type was of short duration throughout most of the area, and typical silty flatbedded quiet-water sediments soon covered the basal beds. Sedimentary structures, regional trends of sorting and grain size, and uniform gradation from the marginal areas toward the center of the basin are all suggestive of quiet-water deposition. Color, composition, and lack of fossils, except worm trails, suggest that the water in which the sediments were deposited was abnormal; it may have been highly saline and of an oxidizing nature. A warm climate is inferred from the occurrence of reptilian remains in the bordering fluvial deposits in the eastern part of the area. A warm climate and restriction of circulation of water between the Rock Point basin and any possible seaway to the southwest could have caused a saline condition.

The development of the Rock Point basin of deposition seems to have been dependent upon uplift to the east and gradual sinking in the area of the Navajo country. This interpretation is based upon the occurrence of fluvial deposits in the eastern part and of quiet-water deposits in the central part of the area. Furthermore, the evidence of greatest erosion of the Chinle formation occurs in the eastern area. Generally, the units of the Glen Canyon group were deposited in basins whose axes shifted progressively westward, suggesting a continuous uplift to the east. This trend culminated in the complete uplift of the Chinle and Glen Canyon basins of deposition in the Navajo country.

During the time of deposition of the sediments of the Rock Point member, dunes which are now a part of the Lukachukai member were deposited to the north in southeastern Utah and to the east in northwestern New Mexico (fig. 18). The dunes were marginal to the shoreline and extended northward into southern Utah and southwestern Colorado farther than into New Mexico. The retreat of the water from the depositional basin of the Rock Point was oscillatory, probably owing to erratic rates of uplift of the area east of the Navajo country. These fluctuations of the shoreline account for the preservation of tongues of the Lukachukai member within the Rock Point member. These crossbedded sandstone tongues appear as lenses when viewed in exposures that are oriented northwest-southeast. To the northeast they coalesce with the main body of the Lukachukai member and to the southwest they pinch out in the Rock Point member.

Streams transported sediments into the Rock Point basin from the northeast, east, and southeast (fig. 18). Heavy minerals suggest that these sediments were derived mainly from older red-bed sediments of the Triassic, although some primary materials must have been introduced from igneous and metamorphic terranes. The most extensive fluvial deposits are in the southeastern part of the Navajo country, near Lupton, Ariz., where lenses of conglomeratic sandstone occur throughout the lower part of the Wingate section. The streams that entered the area from the northeast may have originated in the Uncompahgre highlands in west-central Colorado. These streams apparently flowed through dune areas, as attested by the intertonguing relationships with the Lukachukai member of the Wingate. Locally, vegetation was present, as indicated by concentrations of plant fragments, petrified wood, and phytosaur remains. In the southern part of the Navajo country, anomalies in sphericity, roundness, and composition of the sediments of the Rock Point suggest a local source area to the west or south, but field evidence is lacking to support such a suggestion.

Upon the shifting of the center of deposition to the southwest, dunes of the Lukachukai member of the Wingate sandstone migrated across the Rock Point sediments to the west. These dunes in turn were truncated by streams rejuvenated by uplift to the east and northeast. These streams brought in the initial deposits of the Moenave formation, as the basal deposits of that formation intertongue with the youngest strata of the Wingate sandstone in the western part of the Navajo country.

Sedimentary structure, composition, and a few fossils of the Moenave formation seem to indicate a fluvial origin. The presence of primitive crocodiles would seem to indicate a tropical or subtropical climate. A

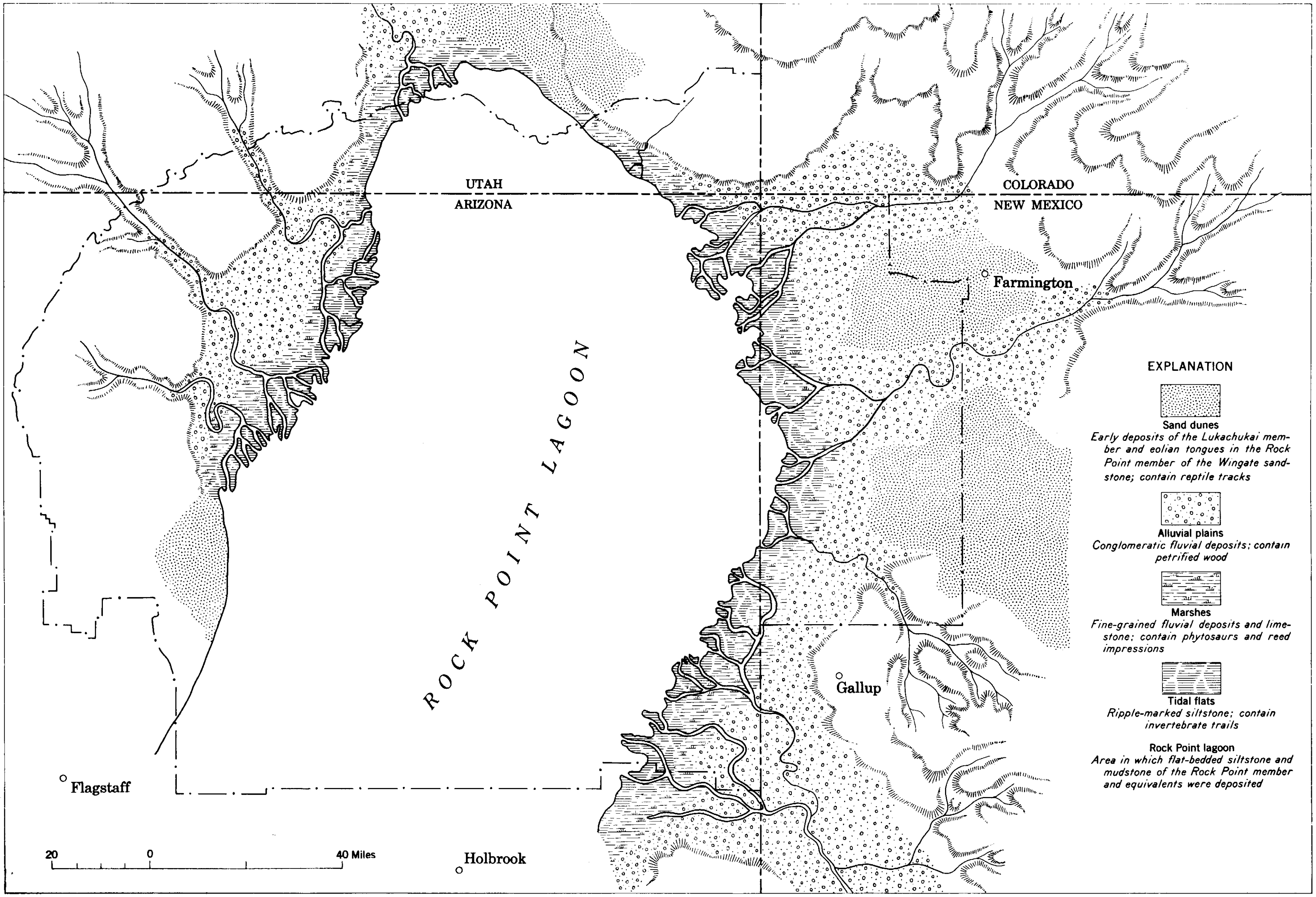

FIGURE 18.—Sketch map showing the hypothetical physiography of the Navajo country in the late stage of deposition of the Rock Point member of the Wingate sandstone.

general lack of plant remains and the presence of tongues and lenses of eolian sandstone in both the basal and upper parts of the Moenave formation suggest sparseness of vegetation. Possibly the areas of more lush vegetation lay farther to the southwest, or else the vegetation was not preserved.

The Moenave formation contains metamorphic minerals, not present in the underlying Wingate, which suggest a new source. This source appears to have been to the east of the Navajo country, although some minerals in the Dinosaur Canyon sandstone member may have been derived from the southeast, as indicated by laboratory studies. Study of differences in thickness and of facies trends suggests a broad fluvial basin whose axis trended roughly southwest (fig. 19). The general orientation of the basin of Moenave deposition is related much more closely to that of the Chinle than to that of the San Rafael group, the axis of which trended roughly northwest. The orientation of the deposits of the Moenave and Kayenta is diametrically opposed to that of the deposits of the Morrison formation (figs. 19, 20, and 37).

The axis of the depositional basin of the Kayenta lies to the northwest of the Navajo country, and only the southeasternmost deposits of this formation lie within the area of this report. The Kayenta streams removed parts of the Wingate sandstone in most of the Navajo country. In the southwestern part of the area the thick silty facies is believed to represent deposition in the lower and more sluggish parts of the stream system. This phase of deposition is believed not to be present in most parts of the Colorado Plateaus province.

Initial deposition of the Kayenta appears to have been continuous with deposition of the underlying Moenave formation. In the northeastern part of the area, where the Moenave is absent, deposits of the Kayenta were laid down on the eroded surface of the Wingate (fig. 21). Near the culmination of Kayenta deposition in the Navajo country, eolian deposition of the Navajo sandstone advanced over the Kayenta deposits from the west toward the east (fig. 20). Presumably, the Kayenta streams were forced progressively eastward across the Navajo country by the advance of the dunes. Apparently, in these last stages of Kayenta deposition, along its eastern limit, material brought in by the waning Kayenta streams was the primary source of material for the Navajo dunes in this area. Both formations pinch out at about the same eastern limits in the Navajo country, and in that area no indication can be found of any appreciable eolian deposition above the Kayenta. However, the Navajo sandstone may have been present in that area and may have been removed by pre-Carmel erosion. Because the prevailing winds depositing the Navajo sandstone in the Navajo country were from the west to northwest, it seems probable that Navajo dunes were deposited to the east of the present limits of the Kayenta, although no such deposits are known.

AGE ASSIGNMENT OF THE GLEN CANYON GROUP

The assignment of the Glen Canyon group to both the Triassic and the Jurassic systems is based on faunal evidence and on the broad correlation of this group with fossiliferous marine rocks of known age in Sonora, western Nevada, and California. The known fauna of the Glen Canyon group is only suggestive of age relationships, and at first glance many of the indications of age seem contradictory. However, the Glen Canyon fauna becomes more understandable and useful as evidence when considered with the evidence from the marine rocks that are correlated with the Glen Canyon group of the Navajo country.

The Glen Canyon group overlies the Chinle formation of Late Triassic age. Most age assignments of the Chinle, based on continental vertebrates, are as young as the Keuper series of Germany (Upper Triassic). The Carmel formation overlies the Glen Canyon group and is Middle and Late Jurassic in central and northeastern Utah, although the Carmel of the Navajo country may represent only the Late Jurassic. R. W. Imlay (1952, p. 964) makes the following statement regarding the age of the Glen Canyon group: "If the basal part of the Carmel formation is of Bajocian age (basal Middle Jurassic), as now seems likely, then the Navajo cannot be younger than Lower Jurassic, and the chances of the Kayenta and Wingate being Jurassic are considerably less than if the Carmel were entirely of Upper Jurassic age."

REVIEW OF FAUNAL EVIDENCE

The fauna of the Glen Canyon group includes mollusks, crustaceans, fish, and reptiles. Reptile tracks are locally common. In addition, a few fragmentary plant remains and some petrified wood have been found.

About half the faunal types known from the Glen Canyon group have been found either in units not previously assigned to the group or in units doubtfully correlated with it. With the exception of an isolated pelecypod, *Trigonia*, reported to have been found in the Nugget (Navajo) sandstone in northern Utah, no marine fossils have ever been found in the Glen Canyon group.

MOLLUSKS

Genus Trigonia.—A. A. L. Mathews (1931, p. 42) reports a single specimen of *Trigonia* (no species mentioned) from the lower part (Navajo sandstone) of the Nugget sandstone in the Wasatch Mountains, Utah.

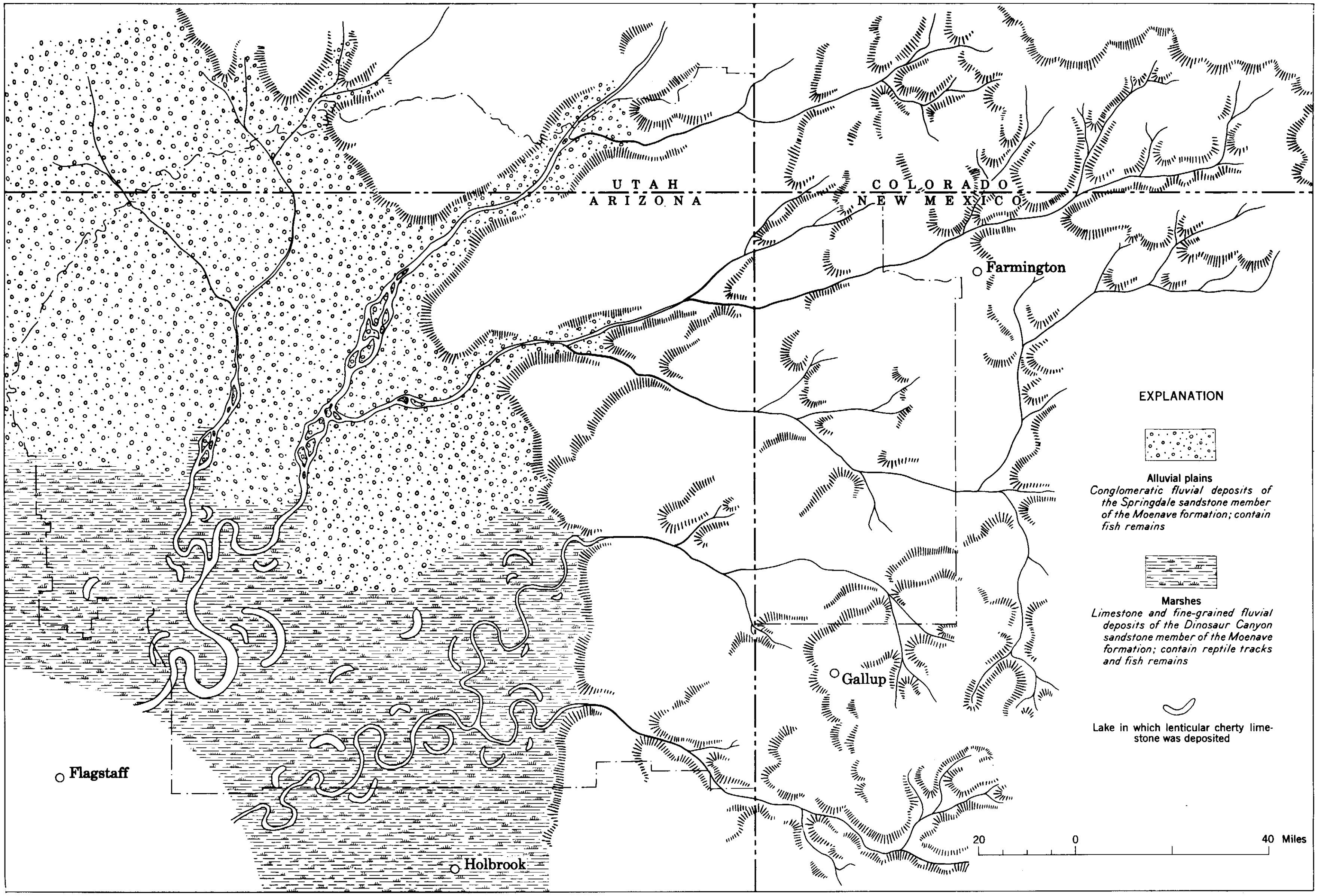

FIGURE 19.—Sketch map showing the hypothetical physiography of the Navajo country in the late stage of deposition of the Moenave formation.

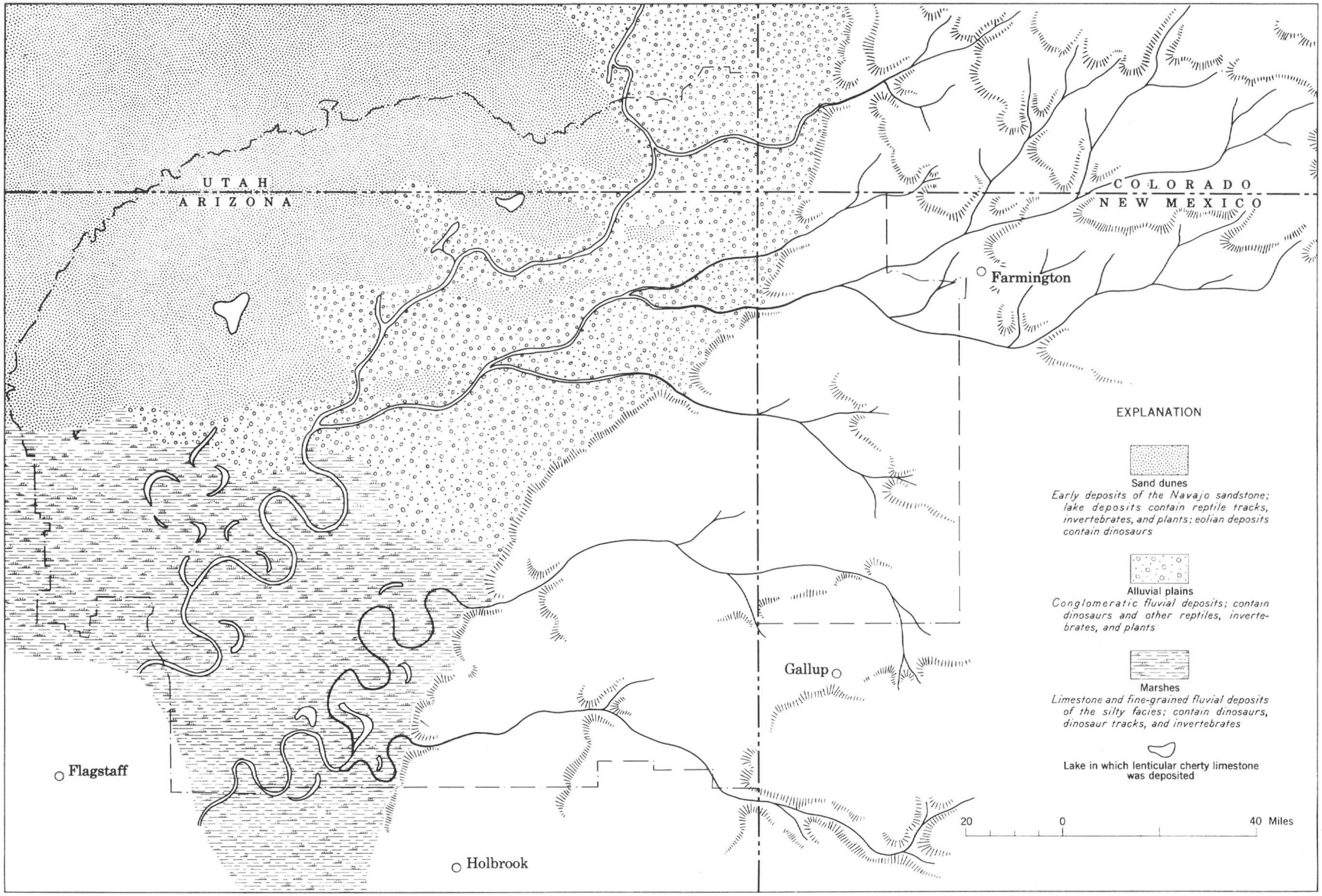

FIGURE 20.—Sketch map showing the hypothetical physiography of the Navajo country in the late stage of deposition of the Kayenta formation.

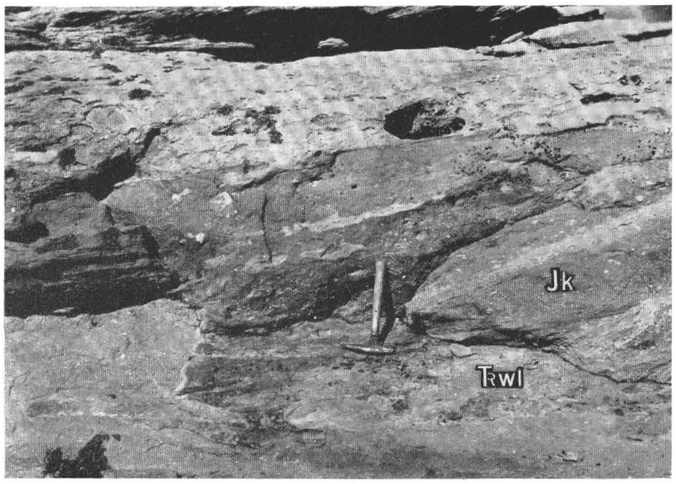

FIGURE 21.—Contact between the Lukachukai member of the Wingate sandstone (T̄Rwl) and the Kayenta formation (Jk), 16 miles east of Rock Point, Ariz.

No other record of any marine organism has been made for the formation, and efforts to check this one have been fruitless (J. B. Reeside, Jr., 1954, personal communication). A species of the genus *Trigonia* occurs in the Carmel formation, as well as in other marine Jurassic units. Its occurrence within continental deposits is incongruous.

Genus Unio.—A. A. Baker (1933, p. 46) reports that three collections of fossils were made in the Kayenta formation south of Moab, Utah. He states that the fossils "were described by J. B. Reeside, Jr., as internal casts of long-ranging types of Unios resembling *U. dumblei*, *U. dockumensis*, and *U. iridoides*." *U. dockumensis* Simpson and *U. dumblei* Simpson were originally described from the Triassic of Texas and have also been found in the Triassic of southwestern Colorado and elsewhere in the Chinle formation. The only other described occurrence of *U. iridoides* White is in the Upper Jurassic Morrison formation. It is considered to be a fresh-water form.

Genera Valvata [1] *and* Lymnaea.—In 1913 and 1914 H. E. Gregory collected an abundance of fresh-water gastropods in the vicinity of Cameron from units originally described as the "Painted Desert beds" by Ward (1901, p. 413), and included in the "Undifferentiated La Plata and McElmo of the Moenkopi Plateau" by Gregory (1917, p. 66–68). These units, as differentiated by the present study, are now assigned to the Dinosaur Canyon sandstone member of the Moenave formation, the silty facies of the Kayenta formation, and the Navajo sandstone. Gregory's description (1917, p. 68), of the fossil locality, "about midway up in the section," unmistakably places the fossils in the silty facies of the Kayenta. W. I. Robinson (1915, p. 649–665) originally described the gastropods, naming two new species, "*Valvata gregorii*" and "*Limnea hopii*," and assigned them to either the Middle or the Late Jurassic because he believed them similar to forms of the Morrison formation.

In 1951, T. C. Yen (p. 673) reassigned these two species to the Late Triassic owing to the discovery of *V. gregorii* in the upper member of the Chinle formation, and, perhaps, to his incorrect belief that the type specimens were from the Chinle (Yen, 1950, p. 27). However, Yen's reassignment of *V. gregorii* to the Triassic was questionable owing to uncertainty as to the stratigraphic horizon at which the specimens were obtained (near Black Falls, south of Cameron; in Museum of Northern Arizona collection G2–4257). The reassignment of *L. hopii* was even more questionable, as this species has not been reported in the Chinle and the reassignment was made purely on similarity to other Chinle forms and to its original association with *V. gregorii.*

Subsequent to Yen's reassignment of the two species, a search was made in the upper member of the Chinle in the spring of 1953 and a collection was obtained from this unit, 60 feet below the top, east of Cedar Ridge, Ariz., which is about 55 miles north of Yen's locality. The collection contained several specimens of *V. gregorii*, which were identified by J. P. E. Morrison, thus definitely establishing this species in the Chinle. *L. hopii* has not been found in the Chinle.

CRUSTACEANS

Genera Candona? *and* Cyzicus.—Nearly all the fossils known from the Navajo sandstone have been found on the Kaibito Plateau, south of the Colorado River between Kayenta and Cedar Ridge. In 1951 Earl Harrison made a collection of plant and invertebrate material from the upper part of the Navajo between Cow Springs and Inscription House, Ariz., and the following year C. A. Repenning and M. E. Cooley made a similar collection from about the same locality, 5 miles southwest of Shonto, Ariz. Both collections were obtained from the beds of lenticular limestone in the Navajo sandstone. J. B. Reeside, Jr., I. G. Sohn, R. E. Peck, and R. W. Brown identified the specimens. The collections contained smooth ostracodes similar to *Candona* sp. but not necessarily generically identical, *Cyzicus* ("*Estheria*") aff. *C. ovata* (Lea), unidentifiable fern and wood fragments, and *Equisetum* sp., too fragmentary for specific assignment. This assemblage is not diagnostic of age, as the forms are long ranging,

[1] T. C. Yen of the U. S. Geological Survey (1951, p. 673) states that the generic status of this species, *V. gregorii* Robinson, is uncertain owing to inadequate preservation of the specimens. J. P. E. Morrison of the U. S. National Museum in a report (Feb. 3, 1954) describing new and more complete material from the Chinle formation states: "I believe that these specimens are much closer in general characters to *Ampularia*, as Crossman stated in 1917, or to *Fluminicola* than they are to *Valvata*."

although Reeside comments: "The association is much like that in the Newark Triassic." *Cyzicus ovata* is abundant in the Newark Triassic of Pennsylvania where it is associated with *Candona*, fresh-water mussels, and fish.

FISH

Genera Semionotus *and* Lepidotus.—In 1879 C. D. Walcott discovered fish remains at Kanab, Utah, in the unit now recognized as the Moenave formation. From this collection C. R. Eastman (1911, p. 35) described a new species, *Lepidotus walcotti*, and concluded that it was of an age comparable to that of the early Liassic (lowermost Jurassic). Later, he (1917, p. 279) reconsidered this age assignment and, on the basis of a "near comparison" to *L. gallineki* from the Triassic of Silesia, he concluded that *L. walcotti* was comparable in age to the upper Keuper.

In 1935 C. J. Hesse described *Semionotus* cf. *S. gigas* from the Springdale sandstone in Zion Park, Utah. Hesse points out that most species of the genus *Semionotus* are from the Upper Triassic. *S. gigas* is found in the Newark group of New Jersey.

In 1950 Bobb Schaeffer and D. H. Dunkle described a second genus of fish from Walcott's original Kanab collection, a fish that Eastman had previously assigned to genus *Pholidophorus*. They reassigned it to the genus *Semionotus*, naming the species *S. kanabensis* and assigning it to the Triassic.

Since 1950 similar fish remains have been found by other workers at the same horizon at many places between Kanab and Lees Ferry. All the fish remains occur either in the Springdale sandstone member or in the upper part of the Dinosaur Canyon sandstone member of the Moenave formation. The fish are found at about the same horizon as the primitive crocodilian *Protosuchus*, which was found in the top of the Dinosaur Canyon sandstone member about 70 miles south of the closest known discovery (near Lees Ferry) of the "Kanab" fish.

