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Stratigraphy of the Cretaceous Rocks and the Tertiary Ojo Alamo Sandstone, Navajo and Hopi Indian Reservations, Arizona, New Mexico, and Utah

GEOLOGICAL SURVEY PROFESSIONAL PAPER 521-E

Prepared in cooperation with the Bureau of Indian Affairs and the Navajo Tribe

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By R. B. O'SULLIVAN, C. A. REPENNING, E. C. BEAUMONT, *and* H. G. PAGE

HYDROGEOLOGY OF THE NAVAJO AND HOPI INDIAN RESERVATIONS, ARIZONA, NEW MEXICO, AND UTAH

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By R. B. O'Sullivan, C. A. Repenning, E. C. Beaumont, and H. G. Page

ABSTRACT

This study of Cretaceous rocks constitutes a part of the ground-water investigation of the Navajo and Hopi Indian Reservations. The Navajo and Hopi Indian Reservations cover about 25,000 square miles, and about one-third of this area is underlain by Cretaceous rocks. The Navajo country—a more general geographic term that encompasses the Navajo and Hopi Indian Reservations—lies principally in northeastern Arizona, but it also includes adjacent parts of northwestern New Mexico, southeastern Utah, and southwestern Colorado.

Cretaceous rocks crop out primarily in two large areas—San Juan Basin and Black Mesa—in the eastern and central parts of the Navajo country, respectively. These rocks are as much as 6,500 feet thick in the San Juan Basin and are about 1,500 feet thick on Black Mesa. At several other places in the mapped area are thin isolated remnants of Cretaceous rock.

The Lower Cretaceous Burro Canyon Formation, as much as 200 feet thick, is the oldest Cretaceous unit in the Navajo country. It occurs in a very limited area of extreme southeastern Utah and adjacent southwestern Colorado. The Burro Canyon consists of conglomerate, sandstone, and green shale and is conformable and intertongues with the underlying Morrison Formation of Late Jurassic age. In northeastern Arizona and northwestern New Mexico, Lower Cretaceous rocks may have been mapped with the Morrison Formation.

Above the Burro Canyon Formation, younger Cretaceous strata are much more widespread and record a detailed history of marine transgression (toward the southwest) and regression (toward the northeast). Two major transgressions are recorded in the San Juan Basin, but only the first of these is recorded on Black Mesa.

During the first major marine transgression, the Dakota Sandstone and much of the Mancos Shale were laid down. During deposition of the lower part of the Mancos Shale, the shore of the sea lay to the south and west of the Navajo country, but during the deposition of the upper part of the Mancos, the shoreline migrated back and forth across the Navajo country, as is recorded in the complex assemblage of intertonguing strata.

In the northeastern part of the Navajo country, the Mancos Shale is about 2,200 feet thick and underlies the Point Lookout Sandstone. In this area the Mancos is divided into upper and lower parts by the Gallup Sandstone and related rocks of the Mesaverde Group. In the southeastern part of the Navajo country, the Mancos Shale is about 600 feet thick and underlies the Gallup Sandstone. The Crevasse Canyon Formation of the Mesaverde Group overlies the Gallup and, in ascending order, consists of the Dilco Coal Member, Dalton Sandstone Member, Bartlett Barren Member, and Gibson Coal Member. The upper part of the Mancos Shale is replaced laterally by marginal marine and continental deposits into which two conspicuous tongues of Mancos Shale wedge out to the southwest. The lower, Mulatto Tongue of the Mancos wedges out into the Crevasse Canyon Formation. The upper shale body—the Satan Tongue—lies above the Hosta Tongue of the Point Lookout Sandstone, and where the Satan Tongue wedges out, the Hosta joins the main body of the Point Lookout Sandstone.

On Black Mesa the Mancos Shale is as much as 670 feet thick and is equivalent to most of the lower part of the Mancos Shale of the San Juan Basin. The Mesaverde Group overlies the Mancos and, in ascending order, consists of the Toreva Formation, Wepo Formation, and Yale Point Sandstone, all older than the Point Lookout Sandstone.

At the end of the first major transgression, the sea retreated far to the northeast of the Navajo country. As the sea withdrew, a thick series of intertonguing marine shale of the Mancos and marginal marine and continental beds of the Point Lookout Sandstone and Menefee Formation was deposited. The Menefee Formation overlies the Point Lookout, and it thickens from 400 feet in the northeastern part of the Navajo country to 3,000 feet in the southeastern part.

