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John W. Harshbarger, C. A. Repenning, and J. H. Irwin
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STRATIGRAPHY OF THE UPPERMOST TRIASSIC AND THE JURASSIC ROCKS OF THE NAVAJO COUNTRY[1]

By J. W. HARSHBARGER, C.A. REPENNING, and J. H. IRWIN[2]

The Navajo country comprises parts of northeastern Arizona, northwestern New Mexico, and southeastern Utah. 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.

INTRODUCTION

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

The uppermost unit of the Chinle formaton, 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 in 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.

GLEN CANYON GROUP

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.

Lower boundary of the Glen Canyon group

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.

Wingate sandstone

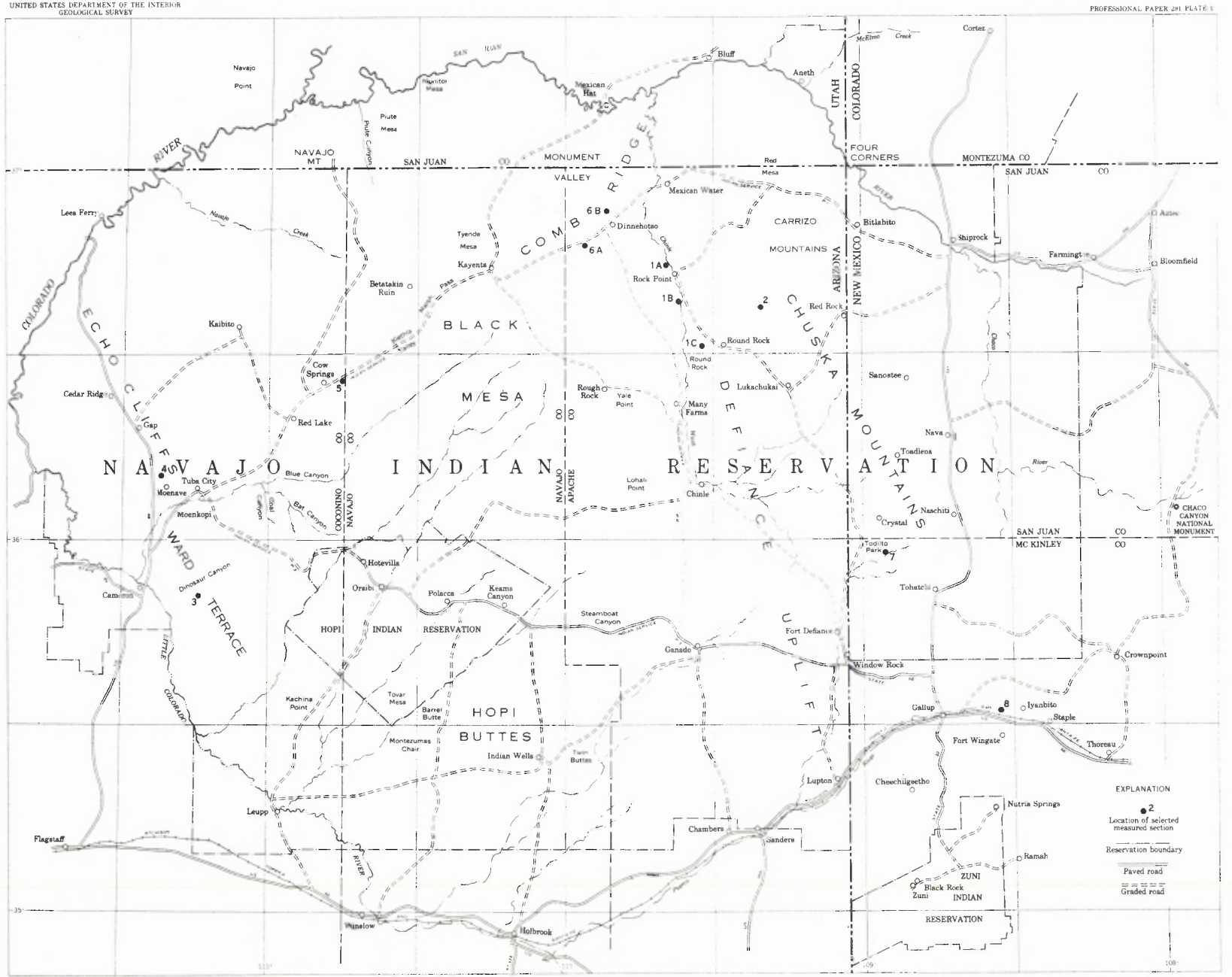
In the Navajo country the Wingate sandstone comprises two mappable units. The lower unit consists of reddish-orange parallel-bedded, thin-bedded siltstone and sandstone. This unit is described as the Rock Point member from typical exposures near Rock Point School, Apache County, Ariz. (fig. 3). The upper unit consists of reddish-brown fine-grained sandstone which is cross-bedded 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. 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.