According to Dunkle (oral communication), "the assignment of the fish to the genus *Semionotus* was based on what must be considered a broad interpretation of the definition of the genus. However, no other decision seemed feasible because, despite numerous referred species of cosmopolitan distribution, the genus is not well studied. *Semionotus* has never been found above the Triassic."

REPTILES

Genus Machaeroprosopus.—In 1952 two collections of fragmentary phytosaur remains were made by C. A. Repenning and P. R. Stevens 7 miles north of Red Rock, Ariz. One of these was from the upper unit of the Chinle, the Chinle "B" of Gregory (1917, p. 42–43), and the other from the overlying Rock Point member of the Wingate sandstone. These fossils were identified by D. H. Dunkle as belonging to the genus *Machaeroprosopus* but were too incomplete for specific identification. They represent, so far as is known, the only occurrence of *Machaeroprosopus* in these units, and they either extend the range of the genus, as defined by Camp (1930), into equivalents of the upper Keuper, or require including, as equivalents of the Lettenkohle (late Middle Triassic) and lower Keuper, the upper unit of the Chinle and the Rock Point member of the Wingate as used in this report.

Genus Protosuchus.—In 1931 Barnum Brown collected from the Dinosaur Canyon sandstone, near Cameron, specimens of a primitive crocodile which he (1933 and 1934) named *Protosuchus richardsoni*, a new genus and species. Since that time several more specimens have been removed from the same unit. This unit is now named the Dinosaur Canyon sandstone member of the Moenave formation. In 1951 E. H. Colbert and C. C. Mook formally described *P. richardsoni* and the Dinosaur Canyon sandstone.

Colbert and Mook compare *Protosuchus* with the South African ancestral crocodilians *Notochampsa* and *Erythrochampsa* from the Stormberg series. According to these authors the Stormberg series is subject to the same controversy over age assignment as is the Dinosaur Canyon; that is, its age either is the same as the Keuper, the Rhaetic (latest Triassic), and the Liassic (Early Jurassic) or is entirely Late Triassic. However, the Stormberg series contains several characteristic Late Triassic types of dinosaurs and "*Semionotus*, a distinctive Triassic holostean fish." They state (p. 180) that "The evidence of these reptiles and of the fish indicates that the Stormberg series is about equivalent to the Keuper of Europe and the Upper Triassic of other regions." They conclude their argument by stating that most of the evidence seems to place the Dinosaur Canyon in the Triassic rather than in the Jurassic system but that age assignment should not be based on primitive crocodilians. When this statement was made Colbert and Mook were not aware that *Semionotus kanabensis* was from the same unit as *Protosuchus*. This occurrence strengthens their comparison of the Dinosaur Canyon with the Stormberg series of Africa. A recent discovery by G. E. Lewis of tritylodontoid skeletons in the overlying Kayenta formation further strengthens their comparison to the Stormberg, as *Tritylodon* itself occurs in the Stormberg. However, there is still some question about the age of the Stormberg series.

Genera Segisaurus, Ammosaurus, *and* Megalosaurus.—Two small coelurosaurian dinosaurs have been recovered from the Navajo sandstone in the Kaibito Plateau of northeastern Arizona. The most complete was *Segisaurus halli*, discovered in 1933 by Milton Wetherill and described in 1936 by C. L. Camp. According to Camp, it was found 500 feet above the base of the formation, or midway in the section. Camp (p. 52–53) questionably assigns the specimen to the Early Jurassic on the basis of the tentative age of the Navajo as stated by Baker, Dane, and Reeside (1936). Camp states that such an unknown upland form as *Segisaurus* should not be used as an indication of age and adds (1936, p. 52) that "it could be placed in either the Triassic or the Jurassic." E. H. Colbert (written communication) believes that *Segisaurus* is somewhat more advanced than *Coelophysis* from the Chinle and that it might easily be an Early Jurassic type. He remarks that "*Segisaurus* looks very much like an ornitholestid. *Ornitholestes* itself comes from the Morrison formation."

In 1935 L. F. Brady described incomplete remains of another small coelurosaur from the Kaibito Plateau, also from the Navajo sandstone. He points out that this individual "resembles very closely," in the few parts preserved, *Ammosaurus* of the Connecticut Triassic; however, he expresses uncertainty concerning identification in view of the paucity of remains. He quotes R. S. Lull as stating that "*Ammosaurus* is at the very summit of the Triassic and I imagine that its Jurassic successor would not have varied greatly in the parts which your specimen [from the Navajo sandstone] shows."

Lull (*in* Gregory, 1917, p. 56) reports on two sets of dinosaur tracks in the Kayenta (Todilto) formation, from the same area in which Camp and Brady obtained their dinosaurs. He concluded that the tracks were not older than latest Triassic, based on a comparison with the Connecticut Valley forms of bipedal dinosaurs.

All of these fossils from the Navajo sandstone have been obtained from localities within a 20-mile radius of the two invertebrate localities, and except for the tracks, occur in the upper half of the Navajo sandstone.

Several years ago S. P. Welles collected two skeletons of carnosaurs from the base of the Kayenta formation near Moenave, a few miles north of the *Protosuchus* locality and somewhat higher in the section. Welles (1954, p. 597) assigns these carnosaurs to *Megalosaurus*, a genus found in the European Jurassic. He states (written communication, 1953) that evolutionary trends make it "obvious that it [the specimen] fits between the Triassic and the Jurassic, and is much closer to the Middle and even Upper Jurassic megalosaurs than to any of the Triassic carnosaurs." On the basis of this interpretation, Wells assigns the Kayenta formation to the Jurassic system.

Undescribed genus of the superfamily Tritylodontoidea.—In 1953, Benjamin C. Hoy of the Bureau of Indian Affairs made an interesting discovery of vertebrate remains in the Kayenta formation 10 feet below the base of the Navajo sandstone and near the town of Kayenta. Quarrying operations in June 1954 by the U. S. Geological Survey yielded several skeletons whose preparation, under the direction of G. Edward Lewis, has gone far enough to allow preliminary identification.

Mr. Lewis's report (written communication, 1955) reads as follows:

> The preliminary, incomplete identification and pertinent stratigraphic information are:
>
> Class REPTILIA*
> Subclass SYNAPSIDA
> Order ICTIDOSAURIA
>
> Superfamily Tritylodontoidea near *Bienotherium* Young
>
> The newly discovered skulls represent the first new-world discovery of tritylodontoids. They seem to be close morphologically to *Tritylodon* of the Stormberg series of South Africa, and even closer to *Bienotherium* of the Lufeng series of Yunnan, China. These old-world vertebrates occur in rocks generally placed in the Upper Triassic.

Here again is a faunal comparison between the Stormberg and the Glen Canyon group. Both contain fish of the genus *Semionotus*, known throughout the world in the Triassic; both contain the earliest known crocodiles; and both contain tritylodontoids.

Summary of the faunal evidence.—The Rock Point member of the Wingate sandstone contains the Triassic phytosaur *Machaeroprosopus*. No diagnostic fossils have been found in the Lukachukai member of the Wingate.

The Dinosaur Canyon sandstone member of the Moenave formation contains the primitive crocodile *Protosuchus*, a new genus which may be of Triassic age. However, if so, its occurrence constitutes a new record for the age of earliest crocodiles. Fish of the genus *Semionotus* have been found in the highest part of this unit and are also fairly common in the overlying Springdale sandstone member of the Moenave. This genus has a wide distribution and has never been found above the Triassic. Although the fish belong to a well-known genus, they represent a new species, *S. kanabensis*.

The Kayenta formation contains dinosaurs of the genus *Megalosaurus*, which have been found in the basal part of the formation near Moenave. This genus is incompletely known from fragmentary remains in the European Jurassic which, as Romer says (1945, p. 236), "tell us little beyond the fact that large flesh-

*Most modern paleontologic opinion somewhat arbitrarily places the tritylodontoids in the Reptilia, but they are on the transitional morphologic boundary between reptiles and mammals.

eaters were abroad in the land." Although the Kayenta dinosaurs are included in a known genus, they represent a new species. The Kayenta also contains a few nonmarine mollusks which represent genera known from Triassic to Tertiary and Recent. Three of the species are known to occur also in the Chinle formation, one is known to occur also in the Morrison formation, and one is an isolated species occuring only in the Kayenta formation. In 1921, H. A. Pilsbry (1921, p. 30–36) suggested that probably the subfamily Unioninae reached North America from Asia during the Jurassic and that the Triassic species of this continent are more nearly related to the living South American fauna. He would, therefore, place the species *Unio dockumensis* and *U. dumblei* in the genus *Antediplodon*, whereas he would leave *U. iridoides*, from the Jurassic, in the genus *Unio*. Although little is known of Mesozoic fresh-water mollusks, this association in the Kayenta of forms known from both Triassic and Jurassic deposits reflects the transition of time from Triassic to Jurassic suggested by the other fauna of the Moenave and Kayenta formations.

At the top of the Kayenta large tritylodonts have been found which, though rare throughout the world, have always been found in beds usually considered to be Upper Triassic or Rhaeto-Liassic at the youngest. Smaller tritylodonts are known from beds as young as medial Middle Jurassic. While the size of tritylodontoids appears to suggest an age difference, the suggestion has exceptions. Young (1946, p. 10) reports a size variation between what he considers to be three separate species of *Bienotherium*, all from the Lufeng series, that is nearly as great as that between all known tritylodonts from Upper Triassic to Middle Jurassic rocks.

The Navajo sandstone contains two long-ranging arthropods, *Candona?* and *Cyzicus;* a dinosaur tentatively assigned to the genus *Ammosaurus*, which may be either latest Triassic or earliest Jurassic; and another dinosaur, *Segisaurus*, which, although it represents a new genus, has several features related to Late Jurassic forms.

The variety of age indications in the Glen Canyon group is great. If a conclusion is drawn from faunal evidence alone, a Triassic-Jurassic boundary between the fish of the Moenave formation and the dinosaurs of the Kayenta formation seems most compatible with all information available to date. However, the Kayenta formation could be as old as the Upper Keuper of Germany (Late Triassic), as suggested by known occurrences of large tritylodontoids, or as young as Middle Jurassic, as suggested by Welles (1954, p. 597). The fauna of the Navajo sandstone is not conclusive, and its age assignment must be based upon the age of the Kayenta and Carmel formations and upon regional stratigraphic evidence.

REVIEW OF REGIONAL STRATIGRAPHIC EVIDENCE

The Chinle formation and the Glen Canyon group represent an essentially continuous sequence of deposits, as indicated by their depositionary history. Prior to the cessation of deposition of the Kayenta formation by streams flowing westward to southwestward toward a marine basin, the same basinal arrangement that had existed since the beginning of Chinle deposition prevailed in the Navajo country. The same highland areas were present and, with only slight modifications, the sediments of the Chinle, Wingate, Moenave, and Kayenta were laid down in the same basin. Within the Navajo country intertonguing of various lithologic facies occurred during the deposition of 2,000 to 3,000 feet of continental beds of the Chinle formation and the Glen Canyon group.

Continuous fluvial deposition was interrupted at the close of Kayenta time by an uplift to the west of the Navajo country, which severed connections with the marine basin into which the Chinle-Kayenta streams flowed. A new highland resulted which was connected northward with the Cordilleran geanticline and with an existing highland area to the south of the Navajo country. The highland area to the south first became prominent at the start of Chinle deposition and has existed since then. The new highland to the west was a source area for the sediments of the Navajo and Carmel formations within the Navajo country. Thick deltaic deposits of sand, derived from this highland area, accumulated over the entire southwestern margin of Carmel deposition (figs. 20 and 30).

The events listed above reflect steps in a major tectonic adjustment which led to three major developments: (1) the severance of all connection with the ocean basin to the west and southwest of the Navajo country, into which the Chinle-Kayenta streams flowed; (2) the deposition of eolian sand, the Navajo sandstone, apparently against the flanks of the rising highlands and across the fluvial deposits; and (3) the gradual development of a drainage system into a depositional basin whose center was to the north of the Navajo country, in which the Carmel formation was deposited. The sea that deposited the Carmel transgressed the Navajo sandstone southward into the Navajo country and was an interior sea far distant from the Pacific Ocean. The resultant restriction of circulation caused an increase in salinity, indicated by evaporite deposits and sparseness of fauna. Depositional history in this interior sea suggests that the Carmel of the Navajo country is entirely of Late Jurassic age. To the north of this area the Carmel contains beds as old as early Middle Jurassic (Bajocian), according to Imlay (1952, p. 936).

The basin into which the Chinle-Kayenta streams flowed and the later one in which the Carmel was deposited apparently had no relation to each other. The Chinle-Kayenta streams apparently flowed into the Pacific Ocean, which extended eastward into western Nevada, California, and western Sonora. No evaporites are reported in Triassic and Jurassic sedimentary rocks in that area, and marine fossils are abundant. R. E. King (1939, p. 1659) describes the paleogeographic relations of the Mexican Upper Triassic and Lower Jurassic Barranca formation with this summary: "Near the supposed northeastern margin of the basin, the Barranca formation consists wholly of continental deposits. Toward the west and south, marine members become intercalated in increasing proportion. Muller and Ferguson (1936) have shown that in west-central Nevada there was 'an uninterrupted mingling of Mediterranean and western American marine faunas near the end of the Triassic period and at the beginning of the Jurassic period.' In Nevada, as in Sonora, there is a conformable sequence of strata from the Karnic [lowermost Upper Triassic] upward into the lower Lias. This represents a distinct marine cycle, the deposits of which are separated by unconformities from the underlying and overlying formations."

In west-central Nevada, Muller and Ferguson (1939, p. 1582) report marine deposition starting at the beginning of Late Triassic (Karnic) time and extending without interruption into the middle part (Pliensbachian) of the Early Jurassic. At the top of the Lower Jurassic Sunrise formation they report local erosional unconformities overlain by more Lower Jurassic rocks which they think possibly (p. 1621) extend into the latest (Toarcian) part of the Early Jurassic. This youngest sedimentary unit in their area, the Dunlap formation, is lithologically variable from place to place and contains many "conglomerates and fanglomerates whose pebbles are of local derivation. In certain areas the upper part of the formation consists largely of volcanic rocks with interbedded sandstone, in part tuffaceous." On page 1632 they state that "the lithology and stratigraphic relations of the Dunlap formation indicate that it was deposited during a period of acute diastrophism which began near the middle of Early Jurassic time." They state (1936, p. 242) that the "area of Triassic rocks is coincident with a belt of complex folding and thrusting of Jurassic age."

The comparison of the tectonic events recorded in the Late Triassic and Early Jurassic marine basins with those recorded in the continental deposits of the Navajo country suggests that the diastrophic event mentioned, which produced the abrupt change in marine deposition recorded in the Dunlap formation, also caused the cessation of the Chinle-Kayenta streams. The depositional change from Kayenta to Navajo would thus be about contemporaneous with the Dunlap formation. If this suggestion is correct the Kayenta formation is Early Jurassic in age, possibly ranging from Late Triassic. Consideration of the faunal evidence, as discussed, places the systemic boundary most probably at the base of the Kayenta. Therefore, the Navajo sandstone probably is Early Jurassic, and where the overlying Carmel is entirely of Late Jurassic age the Navajo may also be Middle Jurassic in part.

Because of the agreement between the faunal evidence for the age of the Glen Canyon group and the regional geologic history in Nevada, Sonora, and the Navajo country, the group is herein assigned to both the Triassic and Jurassic systems. The Wingate sandstone is considered to be Late Triassic in age. The Moenave formation is also considered Late Triassic, but it may extend into the Early Jurassic and for this reason a questionable Triassic age is used. The Kayenta formation is considered to be Early Jurassic but may be, in fact, as old as Late Triassic and for this reason a questionable Jurassic age is used. The Navajo sandstone is considered to be Early Jurassic in age; however, there is a possibility that parts of it may be of Middle Jurassic, and also, because of intertonguing with the underlying Kayenta formation, a basal zone of the Navajo must be considered Jurassic(?), like the Kayenta. For these reasons a Jurassic(?) and Jurassic age is used for the Navajo sandstone.

SAN RAFAEL GROUP

The San Rafael group was established by Gilluly and Reeside (1928, p. 73) and the type locality is in the San Rafael Swell of southeastern Utah. At the type locality the group includes in ascending order the Carmel formation, the Entrada sandstone, the Curtis formation, and the Summerville formation. The Curtis formation is absent in the Navajo country but another formation, the Todilto limestone, is present and occupies the approximate position of the Curtis. Strobell (1955) assigns the Bluff sandstone to the San Rafael group. In the Navajo country the Bluff is the uppermost formation of the group.

The San Rafael group is considered to be of Middle and Late Jurassic age. According to Imlay (1952, p. 963) the basal part of the Twin Creek limestone of northern Utah is Bajocian in age and laterally grades into the Carmel formation, lowermost unit of the group. The Summerville formation is considered to be as young as Oxfordian, on the basis of its close relations with the underlying fossiliferous Curtis formation (Imlay, 1952, p. 968). The Morrison formation, which overlies the San Rafael group, probably ranges in age from Kimmeridgian through Portlandian. For the most part, rocks of the San Rafael group within the Navajo country represent marginal marine deposits in the southern part of Late Jurassic seas.

LOWER BOUNDARY OF THE SAN RAFAEL GROUP

The boundary between the Glen Canyon group and the San Rafael group is the best defined contact within the Upper Triassic and the Jurassic rocks in the Navajo country. Furthermore, the axis of the San Rafael basin is oriented about at right angles to the axis of the Wingate, Moenave, and Kayenta basins of deposition. This shifting of alinement appears to be related to differences in source areas for each group and indicates a major tectonic adjustment.

Where the Carmel formation overlies the Navajo sandstone in the northwestern part of the Navajo country, the boundary between these units is well defined and easily recognized. These formations are separated nearly everywhere by an erosional unconformity, and the contact is well marked by lithologic differences (fig. 22). In most places the high-angle crossbeds of the Navajo sandstone have been eroded to form a nearly planar surface and the flat-bedded deposits of the Carmel rest upon this surface. In many localities these basal flat beds appear to consist of reworked Navajo sandstone, suggesting that the encroaching Carmel waters leveled the sand dunes. No large erosional channels have been observed at the contact, but minor depressions, containing lenticular beds of claystone and sandstone, are present. This unconformity, marking the boundary between the Glen Canyon and San Rafael groups, does not necessarily represent a long hiatus.

Because the Navajo sandstone does not extend over the entire Navajo country, the San Rafael group rests upon the Kayenta formation or the Wingate sandstone in the southeastern part of the area. Near Many Farms and Steamboat Canyon, Ariz., the Carmel formation rests upon the Kayenta formation. In these localities the contact is not everywhere well defined, but usually it can be chosen arbitrarily on the basis of lithologic differences between the two formations. In the area along the Arizona-New Mexico State line and eastward into New Mexico, the lower boundary of the San Rafael group occurs at the contact between the Entrada sandstone and the Wingate sandstone. In parts of this area the contact is apparent because of a difference in grain size and bedding structures between these formations. The medial silty member of the Entrada in most places in this area rests upon truncated high-angle crossbeds of the Wingate sandstone, and southeast of Gallup, N. Mex., erosional channels about 1 foot deep are common at this contact. Many of these channels contain very coarse sandstone and conglomerate of a type that is not present in the underlying Wingate.

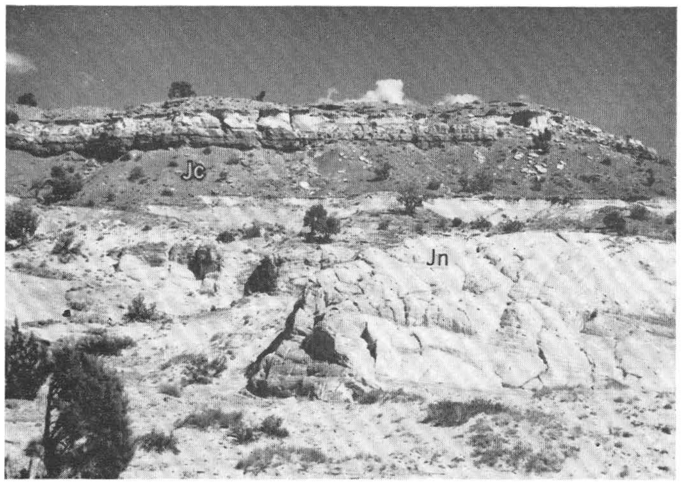

FIGURE 22.—The contact between the Navajo sandstone (Jn) and the Carmel formation (Jc), 8 miles southwest of Red Lake, Ariz.

The amount of time represented by the interval between the Glen Canyon and San Rafael groups cannot be estimated easily. The absence of several formations in the southeastern part of the area seems to indicate a long period of nondeposition; however, the possibility that the missing formations may have been deposited in this area should be taken into consideration. The Navajo sandstone and the Carmel formation may have originally extended eastward into New Mexico and later may have been removed by pre-Entrada erosion, even though the major part of the thinning of these units in this direction appears to be depositional. The significance of this unconformity is that it constitutes the major depositional break within the Upper Triassic and the Jurassic rocks in the Navajo country.

CARMEL FORMATION

The name Carmel formation was proposed by Gregory, Moore, Gilluly, and Reeside. Gregory and Moore (1931, p. 69) described the formation at Mount Carmel, Kane County, Utah. This formation has been traced across southern Utah into northeastern Arizona and western Colorado. In northern Utah it grades into the Twin Creek limestone and is of Middle and Late Jurassic age (Imlay, 1953, p. 54–59). The Carmel formation consists of two facies, a fossiliferous limestone facies and a red silty facies (Baker, Dane, and Reeside, 1936, fig. 11), of which only the latter is present in the Navajo country.

General description and field relations.—The Carmel formation in most of the Navajo country consists of a series of resistant ledge-forming sandstone beds separated by slope-forming siltstone strata. The siltstone beds are grayish red (10*R* 4/2) and weather to pale reddish brown (10*R* 5/4). They are weakly cemented and form smooth slopes. Most of the siltstone is fissile and is flat bedded. The sandstone beds are light greenish gray (5*G* 8/6) and weather to pale yellowish brown. In most places outcrops are stained dark red by debris from the overlying siltstone units. The sandstone is composed of fine-grained subangular quartz and contains mica as an accessory mineral. The calcareous cement in the sandstone is hard, causing the units to form either ledges or long dip slopes. Except in the southwestern part of the area, the sandstone beds form a minor part of the formation, as they are only 1–3 feet thick whereas the intervening siltstone units range from 5 to 20 feet in thickness.

Most of the siltstone units of the Carmel rest on irregular surfaces of small relief on underlying sandstone beds, and the two lithologies are in sharp contrast with each other. Large mud cracks are common in the basal beds of the siltstone units. These have been filled with sand from the underlying sandstone units, suggesting that the sandstone was unconsolidated and somewhat quick at the time of the initial deposition of the superjacent siltstone (fig. 23). The bedding of the sandstone, normally undisturbed in areas where mud cracks are not present, is crinkled and distorted beneath the mud-cracked strata. Lines of flowage curve upward into the sandstone that has filled the mud cracks. The sandstone in the mud cracks is more resistant to weathering than the siltstone in which the mud cracks formed and can be observed over wide dip-slope areas where the siltstone has been removed by erosion. These sandstone remnants form walls as much as 2 feet high and have a roughly hexagonal pattern about 6 feet across. In adjacent areas mud cracks have not been formed in the same units and no difference has been found in the overlying beds to explain their localization of mud cracks.

The localization of the mud-crack areas, the size of the mud cracks, the thickness of the sheet of mud which the cracks penetrated, and the apparently quick condition of the underlying sand which flowed upward to fill the cracks all suggest that the structures were not formed by the desiccation of subaerially exposed mud flats. They were possibly formed under subaqueous conditions.

The sandstone beds of the Carmel formation in many places show a gnarly and irregular structure imposed on the initial bedding. Where the sandstone has not been disturbed it is flat bedded and contains well-preserved ripple marks which are parallel and asymmetrical. The ripple marks locally attain a rather large size, some in the Kaibito area measuring 16 inches from crest to crest.

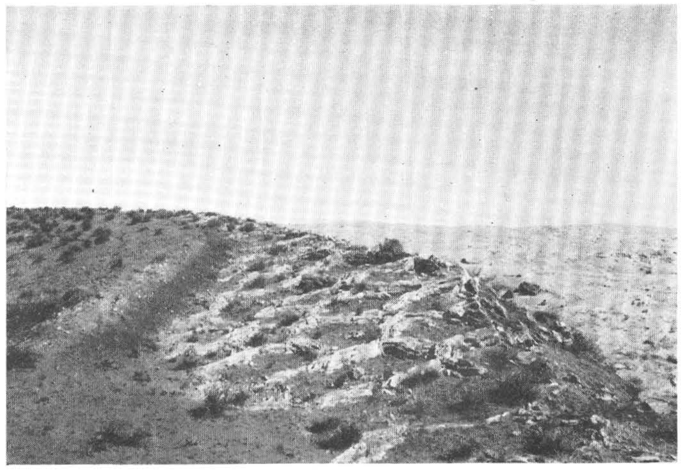

FIGURE 23.—Large sand-filled mud cracks in the basal part of the Carmel formation on the southeast flank of Boundary Butte anticline, 3 miles west of Red Mesa, Ariz. (Photograph by C. H. Dane.)

In the southwestern part of the Navajo country the Carmel formation contains exceptionally large amounts of sand and is predominantly white (figs. 16 and 24). The thickness is greater in this direction than to the north but, because of a similar facies trend in the overlying Entrada sandstone, the upper contact of the Carmel is difficult to determine. In the extreme southwestern part of this area, at Coal Canyon, the Carmel and Entrada are considered inseparable. Here the entire San Rafael sequence consists of friable white cross-bedded and flat-bedded sandstone banded by a few thin, conspicuous beds of rust-colored siltstone. The appearance of these deposits is quite similar to that of the Winsor formation (Gregory, 1950, p. 98) in southern Utah, which apparently is slightly younger at its type locality.

In the area between Red Lake and Coal Canyon, many of the white sandstone beds in the Carmel bear a very striking resemblance to the Navajo sandstone both in composition and in bedding structures, and it is believed that in this area the Navajo sandstone was a source for the Carmel sediments. Perhaps the beds similar to the Navajo in the Carmel represent tongues of eolian sandstone extending from deposits beyond the southern limits of subaqueous Carmel deposition. If this were the case, the Navajo and the Carmel should intertongue in this area; however, erosion in both recent and pre-Dakota times have removed the Jurassic rocks southwest of this area, where these relations would be expected.