As the sea again advanced in the second major transgression, a sequence of continental and marginal marine strata of the upper part of the Mesaverde Group was deposited. This included the upper part of the Menefee Formation and the Cliff House Sandstone, which intertongues with, and is overlain by, the marine Lewis Shale. The sea did not advance as far into the Navajo country as it did during the first trans-

gression, and its withdrawal was more rapid. As the sea retreated to the northeast, the upper part of the marine Lewis Shale, the marginal marine beds of the Pictured Cliffs Sandstone, and the overlying, dominantly continental beds of the Fruitland Formation and the Kirtland Shale were deposited.

A comparison with the standard reference sequence for the Western Interior indicates that the Burro Canyon Formation is of middle Early Cretaceous (Aptian) age. In the northeastern part of the Navajo country, the Dakota Sandstone contains the plant *Tempskya* and, thus, is partly of Early Cretaceous (Albian) age. Elsewhere, at least part of the Dakota Sandstone is equivalent in age to the middle of the Greenhorn Limestone. The Mancos Shale includes rocks ranging in age from equivalents of early Greenhorn age to equivalents as young as the Telegraph Creek Formation. In the southeastern part of the Navajo country, the Mesaverde Group approximates the age span of the beds of the Blue Hill Shale Member of the Carlile Shale to the Fox Hills Sandstone. This age span of the Mesaverde Group represents about half of Late Cretaceous time and is the longest age span known for the group anywhere. Formations above the Mesaverde Group—the Lewis Shale, Pictured Cliffs Sandstone, Fruitland Formation, and Kirtland Shale—are all of Montana age and are equivalent in age to the Pierre Shale and the lower part of the overlying Fox Hills Sandstone of the standard reference sequence. In the Navajo Reservation, the stratigraphically highest beds of the Kirtland Shale are of late, but not latest, Cretaceous age, and the entire Triceratops zone of latest Cretaceous age is apparently missing. The overlying Ojo Alamo Sandstone, which for many years was thought to be of Cretaceous age, is now known to be Paleocene.

The Cretaceous strata, particularly the sandstone beds, are principal sources of ground water for stock and for the large number of trading posts and schools. Most ground water occurs in the marginal marine sandstone beds; some ground water is present in the sandstone beds of the continental deposits; and very small amounts are in the marine strata. The main aquifers are in the Mesaverde Group. On Black Mesa they include the Toreva Formation, and in the San Juan Basin they include the Gallup Sandstone, Point Lookout Sandstone, sandstone beds in the Menefee Formation, and the Cliff House Sandstone. The Dakota Sandstone is widespread in the Navajo country and, locally, is a valuable aquifer.

INTRODUCTION

This report describes the geology of the sedimentary rocks of Cretaceous age that are exposed in the Navajo and Hopi Indian Reservations. These rocks occur within the reservations, primarily on Black Mesa, where they are as much as 1,500 feet thick, and in the San Juan Basin (pl. 1), where they are as much as 6,500 feet thick. The Cretaceous strata consist of lenticular or wedge-shaped layers of shale, sandstone, and carbonaceous shale and siltstone, and they record multiple transgressions and regressions of a major sea that inundated a large part of Western North America during Cretaceous time.

LOCATION AND LAND-NET SYSTEM

The Navajo and Hopi Indian Reservations comprise an area of about 25,000 square miles in the south-central part of the Colorado Plateau. The Navajo Indian Reservation occupies parts of Apache, Navajo, and Coconino Counties in northeastern Arizona, San Juan and McKinley Counties in northwestern New Mexico, and San Juan County in southeastern Utah (fig. 1). The Hopi Indian Reservation is in the central part of the Navajo Indian Reservation in parts of Coconino and Navajo Counties, Ariz. The Navajo country, as defined by Gregory (1917, p. 11), "lies approximately between parallels 34°55′ and 37°17′ and meridians 108° and 111°45′." The term "Navajo country" is here used broadly to include the Navajo and Hopi Indian Reservations and some adjoining areas lying principally between the Colorado, San Juan, and Little Colorado Rivers.

The Navajo country is crossed by only a few main routes of travel. The southern part is traversed by the Atchison, Topeka, and Santa Fe Railway and by U.S. Highway 66, and by the newly constructed Interstate Highway 40. The area is crossed north-south by U.S. Highways 89 and 89A, from Cameron to Navajo Bridge and Glen Canyon Dam, and by U.S. Highway 666, between Gallup and Shiprock. The only scheduled air service on the reservations is to the community of Page, but scheduled air service is available nearby at Farmington and Gallup, N. Mex., and at Winslow and Flagstaff, Ariz. Also, nearly every community in the Navajo country has an airstrip for light planes, and Window Rock, Ariz., has an airport that can accommodate certain larger, heavier planes.