Rock Point member

The name Rock Point member of the Wingate sand-

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[2] Geologists, U. S. Geological Survey.



INDEX MAP OF THE NAVAJO COUNTRY, ARIZONA, NEW MEXICO, AND UTAH

Scale 1:1,000,000

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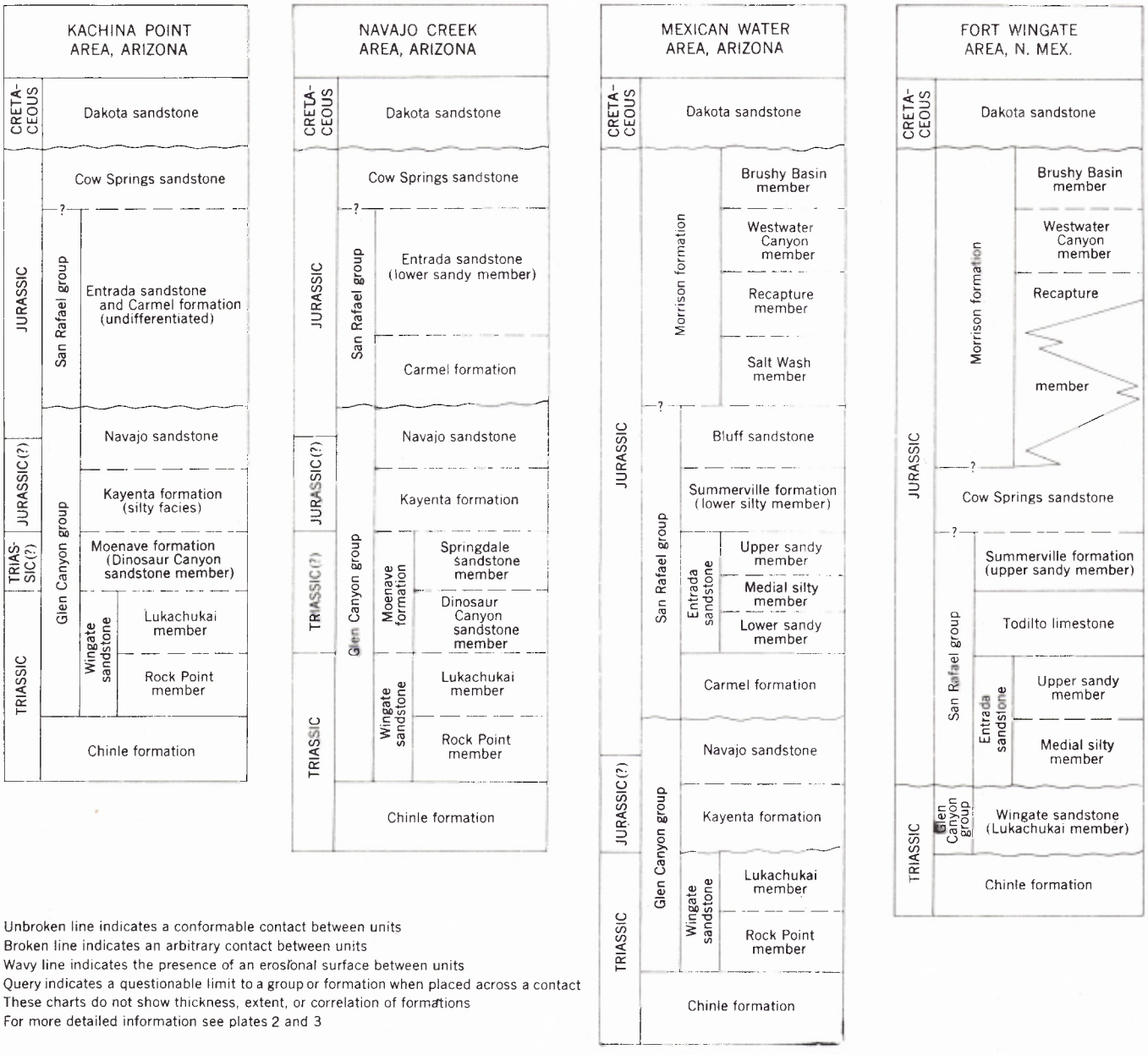