In eastern Utah and western Colorado the red silty facies of the Carmel is massive and shows little tendency to weather differentially along bedding planes (Baker,

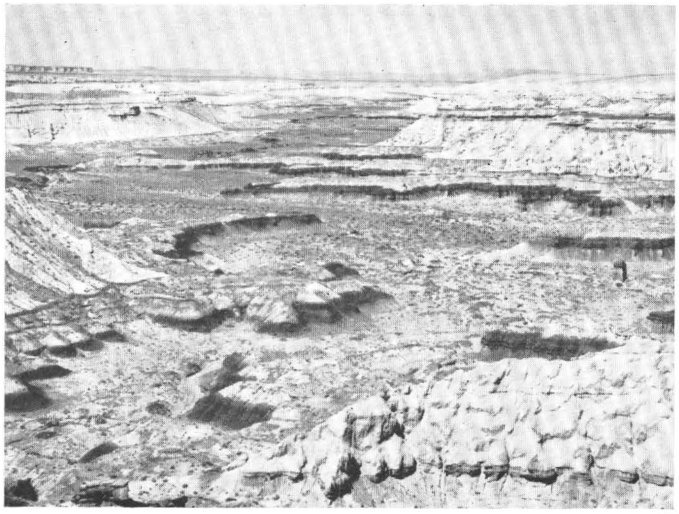

FIGURE 24.—The conspicuous white sandstone facies of the Carmel formation in Bat Canyon, 20 miles east of Tuba City, Ariz. This facies resembles the Winsor formation in southern Utah.

1933). In this area it weathers into rounded forms, often described as hoodoos. This lithology is similar to the silty facies of the overlying Entrada sandstone. Similar facies occur in a unit beneath the sandy facies of the Entrada along the Arizona-New Mexico State line and eastward into New Mexico. In the Fort Wingate area this unit has been considered correlative with the Carmel formation (Baker, and others, 1947, p. 1666), presumably because of the resemblance of the hoodoo weathering to that of the Carmel in the Colorado-Utah State-line area. However, geologic mapping from Bluff, Utah, across the northeastern corner of Arizona and along the east flank of the Defiance uplift has shown no tendency in the red silty facies of the Carmel to develop into a massive hoodoo type of rock, as it apparently does eastward across Utah into Colorado. In addition, the red silty, hoodoo-weathering facies of the Entrada has been recognized throughout this area and in New Mexico. Consequently, the silty unit present at Fort Wingate is herein treated as a facies of the Entrada. This correlation reduces the recognized areal extent of the Carmel in the southeastern part of the Navajo country (fig. 16).

The Carmel formation was deposited over most of the Arizona part of the Navajo country, which is the extreme southeastern part of the Carmel basin. In most places the formation is between 100 and 200 feet thick, but is thinner toward the limits of deposition to the east and southeast (pl. 3). It is thicker toward the southwestern part of the Navajo country, probably because of the presence of a local source of sediment. Here it contains a large percentage of sand. The Carmel is 100 feet thick at Dinnehotso, 113 at Mexican Water, 184 feet near Chinle, and 63 feet at Steamboat Canyon, west of Ganado, Ariz. It is 198 feet thick at Kaibito, 202 feet at Red Lake (near Tuba City), and 249 feet at Blue Canyon, south of Red Lake. South of Blue Canyon it cannot be separated with any reliability from the overlying Entrada sandstone.

Laboratory studies.—Within the Navajo country the sandstone in the Carmel formation contains 30 percent of soluble carbonate minerals and the sand grains have an average median diameter of 0.22 millimeter. Because the grain size of the siltstone was not computed, this average applies to the sandstone only. Contrary to field appearances which would suggest a predominance of silt, about 60 percent of the formation is composed of sand. This percentage is due to the relatively high amount of fine sand in the shaly siltstone and to the concentration of sand in the southwestern part of the area. Roundness studies of the sandstone show that the grains average 20 percent angular, 45 percent subangular, 30 percent subrounded, and 5 percent rounded. The coefficient of sorting averages 1.30. A study of the heavy minerals indicates that magnetite is the predominant mineral, ilmenite-leucoxene, garnet, and tourmaline following in order of abundance. Muscovite, hornblende, sphene, sillimanite, staurolite, siderite, biotite, and zircon are present in most samples but in amounts of less than 5 percent of the heavy-mineral fraction.

In Utah the limestone facies of the Carmel contains abundant fossils dating the formation as of Middle and Late Jurassic age. No fossils have been found in the red silty facies within the Navajo country.

ENTRADA SANDSTONE

The Entrada sandstone of Late Jurassic age was described by Gilluly and Reeside in 1928 (p. 76) from exposures on Entrada Point in the San Rafael Swell, Utah. The Entrada sandstone consists of two conspicuous facies: a red silty spheroidally weathered sandstone which is frequently referred to as the hoodoo Entrada, and a clean sandy facies which weathers into rounded massive cliffs and is often referred to as the slick-rim Entrada. These two facies are recognized by Gilluly and Reeside in their type description and by other workers.

Both facies of the Entrada sandstone are present in the Navajo country (fig. 25). They occur as three distinct members, two of which consist of the clean sandy facies, separated by a third consisting of the red silty facies. The upper clean sandy facies is referred to as the upper sandy member in this report. It is conspicuous in the eastern half of the Navajo country and is recognized throughout northwestern New Mexico, and a correlative unit is believed to be present in southwestern Colorado. The lower clean sandy facies is referred to in this paper as the lower sandy member

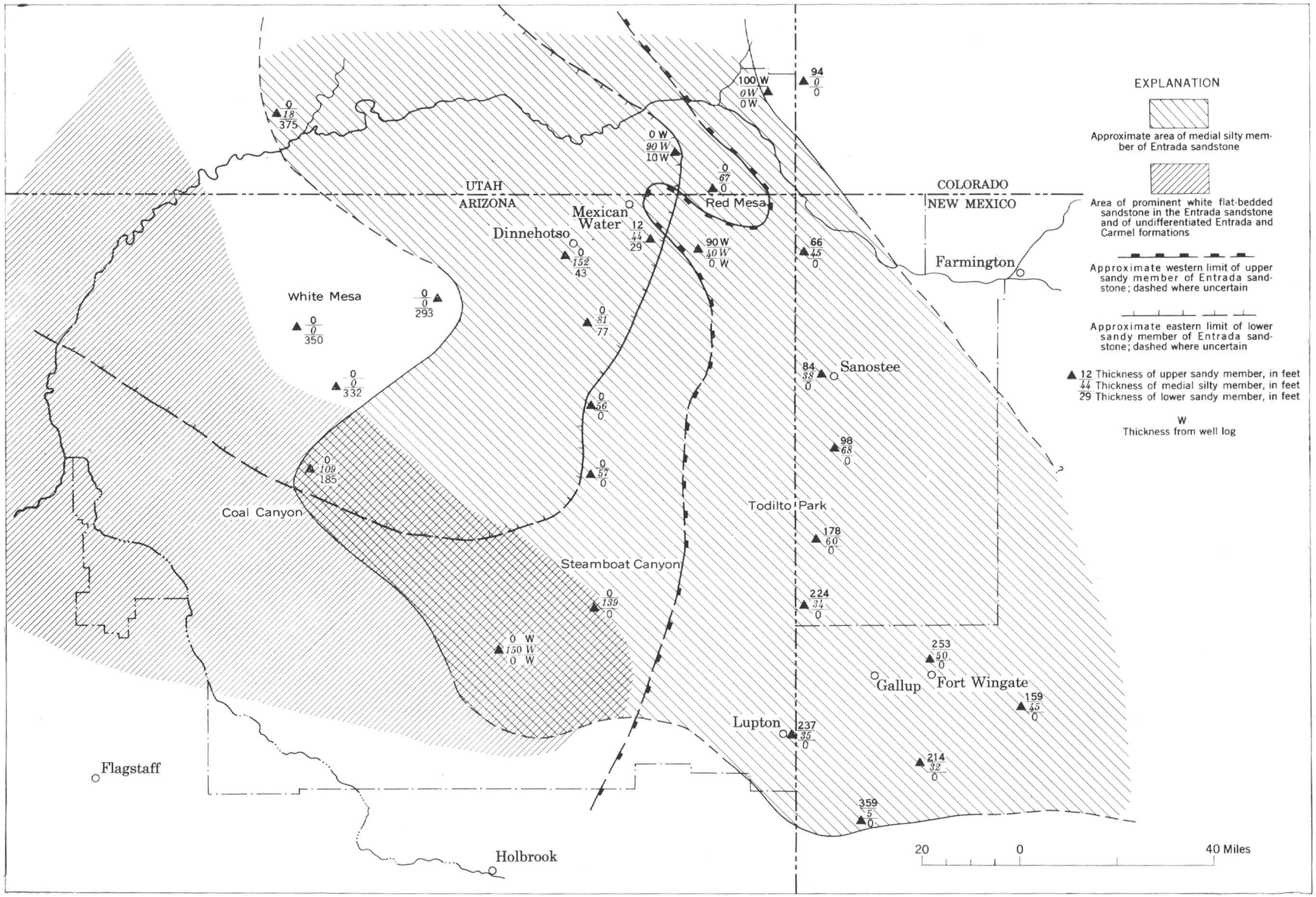

FIGURE 25.—Map of the Navajo country showing approximate depositional areas of the members of the Entrada sandstone.

and occurs in the northwestern part of the Navajo country. This member is correlated with the Entrada present in the central part of the southern border of Utah. North of this area its correlation is extremely uncertain owing to lack of information. The red silty facies is referred to in this paper as the "medial silty member" of the Entrada and is present in the eastern three-fourths of the Navajo country. It is believed to be correlative with the Entrada section at the type locality in the San Rafael Swell. This correlation is based upon a similarity of lithology of the red silty facies in the Navajo country and the type locality, and upon distribution trends of this facies.

General description and field relations.—The upper and lower sandy members of the Entrada sandstone range in color from moderate reddish orange (10*R* 6/6) to grayish orange pink (10*R* 8/2). The sandstone is composed mainly of medium- to fine-grained subrounded to subangular quartz. Coarse well-rounded amber-colored and white quartz grains are concentrated in many places along the bedding planes. Bedding of the units ranges from thin to very thick. Most crossbedding within the units is of the planar or trough type, ranging from small to large in scale. The variation in scale of crossbedding appears to be dependent upon the environment of deposition. The crossbedding in the upper sandy member increases to large scale and is predominantly of the trough type in the southeastern part of the Navajo country. A similar variation of crossbedding development has been observed in the lower sandy member in the western part of the area, although in this member the variation is not as marked as in the upper member. In both of the sandy members in most of the Navajo country one of the most pronounced characteristics of stratification is the abundance and persistence of parallel bedding planes. Such abundant and persistent bedding planes are not common in formations that are considered to be of eolian origin, such as the Navajo and Wingate sandstones. These bedding planes suggest that a considerable amount of the sandy facies of the Entrada may have been deposited in water. They are especially noticeable in areas where the sandy facies grades into the red silty facies without sharp intertonguing relations. Such a relationship is in contrast to that between intertonguing eolian and subaqueous deposits, as between the members of the Wingate or between the Navajo sandstone and the Kayenta formation. In the western part of the Navajo country conspicuous bedding planes decrease in number in the lower sandy member and the unit acquires the general appearance of the Navajo sandstone. In the southeastern part of the area a similar variation occurs in the upper sandy member. This change in type of bedding suggests a gradation into eolian deposition in these areas.

The upper sandy member of the Entrada forms prominent cliffs in the eastern part of the Navajo country. It is 154 feet thick at Thoreau, 253 feet at Fort Wingate, 332 feet at Lupton, 224 feet at Fort Defiance, 178 feet at Todilto Park, 98 feet at Toadlena, 84 feet at Beautiful Mountain, north of Sanostee, and 4 feet in upper McElmo Canyon (pl. 3). It is thickest in the Lupton area and is progessively thinner from there to the east, north, and the northwest (toward Steamboat Canyon), where the sandy members of the Entrada are absent.

The lower sandy member of the Entrada is conspicuous in the western part of the Navajo country. It is 375 feet thick at Navajo Point, Utah, 350 feet near Kaibito, 289 feet at Red Lake, and 185 feet at Blue Canyon. South of Blue Canyon it consists of very fine sand and silt and cannot be separated from the underlying white sandy facies of the Carmel foundation. Both sandy members of the Entrada are absent in the central part of the Navajo country east of Rock Point, at Yale and Lohali Points, and at Steamboat Canyon. The three members of the Entrada are present together only in the vicinity of Mexican Water (pl. 3), where the two sandy members do not have their normal characteristics as they grade into the medial silty member. In all other areas within the Navajo country one or the other of the sandy members is absent (fig. 25).

The medial silty member of the Entrada is moderate-reddish-brown (10*R* 4/6) silty very fine grained sandstone. Its bedding is inconspicuous on weathered surfaces, owing to the well-cemented character of the member. Sorting of the grains in this unit is generally good. Most bedding is flat, although in marginal areas an appreciable amount of small-scale crossbedding is present.

The medial silty member of the Entrada sandstone is 151 feet thick at Dinnehotso, 55 feet at Lohali Point, 139 feet at Steamboat Canyon (its upper contact is questionable here), 109 feet in Blue Canyon, and 18 feet at Navajo Point. In the eastern part of the area it is 60 feet thick at Todilto Park, 35 feet at Lupton, and 50 feet at Fort Wingate, where it is present in the middle of the unit originally defined as the Wingate sandstone (fig. 5). It is absent in the western third of the Navajo country.

The lower contact of the medial silty member appears gradational with underlying units: the Carmel formation and the lower sandy member of the Entrada. The contact with the upper sandy member in most places is marked by a thin, persistent bleached zone. Where the upper sandy member is absent the contact of the medial silty member with the overlying Summerville is arbitrary.

The contact of the upper sandy member with overlying units is sharp in most places, but in the southern part of the area the boundary between the Entrada and the Cow Springs sandstone is arbitrary. Where the upper sandy member of the Entrada is overlain by the Todilto limestone or the silty facies of the Summerville formation the contact is sharp. In New Mexico, Silver (1948, p. 77) and Rapaport, Hadfield, and Olson (1952, p. 27) have mentioned intertonguing between the Entrada and the Todilto.

Preconsolidation slumping and crinkling are common in the medial silty member in certain areas. These structures in the Entrada and similar ones in the overlying Summerville formation are believed to be due to plastic flow of water-soaked sediments downslope along the sea floor. Baker (1946, p. 74) suggests this explanation for similar structures in the Carmel formation. These structures are similar in many respects to those in the marine Silurian siltstone at Aberystwyth, Wales, as described by Rich (1950, p. 731–734), for which he proposed such an origin. Archanguelsky (1930, p. 32–80) has described recent slumping in the Black Sea which could be analogous to that in the sediments of the San Rafael group. He reports flowage as occurring wherever the slope is greater than 2° to 3°, and in places where it is as low as 1°. It seems likely that such dips could have existed locally along the floors of the Entrada and Summerville seas. The possibility that there might be such local variations in slope is suggested by the presence of pronounced belts of crinkled sediments which seem to parallel the depositional limits of the Summerville formation.

Laboratory studies.—Laboratory work done on samples from the sandy members of the Entrada show the following average results: 4.7 percent carbonate minerals; median diameter of the grains, 0.11 millimeter; coefficient of sorting, 1.26; skewness, 0.96; and sphericity, 0.79. Roundness analyses show that the grains are 1 percent rounded, 18 percent subrounded, 62 percent subangular, and 19 percent angular. The medial silty member of the Entrada has an average carbonate-mineral content of 8.75 percent, a median diameter of 0.09 millimeter, a coefficient of sorting of 1.38, and a skewness of 0.84. In general the results are consistent, but no regional trends were observed.

The sandy members of the Entrada are composed chiefly of quartz grains which make up about 95 percent of the disaggregated sample. Feldspar is present in amounts up to about 4 percent and consists mostly of plagioclase which ranges from oligoclase to andesine. The heavy-mineral fraction is somewhat less than 0.5 percent of the sample. The heavy minerals, in order of abundance, are as follows: magnetite in rounded grains, garnet in angular grains showing a conchoidal fracture, limonite and hematite as a thick coating on the quartz grains, euhedral pink and green tourmaline, ilmenite, sphene, sillimanite, and hornblende. Although calcium carbonate is the main bonding cement, limonitic cement is present in appreciable amounts and probably accounts for the firmness of the Entrada in many areas.

TODILTO LIMESTONE

The Todilto limestone of Late Jurassic age was originally described by Gregory in 1917 (p. 55, 56) from exposures of the formation where it overlies the Entrada sandstone in Todilto Park, McKinley County, N. Mex. The rank and stratigraphic assignment of the Todilto limestone have been shifted considerably. The unit first was assigned to the Glen Canyon group as a formation (Baker, Dobbin, McKnight, and Reeside, 1927); later it was given a member rank and assigned to the Morrison formation by Baker, Dane, and Reeside (1936, p. 9); and still later Baker, Dane, and Reeside (1947, p. 1668) placed it in the San Rafael group as a member of the Wanakah formation of southwestern Colorado. Owing to its wide distribution and distinctive lithology, Northrop (1950, p. 36), Harshbarger, Repenning, and Jackson (1951, p. 97), Wright and Becker (1951, p. 610), and Rapaport, Hadfield, and Olson (1952, p. 23–27) have treated the Todilto as a formation, as originally defined, but have placed it in the San Rafael group.

General description and field relations.—At the type locality, Todilto Park, the Todilto limestone, from bottom to top, consists of 16 feet of mudstone, 4 feet of limestone, and 5 feet of mudstone. In this area the upper and lower contacts of the formation are sharp and irregular; the upper one in particular has marked channeling, having about 5 feet of relief.

The lower mudstone contains many beds of lenticular sandstone and is dusky yellowish brown (10*YR* 2/2) to a dark yellowish orange (10*YR* 6/6). In grain size the mudstone ranges from clay to fine sand. The unit weathers readily and forms a slope above the massive, rounded cliff of the Entrada.

The limestone is light olive gray (5*Y* 6/1) and locally is aphanitic. It has a fetid odor in many areas. The basal part of the unit contains abundant red, white, and black quartzite pebbles that are well rounded. The occurrence of these pebbles has been noted in other areas within the Navajo country and elsewhere along the western margins (fig. 26) of the limestone (Rapaport, Hadfield, and Olson, 1952, p. 26). Although the limestone is locally very sandy and the lower mudstone beds are considered to be fluvial, it is difficult to explain the presence of these pebbles in the limestone. Bedding in the limestone is thin and flat, but in many areas it has been warped irregularly so that the dip slope of the limestone shows a series of approximately parallel anticlinal ridges 1–2 feet high. The upper part of the limestone contains many solution cavities and is composed of coarsely crystalline calcite, apparently a secondary development. The unit forms a resistant ledge and is exposed in large dip slopes.

The upper mudstone unit is pale red purple (5*RP* 6/2) and is 5 feet thick at the type locality. Locally it was removed by pre-Summerville channeling. In many places it contains abundant limestone pebbles and clay pellets and appears to be fluvial. Its basal surface is extremely irregular, for it fills solution cavities on the surface of the underlying limestone.

Todilto Park is at the western limit of deposition of the Todilto limestone, and within the Navajo country the limestone unit is present only in the eastern part (fig. 26). Eastward toward the central parts of its depositional basin the limestone unit is thicker. Rapaport, Hadfield, and Olson (1952, p. 23) report a maximum thickness of 25 feet of limestone near Haystack Butte, Prewitt, N. Mex., about 68 miles east of the type locality. East of the Prewitt area the formation includes a thick section of gypsum whose thickness reaches 111 feet near San Ysidro, N. Mex. (Northrop and Wood, 1946). This gypsum unit does not extend as far west as the Navajo country.

Fossil occurences.—Within the Navajo country only one locality has yielded fossils from the Todilto limestone. Swain (1946, p. 553) reports that ostracodes found by Reeside and Wilpolt in Satan Pass, north of Thoreau, N. Mex., are fresh- or brackish-water forms of the genus *Metacypris*. The species, *M. todiltensis*, was new. Several fish found in the Todilto in Guadalupe County, N. Mex. (Koerner, 1930) and on the Piedra River in southwestern Colorado (Imlay, 1952, p. 960) are considered to have marine affinities.

SUMMERVILLE FORMATION

The Summerville formation of Late Jurassic age was named by Gilluly and Reeside (1928, p. 80) from exposures on Summerville Point in the San Rafael Swell, Utah. In the type area, the contact of this formation with the underlying Curtis formation is arbitrary, and these formations appear to have been deposited without a major break in deposition. Beyond the limits of Curtis deposition to the east of the type locality, the basal part of the Summerville probably was deposited during Curtis time (Baker, Dane, and Reeside, 1936, fig. 16); apparently the Summerville contains more nearshore deposits than does the Curtis. This suggestion is substantiated by the stratigraphic relationships of the Summerville within the Navajo country. Throughout this area it is divisible into two parts (fig. 26); an upper sandy facies and a lower silty facies, similar to the type Summerville. This sequence represents a depositional history similar to that represented by the Curtis and Summerville formations at the type locality and suggests that the lower part of the Summerville formation within the Navajo country was deposited during Curtis time.

Various workers, including the authors, recognize the Summerville formation in southwestern Colorado, northwestern New Mexico, and northeastern Arizona. This recognition is based upon lateral tracing and upon correlation across covered areas from known outcrops of the Summerville in southeastern Utah. The unit here assigned to the Summerville, together with the Todilto limestone, has been assigned to the Wanakah formation by other workers (Goldman and Spencer, 1941, p. 1759; Imlay, 1952, p. 960). As previously mentioned, the assignment of the Todilto as a member of the Wanakah does not seem tenable because of its wide distribution and mappable character. The correlation of the Summerville formation from the San Rafael Swell to Bluff, Utah, appears to be no longer in doubt (Imlay, 1952, chart 8–C). From Bluff, the formation is traceable throughout the eastern part of the Navajo country and is here correlated with the "buff shale and brown-buff sandstone members of the Morrison formation" (Kelley and Wood, 1946) in the Laguna-Lucero area of New Mexico.

Within the Navajo country the two facies of the Summerville formation are recognized as mappable units. The lower unit is the silty facies, similar in lithology to the Summerville in the type area; the upper unit is the sandy facies, representing a deposit laid down nearer shore which has bedding features similar to those of the silty facies but is primarily sandstone. However, the two units are gradational and the boundary between them is arbitrary. In the Navajo country, the lower unit is herein referred to as the lower silty member and the upper unit as the upper sandy member.

General description and field relations.—The Summerville formation at the type locality is composed of a sequence of pale-brown flat- thin-bedded sandstone beds and brownish-gray gypsiferous mudstone beds. In the Navajo country this typical lithology occurs only in the northeastern part (fig. 26). South and southeast of the northeastern part of the area the formation contains greater amounts of sand and is more massive. The characteristic flat thin bedding persists as far south as Fort Defiance where the formation grades into the Cow Springs sandstone.

In general, the lower silty member of the Summerville consists of a sequence of grayish-orange-pink (5*YR* 7/2) to moderate-reddish-brown (10*R* 4/6) fine-

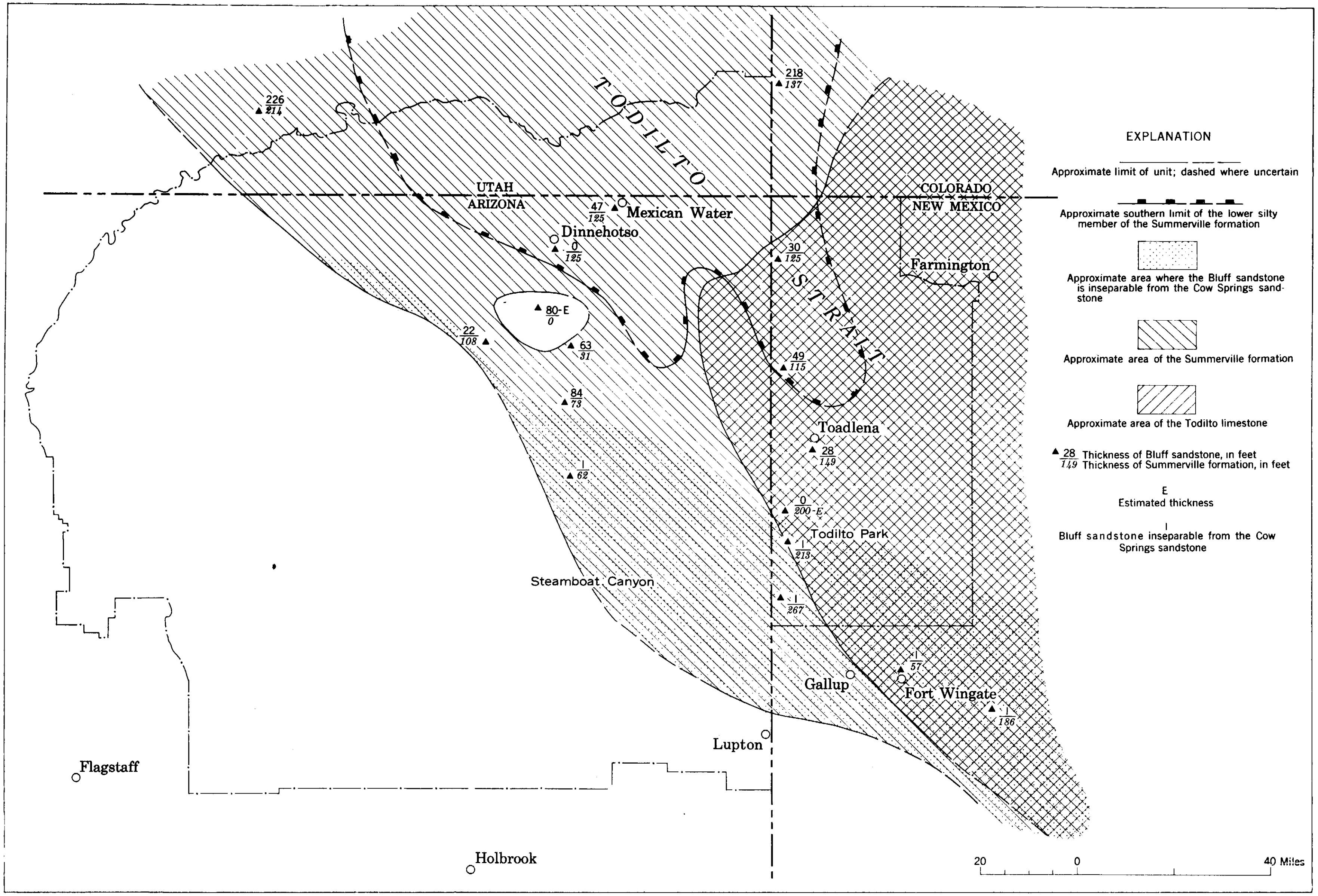

FIGURE 26.—Map of the Navajo country showing approximate depositional areas of the Todilto limestone and the Summerville formation.

grained silty sandstone beds interbedded with dark-reddish-brown (10*R* 3/4) mudstone strata (fig. 27). Most of the sand grains are subangular clear to amber quartz. The sorting is generally poor and the calcareous cement is firm. Bedding is characteristically flat and ranges from laminated in the mudstone beds to thick bedded (as much as 3 feet thick) in the sandstone beds. In the Navajo country there is a 30-foot zone of sediments at the base of the formation which contain mud cracks and ripple marks in many places. The member weathers into a conspicuously ribbed cliff; the resistant sandstone beds form the ribs and the easily weathered mudstone beds form the niches in the cliff.