During the 1950's the Navajo Tribe and the Bureau of Indian Affairs began construction of a network of all-weather highways. Two main arteries cross the reservations: the southern route, Reservation Highway 3, extends from Window Rock through Ganado and the Hopi villages to Tuba City, where it joins the northern route, Reservation Highway 1, which connects Tuba City with Kayenta and Shiprock to the east and with Cameron to the west. Another recently completed highway through the Four Corners area connects Cortez, Colo., with Reservation Highway 1 near the Carrizo Mountains.

The reservations are divided by the Bureau of Indian Affairs into 18 administrative districts (fig. 1). Districts 1 through 5 and 7 through 18 are in the Navajo Indian Reservation, and district 6 is in the Hopi Indian Reservation.

Geologic and hydrologic data used in this study were compiled on 15-minute planimetric maps. The 15-minute quadrangles that make up the Navajo

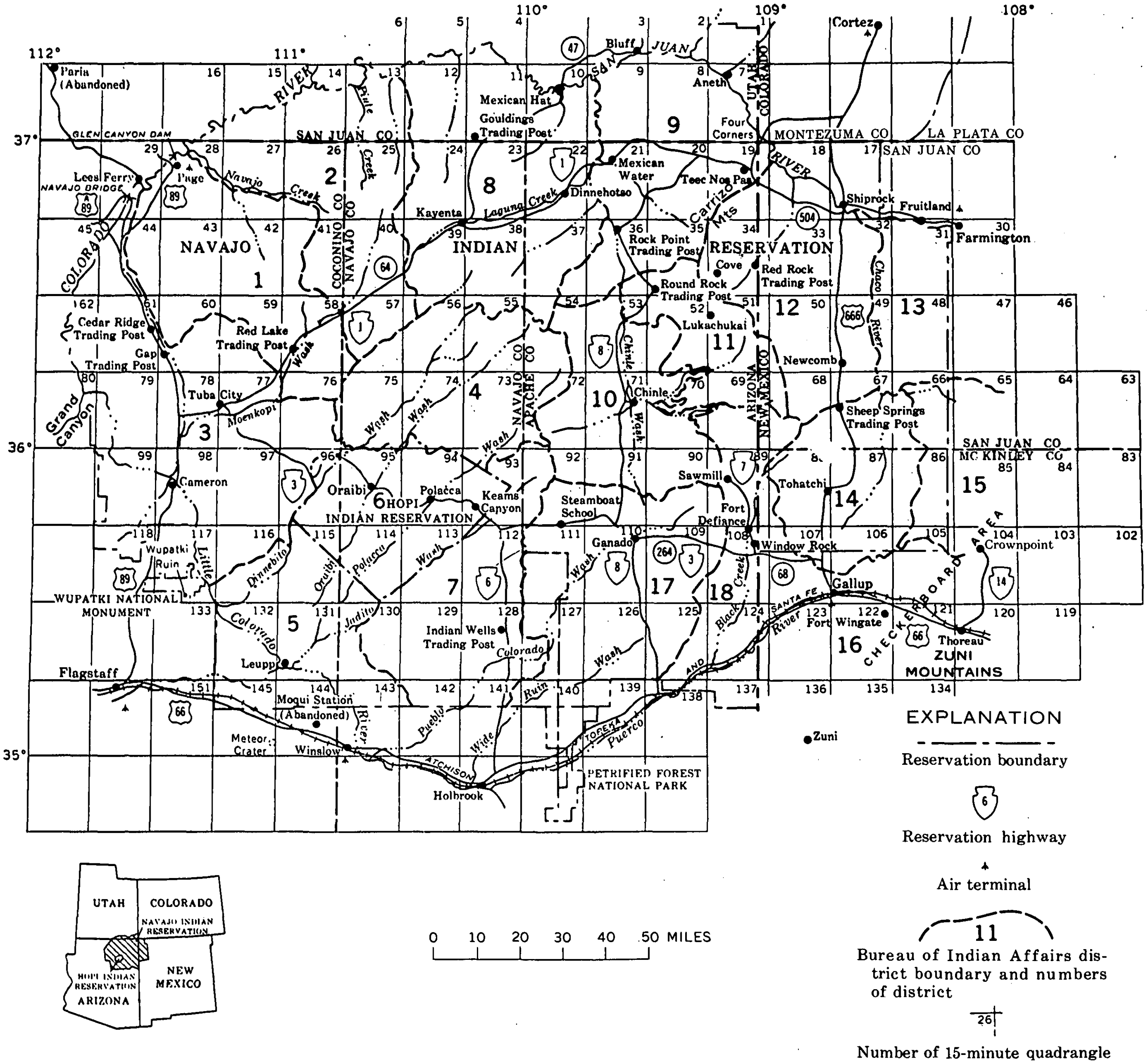

Figure 1.—Bureau of Indian Affairs administration districts and 15-minute quadrangles, by district number and quadrangle number, respectively. Districts 1 through 5 and 7 through 18 are in the Navajo Indian Reservation; district 6 is in the Hopi Indian Reservation. Quadrangles in the reservations and adjacent areas are numbered arbitrarily from 1 to 151, beginning in the northeastern part of the reservations, and numbering consecutively from right to left in rows.

and Hopi Indian Reservations and adjacent areas are numbered arbitrarily from 1 to 151, beginning in the northeastern part of the reservations and numbering consecutively from right to left in rows (fig. 1).

PRESENT WORK

In 1946 the U.S. Geological Survey, at the request of the Bureau of Indian Affairs, made a series of local hydrologic investigations to help alleviate the water shortage at several places on the Navajo and Hopi Indian Reservations. In 1950 the Geological Survey, in cooperation with the Bureau of Indian Affairs, began a comprehensive regional investigation of the geology and ground-water resources of the reservations. The principal objectives were to: (1) Determine the feasibility of developing groundwater supplies for stock, for institutional and industrial use in certain areas, and at the several hundred well sites scattered throughout the reservations and the adjoining areas owned by the Navajo Tribe; (2) describe the existing ground-water supplies; (3) investigate the geology and ground-water hydrology; and (4) appraise the potential for future water development.

Beginning in 1948 the U.S. Geological Survey also investigated the mineral-fuel potential of the Cretaceous rocks of the Navajo country by means of areal mapping and stratigraphic and structural studies. The fuels investigation was made concurrently with the water-resources studies, and the information derived from it was incorporated with the geologic and hydrologic studies to form the basis of this report.