FIGURE 1. Charts showing nomenclature of the uppermost Triassic and the Jurassic in the Navajo country.

stone 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. 3). 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 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. 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).

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. The sandstone is composed primarily of subrounded to subangular quartz grains. The member weathers into a fairly uniform ledgy slope



FIGURE 2. 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 (Trc); the overlying rounded outcrop constitutes the Lukachukai member of the Wingate sandstone (Trwl); 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).

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. 3). 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. The bedding is not lenticular, but the member is very thin bedded to laminated (1-5 cm); also, the thickness of the member increases.

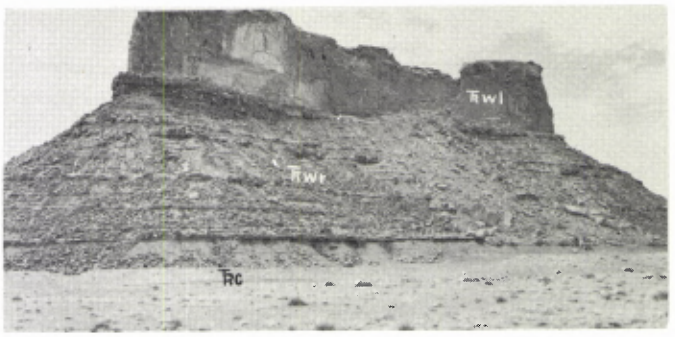


FIGURE 3. Rock Point member of the Wingate sandstone at the type locality, Little Round Rock, 15 miles south of Rock Point, Ariz. Upper part of the Chinle formation (Trc); and Rock Point (Trwr) and Lukachukai (Trwl) members of the Wingate sandstone.

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.

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.

The Lukachukai member of the Wingate sandstone at the type locality is a pale-reddish-brown 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 elsewhere, the Lukachukai member is predominantly crossbedded, although in this area it intertongues with the flat-bedded Rock Point member (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. 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 south west, 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. 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, above 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, 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.

Moenave formation

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. 4). 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 recognizd by other workers in widely separated areas. The names previously established for these two units are used in this paper.

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.



FIGURE 4. Glen Canyon group along Echo Cliffs, 6 miles north of Moenave, Ariz. The upper part of the Chinle formation (Trc); Dinosaur Canyon sandstone member (Tr md) and Springdale sandstone member (Trms) of the Moenave formation; silty facies of the Kayenta formation (Jks); overlain by the Navajo sandstone (Jn).

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 Dinosaur 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.

Dinosaur Canyon sandstone member

The Dinosaur Canyon sandstone member of the Moenave is confined mostly to the southwestern part of the Navajo country. 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.

At the type locality 10 miles east of Cameron, 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; 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. 5), 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 unit. 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 one 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. The unconformity is marked by an erosion surface showing minor channeling. A thin, 2- to 5-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. 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.



FIGURE 5. Dinosaur Canyan 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.

Springdale sandstone member

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 to pale-reddish-brown 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.



FIGURE 6. Type locality of the Kayenta formation, 1 mile northeast of Kayenta, Ariz. Lukachukai member of the Wingate sandstone (Trwl); typical facies of the Kayenta formation (Jk); overlain by the Navajo sandstone (Jn).

Kayenta formation

Two facies of the Kayenta formation are recognized in the Navajo country. At its type locality near Kayenta, Arizona, 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. 7) 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).

The Kayenta formation, at its type locality (fig. 6) 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 to pale-reddish-brown 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.



FIGURE 7. Silty facies of the Kayenta formation, 3 miles southwest of Tuba City, Ariz.

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 the silty facies (fig. 7) 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 and grayish red, but the overall color more nearly approximates pale red.

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. 7).

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. 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.

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.