The lower silty member of the Summerville contains abundant examples of intraformational deformation. The large-scale slumps are believed to be the cumulative effect of sliding of unconsolidated water-saturated sediments along the sloping sea floor which caused smaller scale interstratal crinkling in the marginal areas of deposition. This type of deformation is suggested further by the general occurrence of these slumpage structures near the limits of the lower silty member, where it grades into the sandy member. Some of the slump structures fade out downward into flat-lying sediments; others are in sharp contact with them. However, their upper parts commonly were planed off by erosion prior to deposition of overlying strata (fig. 28). The interested reader is referred to Rich (1950, p. 733) for a discussion of similar occurrences of slumping.

Near Mexican Water (fig. 27) the lower silty member constitutes the entire Summerville formation. South and southwest of this area the upper part of the formation grades into the upper sandy member. Still farther in those directions the sandy member is thicker, and at Marsh Pass, Lohali Point, Todilto Park, and Thoreau it constitutes the entire Summerville formation. Southwest of Dinnehotso the gradation of the silty facies into the sandy facies occurs across a distance of 10 miles. Five miles farther southwest the formation intertongues with the eolian Cow Springs sandstone, which locally replaces the entire Summerville (fig. 26).

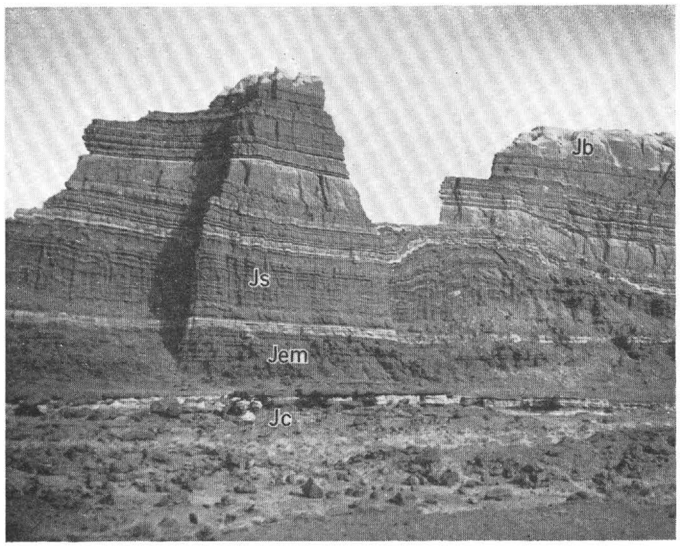

FIGURE 28.—Slumping in the Summerville formation, 2 miles northeast of Red Mesa, Ariz. Carmel formation (Jc); medial silty member of the Entrada sandstone (Jem); Summerville formation (Js); Bluff sandstone (Jb).

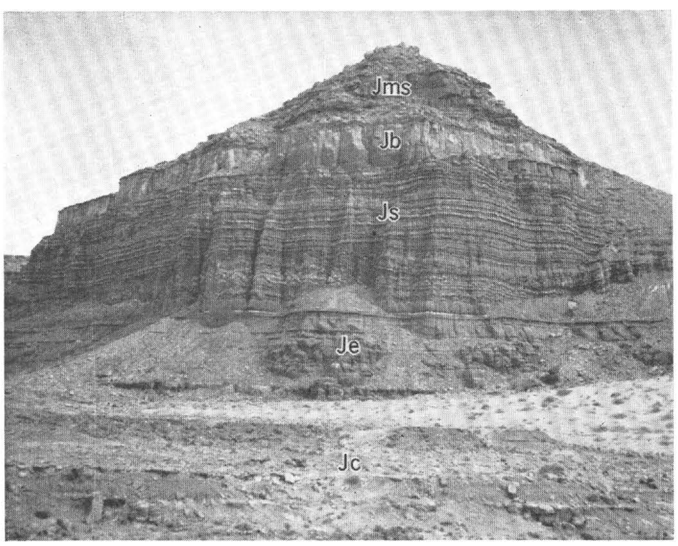

FIGURE 27.—Lower silty member of the Summerville formation, 4 miles east of Mexican Water, Ariz. Carmel formation (Jc); Entrada sandstone (Je); Summerville formation (Js); Bluff sandstone (Jb); and Salt Wash member of the Morrison formation (Jms).

Parallel to the long axis of the basin the lateral transition from the silty to the sandy facies is considerably more gradual. At Crystal, N. Mex., about 90 miles southeast of Mexican Water, the Summerville consists entirely of the upper sandy member, which forms a massive sandstone cliff (fig. 29). South of Crystal it includes deposits of an eolian type, but complete transition into the Cow Springs sandstone does not occur for another 30 to 40 miles. The alinement of the basin is generally southeast, extending as far in this direction as Laguna, N. Mex. In that locality the Summerville formation consists of a mixture of silty and sandy deposits. According to Silver (1948, fig. 2), the unit is absent 40 miles south of Laguna. The present authors believe that its absence is due to both lateral gradation into the Cow Springs sandstone and removal by pre-Dakota erosion.

The upper sandy member is a moderate-reddish-brown (10*R* 5/6) fine-grained sandstone composed of well-sorted subrounded to subangular amber-colored and clear quartz grains. The bedding is flat but wavy, and small-scale crossbedding is present in individual beds, particularly in the uppermost part of the member. Intrastratal deformation is common within the member,

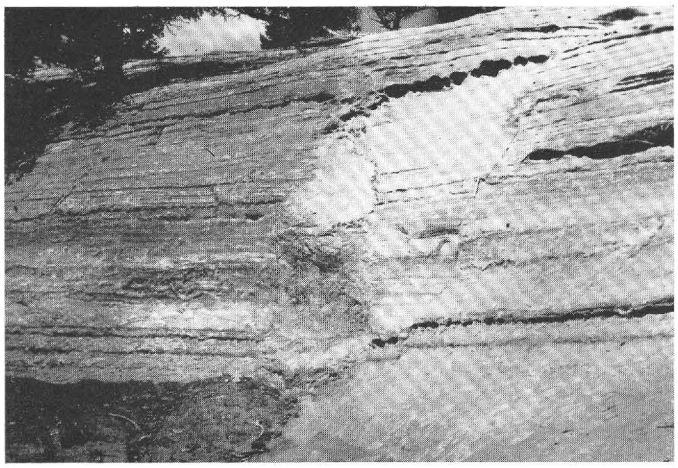

FIGURE 29.—Upper sandy member of the Summerville formation 1 mile southwest of Crystal, N. Mex.

and large-scale slumping and intraformational faults occur throughout it.

The Cow Springs sandstone intertongues with the upper sandy member of the Summerville formation, and tongues of sandstone extend varying distances northward from the main mass of the Cow Springs (pl. 3). The lowermost and most conspicuous of these tongues is the Bluff sandstone of the San Rafael group, which overlies the Summerville formation throughout most of the Navajo country.

The Summerville formation is 125 feet thick at Mexican Water, 149 feet at Toadlena, 213 feet at Todilto Park, and 267 feet (including tongues of the Cow Springs sandstone) at Fort Defiance (pl. 3). It is 124 feet thick in McElmo Canyon and 214 feet on Navajo Point. Generally it is thickest where the sandy member is conspicuous, and its thickness is variable where tongues of the Cow Springs constitute a part of the formation. The Summerville formation is not present in the southwestern part of the Navajo country; there, the Cow Springs sandstone occupies its stratigraphic position.

At Bluff, Utah, the Summerville formation consists of the lower silty member and the upper sandy member. Gregory's section number 19 (1938, p. 74), measured at the village of Bluff, shows the Summerville formation to be 161 feet thick. Units 2 and 3, 79 feet thick, are here correlated with the lower silty member; and units 4, 5, and 6, 82 feet thick, are correlated with the upper sandy member. This sequence is overlain by an uneven, slightly eroded surface beneath the Bluff sandstone; Gregory believed that the erosion surface possibly represented an unconformity. The twofold division of the Summerville is recognized throughout the Navajo country.

It is believed that these two facies of the Summerville represent transgressive and regressive phases within the same depositional basin. The deposits laid down during the earlier, transgressional, phase are believed to be roughly contemporaneous with the Curtis formation to the north. The deposits formed during the later, regressional, phase are believed to be roughly contemporaneous with the deposits of the Summerville in the San Rafael Swell. In its final stages, the Curtis-Summerville sea apparently was shallow and interrupted in the vicinity of the San Rafael Swell. This belief is based upon the occurrence of extensive gypsum deposits in that area. In the Navajo country this age is believed to be represented by the continental deposits of the Bluff sandstone and its equivalent in the Cow Springs sandstone.

BLUFF SANDSTONE

The Bluff sandstone of Late Jurassic age was described by Gregory (1938, p. 58) from exposures of beds which form the cap rock of the ciffs at Bluff, Utah. He assigned the Bluff sandstone to the Morrison formation as its basal member, owing to the stratigraphic relationships in the San Juan country. Later workers observed that the Bluff sandstone intertongues with the underlying Summerville formation as well as with the basal part of the Morrison formation, and in recent years many have considered the Bluff sandstone as a separate and mappable unit, although their opinions have not been formally published. Craig and others (1955) assigned the Bluff to the upper part of the San Rafael group throughout the San Juan and Navajo countries.

The authors of the present report believe the Bluff sandstone to be a tongue of the Cow Springs sandstone, extending northward from the main mass of the Cow Springs. However, owing to its homogenous and mappable character and its areal extent the Bluff is considered a separate formation and is assigned to the upper part of the San Rafael group. The lithology of the Bluff is similar to that of the Cow Springs. It is a gray well-sorted highly crossbedded sandstone which has weathered into a massive cliff. Both deposits are considered to be of eolian origin and, because of their similar lithology, they are inseparable where the Bluff coalesces with the Cow Springs in the southwestern part of the Navajo country. In that area the Bluff is included in the Cow Springs sandstone (pl. 3).

General description and field relations.—Gregory states that, at the type locality, the town of Bluff, Utah, the Bluff sandstone is "white, brown-stained, commonly crossbedded, and made up of medium-to-coarse quartz grains. Typically it is one massive bed 200 to 350 feet thick that here and there includes aggregates of large quartz grains, clay balls, and short thin lenses of red mudstone." In Gregory's section number 18

(1938, p. 74), measured on the south face of Tank Mesa, he shows the Bluff as one unit which is 200+ feet thick. Underlying the Bluff he describes two units (14 and 15) which also consist of white to brown sandstone containing crossbedding and minor units of shale. He has assigned these units to the Summerville formation, and they correspond to the upper sandy member of the Summerville as described in this report.

The Bluff sandstone is quite similar to the Cow Springs sandstone and is composed of greenish-gray (5*G* 6/1) to yellowish-gray (5*Y* 8/1) medium-to fine-grained well-sorted crossbedded firmly cemented sandstone. It consists of subangular to rounded grains of quartz and minor amounts of feldspar and black accessory minerals. The cementing material consists mainly of grayish-green calcium carbonate but in some places it is yellowish gray to yellowish orange, probably owing to the presence of ferruginous material in the cement. One of the conspicuous features of the Bluff is its crossbedding, which in most places is of the wedge-planar or asymmetrical-trough types. The crossbeds are large scale and high angle. The lower part of the formation commonly contains flat-bedded units, particularly where the Bluff grades into the upper sandy member of the Summerville formation. The Bluff characteristically weathers into a massive, smooth, rounded cliff or slope.

The Bluff as a mappable unit is confined to northeastern Arizona, the northwestern corner of New Mexico, and southeastern Utah (pl. 3). In the area between Todilto Park and Dinnehotso, the Bluff was not deposited and the formation is not connected with the Cow Springs to the southwest of that area. In the southeastern part of the Navajo country the Bluff is inseparable from the Cow Springs sandstone (fig. 26). It is believed that the Bluff may extend northward, as a tongue of the Cow Springs sandstone, from the southeastern part of the Navajo country into the Four Corners area. The best exposures of the Bluff as a distinct unit are in southeastern Utah.

Both the upper and lower boundaries of the Bluff sandstone are arbitrary in some areas, as they represent a transition zone of both subaqueous and eolian deposition. In most places the lower boundary overlies the upper sandy member of the Summerville. The most significant criterion for determining this boundary is the difference in the bedding structure. The upper sandy member of the Summerville is predominantly flat bedded and thin bedded and contains small-scale low-angle crossbedding, which contrasts with the high-angle large-scale crossbedding in the Bluff sandstone. Southwestward from the Four Corners area the Bluff grades into the upper part of the Summerville and at Dinnehotso the Bluff is absent (pl. 3). These two units probably intertongue, but to determine whether they do would require careful tracing of the beds characteristic of each formation.

The upper boundary of the Bluff sandstone is clearly marked where it is formed by the base of the Salt Wash member of the Morrison formation. The boundary is easily discernible, as the base of the Salt Wash is commonly marked by a thin claystone. In those areas where the basal Salt Wash consists of sandstone, the difference in grain size, bedding structures, and topographic expression makes it possible to determine the upper boundary. Where the Cow Springs overlies the Bluff, however, the boundary is not readily discernible.

The Bluff ranges in thickness from a few feet to about 300 feet. In McElmo Creek, Colo., it is 218 feet thick; at Bitlabito, N. Mex., 30 feet; and at Toadlena, 28 feet. It grades into the Summerville formation several miles south of Toadlena. Near Mexican Water the Bluff is only 47 feet thick; within a short distance southwest of there it grades into the Summerville. At Tyende Creek, south of Dinnehotso, it is 64 feet thick, but it coalesces with the Cow Springs sandstone near Yale Point, where the units are inseparable. In the northwestern part of the Navajo country the Bluff is 227 feet thick at Navajo Point and is thicker to the south, but it coalesces with the Cow Springs sandstone several miles south of the Utah-Arizona State line.

Only a few random samples of the Bluff sandstone were examined in the laboratory for composition and grain character. In general these results are quite similar to those listed for the Cow Springs sandstone, and for all practical purposes the results of those studies are applicable to the Bluff sandstone.

SEDIMENTATIONAL HISTORY OF THE SAN RAFAEL GROUP

Prior to the deposition of the basal San Rafael strata in the Navajo country, a highland was developed to the west and southwest of the area. The initial development of this highland caused the cessation of the Kayenta streams by severing their connection with the Pacific ocean and led to a general shifting of the depositional basin eastward. New streams developed in this highland area and traversed the dunes of the Navajo sandstone, flowing into the San Rafael basin of deposition north of the Navajo country.

At the beginning of San Rafael deposition, the ancient Uncompahgre Range to the northeast of the Navajo country was not an active contributor to the deposits within the Navajo country. However, it was a positive element and partially delimited the basin in which the San Rafael group was deposited. The highlands to the south and southwest, especially the southwest part of the Navajo country, were substantial contributors of sediment. Because of the arrangement of positive areas, the marine deposits of the San Rafael group were confined to a trough that plunged northward. The southeastern part of this trough extended across the northeastern half of the Navajo country.

The highland area south of the Navajo country, which was a southeastern extension of the Cordilleran geanticline (Eardley, 1951, p. 21–23; pls. 13 and 15), remained prominent throughout Late Jurassic and Cretaceous time. Previously, during Late Triassic time and until the cessation of Kayenta deposition, this highland area was also prominent but was not connected with positive areas to the west. The uplift to the southwest of the Navajo country which caused cessation of Kayenta deposition provided an important source for the San Rafael sediments and bridged the gap between the Cordilleran geanticline and the highland area to the south of the Navajo country. This southwestern uplift occurred in an area called Mohavia by Eardley (1951, pl. 13). Mohavia was one of the most important source areas for the Upper Jurassic sediments in the Navajo country.

The highland area south of the Navajo country generally paralleled the present Mogollon Plateau, which forms the southern border of the Colorado Plateaus province. The northern boundary of the highland probably lay in the area now occupied by the Mogollon Plateau, although its boundary was variable from Late Triassic through Cretaceous time. It is proposed that this highland area, which extended across parts of central Arizona and New Mexico during the Mesozoic era, be called the Mogollon Highlands.

The basal deposits of the San Rafael group, the Carmel formation, did not extend as far southeast as did subsequent formations of the San Rafael group. Sedimentary structures within the Carmel formation suggest deposition in a lagoonal or estuarine environment, although fossils are lacking in the formation in the Navajo country to corroborate this idea. Within the Navajo country sedimentary material apparently was transported into the Carmel basin by streams (fig. 30). The material was derived primarily from the Navajo sandstone to the southwest. Where these streams entered the marine waters they deposited cross-bedded sand and interbedded flat-bedded sand and mud. These deposits seem most suggestive of deltaic deposition and they interfinger to the north with the typical red deposits of the Carmel. To a large extent the typical red of the Carmel is due to limonitic coating of the grains.

Because the Carmel of the Navajo country represents deposits formed near the margins of the sea, it probably does not represent the earliest Carmel deposition. As the Carmel sea regressed, windblown sands from the west apparently covered the southern part of the basin, as shown by the presence of the lower sandy member of the Entrada. During the regression of the Carmel sea (Early Callovian time) streams continued to introduce new material from the southwest, and fluvial deposits were laid down on the marine Carmel sediments. In the areas where the Carmel sea remained the longest its circulation seems to have been restricted, and the formation contains gypsum deposits in central Utah. A lack of gypsum in the Carmel of the Navajo country was perhaps due to the introduction of fresh water from streams in the area, which diluted the water enough to prevent precipitation of the dissolved salts.

Where the lower sandy member of the Entrada is absent the contact of the Carmel with the overlying subaqueous deposits of the Entrada is gradational, and no indication of subaerial erosion or break in deposition occurs at this horizon. It appears that the end of Carmel deposition was marked by the termination of restricted circulation caused by the partial withdrawal of the marine waters. Upon the return of the sea (in Late Callovian time) to the Navajo country the medial silty member was deposited on the lower sandy member of the Entrada. The deposits of this phase of San Rafael deposition extend farther to the southeast than does the Carmel formation. However, deposits of the Carmel may have extended farther southeast and may have been removed subsequently, although evidence on this point is lacking.

The medial silty member of the Entrada appears to have been deposited under more stable conditions than existed in Carmel time, as it does not contain interbedded sands and silts such as occur in the Carmel. However, it contains tongues of the sandy facies whose relation to the silty facies seems to indicate shallow-water deposition. The regular gradation of grain size and bedding structures, and the absence of fine-grained particles, suggest deposition effected by wave action. Such an interpretation would account for the lateral gradation of tongues of the sandy facies into the red silty facies. However, high-angle large-scale cross-bedding in some parts of the sandy facies of the Entrada appears typically eolian, and horizontal bedding planes are absent. Because of these relationships it is believed that the sandy facies of the Entrada represents deposits of both eolian and marine origin along the margins of the Carmel-Entrada sea.

After the withdrawal of the waters in which the medial silty member of the Entrada was deposited, eolian deposits from the east migrated across the eastern part of the medial silty member to form the upper sandy member. Why the eolian deposits of the lower sandy member advanced from the west over the marine de-

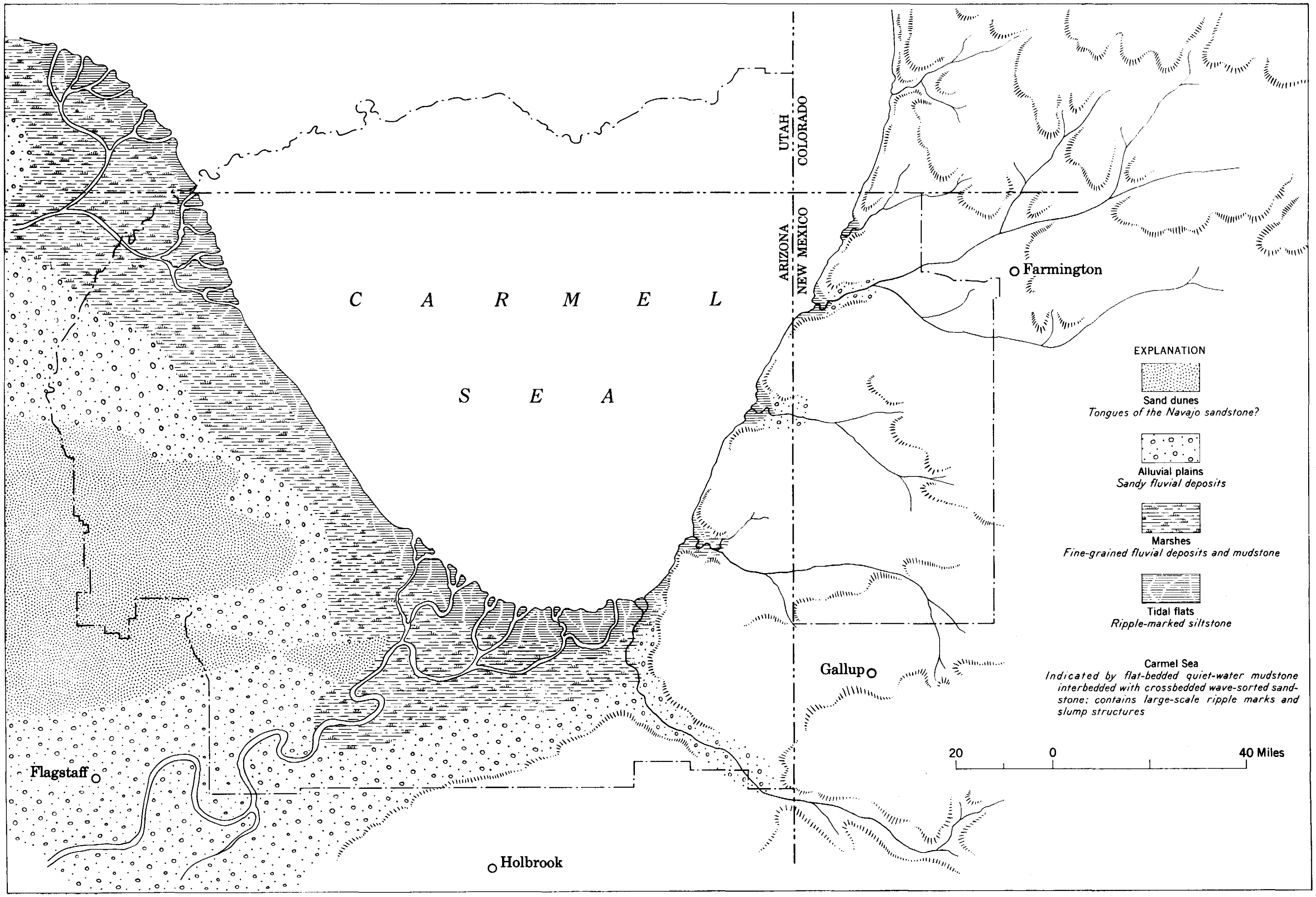

FIGURE 30.—Sketch map showing the hypothetical physiography of the Navajo country during deposition of the Carmel formation.

posits of the Carmel, while other eolian deposits advanced from the east over the marine deposits of the Entrada is not clear. One or both of the following possibilities may be the answer, although conclusive information to substantiate either is not available. (1.) Streams may have removed any dune deposits that formed to the southwest. Strong fluvial activity in that area may have continued during the regression of the Entrada sea and retarded the accumulation of eolian deposits there. Fluvial deposits have been noted between the medial silty member of the Entrada and the Summerville in the western part of the Navajo country, and these might have been laid down by streams which removed most of the eolian deposits in that area. (2.) It is possible that eolian deposits of Entrada time are present but have not been distinguished from the overlying eolian Cow Springs sandstone.

The Curtis-Summerville inundation (Oxfordian), last transgressive phase of the sea in which deposits of the San Rafael were laid down in the Navajo country, apparently followed a complete withdrawal of the Entrada sea. Gilluly and Reeside (1928, p. 78) report that the unconformity between the Entrada sandstone and the Curtis formation has as much as 50 feet of relief in the San Rafael Swell, to the north of the Navajo country in the main San Rafael Basin. No such indication of a pronounced break in sedimentation at the contact appears to be present in the Navajo country. However, where marine deposits of the Entrada underlie the Summerville formation, a mud-cracked, ripple-marked lenticular fluvial deposit usually separates them, indicating a break in marine deposition. For convenience in mapping, this fluvial deposit has been included in the Summerville, although its assignment is arbitrary.

The Todilto limestone was deposited during the final stages of continental Entrada deposition, as evidenced by intertonguing relations in areas east of the Navajo country (Rapaport, Hadfield, and Olson, 1952, p. 27); and during early Curtis-Summerville deposition, as indicated by renewed subaqueous deposition. Considerable controversy has existed over the origin of the Todilto. Both abnormal marine and abnormal lacustrine origins have been proposed. The water within the Todilto basin seems to have been high in hydrogen sulfide, calcium bicarbonate, and calcium sulfate. The formation contains few remains of living organisms.

The presence of fresh- or brackish-water ostracodes within such a fetid body of water seems unusual, and they probably existed only at or near the surface in the better aerated water. Within a basin that has restricted connection with the main sea such brackish aerated waters may occur at the surface where streams enter the basin. It would seem unusual to find water in a toxic and closed basin concentrated by evaporation to the point of precipitation of gypsum, yet having a habitable zone at the surface. A predominant characteristic of a basin having restricted connection with the sea is the presence of rotted organic matter; hence, the fetid nature of its sediments. The interbedded limestone and gypsum observed in some areas, and the lack of chloride salts, seems more indicative of a basin connected to the sea. Restricted circulation to the sea could prevent sufficient concentration for precipitation of chloride salts. Only under rare conditions could the salts that occur in the Todilto have been precipitated in a lacustrine basin. For these reasons it is believed that the Todilto was deposited in a gulf, connected to the sea, that contained abnormal marine waters (fig. 31).

The preservation of fish in the Todilto seems pertinent to the problem of environment. However, more than likely they could not have lived within the basin; thus they probably entered during periods of marine inflow, died, and were preserved in the bottom sediments. A characteristic feature of modern basins similar to that in which the Todilto limestone is believed to have been formed is the excellent preservation of such vertebrates as fish, owing to the complete lack of bottom scavengers. The absence of marine invertebrates in the Todilto, particularly bottom dwellers, may be due to the inhospitable environment provided by the toxic water.