The present report on the Cretaceous rocks is one of several chapters of U.S. Geological Survey Professional Paper 521 that describe the different aspects of the geology and hydrology of the Navajo country. The stratigraphy of the uppermost Triassic and Jurassic rocks was described by Harshbarger, Repenning, and Irwin (1957), and the basic geohydrologic data—the records of wells and springs and selected chemical analyses, drillers' logs, lithologic logs, and stratigraphic sections—have also been published (Davis and others, 1963; Kister and Hatchett, 1963; Cooley and others, 1964). Locations of springs, wells, and stratigraphic sections are shown on the maps by Cooley and others (1966).

The present report is a synthesis, prepared by Repenning and O'Sullivan, of several separate studies by the writers and their associates of the Cretaceous rocks in northeastern Arizona, southeastern Utah, and parts of northwestern New Mexico. Parts of these studies were published in a report by Beaumont (1957) on the Gallup Sandstone and as a map of the western San Juan Basin by O'Sullivan and Beaumont (1957). The Toadlena quadrangle, New Mexico (fig. 1, No. 68), which is in the area of this report, was mapped by Zieglar (1955). Zieglar's unpublished description of the rocks of the Toadlena quadrangle was also utilized in preparing the present report. The Cretaceous rocks of the Black Mesa area were described by Repenning and Page (1956). In addition, information obtained by O'Sullivan in the Black Mesa area and a discussion of the lower Cretaceous rocks by Repenning are included.

This report mainly describes the geology of the Cretaceous sedimentary rocks; however, some of the more significant geologic-hydrologic relations, as determined by M. E. Cooley, are also mentioned. The ground-water hydrology of the area was discussed in detail by Cooley, Harshbarger, Akers, and Hardt (1969).

Most of the information presented in this report was obtained during 1950–55 and represents the collective efforts of several people who worked on the project during all or part of that period. The writers gratefully acknowledge the help of J. P. Akers, J. T. Callahan, M. E. Cooley, O. L. Dilworth, J. H. Irwin, and P. R. Stevens in the Black Mesa area, and the help of E. H. Baltz, A. E. Burford and P. T. Hayes in the San Juan Basin area. In particular, E. C. Beaumont acknowledges the helpful supervision of Paul Averitt and J. D. Sears and the field assistance given by Ralph Brown, R. L. Harbour, E. I. Rich, R. S. Sears, and D. L. Zieglar. During separate field seasons, Sr. Ruben Pesquera of Mexico and Mr. Pumwarn Remalarjun of Thailand served as field assistants and were, at the same time, instructed in the techniques of field mapping by E. C. Beaumont.