The Navajo sandstone ranges from very pale orange to pale reddish brown. 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 scale and high angle and of the trough type. 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 patterns which appear to be due to a combination of 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.

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 Defiance uplift, and it is absent in most of New Mexico. 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.

Age assignment of the Glen Canyon group

The sequence of beds included in this discussion ranges in age from Late Triassic into the Jurassic, but evidence for precise determination of the age of most units and for the location of the systematic boundary is fragmentary and inconclusive. For this reason, age designations of the various units have been changed several times in the past. In most published reports the Chinle has been designated as Triassic and the Wingate, Kayenta, and Navajo as Jurassic(?). On the basis of new evidence the United States Geological Survey now assigns a Triassic age to the Wingate; assigns Triassic(?) age to the newly defined Moenave formation; retains a Jurassic (?) age for the Kayenta formation; and assigns a Jurassic and Jurassic(?) age to the Navajo sandstone. These changes reduce the number of units of questionable age and serve to focus attention on the contact between the Moenave and Kayenta formations as the approximate position of the systematic boundary.

The new assignments are based upon a variety of evidence, the most recent having been obtained from discoveries described by Welles (1954) and by Lewis (1954). In June, 1954, Welles (p. 591-98) described a new species of dinosaur from the Kayenta formation. He suggests that its limb proportions are indicative of a stage in develop-

ment to be expected in Early or Middle Jurassic time. More recently, Lewis (1954) announced the discovery of a tritylodontoid in the Kayenta formation. He states (written communication, 1955) that this new discovery represents an animal most closely related to Bienotherium of the Lufeng series (Keuper) of China, closely related to Tritylodon of the Stormberg series (Keuper of most authors, Rhaetic to Liassic of others) of South Africa, less closely related to Oligokyphus of the Rhaeto-Liassic of England and Germany, and least closely related to Stereognathus of the Stonefield slate (Bathonian) of England. Thus, the age designations of the Moenave, Kayenta, and basal part of the Navajo formations still remain questionable and subject to change.

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 northwest part of the Navajo country, the boundary between these units is well defined and easily recognized. These formations are seperated nearly everywhere by an erosional unconformity, and the contact is well marked by lithologic differences. 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 enroaching 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.

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.

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 and weather to pale reddish brown. 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 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.

In the southwestern part of the Navajo country the Carmel formation contains exceptionally large amounts of

sand and is predominantly white. 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, 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.

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 is 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.

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. 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 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.

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 progressively 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.

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. 2). 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.

Todilto limestone

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 to a dark yellowish orange. 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 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 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 cavaties 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 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. 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.

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 near-shore 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; 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.

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. 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 to moderate-reddish-brown fine-grained silty sandstone beds interbed-

ded with dark-reddish-brown mudstone strata (fig. 8).

Near Mexican Water (fig. 8) 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.



FIGURE 8. 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. 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 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, 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 at 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.

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 cliffs 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).

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 to yellowish-gray 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, paticularly 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. 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.

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, 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.

At the type locality, 4 miles east of Cow Springs Trading Post, Coconino County, Ariz. (fig. 9), the Cow Springs sandstone appears as a single massive unit 342 feet thick.

It is composed of greenish-gray to yellowish-gray 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 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 erosion, 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.



FIGURE 9. Type locality of the Cow Springs sandstone, 4 miles east of Cow Springs, Ariz.

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. 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.

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, the contact is not discernible. The Morrison appears to be overlain conformably by Lower Cretaceous rocks in the north-eastern 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. 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 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.

The Salt Wash member is present only in the northern part of the Navajo country. 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. 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 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 to grayish pink and consists chiefly of fine- to medium-grained quartz sand, but in the southeastern part of the Navajo country 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 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 and greenish gray. 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.

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

At the type locality, in Westwater Canyon, 15 miles southwest of Blanding, Utah, 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 and moderate-greenish-yellow 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. 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 southeastern Utah. 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, 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. It is present in western Colorado, eastern Utah, northern New Mexico, and part of northeastern Arizona (Craig and others, 1955).

At the type locality in Utah, 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 greenish-gray and moderate-pink 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 freshwater 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 deep multicolored slope.

The Brushy Basin member is present in the northeastern and eastern parts of the Navajo country.

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 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.

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 channels 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.

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 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. 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.

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