Imlay (1952, p. 961) points out that the connection between the Todilto basin and the Curtis sea most likely existed in the southeastern part of Utah. This connection, in order to produce a basin such as that in which the Todilto was deposited, would have consisted of a shallow body of water extending across a broad submerged ridge between the two basins (Fleming and Revelle, 1939, p. 96, fig. 10). As such a ridge would have been bounded on either side by deeper waters and would have been subjected to the effects of the most intense currents within the basins, the ridge is more likely to have been eroded than to have received sediments. Evidence suggesting such erosion is present in northeastern Arizona in the vicinity of the area where Imlay believed the connection existed. Between Mexican Water, Ariz., and Cortez, Colo., the Entrada is abnormally thin and, in parts of this area, the upper sandy member is entirely absent. In this area the lower silty member of the Summerville rests upon the medial silty member of the Entrada, as at Red Mesa, Utah-Arizona. The upper sandy member is present both to the north and to the south and becomes progressively thicker away from this area. A further indication of the position of the outlet is supplied by deposits to the southeast of this area near Red Rock, Ariz., where the

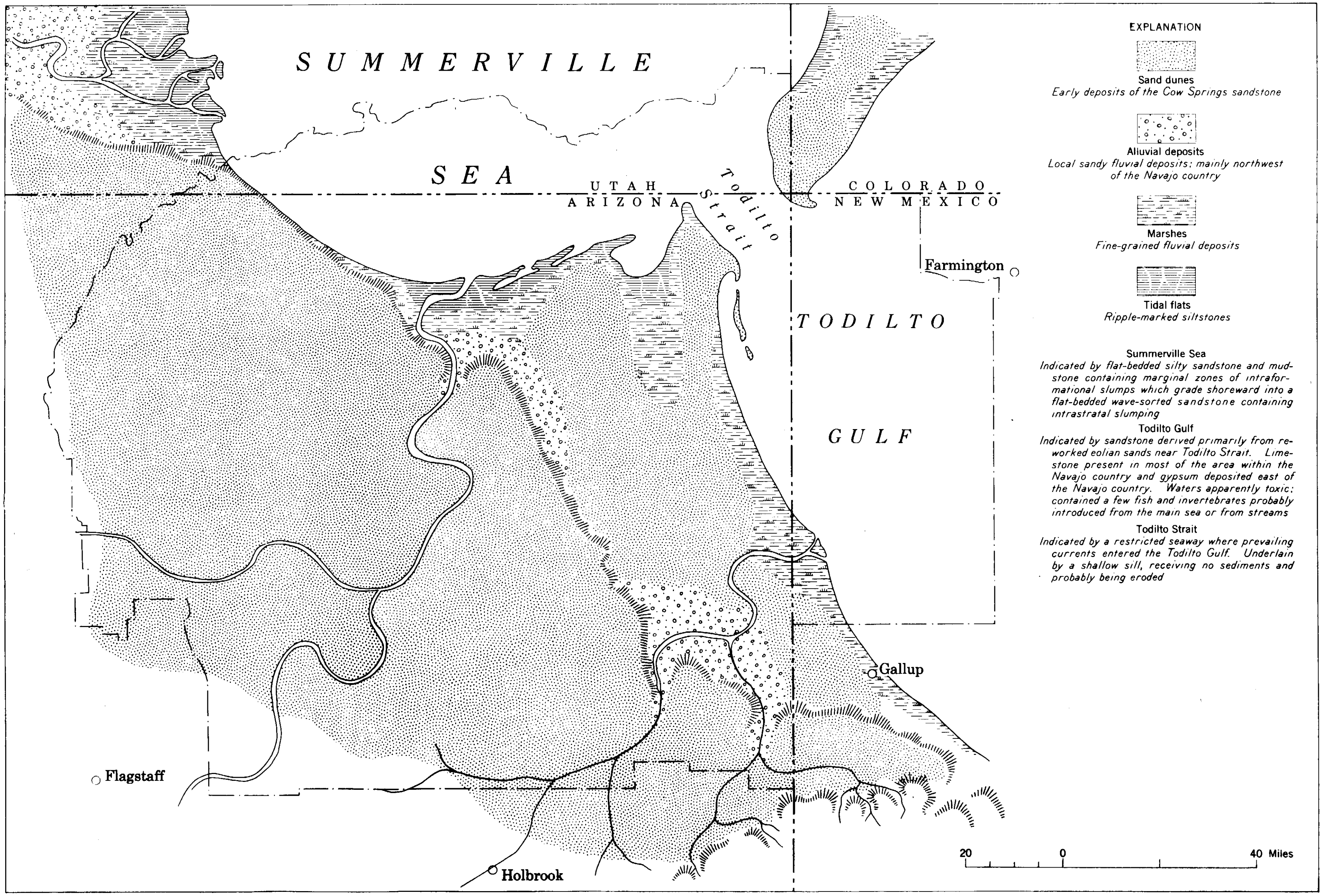

FIGURE 31.—Sketch map showing the hypothetical physiography of the Navajo country in the earliest stage of deposition of the Summerville and during deposition of the Todilto.

sandstone that overlies the Todilto limestone appears to be reworked Entrada. This sandstone seems to represent the earliest deposition of the Summerville within the area of Todilto deposition. Sediments more typical of the Summerville overlie these sandy sediments. Facies relationships (fig. 26) and thickness trends of the Summerville formation in the Navajo country suggest that the connection between the deposition basin of the Todilto and the sea lay about on the axis of the Summerville basin.

The initial transgression of the Summerville sea into the Navajo country was accompanied by the deposition of the lower silty member. The upper sandy member was deposited during the regression of the Summerville sea. In the Navajo country this regression of the sea was followed by the advance of dunes which formed the Bluff sandstone. Farther north, in the San Rafael Swell, the final deposits in the Summerville sea consist of interbedded evaporites and siltstone unconformably overlain by the Morrison formation.

COW SPRINGS SANDSTONE

The Cow Springs sandstone of Late Jurassic age was defined by Harshbarger, Repenning, and Jackson (1951, p. 97) as a crossbedded sandstone which intertongues with several Upper Jurassic units. These units include the Summerville formation and the lower members of the Morrison formation. Because of the intertonguing, the Cow Springs sandstone cannot be considered either a formation of the San Rafael group or a member of the Morrison formation and, therefore, as in the original description, it is considered a separate formation. Within the Navajo country, dunes from the south have advanced northward several times across the older deposits. Such depositional conditions resulted in the development of conspicuous tongues of crossbedded sandstone which extend great distances to the north from the main mass of the Cow Springs sandstone (pl. 3). The Bluff sandstone is believed to be the earliest and most conspicuous of these tongues.

Another conspicuous tongue of the Cow Springs sandstone has been recognized over a considerable area. In a few localities in the Navajo country it overlies the Salt Wash member of the Morrison formation. Where the Salt Wash is absent (fig. 32), this tongue constitutes the basal unit of the Morrison. In some areas it overlies the Bluff sandstone and they are essentially inseparable. Recognition of the "white sandstone" as a separate tongue is based mainly upon its relationship to the Morrison formation. Kelley and Wood (1946) and Silver (1948, p. 78) refer to a similar unit along the southern flank of the San Juan Basin, New Mexico as the white sandstone member of the Morrison.

In some areas the Cow Springs sandstone is roughly equivalent to the Zuni sandstone as defined by Dutton (1885, p. 137), although in some other areas, as pointed out by Baker, Dane, and Reeside (1936, p. 43), the Zuni sandstone includes the Morrison formation; one such locality is Fort Wingate. Although the stratigraphic relationships are not well known, they suggest that the Cow Springs sandstone is equivalent in part to the Winsor formation (Gregory, 1950, p. 96–98) of southern Utah. However, Gregory describes the Winsor as regularly bedded, "suggesting marine deposition," so it probably developed in an environment different from that in which the Cow Springs sandstone was formed in the Navajo country. The white sandy facies of undifferentiated Carmel and Entrada in the southwestern part of the Navajo country has a striking resemblance to the Winsor, although evidence presented by Gregory indicates a younger age for the Winsor.

General description and field relations.—At the type locality, 4 miles east of Cow Springs Trading Post, Coconino County, Ariz. (fig. 33), the Cow Springs sandstone appears as a single massive unit 342 feet thick. It is composed of greenish-gray (5*G* 6/1) to yellowish-gray (5*Y* 8/1) fine-grained crossbedded firmly cemented sandstone. It contains subangular to rounded well-sorted grains of quartz and minor amounts of feldspar. The cement is grayish-green calcium carbonate which gives the sandstone its characteristic greenish color. The crossbedding of the Cow Springs is one of its most distinctive characteristics and in most places consists of the wedge-planar or asymmetrical-trough type. The crossbeds are large scale and high angle. The unit as a whole is strikingly similar to the Navajo sandstone and has often been mistaken for it. Flat-bedded units are locally common within the Cow Springs, particularly in areas where the unit intertongues with members of the Morrison formation and the Summerville formation. The Cow Springs sandstone commonly weathers into smooth, rounded slopes but it forms vertical cliffs where protected by the more resistant Dakota sandstone.

In the southwestern part of the Navajo country (figs. 26 and 32) the entire interval between the Dakota sandstone and the Entrada sandstone is occupied by the Cow Springs. Northeastward from that area the lower members of the Morrison formation, the Recapture and the Salt Wash, appear as tongues within the Cow Springs and they are increasingly conspicuous northeastward. Also northeasterly, the Summerville formation is recognizable as the sandy facies, equivalent to the basal part of the Cow Springs. In the southwestern part of the Navajo country the upper units of the Morrison formation were removed by pre-Dakota ero-

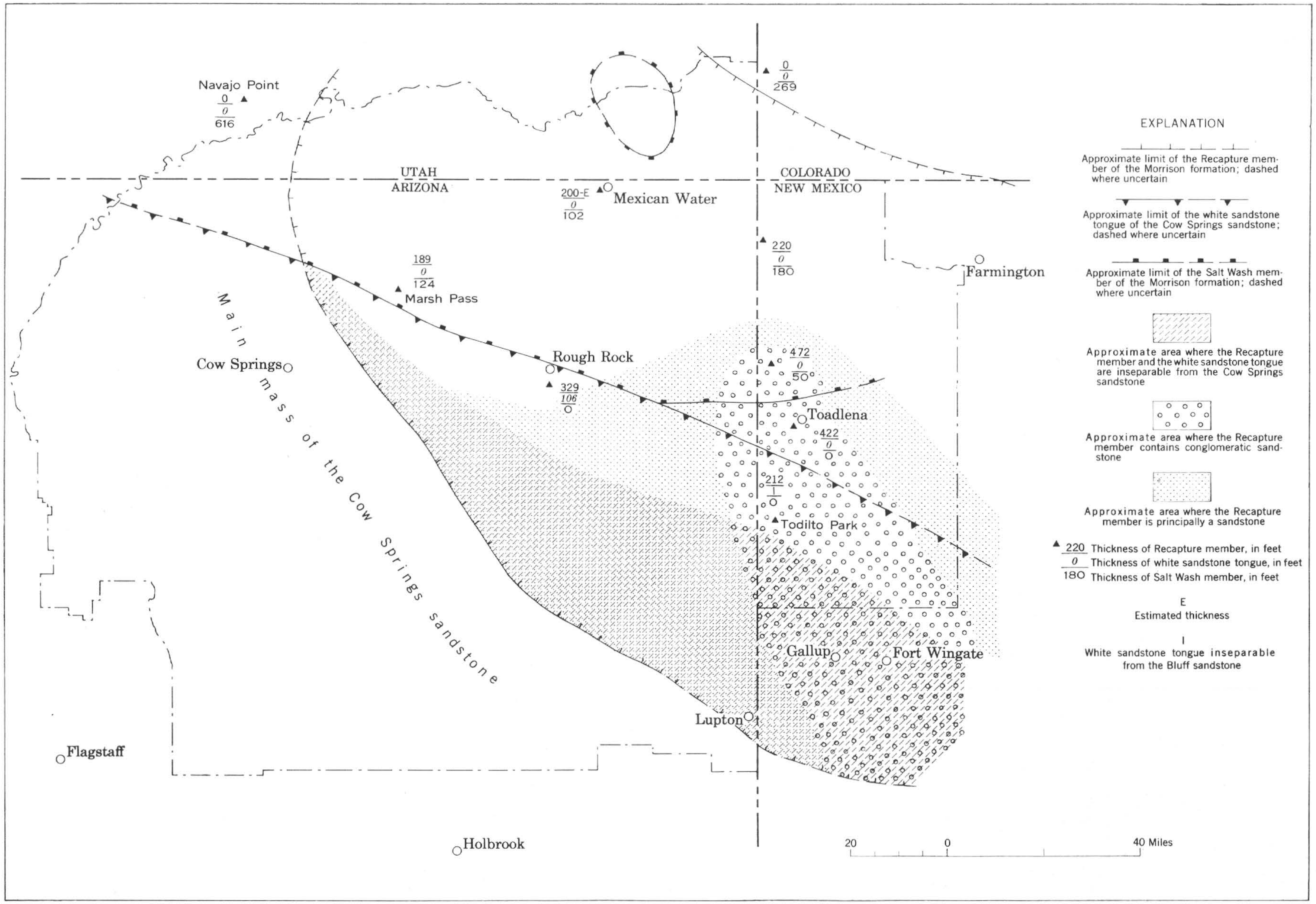

FIGURE 32.—Map of the Navajo country showing approximate depositional limits of the white sandstone tongue of the Cow Springs sandstone and the Salt Wash and Recapture members of the Morrison formation.

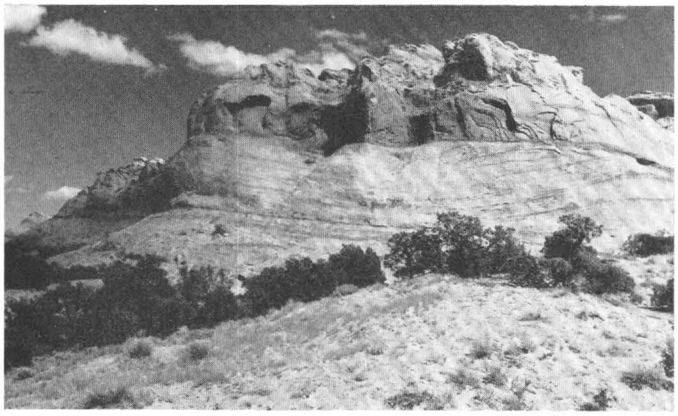

FIGURE 33.—The type locality of the Cow Springs sandstone, 4 miles east of Cow Springs, Ariz.

sion, as was the Cow Springs in some areas. Because of this erosion, intertonguing relations of the Cow Springs sandstone with the Westwater Canyon and Brushy Basin members of the Morrison formation cannot be established. However, along the New Mexico-Arizona State line from Lupton north to Todilto Park, the Westwater Canyon member of the Morrison appears to intertongue with the Cow Springs. The upper members of the Morrison presumably intertongued with the Cow Springs in many places, for these units are believed to be contemporaneous eolian and fluvial deposits. In the area of Red Mesa on the Arizona-Utah State line, the Bluff sandstone intertongues with the Salt Wash member of the Morrison.

The pre-Dakota removal of Jurassic and older rocks southwesterly across the Navajo country and southward into other parts of Arizona (Pike, 1947, p. 91) makes it difficult to interpret variations in the thickness of the Cow Springs sandstone. Furthermore, the intertonguing relationships with other units in the northeastern part of the area make it impossible to determine the thickness of deposits of the Cow Springs type. Several representative thicknesses of the tongue formed by the Bluff sandstone and white sandstone tongue are shown in figures 26 and 32. No attempt has been made to show the thicknesses of other tongues of the Cow Springs, although an approximate idea may be obtained from the fence diagram, plate 3, and from the stratigraphic sections given later in the report. Within the area of the main mass of the Cow Springs sandstone the following thicknesses are perhaps most representative: at the type locality, 342 feet; at Square Butte, 11 miles east of Kaibito, 230 feet; and at Black Rock, N. Mex., 449 feet. Elsewhere the formation is either transitional into units with which it intertongues, or pre-Dakota erosion has removed an appreciable thickness of it. For example, the Cow Springs is only 113 feet thick at Coal Canyon.

Laboratory studies.—The average median diameter of grains obtained from the analyses of 37 samples of the Cow Springs sandstone is 0.20 millimeter. The range in grain size is between 0.50 and 0.06 millimeter. The average sorting coefficient of the Cow Springs sandstone is 1.21. In degree of roundness the sand grains average: angular 5 percent, subangular 30 percent, subrounded 45 percent, and rounded 20 percent. The coefficient of sphericity ranges from 0.83 to 0.95. The coefficient of skewness averages 0.97. About 40 percent of the quartz grains are pitted, scratched, or frosted.

Quartz makes up 95 to 98 percent of the Cow Springs sandstone. Feldspar makes up 2 to 4 percent and commonly is altered to clay minerals. Most heavy-mineral separates amount to less than one-half percent of the total sample. The heavy minerals that have been observed, in order of abundance, are as follows: garnet as angular to subrounded grains, many showing a distinct conchoidal fracture and some marked by pits or scratches; magnetite chiefly as rounded grains; tourmaline that is pink to amber and occurs as prisms having fractured ends; limonite and hematite, chiefly as thick cement coatings on quartz grains but in part as individual grains; staurolite in grains that appear to have a porous surface; an abnormally high percentage of rutile; and muscovite, sillimanite, zircon, and hornblende, all present in amounts of less than 5 percent of the heavy-mineral separate.

SUMMARY OF THE COW SPRINGS SANDSTONE

The Cow Springs sandstone is highly crossbedded and well sorted, and is essentially identical in its principal characteristics to such formations as the Lukachukai member of the Wingate sandstone, the Navajo sandstone, and the Coconino sandstone of Permian age, whose lithologies and fossils have established an eolian origin of deposition. The lower part of the Cow Springs appears to have been deposited along the southwestern side of the basin in which the upper part of the San Rafael group was deposited. Eolian deposition continued into Morrison time, for the upper part of the Cow Springs occurs also along what was the southern margin of Morrison deposition. Frequent advances and retreats of the water that deposited the sediments of the San Rafael and Morrison are attested by the occurrence of many tongues of these subaqueous sediments extending southward into the Cow Springs. During the regressive periods eolian deposition progressed from the main dune area many miles northward into the areas of the major subaqueous deposition, as evidenced by the presence of the Bluff sandstone and the white sandstone tongue. The intertonguing relationships of the Summerville and Morrison with the Cow Springs indicate that these units were deposited contemporaneously.

The eolian origin of the Cow Springs is demonstrated by the following salient features: The crossbedding is large scale, similar to that in modern barchans. Results of statistical analyses show that the large-scale steeply dipping crossbeds lie at an angle that is consistently between 25° and 30° from the horizontal—comparable to measurements of the crossbedding in modern dunes. Particle-size analyses of the sand grains show that good sorting occurs throughout the formation and that the coefficients of sorting are remarkably similar to those in modern dunes. The spatial relations of this deposit to areas of subaqueous deposition to the north, and to the Mogollon Highland to the south, suggest conditions favorable for dune deposition. Streams from the Mogollon Highland apparently traversed the dune area and contributed sediments to the area of Morrison deposition beyond. They deposited the coarse-grained facies of the Recapture and Westwater Canyon members in the southeastern part of the Navajo country.

The Cow Springs sandstone represents the fourth major period of eolian deposition in Late Triassic and Jurassic time in the Navajo country. The Lukachukai member of the Wingate sandstone was deposited during the first. The second is represented by the Navajo sandstone. The eolian beds of the Carmel and Entrada formations in the southern part of the region, whose source material was derived by erosion of the Navajo sandstone, were deposited during the third, and the Cow Springs during the fourth. The Cow Springs sandstone seems to have been deposited on the flanks of the elevated Mogollon Highland. As this highland was south of the areas of San Rafael and Morrison deposition, dunes probably persisted from the time of Navajo deposition to the close of the Jurassic period in this region. Although the relationships cannot be observed, owing to the removal of the strata by pre-Dakota erosion, the Navajo sandstone, the eolian facies of the Entrada, and the Cow Springs at one time may have formed one continuous deposit of crossbedded sandstone south of the Navajo country.

MORRISON FORMATION

The name Morrison formation was first published in a paper by Cross (1894, p. 2) for the exposures near the town of Morrison in east-central Colorado. The formation since has been recognized over most of the western interior of the United States, and its age, relationships, and correlation have been the object of a great amount of work and discussion. The age of the Morrison formation is now accepted as Late Jurassic, without question, but the exact date of its upper limit has not been established (Imlay, 1952, p. 953). A detailed discussion of the stratigraphic relationships and overall distribution of the Morrison is presented by Craig and others (1955).

In the Navajo country, the Morrison formation overlies the San Rafael group with no apparent unconformity, although fluvial channeling, such as occurs throughout the formation, is locally present at the contact. The Morrison in most areas can be distinguished readily from the underlying San Rafael group because of differences in lithology. In the southern part of the outcrop area of the Morrison, where the Cow Springs sandstone is fully developed (fig. 32), the contact is not discernible. The Morrison appears to be overlain conformably by Lower Cretaceous rocks in the northeastern part of the Navajo country. The Jurassic-Cretaceous boundary is discussed by Stokes (1944, p. 957).

In the Navajo country the Morrison comprises four members. These are, from bottom to top, the Salt Wash member, the Recapture member, the Westwater Canyon member, and the Brushy Basin member (fig. 34). On the basis of lithology and fossils the members are considered to be fluviatile and they all intertongue. Contacts between the members therefore are arbitrary and are determined on the basis of lithologic differences and weathering properties in gross aspect.

The lithologic adjectives originally used in the names of the members of the Morrison formation (Salt Wash sandstone member, Recapture shale member, Westwater Canyon sandstone member, and Brushy Basin shale

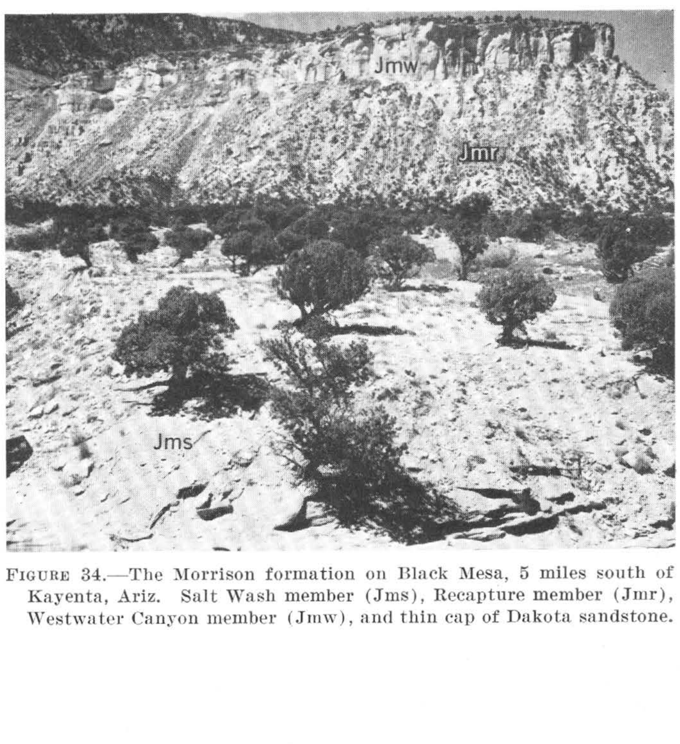

FIGURE 34.—The Morrison formation on Black Mesa, 5 miles south of Kayenta, Ariz. Salt Wash member (Jms), Recapture member (Jmr), Westwater Canyon member (Jmw), and thin cap of Dakota sandstone.

member) have led to considerable confusion because they do not describe the actual lithology in many areas. Therefore, it has been agreed to delete the lithologic adjectives from the member names. A thorough study of the Morrison formation of the Colorado Plateau, including the Navajo country, has been made by the U. S. Geological Survey, under the direction of L. C. Craig. The results of this study have been published (Craig and others, 1955), so the treatment of the Morrison in the present paper is brief.

SALT WASH MEMBER

The Salt Wash member (Lupton, 1914; Gilluly and Reeside, 1928) of the Morrison formation consists of interbedded lenticular sandstone and mudstone beds which in most places form a characteristic ledge-slope outcrop. The type locality is in Salt Wash, 30 miles southeast of Green River, Utah. Stokes (1944) correlates the Salt Wash member with parts of Gregory's (1938) Recapture member in the San Juan country, and this correlation is used in this paper on the Navajo country.

General description and field relations.—The sandstone of the Salt Wash consists of yellowish-gray (5*Y* 8/1) fine- to coarse-grained lenticular beds. It is conglomeratic in the northwestern part of the Navajo country. The sand is composed mainly of clear subangular quartz grains. Stringers of pebbles, clay pellets, and chert fragments are common throughout the sandstone units. Crossbedding, which is a characteristic feature, is considered to be primarily of fluvial origin (Weir, 1951) and is generally medium scale, low angle, and of the trough type, with curved surfaces of erosion bounding individual sets of crossbeds.

The mudstone of the Salt Wash member is greenish gray (5*GY* 6/1) and dark reddish brown (10*R* 3/4) and occurs as lenticular, generally flat-bedded, fissile units. Commonly these overlie ripple-marked surfaces on the tops of the sandstone beds. The member is believed to have been deposited under fluvial conditions, for channel and flood-plain deposits are common. Within the Navajo country, eolian deposits are interbedded with the fluvial deposits in places.

The Salt Wash member is present only in the northern part of the Navajo country (fig. 32). To the south it intertongues with and grades into the overlying Recapture member. In the vicinity of Marsh Pass there is indication that the Salt Wash intertongues with the Cow Springs sandstone, and at Red Mesa, Ariz., it intertongues with the upper part of the Bluff sandstone. Eight miles north of Red Mesa the Salt Wash is absent and the Recapture member rests on the Bluff sandstone (fig. 35). The Salt Wash is 616 feet thick on Navajo Point, Utah, and thins southeastward. Near Rough Rock, Ariz., it is 125 feet thick and at Many Farms, Ariz., it is absent. Near Lukachukai, Ariz., it has been removed by Tertiary erosion, and it is not recognizable at the base of the Morrison formation at Toadlena, N. Mex. To the north of the Navajo country the Salt Wash member extends over most of eastern Utah and western Colorado.

RECAPTURE MEMBER

The type locality of the Recapture member of the Morrison formation is near the mouth of Recapture Creek, 4 miles east of Bluff, San Juan County, Utah. The Recapture was proposed as a member of the Morrison by Gregory (1938, p. 58); however, he apparently included in the type section some basal sands that are now correlated with the Salt Wash member (Stokes, 1944). Usage in this paper will follow that of Stokes, in considering as Recapture only the upper sandstone and shale at Gregory's type locality. The lower sandstone beds are referred to as the Salt Wash member.