Appreciation is extended for the assistance, cooperation, and information given by the late J. J. Schwartz, former coordinator of the Bureau of Indian Affairs water-development program for the Navajo Indian Tribe; M. H. Miller, Bureau of Indian Affairs engineer; C. M. Sells, superintendent, Ground-Water Development Department of the Navajo Tribe; and other personnel of the Bureau of Indian Affairs and the Navajo Tribe who supplied well logs and other information. Special credit is given to S. H. Congdon, who operated a laboratory for the study of the sedimentary rocks of the Navajo and Hopi Indian Reservations, and who made the laboratory analyses, as well as most of the interpretations of the resulting analytical data.

Fieldwork consisted primarily of measuring and describing stratigraphic sections, examining sample cuttings from wells drilled in the area, correlating stratigraphic units in the subsurface, and geologic mapping. The geology was plotted in the field at a scale of 1:31,680 on aerial stereophotos furnished by the U.S. Soil Conservation Service. Planimetric maps of 15-minute quadrangles were used as bases on which to assemble the geologic and hydrologic data. Results of the field mapping were subsequently combined in a detailed geologic map of the Navajo country at a scale of 1:125,000 (Cooley and others, 1969, pl. 1). Plate 1, showing the generalized areal distribution of Cretaceous and some related rocks, was mapped at a scale of 1:500,000, thereby covering a larger part of the San Juan Basin area (fig. 2) than that mapped by Cooley, Harshbarger, Akers, and Hardt (1966, pl. 1), so that the many localities mentioned in the text would be shown.

In the following description of Cretaceous rocks, the colors and their numerical designations are those

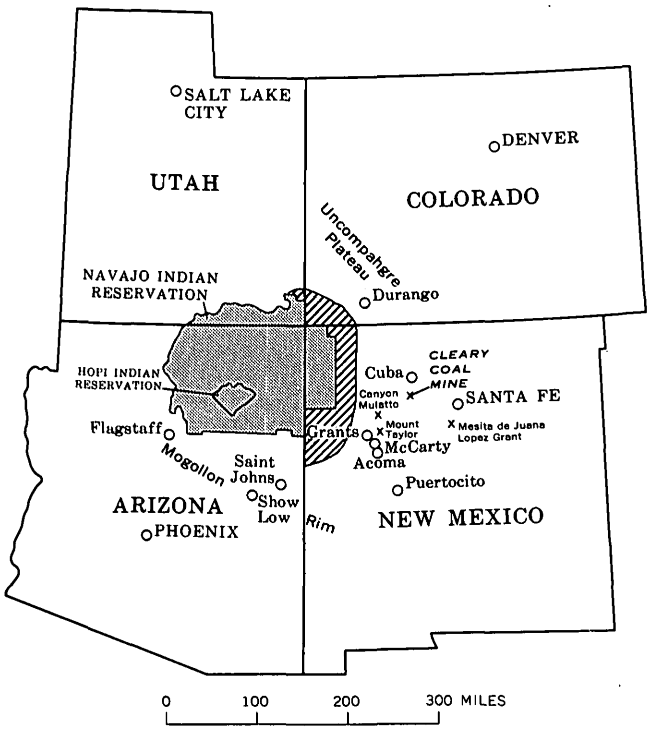

FIGURE 2.—Location of the Navajo and Hopi Indian Reservations (stippled) and the additional area (lined) studied in this report (as shown on pl. 1).

shown on the "Rock-Color Chart" distributed by the National Research Council (Goddard and others, 1948). The descriptive terminology for stratification and cross-stratification is that of McKee and Weir (1953), except that in the present report the term "high angle" applies to crossbeds that dip at angles of greater than 30° from horizontal; "medium angle" applies to beds that dip at angles of 30°–20°; "low angle" applies to beds that dip at angles of 20°–10°; and "very low angle," to beds that dip less than 10° from horizontal. This is a somewhat more detailed terminology than that used for rocks of other systems described in other chapters of this series on the geology of the Navajo country. The greater differentiation in recording the angle of dip of crossbeds is believed to be significant in characterizing the marine and continental deposits, which alternate so prominently in the Cretaceous rocks.