General description and field relations.—The Recapture member is composed, in general, of interstratified sandstone and shaly mudstone. The sandstone is friable and, with the mudstone, weathers into steep earthy slopes which form a modified badland topography containing many demoiselles capped by relatively resistant sandstone. The sandstone is pale reddish brown (10*R* 5/4) to grayish pink (5*R* 8/2) and consists chiefly of fine- to medium-grained quartz sand, but in the southeastern part of the Navajo country (fig. 32) it contains large amounts of coarse-grained conglomeratic material which includes appreciable amounts of granitic minerals. The sandstone units are lenticular and have low-angle-trough and wedge-planar types of

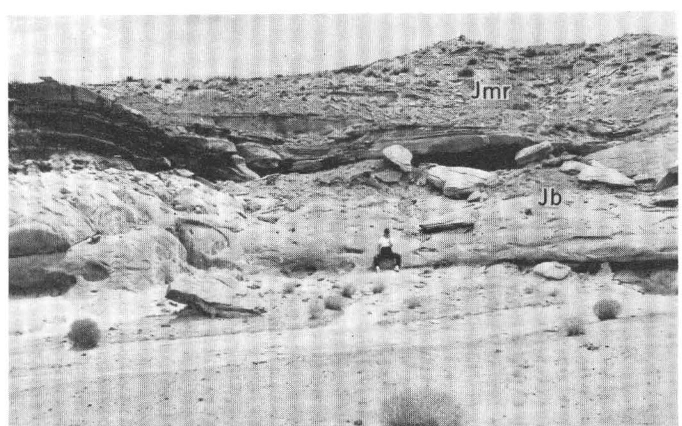

FIGURE 35.—The Bluff sandstone and the Recapture member of the Morrison formation, 8 miles north of Red Mesa, Ariz. Bluff sandstone (Jb) and Recapture member (Jmr). The Salt Wash member of the Morrison is absent in this area.

crossbedding, similar to those in the Salt Wash member. Some of the sandstone units are considered to be eolian, and toward the southern edge of the Navajo country these predominate over the fluvial deposits. South of the Navajo country the entire Recapture interval is occupied by the eolian Cow Springs sandstone.

The mudstone units of the Recapture are dark reddish brown (10*R* 3/4) and greenish gray (5*GY* 6/1). In general these units are lenticularly bedded. In the area north of Gallup, N. Mex., the Recapture contains coarse-grained sandstone with stringers of pebbles as much as 1 inch in diameter. In areas surrounding those containing the coarse-grained sandstone, pebbles are absent and the unit is principally a fine-grained sandstone. To the north, west, and east of these areas mudstone is common, and the unit consists of alternating sandstone and shaly mudstone throughout about three-fourths of its extent (fig. 32).

The Recapture member is present in the northeastern part of the Navajo country. It intertongues with and grades into the Salt Wash member where both members are present. The upper part of the Recapture also intertongues with the overlying Westwater Canyon member. Thus a close relationship is indicated in the deposition of the three members. The Recapture is not present in the northwestern part of the Navajo country because the Salt Wash sandstone member occupies the entire Morrison interval. Furthermore, the Recapture is not recognizable in the southwestern part of the Navajo country, where it grades into the main mass of the Cow Springs sandstone. In the area of this gradation it is difficult to obtain a representative thickness of the formation because of the mixture of lithologic types. The white sandstone tongue of the Cow Springs, at the base of the Morrison, is the only tongue of the Cow Springs that can be separated from the Recapture on a regional scale. In the southeastern part of the Navajo country, near Fort Wingate, the upper tongues of the Cow Springs grade into the Recapture, and the Recapture is thicker toward the east.

Exclusive of the white sandstone tongue, but including all other tongues and lenses of the Cow Springs that are present, the Recapture is 483 feet thick at the northern end of the Chuska Mountains and thins southward to 215 feet at Todilto Park and 104 feet at Lupton, Ariz. The Recapture is not recognizable at Black Rock, N. Mex. It is 59 feet thick at Fort Wingate and thickens eastward to 207 feet at Thoreau, N. Mex.

WESTWATER CANYON MEMBER

The Westwater Canyon member of the Morrison formation was defined by Gregory (1938, p. 59) from the exposures in Westwater Canyon, 5 miles southwest of Blanding, San Juan County, Utah. Gregory suggests that possibly the Westwater is correlative with the Salt Wash, but in view of regional relationships presented by Stokes (1944, p. 964) the Salt Wash appears to be correlative with the basal part of Gregory's Recapture. In this paper the name Westwater Canyon member is applied to the cliff-forming sandstone of the Morrison lying below the variegated shale of the Brushy Basin member and above the Recapture member.

General description and field relations.—At the type locality, in Westwater Canyon, the unit consists of a series of white and greenish-yellow coarse to medium-grained sandstone (Gregory, 1938). In the Navajo country the Westwater is composed of light-gray (*N* 7) and moderate-greenish-yellow (10*Y* 7/4) sandstone and minor shaly mudstone. The sandstone units are composed of clear fine- to coarse-grained quartz sand and abundant black accessory minerals. Stringers of pebble conglomerate are present locally. The pebbles are larger and more abundant toward the southeastern part of the area. The member is relatively coarse grained in a wide area from Todilto Park to Lupton, Ariz., and Fort Wingate, N. Mex. (fig. 36). In that area pebbles and cobbles ranging from 1 to 4 inches in diameter are common and consist predominantly of quartz, feldspar, granite, and quartzite. The conglomerate is absent in the surrounding areas to the north, west, and east, and the percentage of mudstone units is greater in those directions. Crossbedding within the Westwater Canyon member is believed to be fluvial and consists of the trough and wedge-planar types. In contrast to the slopes of the underlying Recapture member, the strata of the Westwater Canyon weather into cliffs, with minor recessions caused by the less resistant mudstone units.

In the northern part of the Navajo country the upper part of the Westwater Canyon member intertongues with the Brushy Basin member, and in the vicinity of McElmo, Colo., it grades into the basal part of the Brushy Basin member. Throughout its area of occurrence in the Navajo country, the lower part of the Westwater Canyon intertongues with the upper part of the Recapture member (pl. 3). No positive evidence has been found to indicate that the Westwater Canyon member intertongues with the Cow Springs sandstone in the southwestern part of the Navajo country, as do the underlying Recapture and Salt Wash members. However, such a relation between the Westwater Canyon and the Cow Springs appears to exist in exposures between Todilto Park and Lupton.

The Westwater Canyon member is present in northeastern Arizona, northwestern New Mexico, and south-

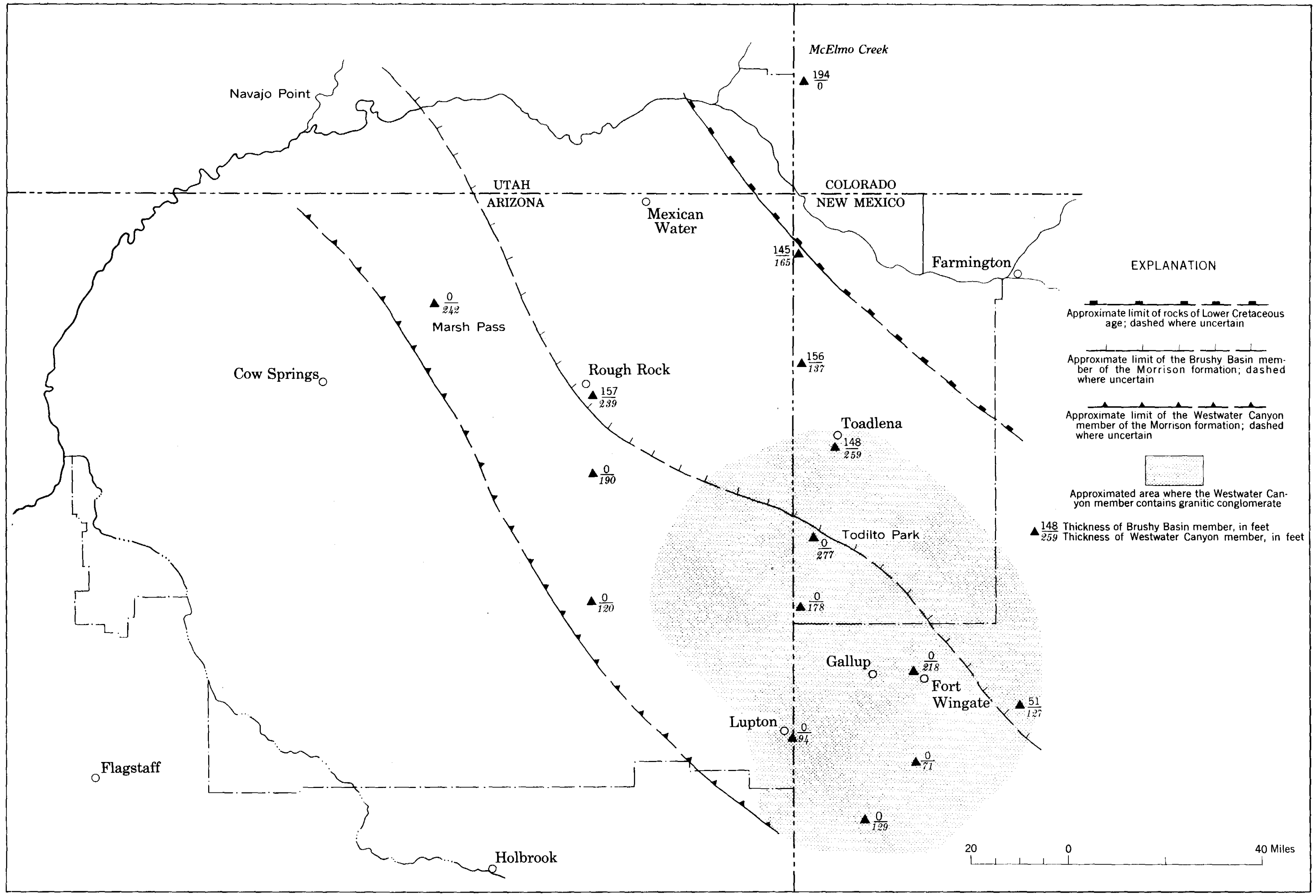

FIGURE 36.—Map of the Navajo country showing the approximate limit of the Westwater Canyon and Brushy Basin members of the Morrison formation and Lower Cretaceous rocks, after pre-Dakota erosion.

eastern Utah (fig. 36). To the north of the Navajo country the Westwater has not been recognized beyond Monticello, Utah (Craig and others, 1955) and McElmo Canyon, Colo., for in those areas it intertongues with and grades into the Brushy Basin member (pl. 3). In the southwestern part of the Navajo country the Westwater Canyon is not present, apparently having been removed by pre-Dakota erosion. Northeast of that area the Westwater Canyon is present but the Brushy Basin was removed by pre-Dakota erosion (fig. 36), and the Dakota lies unconformably on the Westwater Canyon. The Westwater Canyon is believed to be absent in the northwestern part of the area, where a thick sequence of the Salt Wash member appears to occupy the entire Morrison interval. The Westwater Canyon member is 155 feet thick south of Kayenta and 239 feet at Yale Point and attains its maximum measured thickness of 277 feet at Todilto Park. To the southeast it is thinner—127 feet at Thoreau, N. Mex.

BRUSHY BASIN MEMBER

The Brushy Basin member is the uppermost unit of the Morrison formation and the most extensive, although it does not extend as far southwest as the Westwater Canyon (fig. 36). It is present in western Colorado, eastern Utah, northern New Mexico, and part of northeastern Arizona (Craig and others, 1955). It was defined by Gregory (1938, p. 59). At the type locality, Brushy Basin, about 8 miles west of Blanding, San Juan County, Utah, it consists of 450 feet of well-exposed variegated shale which forms a rounded slope beneath the Lower Cretaceous Burro Canyon formation (Stokes and Phoenix, 1948).

General description and field relations.—At the type locality the Brushy Basin consists of white, gray, green, purple, and red sandy shale (Gregory, 1938, p. 59). In the Navajo country the Brushy Basin has characteristics similar to those in the type area, for it contains pale-green (*5G* 7/2), greenish-gray (*5GY* 6/1), and moderate-pink (*5R* 7/4) mudstone and sandstone and has a fairly consistent lithology. The sandstone is mostly fine to medium grained, but the member contains lenses and stringers of greenish conglomeratic sandstone. The member is considered to be a fluvial deposit but contains some thin lenses of siliceous limestone which possibly indicate deposition in fresh-water lakes during Brushy Basin time. The Brushy Basin commonly weathers into barren low rounded hills and badlands; however, where the member is capped by resistant Cretaceous sandstone, the shales form a steep multicolored slope.

The Brushy Basin member is present in the northeastern and eastern parts of the Navajo country (fig. 36). In the area north of Aneth, Utah, the Brushy Basin intertongues with the upper part of the Westwater Canyon member and, to the north, the Westwater Canyon is absent. In this same area the Brushy Basin member appears to be conformably overlain by Lower Cretaceous strata called the Burro Canyon formation. To the southwest, the Burro Canyon was removed by pre-Dakota erosion and the Upper Cretaceous [2] Dakota sandstone rests unconformably on the Brushy Basin.

The Brushy Basin member is about 194 feet thick at McElmo Creek, 156 feet in the Carrizo Mountains area, 148 feet at Toadlena, and 51 feet at Thoreau. On the northeast corner of Black Mesa, southeast of Rough Rock, there is a unit below the Dakota that is 157 feet thick and possibly represents the southwesternmost exposure of the Brushy Basin member within the Navajo country.

SUMMARY OF THE MORRISON FORMATION

The Morrison formation was deposited by a system of braided streams on a generally flat surface, overlying the deposits of the San Rafael group. The sediments are primarily fluvial, consisting of alternating flood-plain and channel deposits. The stream system seems to have developed with the uplift of source areas along the Mogollon Highland, especially in west-central New Mexico, and in Mohavia, which first appeared at the close of Kayenta deposition. The members of the Morrison in the Navajo country are considered to be a series of coalescing alluvial deposits arising from these two main sources and spreading out from them to the north and east. The source area for the Salt Wash member is thought to be to the west of the Navajo country; from it low-gradient streams spread flood-plain deposits and channel sediments to the east, across the northern part of the Navajo country (fig. 37).

The deposition of the Recapture and Westwater Canyon members was contemporaneous with the deposition of the Salt Wash and, later, with that of the basal part of the Brushy Basin member to the north. As a result, the Recapture and Westwater Canyon members coalesce to the northeast with the Salt Wash and basal Brushy Basin members. Westwater Canyon deposition is thought to have been continuous with that of the Recapture, but the Westwater contains coarser material, possibly due to rejuvenation of the source areas. According to Craig and others (1955) in their studies of the Morrison, the source area for the Brushy Basin member is not clearly indicated but may be essentially the same as that of the Salt Wash member. The

[2] Some question has been raised as to whether the Dakota sandstone of the Colorado Plateaus is entirely Late Cretaceous in age (Cobban and Reeside, 1952, p. 1028).

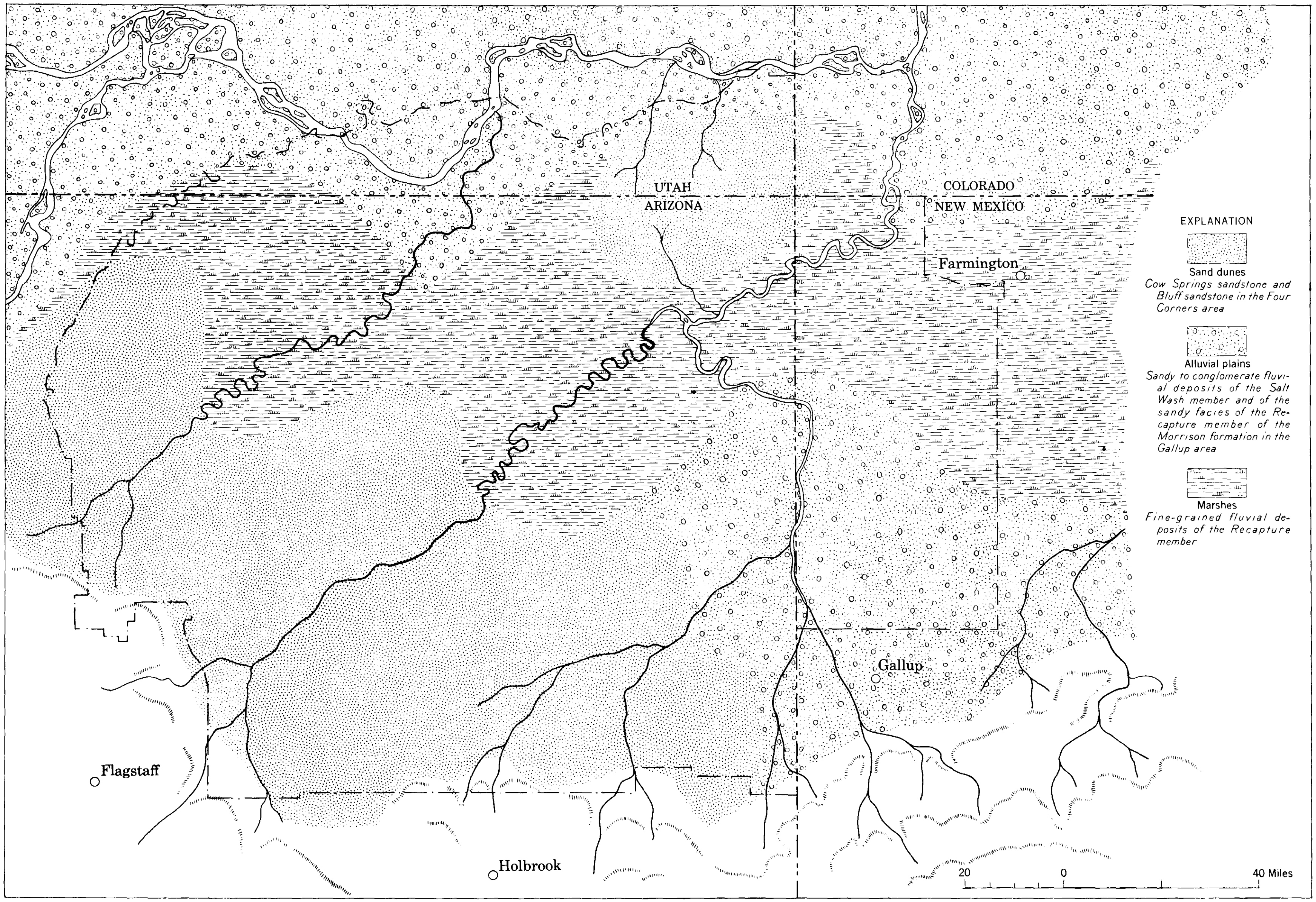

FIGURE 37.—Sketch map showing the hypothetical physiography of the Navajo country in the late stage of deposition of the Salt Wash member and the early stage of deposition of the Recapture member of the Morrison formation.

finer grained nature of the sediments in the Brushy Basin seem to indicate that the source area had been eroded to a mature stage.

In the Navajo country, fossil bones and invertebrates have been found in the Salt Wash member but have not been studied. Beyond the Navajo country the Brushy Basin member is the most fossiliferous unit and has yielded abundant vertebrate remains in several areas. These fossils have been used for establishing the Late Jurassic age of the Morrison formation.

JURASSIC-CRETACEOUS BOUNDARY

In most parts of the Navajo country the Jurassic-Cretaceous boundary is marked by an erosional unconformity at the base of the Dakota sandstone (fig. 38). The unconformity cuts across progressively older rocks to the southwest across the Navajo country. Still farther south, near Showlow, Ariz., the Dakota rests on the Upper Triassic Chinle formation or rocks of Early Triassic age, and at McNary, Ariz., the Dakota rests on Paleozoic rocks. Within the Navajo country the Dakota overlies the undifferentiated Entrada and Carmel at Montezuma's Chair; 22 miles farther north, where the Dakota crops out in Polacca Wash, it rests on the medial silty member of the Entrada; 6 miles south of Steamboat Canyon it rests on the Cow Springs sandstone; in Steamboat Canyon it rests on the Westwater Canyon member of the Morrison formation; 90 miles north of Steamboat Canyon on Yale Point the Dakota sandstone overlies what is believed to be the southwesternmost exposure of the Brushy Basin member of the Morrison; and at McElmo Creek, Colo., the Dakota overlies the Lower Cretaceous Burro Canyon formation. North of this point a considerable thickness of Lower Cretaceous sedimentary rocks is found beneath the Dakota sandstone. Although these relationships establish the angularity of the pre-Dakota unconformity, the angularity is so small that it is not apparent at most outcrops within the Navajo country.

Where the Jurassic rocks are overlain by the Burro Canyon formation, the contact is extremely arbitrary, and no indication of a break in sedimentation can be found. Therefore, the upper boundary of the Brushy Basin member of the Morrison is questionable, and the time boundary between the Cretaceous and Jurassic periods cannot be precisely located.

STRATIGRAPHIC SECTIONS

The descriptive terminology used in the stratigraphic sections, and throughout the report, is generally similar to that proposed by McKee and Weir (1953) in a paper on descriptive terms applied to stratification of sedimentary rocks. As a result, much of the explanation of

FIGURE 38.—The unconformity at the base of the Dakota sandstone, 4 miles north of Red Lake, Ariz. Cow Springs sandstone (Jcs), Dakota sandstone (Kd), and Mancos shale (Km).

descriptive terminology that follows should be credited to McKee and Weir, although no specific references are made.

Grain size of the detrital rocks of the Navajo country has been described in accordance with the system of Wentworth (1926). In that system, all detrital rocks can be described as claystone, siltstone, sandstone, granule conglomerate, or pebble conglomerate, or mixtures of these. A mixture of grains ranging from clay to sand is termed a mudstone. Other mixtures are designated by modifying terms—for example, a silty sandstone or a conglomerate sandstone. The degrees of roundness and sorting indicated in the sections are field estimates only.

Important properties of sedimentary particles are roundness and sphericity. Roundness of a grain refers to the sharpness or lack of sharpness of its corners and edges—that is, the boundaries of a rounded grain in cross section are more or less curved. Sphericity refers to the shape of the grain as a whole—that is, the shape of the grain in comparison to that of a perfect sphere—and is independent of the sharpness of its edges. A particle may approach a sphere in shape but not have any rounded surfaces, whereas a particle may be well rounded but depart widely from being spherical. There are a number of methods to accurately determine the degree of roundness and sphericity, but most of these are time-consuming. It was decided that data on these physical properties of sedimentary particles that would be adequate for the purpose of this report could be obtained by visual examination. The degree of roundness of the grains was determined by comparing them with a suite of reference pictures illustrating varying degrees of roundness (Russell and Taylor, 1937, p. 239), and expressing the degree of roundness as a percentage. The sphericity coefficient of the grains was obtained by the visual method of Rittenhouse (1943, p. 80). In this method unity (1.0) is the coefficient for a perfectly spherical grain.

The degree of sorting of sedimentary particles has been useful in the determination of source areas of the many units studied and in determining their depositional environments. Sorting is defined as a measure of the spread in particle size of a sediment. The coefficient of sorting expresses the measure of the average quartile spread. The coefficients of sorting recorded in this report have been made by employing the Trask method (1932, p. 67–76). ($S_0=\sqrt{Q_3/Q_1}$; S_0=coefficient of sorting, Q_3=the third quartile diameter, Q_1=the first quartile diameter.) The classification as given by Payne (1942, p. 1707) is used in this report as it appears to be more applicable for expressing the degree of sorting of the sediments of the Navajo country. This classification (good sorting=90 percent of the sediment concentrated in 1 or 2 particle size classes; fair sorting=90 percent of the sediment concentrated in 3 or 4 size classes; and poor sorting=90 percent of the sediment concentrated in 5 or more size classes) made it possible to note more specific trends, and it could be better used for interpretation of the depositional environment of the sediments.

The physical features of each sedimentary unit are divided into two general types in the manner devised by Krynine (1948, p. 145–147). He classifies the gross features of the lithologic unit as a whole—its shape and size and the nature of its boundaries—as external. In features classified as internal he includes stratification and other features within the unit. Thus, an individual unit may be tabular in form and be composed of flat-bedded strata. As the tabular form of sedimentary-rock units is by far the most common of external shapes, it has usually not been noted in the descriptions. However, note has been made of external form in the case of lenticular units.

In the above example of a tabular unit composed of flat-bedded strata, each individual stratum may have internal features of its own, such as crossbedding. If it is desirable, in the description of the unit, to describe this crossbedding within individual strata, considerable confusion may arise, for it seems contradictory to say that a unit is both flat bedded and crossbedded. In order to avoid the burden of describing each different stratum, it seems desirable to describe the sequence as a whole but to include qualifying statements to record variations within the unit. Therefore, to indicate that variation exists within a unit, the unit is referred to as a coset and the minor units, containing the variations, are referred to as sets. Thus, the hypothetical unit described above would be a flat-bedded coset; an individual tabular crossbedded stratum within it would be considered as a crossbedded set. The definition of a set, as used herein, is a stratum or a group of strata having a uniform lithology, distinguished from other sets by a difference in lithologic character, and included in the description of a larger stratigraphic unit, referred to as a coset. A coset is a sedimentary unit that contains two or more sets and differs recognizably in lithology from adjacent strata or cosets. The advantage in using the terms "set" and "coset" is that they permit a brevity of description of sedimentary units and still allow preservation of important lithologic detail.

Stratification or bedding is classified according to thickness of the individual beds or strata. Splitting properties are classified according to thickness of individual fracture units, which may or may not correspond to the thickness of bedding. These classifications are shown in the following table.

Classification of bedding and splitting properties of layered rocks

[Modified after McKee and Weir (1953)]

Bedding	Splitting property	Thickness
Very thick	Massive	More than 120 cm (4 ft.).
Thick	Blocky	60–120 cm (2 ft.–4 ft.).
Thin	Slabby	6–60 cm (2 in.–2 ft.).
Very thin	Flaggy	1–5 cm (½ in.–2 in.).
Laminated	Shaly (mudstone)	2 mm–1 cm.
	Platy (limestone and sandstone).	2 mm–1 cm.
Thinly laminated	Fissile	Less than 2 mm (paper thin).

Crossbedding is further classified into three main types. These are simple, planar, and trough. The distinguishing characteristics of these types are found in the external features of an individually oriented group of crossbeds. The simple type shows no apparent signs of erosion along the bounding surfaces of the individual group of crossbeds. The planar type is marked by flat surfaces of erosion bounding the group. The trough type is marked by curved surfaces of erosion bounding the group. Festoon crossbedding would be a specialization within the trough type, as its lower boundary is obviously a curved surface of erosion. What has often been referred to as torrential crossbedding ordinarily falls into the planar type. Minor descriptive terms used to modify the three major types are tabular (parallel planar surfaces), wedge (converging planar surfaces), and lenticular (converging curved surfaces).

In addition to the classification of crossbedding it has been the practice, in describing rock units, to classify the characteristics of an individual crossbed considered typical of the group. These characteristics of a crossbed are:

1. Concave or convex (upward).
2. High (more than 20°) or low angle of dip.
3. Small (less than 1 ft long), medium (1 ft to 20 ft in length), or large (over 20 ft in length) scale.
4. Thickness (following classification used for layered rocks).