PREVIOUS INVESTIGATIONS AND NOMENCLATURE

Cretaceous rocks are exposed mainly in two large areas in the Navajo country: on and around Black Mesa and in the San Juan Basin. Parts of the Cretaceous System—specifically, the formations of the Mesaverde Group—are described by different names in these two areas, but other stratigraphic units common to both areas are described by the same formational names and are herein discussed as single units.

More than 100 years ago, Marcou (1856) described Cretaceous rocks near Gallup. Newberry (1861) noted Cretaceous strata in the vicinity of the Hopi villages, as well as along the San Juan River above Bluff (Newberry, 1876). The earliest application of now-familiar geologic names was by Holmes (1877), who used "Dakota sandstone," "Mesa Verde group," and "Pictured Cliffs sandstone" in the area of the San Juan River near Shiprock. Dutton (1885) applied the name "Dakota" to rocks in the Gallup area. Still later, the names "Mancos shale" and "Mesaverde formation" were used in the Gallup area by Shaler (1907). In the same report, Shaler included Holmes' Pictured Cliffs Sandstone and overlying Cretaceous beds in the Laramie Formation. Bauer (1917) discontinued the use of the name Laramie in the San Juan Basin and delineated the units above the Lewis Shale approximately the same as they are delineated today.

Campbell and Gregory (1911) tentatively called the sequence of Cretaceous rocks of Black Mesa, in ascending order, the Dakota Sandstone, the Mancos Shale, and the Mesaverde Formation. Lee (1915) used the names again and presented more evidence for approximately correlating them with their counterparts in the San Juan Basin, but not until some years later were the correlations between the two areas firmly established in reasonable detail (Reeside and Baker, 1929). In the meantime, major subdivisions of the Mesaverde Formation in the Gallup area were defined by Sears (1925). Intertonguing relationships of the Mesaverde with the Mancos from Gallup eastward along the south side of the San Juan Basin were described by Sears, Hunt and Hendricks (1941). A more detailed correlation of the units of the Mesaverde Formation in the Gallup area with Cretaceous rocks in the San Juan River area along the west side of the San Juan Basin, and clear documentation of the intertonguing relations were discussed by Pike (1947). Subdivision of the Mesaverde in the Black Mesa area and correlation of tongues of the Mancos and Mesaverde with those in the same sequence in the San Juan Basin were made by Repenning and Page (1956). Beaumont, Dane, and Sears (1956) introduced a few changes in nomenclature within the Mesaverde and younger rocks of the San Juan Basin and established the stratigraphic nomenclature used in this report (fig. 3).

LOWER BOUNDARY OF CRETACEOUS ROCKS

In Late Jurassic time, terrigenous rocks of the Morrison Formation were deposited in streams and

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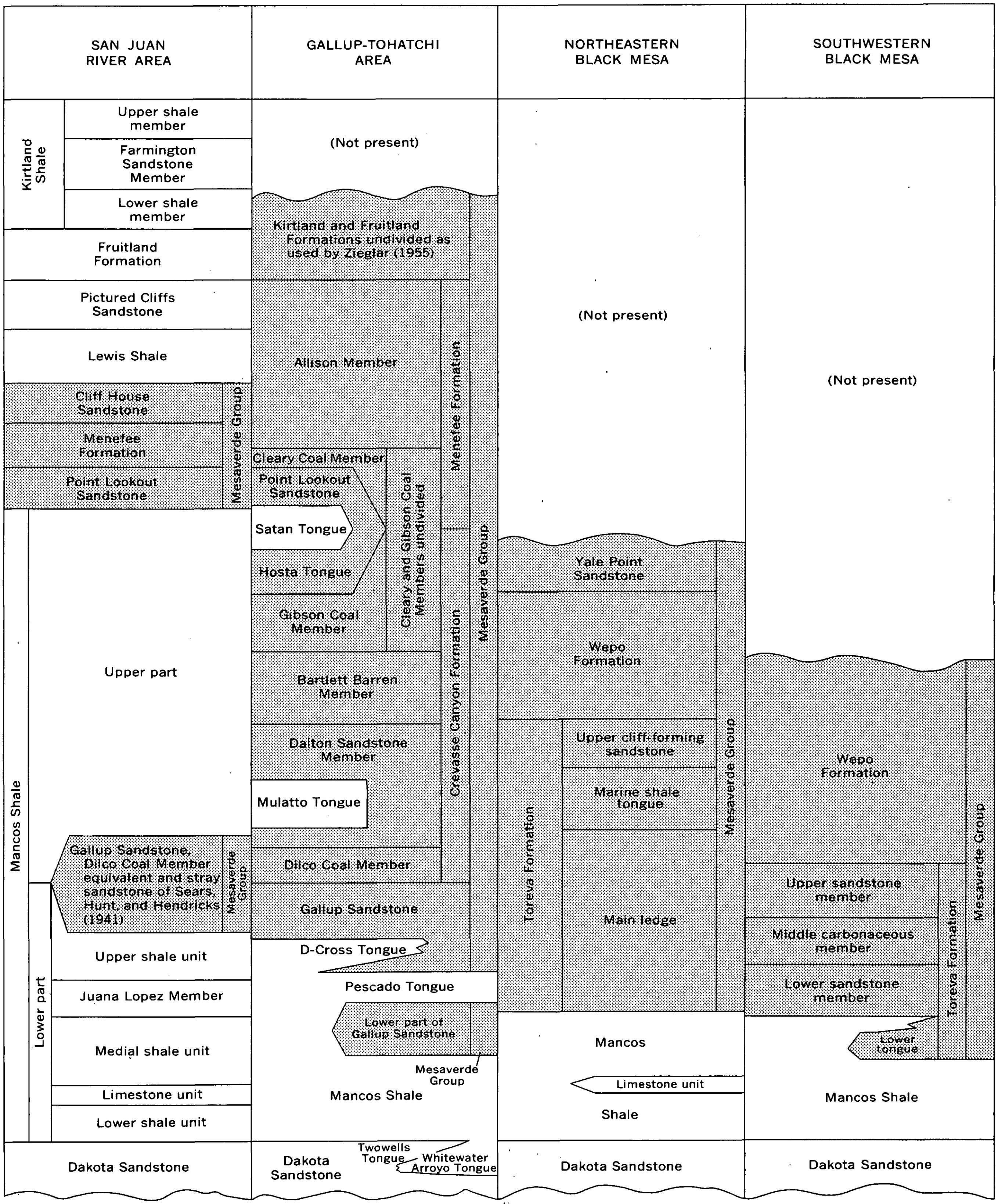

FIGURE 3.—Nomenclature of the Upper Cretaceous rocks in the Navajo country.

fresh-water ponds over most or all of the Navajo country. Deposition appears to have continued into the Early Cretaceous, so separation of Jurassic and Cretaceous rocks is difficult or impossible at some places in the Navajo country.

In the vicinity of McElmo Creek, at the Utah-Colorado State line, the basal boundary of the Cretaceous System is drawn within a gradational zone between shale of the underlying Morrison Formation of Late Jurassic age and conglomeratic sandstone of the overlying Burro Canyon Formation of Early Cretaceous age. Ekren and Houser (1959) believed not only that deposition in this area was continuous from Jurassic into Cretaceous time, but also that the Burro Canyon Formation intertongues laterally with the youngest member of the Morrison Formation in this part of the Navajo country. Locally, the basal conglomeratic sandstone of the Burro Canyon Formation is separated from the underlying shale by an obvious erosion surface that indicates at least local channeling at the contact. At other places, however, the basal conglomeratic sandstone is absent and the shale of the Morrison is generally difficult to distinguish from the shale of the Burro Canyon Formation.

South of the McElmo Creek area, conglomeratic sandstone beds are less abundant in the Burro Canyon Formation than they are to the north, and 7 miles southeast of the junction of McElmo Creek with the San Juan River, the lower boundary of Cretaceous rocks is so difficult to recognize that it was not mapped. Therefore, any Lower Cretaceous rocks in this area are included in the Morrison Formation. Lithofacies trends indicate the same relation in the northern Carrizo Mountains, where the upper part of the sequence included in the Morrison is probably equivalent to the Burro Canyon at McElmo Creek (Strobell, 1956). In the southern Carrizo Mountains and throughout most of the Navajo country, Lower Cretaceous rocks were probably eroded before the deposition of the overlying Dakota Sandstone of late Early(?) Cretaceous and early Late Cretaceous age.

In summary, it appears that where Jurassic rocks are overlain by the Burro Canyon Formation, the contact is placed arbitrarily, and no consistent indication of a break in sedimentation can be found.

Still later in the Cretaceous, however, epeirogenic uplift of the highlands occurred to the southwest and west, which produced tilting of the Navajo country to the northeast and the widespread unconformity between the Cretaceous Dakota Sandstone and all underlying formations. The Dakota Sandstone overlies progressively older formations from northeast to southwest. In outcrops between McElmo Creek and the northern Carrizo Mountains, and in the subsurface east of there, the Dakota rests on the Burro Canyon Formation. At Yale Point, on the northeast corner of Black Mesa, the Dakota overlies the upper part of the Morrison Formation; in the Hopi Buttes area, just south of the south edge of Black Mesa, the Dakota rests on a thin equivalent of the Carmel Formation of Middle and Late Jurassic age. The Dakota Sandstone rests on Triassic sedimentary rocks near Show Low, Ariz., about 60 miles south of the limits of the Navajo Reservation, and on Paleozoic rocks south of Show Low.