Colors and their numerical designation have been established by comparison with the color chips on the rock-color chart distributed by the National Research Council (Goddard 1948). Other terms used in the stratigraphic sections are believed to be self-explanatory. The following stratigraphic sections were selected as being most descriptive of the Jurassic and uppermost Triassic rocks of the Navajo country. Many are considered as type sections of new units which have been introduced in this report. The remainder are included to record the detailed lithology of units previous established.

1.—Three miles northwest of Rock Point Trading Post

[Measured by C. A. Repenning]

Jurassic:
Carmel formation: Undescribed.
Unconformity: Concealed.

Jurassic and Jurassic (?):
Navajo sandstone:

	Feet
36. Sandstone, moderate-reddish-orange (10*R* 5/6), fine-grained, well-sorted; composed of subrounded clear quartz; firmly cemented, calcareous; wedge planar crossbedding, trough type toward base, high-angle and large-scale crossbeds; weathers massive; forms rounded cliff. Base sharp and flat	61
35. Limestone, light-bluish-gray (5*B* 7/1), finely crystalline; flat, gnarly, very thinly bedded; weathers flaggy; forms ledge. Unit broadly lenticular. Base sharp and flat	2
34. Sandstone, moderate-reddish-orange (10*R* 5/6), fine-grained, well-sorted; composed of subrounded clear quartz; firmly cemented, calcareous; tabular planar crossbedding, high-angle, large-scale laminated crossbeds; weathers massive; forms rounded cliff. Conspicuous parting plane 117 feet below top of unit	221
33. Sandstone, dark-yellowish-orange (10*YR* 7/6), very fine grained, well-sorted; composed of subrounded clear quartz; firmly cemented, calcareous; trough crossbedding, high- to low-angle large-scale laminated crossbeds; weathers massive; forms rounded cliff that projects over top unit of the Kayenta. Base sharp and irregular with about 6-in. relief	51
Total Navajo sandstone	335

Jurassic (?):
Kayenta formation:
Typical facies:

	Feet
32. Sandstone, very light gray (*N*8), fine-grained, well-sorted; composed of subrounded to subangular stained quartz; poorly cemented, calcareous; structureless; weathers massive; forms vertical cliff. Base sharp and flat	6
31. Mudstone, very dusky red (10*R* 2/2), flat and gnarly, very thinly bedded; weathers shaly; forms a covered slope. Base sharp and flat	2
30. Sandstone, medium-bluish-gray (5*B* 5/1), very fine grained, well-sorted; composed of subangular stained quartz; well cemented, siliceous; flat, thinly bedded; weathers massive; forms a ledge. Contains ripple marks and invertebrate trails. Base sharp and flat	5
29. Limestone, very light gray (*N*8), arenaceous (50 percent sand) in parts and cherty in others; gnarly, thin bedded; weathers flaggy; forms ledge. Unit lenticular. Base sharp and irregular	3
28. Sandstone, very pale orange (10*YR* 8/2), very fine grained, well-sorted; composed of subangular stained quartz; poorly cemented, calcareous; flat very thinly bedded; weathers massive; forms ledge. Base gradational	12
27. Sandstone, pale-red (10*R* 6/2), speckled with spots of pale reddish brown (10*R* 5/4), very fine grained, well-sorted; composed of subrounded clear quartz; well cemented, calcareous; trough crossbedding, low-angle and small-scale crossbeds; weathers massive; forms a rounded cliff. Unit contains frequent well-rounded boulders along its base derived from underlying Wingate sandstone. Base sharp and irregular, 20-foot relief	26
Total Kayenta formation	54

(Section continued 5 miles south of Rock Point Trading Post.)

Unconformity: Erosional, 20-foot relief.

Triassic:
Wingate sandstone:
Lukachukai member:

26. Sandstone, light brown (5*YR* 6/4), very fine grained, well-sorted; composed of subrounded clear quartz; firmly cemented, calcareous; trough crossbedding, high-angle and large-scale crossbeds; weathers massive; forms a rounded cliff. Base sharp and irregular, a prominent spring horizon	117
25. Sandstone, similar to unit 23 except crossbeds are somewhat smaller in size, but still large. Base sharp and flat beneath thin bleached zone	235
Total Lukachukai member	352

(Section continued on the slope of Little Round Rock, 14 miles south of Rock Point Trading Post.)

	Feet
Triassic—Continued	
Wingate sandstone—Continued	
Rock Point member:	
24. Siltstone, light-brown (5YR 6/4), with some clay and very fine sand, well-sorted; firmly cemented, calcareous; flat, gnarly, laminated bedding; weathers shaly to hackly; forms niche below vertical cliff of the Lukachukai member. Base gradational	7
23. Sandstone, light-brown (5YR 6/4), silty; silt with very fine sand, well sorted; well cemented, calcareous; flat, thinly bedded; weathers massive, forms cliff. Unit lenticular. Base sharp and irregular	18
22. Silty sandstone, moderate-reddish-brown (10R 5/6), silty with very fine sand, well-sorted; firmly cemented, calcareous; flat laminated bedding; weathers flaggy to shaly, tends to weather massive in places due to cementing variation; forms a series of ledges of either flagstone or rounded forms. Unit lenticular. Base gradational	33
21. Mudstone, moderate-reddish-brown (10R 5/6), silt, clay, and very fine sand, well-sorted; poorly cemented, calcareous; flat laminated bedding; weathers shaly; forms regular slope. Unit lenticular. Base sharp and irregular	5
20. Sandstone, silty; same as unit 22, weathers flaggy at base and massive at top	17
19. Mudstone, same as unit 21	13
18. Sandstone, silty; same as unit 23	38
17. Sandstone, silty; same as unit 22	38
16. Mudstone, same as unit 21	33
15. Sandstone, silty; same as unit 20	11
14. Mudstone, same as unit 21	11
13. Sandstone, silty; same as unit 20	8
12. Mudstone, same as unit 21	13
11. Sandstone, silty; same as unit 22	19
10. Mudstone, same as unit 21, white line at top	11
9. Sandstone, silty; same as unit 22	5
8. Mudstone, same as unit 21	10
7. Sandstone, silty; same as unit 22	19
6. Mudstone, same as unit 21	10
5. Sandstone, silty; same as unit 22	3
4. Mudstone, same as unit 21	13
3. Sandstone, silty; same as unit 22	3
2. Mudstone, same as unit 21	6
Total Rock Point member	344
Total Wingate sandstone	696
(Contact is arbitrary.)	
Chinle formation (incomplete):	
1. Limestone, arenaceous, very pale green (10G 8/2), and grayish-orange (5YR 7/2), gnarly, thin-bedded. Conglomeratic at top.	

2.—Eleven miles northeast of Round Rock Trading Post

[Measured by J. W. Harshbarger, C. A. Repenning, and J. H. Irwin]

	Feet
Jurassic and Jurassic(?):	
Navajo sandstone:	
12. Sandstone (undescribed). Base sharp and irregular.	
Jurassic(?):	
Kayenta formation:	
Typical facies:	
11. Sandstone, pale-red (5R 6/2), course- to very fine-grained, poorly sorted; composed of subrounded to subangular clear and stained quartz, well cemented, calcareous; unit is a coset with flat, gnarly, thin to very thick bedding; weathers massive; forms rounded slope. Contains abundant gravel stringers. Base gradational	18
10. Conglomerate, light-bluish-gray (5YR 6/1); unit is a set; irregular and thick bedded; weathers massive; forms rounded ledge. Base sharp and irregular. Matrix: Coarse to fine grained; poorly sorted; composed of rounded to subrounded clear quartz; well cemented, calcareous. Gravel: Limestone and sandstone pebbles	2
Total Kayenta formation	20
Unconformity: Three feet relief on the weathered surface of the Wingate sandstone.	
Triassic:	
Wingate sandstone:	
Lukachukai member:	
9. Siltstone, pale-red (5R 6/2) in top part grading downward into a moderate red (5R 5/4) silt to fine sand, fair sorting; composed of subrounded to subangular clear and stained quartz; well cemented, calcareous; unit is structureless, any bedding that was originally present is apparently masked by the weathering; weathers massive; forms rounded cliff. Contains abundant limestone nodules and stringers. The unit is commonly bleached along cracks, many of which are filled with limestone. Base gradational	10
8. Sandstone, very pale orange (10YR 8/2) to grayish-orange (10YR 7/4), fine-grained, well-sorted; composed of well-rounded to subangular clear and amber quartz; firmly cemented, calcareous; unit is a coset; very thick bedding; lenticular and symmetrical trough crossbedding, high- to medium-angle and large-scale crossbeds; generally weathers massive but weathers flaggy where exposure parallels crossbedding; weathers smooth; forms rounded cliff. Base sharp and irregular	47
7. Sandstone, light-brown (5YR 6/4), medium- to very fine-grained, poorly sorted; composed of subrounded to subangular clear and amber quartz; firmly cemented, calcareous; flat and slightly wavy, very thin- to thin-bedded; weathers massive; form rounded ledge. Commonly contains coarse-grained, well-rounded quartz grains along bedding. Base sharp and irregular	3

Triassic—Continued — Feet

Wingate sandstone—Continued

Lukachukai member—Continued

6. Sandstone, very pale orange (10*YR* 8/2) and grayish-orange (10*YR* 7/4) medium- to fine-grained, well-sorted; composed of well-rounded to subangular clear and amber quartz; firmly cemented, calcareous; very thick bedded (beds as much as 30 feet thick); unit is a coset; lenticular and symmetrical trough crossbedding, medium- to high-angle and large-scale (as much as 300 feet lateral extent of individual crossbeds); weathers massive except where outcrop parallels crossbedding where it weathers flaggy; forms vertical cliff. Crossbed surfaces often marked by parallel wind ripples or by slump ridges on foreset slope. Worm trails common. One exposure contains small vertebrate tracks which traverse dune slope obliquely and cross smaller tracks, suggestive of large insect trail. These smaller tracks lie in trough between ripple marks. Base sharp and irregular — 286
5. Siltstone, reddish-brown (10*R* 4/5), weathering moderate reddish orange (10*R* 6/6), silt to very fine grained sand, well-sorted; composed of clear and amber quartz and argillaceous material; poorly cemented, calcareous and argillaceous; laminated to very thin bedded; weathers shaly to crumbly; forms smooth slope. Unit lenticular and pinches out laterally along the strike. Base sharp and irregular — 16
4. Sandstone, moderate-reddish-orange (10*R* 6/6), weathering moderate orange pink (10*R* 7/4), very fine grained, well-sorted; composed of subrounded to subangular clear, amber, and white quartz with about 2 percent black accessory minerals; firmly cemented, calcareous; thin- to thick-bedded; tabular and wedge planar crossbedding, medium- to very low-angle small-scale crossbeds, contains some lenticular trough crossbedding in upper part; weathers massive; forms vertical cliff. Contains longitudinal ripple marks in some horizons. Base sharp and irregular — 62
3. Sandstone, same as unit 5; very thick bedded; lenticular trough crossbedding, medium- to low-angle large-scale crossbeds; weathers massive; forms vertical cliff. Base sharp and irregular — 31
2. Sandstone, same as unit 5; thin- to thick-bedded; tabular planar crossbedding, medium- to low-angle large-scale crossbeds; weathers trough crossbedding in upper part; weathers massive; forms vertical cliff. Base sharp and flat — 24

Total Lukachukai member — 479

Triassic—Continued — Feet

Wingate sandstone—Continued

Rock Point member (incomplete):

1. Sandstone, reddish-brown (10*R* 4/5), weathering moderate reddish orange (10*R* 6/6), very fine grained, with silt, well-sorted; composed of clear and amber quartz; well-cemented, calcareous; irregular, flat, thin- to very thin-bedded; weathers knobby or massive; forms an irregular cliff. Commonly contains white spots and streaks. Base concealed.

3.—*Three miles south of Dinosaur Canyon*

[Measured by J. T. Callahan and R. L. Jackson]

Jurassic and Jurassic(?):

Navajo sandstone (incomplete):

6. Sandstone, light-gray (*N* 7), medium- to fine-grained, fair sorting; composed of rounded to subrounded clear quartz with rare black accessory minerals; firmly cemented; trough crossbedding, high-angle large-scale crossbeds; weathers massive and blocky; forms a vertical cliff. Contains 4 thin aphanitic light-gray limestone beds and one 3-foot bed of dark-reddish-brown mudstone which wedges out along exposure. Base sharp and flat — 314

Jurassic(?):

Kayenta formation:

Silty facies:

5. Sandstone and mudstone with some limestone, sandstone predominates near base; colors are banded brown and gray and some reddish brown; flat lenticular bedding; weathers rounded, blocky, and knobby; forms irregular slope. Limestone contains abundant bedded chert. Channeling common — 89

Tongue of Navajo sandstone:

4. Sandstone, light-brown (5*YR* 6/4), very fine grained, well-sorted; composed of subrounded to subangular clear and stained quartz with rare black accessory minerals; poorly cemented; trough crossbedding, small-scale low-angle crossbeds; weathers massive; forms a vertical cliff. Contains rare chert fragments 1 inch in diameter. Base sharp — 26

Silty facies continued:

3. Siltstone and mudstone, with some limestone; colors are banded brown, gray, and reddish brown; flat lenticular bedding; weathers rounded, blocky, and knobby; forms irregular slope. Limestone contains abundant flat-bedded chert. Channeling common. Base sharp and flat — 563

Total Kayenta formation (includes tongue of Navajo sandstone) — 678

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	Feet
Triassic(?):	
Moenave formation:	
Dinosaur Canyon sandstone member:	
2. Sandstone, siltstone, and cherty limestone, moderate-reddish-brown (10*R* 4/6) to gray (*N* 6); comprises from top to bottom: Limestone, moderate-gray (*N* 7), aphanitic; flat, thin bedded; weathers knobby and pitted; contains jasper and chert. Caps unit. Sandstone, very fine grained, trough crossbedding, small- to medium-scale low-angle crossbeds. Siltstone, very thick bedded, weathers irregular; forms irregular rolling slope. Base sharp and irregular	202
Total Moenave formation	202
Triassic:	
Wingate sandstone:	
Lukachukai member:	
1. Sandstone, pale-reddish-brown (10*R* 5/4), medium- to very fine-grained, poorly sorted; contains subrounded to subangular stained and frosted quartz with rare black accessory minerals; firmly cemented, calcareous; unit is a coset with flat, lenticular, very thick bedding; crossbedded sets show trough crossbedding, low- to high-angle small- to large-scale crossbeds; weathers massive and blocky; forms rounded cliff. Base of the unit contains a 2–6-inch bed of flat mud pellets, as much as 1 inch in diameter, with rare chert pebbles (5 mm) in a matrix of coarse clear quartz and red chert sand. This bed overlies the unconformity. This unit is not representative of the Lukachukai member of the Wingate as it is at its marginal limits and is not present a short distance to the northwest. Base sharp and irregular	74
Total Wingate sandstone	74
Unconformity: Slight relief.	
Chinle formation: Undescribed.	

4.—One mile northwest of Moenave

[Measured by J. T. Callahan]

	Feet
Jurassic and Jurassic(?):	
Navajo sandstone (incomplete):	
25. Sandstone, moderate-reddish-orange (10*R* 6/6), very fine grained; trough crossbedding, large-scale high-angle crossbeds; weathers blocky and pitted; forms cliff. Base sharp and flat	105
Jurassic(?):	
Kayenta formation:	
Silty facies:	
24. Sandstone, pale-reddish-brown (10*R* 5/4), very fine grained; gnarly, flat-bedded; weathers massive; forms ledge	2
23. Sandstone, moderate-reddish-orange (10*R* 6/6), very fine grained; unit is a coset with thin bedding; crossbedded sets contain trough crossbedding, small- to medium-scale crossbeds; weathers massive to blocky; forms ledge	11
Jurassic(?)—Continued	
Kayenta formation—Continued	
Silty facies—Continued	
22. Siltstone, pale-reddish-brown (10*R* 5/4); flat, thin bedded; weathers massive; forms slope. Contains abundant gray spots	5
21. Limestone, light-gray (*N* 7), finely crystalline; flat, thin bedded; weathers pitted; forms ledge	1
20. Sandstone, light-brown (5*YR* 5/6), very fine grained; structureless; weathers massive; forms ledge. Commonly contains leached streaks and spots	11
19. Sandstone and siltstone, interbedded; sandstones 1–10 feet thick; siltstones 1–20 feet thick; unit is a flat-bedded coset; crossbedded sets contain trough crossbedding, medium-scale crossbeds; forms a partly covered slope	156
18. Covered slope	84
17. Sandstone, white (*N* 9), very fine grained; trough crossbedding, medium-scale crossbeds; weathers massive to blocky; forms ledge	4
16. Sandstone, pale-red (10*R* 6/2), fine-grained; gnarly, flat, thin bedded; forms slope. Contains abundant light-green streaks	3
15. Sandstone, pale-red (10*R* 6/2), fine-grained; gnarly, flat, thin bedded; weathers massive to blocky; forms ledge. Contains abundant leached streaks	6
14. Covered slope	33
13. Sandstone, pale-red (10*R* 6/2), very fine grained; very thick bedded; weathers massive to blocky; forms ledge	4
12. Covered slope	21
11. Sandstone, pale-red (10*R* 6/2), very fine grained; flat, thin bedded; weathers massive to blocky; forms ledge. Contains abundant leached spots. Base sharp and irregular	30
10. Sandstone, pale-red (10*R* 6/2), very fine grained; planar crossbedding, medium-scale crossbeds; forms irregular cliff. Contains mud-cracked surfaces	12
9. Mudstone, grayish-red (5*R* 4/2), flat laminated bedding; weathers massive; forms ledge. Contains green leached spots	2
8. Covered; forms a bench and slope	110
Total Kayenta formation	495
Triassic(?):	
Moenave formation:	
Springdale sandstone member:	
7. Sandstone, light-brown (5*YR* 6/4), fine-grained; trough crossbedding, medium-scale low-angle crossbeds; weathers massive; forms cliff. Contains mud lenses at bottom. Unit lenticular	40
6. Sandstone, pale-red (10*R* 6/2), very fine grained; trough crossbedding, medium-scale low-angle crossbeds; weathers massive to blocky; forms cliff. Contains interbedded lenses of sandstone and mud pellet conglomerate. Unit lenticular	37
Total Springdale sandstone member	77

	Feet
Triassic (?)—Continued	
Moenave formation—Continued	
Dinosaur Canyon sandstone member:	
5. Sandstone and siltstone, interbedded; unit is a flat lenticularly bedded coset; crossbedded sets contain trough crossbedding, small- to medium-scale crossbeds; forms slope. Contains a few thin mudstone beds	89
4. Covered slope	182
3. Sandstone, very light gray (*N* 8), very fine- to medium-grained; trough crossbedding, medium-scale crossbeds; weathers massive to rounded; forms cliff. Contains stringers of coarse sand and ripple-marked surfaces	34
2. Siltstone, moderate-brown (5*YR* 4/4); flat laminated bedding; weathers shaly; forms slope. Top of unit is leached gray	2
1. Conglomerate, pale-reddish-brown (10*R* 5/4); trough crossbedding, small-scale crossbeds; weathers massive and pitted; forms ledge. Matrix: Medium-grained sandstone. Gravel: Siltstone pebbles, 20–37 mm in diameter; mudstone pellets, 7–13 mm in diameter; red chert pebbles, subrounded, 10 mm in diameter; colorless quartz granules	1
Total Dinosaur Canyon sandstone member	308
Total Moenave formation	385
Unconformity: 1 to 2 feet of relief.	
Triassic:	
Chinle formation (incomplete):	
Siltstone, light-brown (5*YR* 6/4); flat, thin bedded; weathers knobby; forms slope. Commonly contains leach spots	5

5.—Four miles east of Cow Springs Trading Post

[Measured by J. W. Harshbarger]

	Feet
Cretaceous:	
Dakota sandstone (incomplete):	
10. Sandstone, pale-yellowish-orange (10*YR* 8/6), fine-grained; calcareous-ferruginous cement; unit is a thin-bedded coset; sets are crossbedded; forms rough cliff. Contains abundant limonite streaks	15
Unconformity: Erosional relief, 4 inches to 1.5 feet; marked by coarse-grained sandstone and granule conglomerate.	
Jurassic:	
Cow Springs sandstone:	
9. Sandstone, light-gray (*N* 7), fine-grained; firmly cemented, calcareous-ferruginous; unit is a thin-bedded coset, contains flat-bedded and crossbedded sets; weathers massive; forms rough, pitted, rounded cliff. Contains lenticular manganiferous beds (2–12 inches thick, 50–100 feet long) near base. Also commonly contains manganiferous concretions (6 inches–3 feet)	104
8. Sandstone, dusky-yellow (5*Y* 6/4), fine-grained; poorly cemented; flat, very thick bedded; weathers massive; forms a smooth rounded cliff. Contains manganiferous stringers near top and abundant black ferruginous specks	28
Jurassic—Continued	
Cow Springs sandstone—Continued	
7. Sandstone, pinkish-gray (5*YR* 8/1), very fine grained; firmly cemented; unit is a very thick-bedded coset; sets contain trough crossbedding, large-scale crossbeds; weathers massive, forms a smooth, rounded, cliff. Contains several green poorly cemented silty stringers (1–2 inches) and abundant limonite nodules (½–¾ inches)	51
6. Siltstone, greenish-gray (5*G* 6/1); poorly cemented, calcareous; flat, thin bedded; forms niche in the main rounded cliff	2
5. Sandstone, greenish-gray (5*G* 6/1), very fine grained; firmly cemented, calcareous; trough crossbedding. large-scale crossbeds; forms smooth, rounded, slick cliff. Contains green hard calcareous pods (1 x 6 inches)	94
4. Sandstone, same as unit 7 except does not contain limonite nodules	40
3. Sandstone and siltstone, grayish-red (10*R* 4/2), very fine grained; very poorly cemented; unit is a coset containing flat-bedded and crossbedded sets; forms poorly exposed slope. Gradational unit between the Entrada sandstone and Cow Springs sandstone	23
Total Cow Springs sandstone	342
Entrada sandstone:	
Lower sandy member:	
2. Sandstone, light-brown (5*YR* 6/4), fine-grained; very poorly cemented, calcareous; unit is a thin-bedded coset; sets are crossbedded; forms poorly exposed, color-banded smooth slope. Contains light-gray sandstone beds and several reddish-brown shale partings (¼–1 inch)	67
1. Sandstone, light-brown (5*YR* 6/4), very fine grained; firmly cemented, calcareous; unit is a very thick bedded coset; sets are crossbedded, large-scale crossbeds; forms a smooth, rounded, steep slope. Contains abundant criss cross light-gray streaks or bands	134
Total incomplete Entrada sandstone	201

6.—Six miles southwest of Dinnehotso

[Measured by C. A. Repenning and J. H. Irwin]

	Feet
Jurassic:	
Morrison formation:	
Salt Wash member:	
27. Sandstone, very pale orange (10*YR* 8/2), medium-grained, poorly sorted; composed of subangular clear quartz with black accessory minerals; well cemented, calcareous; unit is a very thick bedded coset; sets contain trough crossbedding, low- to high-angle medium- to large-scale crossbeds; weathers massive to blocky; forms ledge in the cliff and an irregular rolling surface on mesa top. Contains abundant lenses and stringers of pebble conglomerate and frequent lenses of argillaceous material. Base gradational and flat	20

	Feet
Jurassic—Continued	
Morrison formation—Continued	
Salt Wash member—Continued	
26. Claystone, pale-reddish-brown (10*R* 5/4) and very pale blue (5*B* 8/2), composed of clay with some silt; flat-bedded; forms a niche in the cliff. This unit intertongues with unit 25. Base sharp________________________________	5
25. Sandstone, very pale orange (10*YR* 8/2), weathering pale yellowish brown (10*YR* 6/2), poorly sorted; composed of subangular clear quartz with some feldspar; firmly cemented, calcareous; unit is a very thick bedded coset; sets contain trough crossbedding, low-angle medium-scale crossbeds; weathers blocky; forms vertical cliff. Base sharp, an irregular erosion surface_________	17
24. Siltstone, very pale blue (5*B* 8/2), and pale-reddish-brown (10*R* 5/4); flat bedded; forms a niche in cliff. Base sharp and flat_______	3
23. Sandstone, pale-greenish-yellow (10*Y* 8/2) to grayish-yellow (5*Y* 8/4), medium- to fine-grained, poorly sorted; composed of subrounded to subangular clear quartz with feldspar and black accessory minerals; firmly cemented, calcareous and ferruginous; unit is a very thick bedded coset; sets contain trough crossbedding, high and low-angle small-scale crossbeds; weathers massive and pitted; forms ledge. Base sharp and flat____	12
22. Claystone, medium-bluish-gray (5*B* 5/1), weathering light bluish gray (5*B* 7/1); flat bedded; forms a regular covered slope. Contains lenses of small-scale crossbedded sandstone. Base sharp and flat_______________	14
21. Sandstone, light-greenish-gray (5*GY* 8/1), medium- to fine-grained, poorly sorted; composed of subangular clear quartz with red and black accessory minerals; firmly cemented, calcareous; unit is a thick-bedded coset; cosets contain flat gnarly thin-bedded sets and trough crossbedded sets, high and low-angle small-scale crossbeds; weathers massive; forms a ledge. Silty in middle part. Contains abundant ripple marks. Base sharp and irregular____________________________________	11
20. Claystone, very dusky red (10*R* 2/2); composed of silt and clay; flat bedded; forms smooth slope. Contains abundant reddish brown sand lenses. Base sharp and flat___________	4
19. Sandstone, light-brown (5*YR* 6/4), medium-grained, poorly sorted; composed of angular clear quartz; firmly cemented, calcareous; unit is a lenticular thin-bedded coset; sets contain trough crossbedding, high and low-angle small-scale crossbeds; weathers massive, with etching along crossbedding; forms ledge. Contains abundant lenses of very dusky red (10*R* 2/2) claystone. Base sharp and flat with no apparent channeling but contains some reworked sands from unit 18__	4
Total incomplete Morrison formation____	90

	Feet
Jurassic—Continued	
Summerville formation:	
Lower silty member:	
18. Sandstone, moderate-reddish-brown (10*R* 4/6), weathering pale reddish brown (10*R* 5/4) fine grained, poorly sorted; composed of subangular clear quartz with common amber quartz and black accessory minerals and rare feldspar; firmly cemented, calcareous; flat, thin bedded; contains silt and clay partings that weather into niches; weathers knobby in siltier parts and blocky in sandy parts; forms vertical cliff horizontally ribbed by many niches. Base gradational and flat_________	95
17. Sandstone, moderate-reddish-brown (10*R* 4/6), very fine grained, well-sorted; composed of subangular clear and amber quartz with abundant argillaceous material; poorly cemented, calcareous; flat bedded; weathers shaly; forms ledgy slope. Locally contains mud cracks. Base sharp and flat___________	30
Total Summerville formation____________	125
Entrada sandstone:	
Medial silty member:	
16. Sandstone, moderate-reddish-brown (10*R* 4/6), fine-grained, well-sorted; composed of subangular rust-stained clear quartz with black accessory minerals; well cemented, calcareous; flat distorted bedding; trough crossbedding in bottom 5 feet only, low-angle small-scale crossbeds; weathers knobby into hoodoos; forms rounded cliff. Base sharp and flat__________________________________	84
15. Sandstone, moderate-reddish-brown (10*R* 4/6), medium- to fine-grained, poorly sorted; composed of subangular clear and amber quartz with white quartz accessory minerals; firmly cemented, siliceous and calcareous; unit is a very thick bedded coset; sets contain trough crossbedding, low-angle small-scale crossbeds; forms rounded cliff and rolling slope. Base gradational__________________________	50
14. Siltstone, light-brown (5*YR* 5/6), poorly sorted; composed of silt with abundant argillaceous material; firmly cemented, calcareous; very thick bedded; weathers into hoodoos; forms rounded cliff. Base gradational____________________________________	15
13. Sandstone, light-brown (5*YR* 5/6), weathering light olive gray (5*Y* 6/1), fine-grained, well-sorted; composed of subangular clear quartz; firmly cemented, calcareous; gnarly, bedded; weathers into balls (2 mm–1 inch in diameter); forms ledge. Base sharp and flat_	2
Total medial silty member______________	151
Lower sandy member:	
12. Sandstone, light-brown (5*YR* 5/6), fine-grained, well-sorted; composed of rounded clear quartz; poorly cemented, siliceous; trough crossbedding, low-angle large-scale crossbeds; weathers massive; forms rounded cliff or rolling slope. Base sharp and flat___	43
Total Entrada sandstone_______________	194

	Feet
Jurassic—Continued	
Entrada sandstone—Continued	
(Section continued on Garnet Ridge, 3½ miles north of Dinnehotso)	
Carmel formation:	
11. Siltstone, grayish-red (10*R* 4/2), weathering pale reddish brown (10*R* 5/4); composed of quartz with mica accessory minerals; flat bedded; weathers shaly; forms regular slope. Base sharp and irregular	16
10. Sandstone, light-greenish-gray (5*G* 8/1), weathering pale yellowish brown (10*YR* 6/2), fine-grained, fair sorting; composed of subangular clear quartz with black accessory minerals; firmly cemented, calcareous; flat and gnarly bedded; weathers blocky; forms ledge. Prior to consolidation sandstone was squeezed upward into large-scale mud cracks in the overlying unit. Mud crack patterns are roughly hexagonal, from 4 to 6 feet across. Contains asymmetrical ripple marks. Base gradational	6
9. Siltstone, same as unit 11	10
8. Sandstone, same as unit 10	1
7. Siltstone, same as unit 11	7
6. Sandstone, same as unit 10	1
5. Siltstone, same as unit 11	21
4. Sandstone, same as unit 10	7
3. Siltstone, same as unit 11	12
2. Sandstone, same as unit 10	2
1. Siltstone, same as unit 11	17
Total Carmel formation	100
Unconformity: Erosional relief, 3 feet.	
Jurassic(?) and Jurassic:	
Navajo sandstone: Undescribed	478

7.—East side of Todilto Park

[Measured by C. A. Repenning and J. H. Irwin]

	Feet
Cretaceous:	
Dakota sandstone: Undescribed.	
Unconformity: Erosional relief, 2–3 feet.	
Jurassic:	
Morrison formation:	
Westwater Canyon member:	
31. Sandstone, light-bluish-gray (5*B* 7/1), banded with pinkish gray (5*YR* 8/1) and bluish white (5*B* 9/1), coarse- to medium-grained, fair sorting; composed of subangular stained quartz with 5 percent feldspar; poorly cemented; very thick bedded; unit is a coset; sets contain trough crossbedding, low-angle and medium-scale crossbeds; weathers massive; forms a niche below the Dakota. Contains some granules. Base concealed	15
30. Covered interval	11
29. Sandstone, very pale orange (10*YR* 8/2), medium- to very coarse-grained, poorly sorted; composed of subangular clear and white stained quartz with feldspar accessory minerals; very thick bedded; unit is a coset; sets contain trough crossbedding, low-angle and small- to medium-scale crossbeds; weathers massive; forms rolling slope. Contains abundant granite pebbles and clay pods. Base sharp	56

	Feet
Jurassic—Continued	
Morrison formation—Continued	
Westwater Canyon member—Continued	
28. Sandy claystone, dark-reddish-brown (10*R* 3/4) poorly sorted; composed of clay and fine-grained subangular clear and white frosted quartz; poorly cemented; flat, lenticular, thick- to very thick-bedded; forms regular slope. Contains abundant lime concretions. Unit is banded. Base gradational	25
27. Conglomerate, grayish-yellow (5*Y* 8/4); lenticular bedding; unit is a coset; sets contain trough crossbedding, low-angle and small- to medium-scale crossbeds; weathers massive and blocky; forms irregular rounded cliff. Base flat and gradational.	
Matrix: Coarse-grained sandstone, poorly sorted; contains subangular clear and white frosted quartz with 2 percent feldspar; firmly to well cemented.	
Gravel: Contains subangular granule to cobble-sized gray quartzite, pink and gray feldspar, white quartz and granite	119
26. Sandy claystone, dark-reddish-brown (10*R* 3/4), poorly sorted; composed of clay with subangular clear and white frosted quartz; poorly cemented; lenticular bedding; forms a niche in the base of the cliff. Base gradational	2
25. Sandstone, grayish-yellow (5*Y* 8/4), medium-grained, well-sorted; composed of subangular clear and white frosted quartz; poorly cemented; very thick bedded; unit is a coset; sets contain trough crossbedding, low-angle and small-scale crossbeds; weathers massive; forms rolling slope. Base concealed	49
Total Westwater Canyon member	277
Recapture member:	
24. Claystone, sandy, and argillaceous sandstone interbedded; unit weathers massive; forms smooth slope which is mostly covered. Base sharp and irregular with a relief of 10 feet. Sandy claystone, dark reddish brown (10*R* 3/4), poorly sorted; composed of clay with subangular clear and white frosted quartz; poorly cemented; flat, lenticular, thick- to very thick-bedded; contains abundant lime concretions. Argillaceous sandstone, light yellowish gray (5*Y* 8/2), fine- to medium-grained, fair to good sorting; composed of subangular clear quartz with 10 percent white quartz and 5 percent black accessory minerals; poorly cemented; flat, thick bedded	212
Tongue of the Cow Springs sandstone:	
23. Sandstone, pale-yellowish-orange (10*YR* 8/6), medium- to fine-grained, well-sorted; composed of subangular clear quartz with black accessory minerals; firmly cemented; unit is a very thick bedded coset; sets contain wedge planar crossbedding, high-angle and large-scale crossbeds; weathers rounded; forms rounded cliff. Base sharp and flat	55

	Feet
Jurassic—Continued	
Morrison formation—Continued	
Recapture member—Continued	
22. Sandstone, grayish-orange-pink (5*YR* 7/2), medium- to fine-grained, fair to poor sorting; composed of subangular quartz with black and white accessory minerals; firmly cemented, calcareous and argillaceous; flat and irregular bedding; weathers massive; forms rounded cliff. Contains abundant granules of white chert. Base sharp and flat	36
Tongue of the Cow Springs sandstone:	
21. Sandstone, pale-yellowish-orange (10*YR* 8/6), medium- to fine-grained, well-sorted; composed of subrounded to subangular clear quartz with red and white accessory minerals; firmly cemented; unit is a very thick bedded coset; sets contain symmetrical and asymmetrical trough crossbedding, high- to low-angle and medium- to large-scale crossbeds; weathers rounded; forms rounded cliff. Base sharp and flat	18
Recapture member continued:	
20. Sandstone, same as unit 22 but contains abundant clay galls and sand pellets. Contains no granules of white chert	38
Total Recapture member (including tongues of Cow Springs sandstone)	359
Total Morrison formation	636
Summerville formation:	
Upper sandy member:	
19. Sandstone, moderate-reddish-brown (10*R* 5/6), fine-grained, well-sorted; composed of subrounded to subangular amber and white quartz with black accessory minerals; well cemented; unit is a flat thin-bedded coset; sets contain tabular planar crossbedding, high- to low-angle and medium-scale crossbeds; weathers massive; forms rounded cliff. Contains occasional intraformational slumpage and faulting. Base sharp and irregular, erosion surface with 3 feet of relief	213
Todilto limestone:	
18. Mudstone, pale-reddish-purple (5*RP* 6/2); poorly cemented; gnarly bedded; forms irregular slope. Contains abundant lime and clay pellets. Base sharp and irregular on pitted surface of limestone of unit 17	5
17. Limestone, light-olive-gray (5*Y* 6/1), aphanitic; flat, irregular, thin bedded; weathers flaggy, blocky, and pitted; forms ledge. Occasionally contains white quartz grains. Commonly contains white crystalline zones, and, in the base, red, white, and black quartzite pebbles. Top marked with solution pits. Base sharp and irregular	4
16. Mudstone and sandstone, dusky-yellowish-brown (10*YR* 2/2) and dark-yellowish-orange (10*YR* 6/6), fine-grained to clay, fair sorted; composed of subrounded to subangular clear and amber stained quartz with white accessory minerals; flat lenticular bedding; weathers shaly; forms smooth slope. Base sharp and irregular	16
Total Todilto limestone	25

	Feet
Jurassic—Continued	
Entrada sandstone:	
Upper sandy member:	
15. Sandstone, dark-yellowish-orange (10*YR* 6/6), medium-grained, fair sorting; composed of rounded to subrounded clear quartz with black and red accessory minerals; well cemented; unit is a thick-bedded coset; sets contain trough crossbedding, high- to low-angle and large-scale crossbeds; weathers massive; forms cliff. Base sharp and flat	178
Medial silty member:	
14. Sandstone, reddish-brown (10*R* 4/5), fine- to very fine-grained, fair sorting; composed of subrounded to subangular amber quartz with white chert; very thinbedded; weathers blocky and knobby; forms vertical cliff. Contains abundant calcite geodes (¼–3 inches in diameter). Base sharp and flat	33
13. Sandstone, reddish-brown (10*R* 4/5), medium-grained, well-sorted; composed of subrounded to subangular clear and stained quartz with white chert; firmly cemented; lenticular bedding; wedge planar crossbedding, low-angle and large-scale crossbeds; weathers massive; forms rounded ledge. Contains rare calcite geodes (¼ inch in diameter) and white bleached zones. Base sharp and flat	8
12. Sandstone, reddish-brown (10*R* 4/5), fine-grained, well-sorted; composed of subrounded to subangular amber quartz with white chert; firmly cemented; very thick bedded; weathers massive; forms smooth slope. Contains calcite geodes (¼–1 inch in diameter) and white bleached spots. Base sharp and flat	12
11. Sandstone, grayish-orange-pink (5*YR* 7/2); coarse- to medium-grained, fair sorting; contains subrounded to subangular clear and amber quartz with white chert; firmly cemented; tabular planar crossbedding, low-angle and medium-scale crossbeds; weathers flaggy along crossbeds; forms ledge. Base gradational	2
10. Sandstone, dark-reddish-brown (10*R* 3/4), moderate-reddish-brown (10*R* 4/6), bimodal, coarse- to very coarse-grained and fine- to very fine-grained, poorly sorted; composed of subrounded to subangular stained and amber quartz with white chert and black and white accessory minerals; firmly cemented; unit is a flat irregularly bedded coset, very thin- to thin-bedded; sets contain trough crossbedding, low-angle and medium-scale crossbeds; weathers flaggy; forms ledge. Contains abundant granules and pebbles of sandstone. Base sharp and irregular, with 3 feet relief	5
Total medial silty member	60
Total Entrada sandstone	238

Unconformity: Not apparent in most areas.

	Feet
Triassic:	
Wingate sandstone:	
Rock Point member:	
9. Sandstone, reddish-brown (10*R* 4/5), very fine grained, well-sorted; composed of subrounded to subangular amber quartz; poorly cemented; flat, thick bedded; weathers massive and rounded; forms rounded cliff. Contains bleached spots. Base sharp and flat	28
Tongue of Lukachukai member:	
8. Sandstone, reddish-brown (10*R* 4/5), very fine grained, well-sorted; composed of subrounded to subangular amber quartz; poorly cemented; very thick bedded; asymmetrical trough crossbedding; forms rounded cliff. Base sharp and flat	35
Rock Point member continued:	
7. Sandstone, same as unit 9 but contains alternating silty beds; forms rolling partially covered silty slope with sandy ledges	9
6. Sandstone, grayish-orange-pink (5*YR* 7/2) and reddish-brown (10*R* 4/5), a very fine grained, well-sorted; composed of subrounded to subangular clear and amber quartz with black accessory minerals; firmly cemented; trough crossbedding, low-angle and small-scale crossbeds; weathers flaggy; forms ledge. Contains invertebrate trails and borings. Unit is lenticular. Base sharp and irregular, a channeled surface	3
5. Sandstone, same as unit 7	75
4. Sandstone, very pale green (10*G* 8/2) and yellowish-gray (5*Y* 8/1), very fine grained, well-sorted; composed of subrounded to subangular clear quartz with red and black accessory minerals; firmly cemented; flat, lenticular, thick bedded; weathers pitted; forms ledge. Base sharp and flat	⅙
3. Sandstone, same as unit 6 but contains a granule conglomerate 1 inch thick near the base composed of siltstone granules. Invertebrate trails on mud-slick surface of the beds. Base sharp and irregular	11
2. Sandstone, same as unit 7. Contains asymmetrical and cusp ripple marks	112
Total Wingate sandstone	273⅙
(Arbitrary contact)	
Chinle formation (incomplete):	
1. Siltstone, with lenses of limestone, grayish-red (10*R* 4/2); contains silt and clay, poorly cemented; very thin bedded; weathers rounded; forms regular slope. Base sharp and irregular	7

8.—One mile north of Fort Wingate Station

[Measured by J. W. Harshbarger, R. L. Jackson, and S. A. Johnson]

	Feet
Cretaceous:	
Dakota sandstone (incomplete):	
52. Sandstone, dark-yellowish-orange (10*YR* 6/6), medium- to fine-grained, poorly sorted; composed of subrounded to subangular frosted quartz with rare white accessory minerals and common quartz granules; poorly cemented; unit is a coset with flat irregularly bedded sets and crossbedded sets; trough crossbedding, low-angle and small-scale crossbeds; forms irregular cliff. Commonly contains plant and carbonaceous material	50
Unconformity (Concealed).	
Jurassic:	
Morrison formation:	
Westwater Canyon member:	
51. Sandstone, very light gray (*N* 8), coarse- to very fine-grained, poorly sorted; composed of subrounded to subangular frosted quartz with rare red accessory minerals; poorly cemented; trough crossbedding, low-angle and large-scale crossbeds; forms rounded vertical cliff. Commonly contains argillaceous material and lenses of rounded quartz pebbles (chalcedony, jasper, and quartz). Base flat	29
50. Siltstone, light-olive (10*Y* 5/4), poorly sorted; composed of frosted amber quartz with rare red accessory minerals; firmly cemented, highly calcareous; flat, very thin bedded; forms ledge. Contains rare argillaceous material. Base gradational	1
49. Siltstone and mudstone, pale-reddish-purple (5*RP* 6/2), dark-yellowish-green (10*GY* 4/4), and grayish-red-purple (5*RP* 4/2); poorly cemented; thinly laminated to very thin bedded; form irregular slope. Base irregular	11
48. Sandstone, moderate-reddish-brown (10R–5/6), coarse- to very fine-grained, poorly sorted; composed of subrounded to subangular white and red stained quartz with rare black accessory minerals; poorly cemented; trough crossbedding, low-angle and large-scale crossbeds; forms rounded cliff. Contains lenses of rounded quartz pebbles (chalcedony, jasper, and quartz) and subrounded siltstone pebbles. Contains large boulders of pale-reddish-purple (5*RP* 6/2) conglomerate with random arrangement throughout the unit, 1–4 feet in diameter and described as follows:	
Matrix: sandstone, coarse- to very fine-grained, poorly sorted; contains subrounded to subangular quartz with common red and black accessory minerals.	
Gravel: quartz pebbles (quartz, chalcedony, and jasper), subrounded to subangular (¼–1 inch in diameter).	
Base irregular	120
47. Sandstone, moderate-reddish-brown (10*R* 5/6), contains granite pebbles	34
46. Sandstone, pale-reddish-brown (10*R* 5/4), very coarse- to very fine-grained, poorly sorted; composed of subrounded to subangular quartz; poorly cemented; flat, irregular, very thin bedded; forms a parting between massive units. Contains random clay galls and irregular mudstone pockets. Base irregular	4

Jurassic—Continued — Feet

Morrison formation—Continued

Westwater Canyon member—Continued

45. Sandstone, pale-reddish-brown (10*R* 5/4), medium- to fine-grained, poorly sorted; composed of subangular frosted and red-stained quartz which is spotted white by argillaceous material; poorly cemented; trough crossbedding, small-scale crossbeds; forms vertical irregular cliffs. Base flat — 11
44. Sandstone, pale-reddish-purple (5*RP* 6/2), medium- to very fine-grained, poorly sorted; contains subrounded quartz with common black accessory minerals and argillaceous material; poorly cemented; gnarly irregular bedding; forms rounded ledge. Contains abundant carbonaceous plant material and common petrified wood. Contains rare rounded pebbles, white and black quartz (½–1½ inches in diameter). Base irregular — 8

Total Westwater Canyon member — 218

Tongue of the Cow Springs sandstone:

43. Sandstone, moderate-pink (5*R* 7/4), fine- to very fine-grained, poorly sorted; composed of subrounded frosted quartz with common argillaceous material and rare black accessory minerals; poorly cemented; trough crossbedding and large-scale, low-angle crossbeds; forms rounded to vertical cliff. Base flat — 104
42. Sandstone, pale-greenish-yellow (10*Y* 8/2), fine- to very fine-grained, poorly sorted; composed of subangular frosted quartz with rare red and black accessory minerals; poorly cemented; unit is a coset containing flat-bedded sets and trough crossbedded sets with large-scale crossbeds near the base; forms rounded cliff. Contains zone of nodules (¼–½ inch in diameter) near top. Base flat — 126

Total tongue of Cow Springs sandstone — 230

Recapture member:

41. Mudstone, dark-reddish-brown (10*R* 3/4); firmly cemented; structureless; weathers massive; forms slope. Base flat — 3
40. Limestone, arenaceous, light-greenish-gray (5*GY* 8/1), aphanitic to medium crystalline; composed of quartz and rare black accessory minerals in the limestone matrix; firmly cemented; flat irregularly bedded; forms weak ledge. Base irregular — 3
39. Siltstone, dark-reddish-brown (10*R* 3/4), composed of quartz grains; firmly cemented; flat thinly laminated bedding; forms slope — 8
38. Limestone, arenaceous, grayish-red (5*R* 4/2), medium crystalline; contains quartz grains in the limestone matrix; forms weak ledge — 11
37. Siltstone, same as unit 39 — 7
36. Silty sandstone, dark-gray (*N* 3), very fine grained to silt, poorly sorted; composed of rounded green-stained quartz with rare red and black accessory minerals; firmly cemented; weathers massive; forms slope. Base flat — 1

Jurassic—Continued — Feet

Morrison formation—Continued

Recapture member—Continued

35. Sandstone, white (*N* 9), weathering pale brown (5*YR* 5/2), fine-grained, fair sorting; composed of subangular clear and frosted quartz with common black and red accessory minerals and some argillaceous material; crossbedded, medium-scale and low-angle crossbeds; forms ledge. Base irregular — 7
34. Sandstone, mottled-red, light-gray and green, very fine grained, poorly sorted; composed of subrounded clear and frosted quartz with abundant green and red, and rare black accessory minerals; poorly cemented; very thin bedded; forms steep slope. Base flat — 19
33. Silty sandstone, same as unit 36 — 1

Total Recapture member — 60

Total Morrison formation (including tongue of Cow Springs sandstone) — 508

Cow Springs sandstone:

32. Sandstone, pale-reddish-brown (10*R* 5/4) and very light-gray (*N* 8), weathering to pale brown (5*YR* 5/2) and light olive gray (5*Y* 6/1) respectively, very fine grained, fair sorting; composed of subrounded quartz with common amber and black accessory minerals; poorly cemented; unit is a flat very thin- to thick-bedded coset; sets contain trough crossbedding, small- to medium-scale and low-angle crossbeds; forms rounded to vertical cliff. Base irregular — 9
31. Sandstone, light-brown (5*YR* 6/4), very fine grained, fair sorting; composed of subangular to subrounded clear and frosted quartz with rare black and red accessory minerals; poorly cemented; thinly laminated bedding; trough crossbedding, large-scale crossbeds; forms ledgy slope. Base irregular — 6
30. Sandstone, same as unit 32 — 14
29. Sandstone, same as unit 31 — 29
28. Sandstone, same as unit 32 — 137

Total Cow Springs sandstone — 195

Summerville formation:

Upper sandy member:

27. Sandstone, light-brown (5*YR* 6/4), very fine grained, poorly sorted; composed of subangular clear and amber quartz with common black accessory minerals; poorly cemented; weathers massive. Unit is capped by 6 inch highly calcareous sandstone ledge with similar ledge 8 inches thick 9 feet below top of unit. Base irregular — 40
26. Sandstone, light-brown (5*YR* 6/4), very fine grained, poorly sorted; composed of subrounded clear and amber quartz with common black and rare red accessory minerals; poorly cemented; flat bedded; unit is a coset containing small-scale crossbedded sets; forms prominent ledge. Base irregular — 3
25. Sandstone, light-brown (5*YR* 6/4), fine- to very fine-grained, fair sorting; composed of sub-

Jurassic—Continued | Feet
Summerville formation—Continued
Upper sandy member—Continued
rounded white and amber quartz with common black accessory minerals; poorly cemented; weathers massive; forms rounded cliff. Base irregular ---- 7

24. Sandstone, dark-reddish-brown (10*R* 3/4), very fine grained, poorly sorted; composed of subangular to subrounded amber quartz with common black accessory minerals; firmly to poorly cemented; flat, irregular, thin bedded; weathers shaly and hackly; forms slope. Base irregular ---- 7

Total Summerville formation ---- 57

Todilto limestone:

23. Limestone, light-olive-gray (5*Y* 6/1), medium-crystalline; firmly cemented; flat, irregular, very thin- to thin-bedded; forms ledge which caps mesa. Unit arenaceous toward the base:
Basal arenaceous zone (1 inch): Limestone, light-gray (*N* 7), fine-grained, poorly sorted; subrounded; contains common amber quartz with rare black accessory minerals ---- 5

Entrada sandstone:
Upper sandy member:

22. Sandstone, light-brown (5*YR* 6/4), very fine grained, fair to poor sorting; composed of subangular quartz with common black accessory minerals; firmly cemented; asymmetrical trough crossbedding, large-scale crossbeds; forms rounded and vertical cliff ---- 31
21. Sandstone, light-brown (5*YR* 6/4), very fine grained, fair to poor sorting; composed of subangular quartz with common black accessory minerals; unit is a coset containing flat-bedded sets and very small-scale crossbedded (about 3 inches long) sets; forms rounded and vertical cliff ---- 10
20. Sandstone, same as unit 22 ---- 4
19. Sandstone, same as unit 21; contains conspicuous niche 6 feet above base ---- 21
18. Sandstone, same as unit 22 ---- 3
17. Sandstone, same as unit 21 ---- 7
16. Sandstone, same as unit 22 ---- 7
15. Sandstone, same as unit 21 ---- 18
14. Sandstone, light-brown (5*YR* 6/4), very fine grained, poorly sorted; composed of subangular quartz with rare black accessory minerals; poorly cemented; trough crossbedding, medium-scale crossbeds ---- 2
13. Sandstone, same as unit 21 ---- 32
12. Sandstone, same as unit 22 but contains a bleached zone about 1 foot thick at the base. Base irregular ---- 118

Total upper sandy member ---- 253

Medial silty member:

11. Siltstone, pale-reddish-brown (10*R* 5/4), poorly sorted; composed of subangular quartz with common black accessory minerals; firmly cemented; very thin bedded; weathers fissile to shaly; forms hoodoo cliff. One-inch layer of mudstone near base and 4-inch band 8 feet above base described as follows:
Sandstone, yellowish-gray (5*Y* 7/2); firmly cemented, siliceous; very thin bedded; forms ledge. Base irregular. Base of entire unit flat ---- 50

Total Entrada sandstone ---- 303

Unconformity: Not apparent in most areas.

Triassic:
Wingate sandstone:
Lukachukai member:

10. Sandstone, pale-reddish-brown (10*R* 5/4), fine- to very fine-grained, fair sorting; composed of subangular white and amber quartz with rare black and green accessory minerals; poorly cemented; unit is a flat-parallel-bedded coset; upper part of unit contains wedge planar crossbedded sets, high-angle and small- to medium-scale crossbeds; forms rounded cliff. Contains a thin claystone parting (¼–½ inch) 21 feet above the base that forms conspicuous niche. Base flat ---- 39
9. Sandstone, pale-reddish-brown (10*R* 5/4), fine- to very fine-grained, fair sorting; composed of subangular white and amber quartz with rare black and green accessory minerals; poorly cemented; wedge-planar crossbedding, high-angle and large-scale crossbeds; forms rounded cliff. Base flat ---- 4
8. Sandstone, same as unit 9 except is flat bedded ---- 24
7. Sandstone, same as unit 9 ---- 245
6. Sandstone, same as unit 9 except is a flat-bedded coset with occasional low-angle crossbedded sets ---- 14
5. Sandstone, same as unit 9 ---- 29
4. Sandstone, very light gray (*N* 8), very fine grained, poorly sorted; composed of subrounded quartz with rare black and red accessory minerals; poorly cemented, friable; flat, irregular, very thin bedded; forms slope. Base flat ---- 1
3. Sandstone, pale-reddish-brown (10*R* 5/4), coarse- to fine-grained, poorly sorted; composed of subrounded to subangular clear and white quartz in a matrix of red-stained very fine sand; firmly cemented; flat irregularly bedded; forms weak ledge. Base irregular ---- 3

Total Wingate sandstone ---- 359

Unconformity: Erosional relief, 3 feet. Overlain by pebbles of reworked Chinle.

Chinle formation (incomplete):

2. Mudstone, banded grayish-red (5*R* 4/2) and light-greenish-gray (5*GY* 8/1); composed of silt and clay; poorly cemented; flat irregularly bedded; forms slope. Base irregular ---- 8
1. Limestone, pale-reddish-purple (5*RP* 6/2); contains some medium crystalline calcite and silt; flat irregularly bedded; weathers blocky; forms ledgy slope ---- 10

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INDEX