Beveling of underlying formations prior to the deposition of the Dakota Sandstone was at such a slight angle to the stratification of the older rocks that no local angularity beneath the Dakota Sandstone can be detected. The surface of the unconformity, however, is rolling and channeled; the relief is as much as 40 feet in the vicinity of some channels as much as 300 feet wide. However, such erosional relief is not common, as most channels are shallow, with a maximum relief of perhaps 5 feet. Many channels are filled with conglomeratic sandstone, but some are filled with finer detritus, including carbonaceous shale and coal. Jurassic rocks directly beneath carbonaceous material in the Dakota ordinarily are bleached almost white; however, beds within the Dakota are not bleached where overlain by coal.

LOWER CRETACEOUS ROCKS

Lower Cretaceous rocks of the Navajo country consist of the Burro Canyon Formation. Also, the youngest beds included in the Morrison Formation of the Black Mesa and, locally, in the area between the Four Corners and the Carrizo Mountains may be Early Cretaceous in age.

BURRO CANYON FORMATION

At its type locality in the Egnar–Gypsum Valley area of southwestern Colorado, the Burro Canyon Formation was defined by Stokes and Phoenix (1948) as consisting of "alternating conglomerate, sandstone, shale, limestone, and chert ranging from 150 to 260 feet in thickness." They described the sandstone beds as gray to brown and the interbedded shale as purple and green. Simmons (1957, p. 2522) pointed out that, at the type locality, the lithology of the Burro Canyon varies considerably, and in some places the unit is a conglomerate containing only a few shale partings. Lithologic variability is characteristic of the formation in the Navajo country (fig. 4). Ekren and Houser (1959,

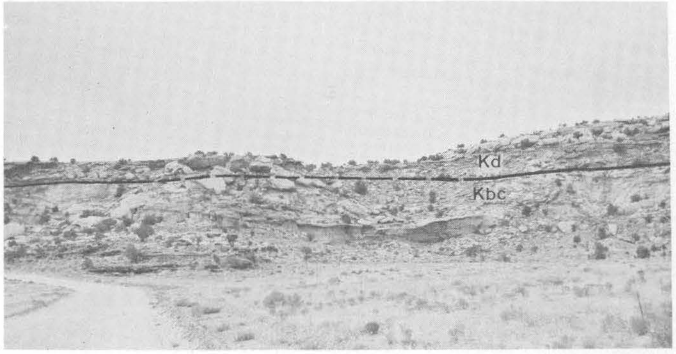

FIGURE 4.—Burro Canyon Formation in southeast Utah. Northward view, about 1.5 miles west of Ismay. Lighter colored Burro Canyon Formation (Kbc), here about 150 feet thick, and Dakota Sandstone (Kd). Slope in foreground formed on Brushy Basin Member of the Morrison Formation.

1965) gave detailed description of the formation in part of the area of its occurrence in the Navajo country, and the following comments are largely a summary of their description.

GENERAL DESCRIPTION AND FIELD RELATIONS

The Burro Canyon Formation crops out in southeastern Utah and adjacent parts of southwestern Colorado. On the geologic map in the present report (pl. 1), the Burro Canyon and the overlying Dakota Sandstone are shown as one unit for convenience, but on the detailed geologic map by Cooley, Harshbarger, Akers, and Hardt (1969), the Burro Canyon is shown separately. In the Navajo country the Burro Canyon Formation consists of a sequence of alternating beds of sandstone and mudstone. The sandstone is grayish green to tan, conglomeratic, fine to medium grained, and crossbedded. The crossbedding is of the asymmetrical trough type with low-angle to very low angle small- to medium-scale crossbeds. Carbonized plant fragments are rare, but silicified wood and bone fragments are fairly common. Pebbles in the sandstone are gravel sized and consist mostly of white, brown, gray, or gray-green chert and quartzite or silicified mudstone.

The mudstone of the Burro Canyon Formation is shaly and is predominantly gray green and subordinately moderate red. This mudstone is difficult to distinguish from the mudstone of the underlying Brushy Basin Member of the Morrison, but the Morrison mudstone contains much more montmorillonite than does the Burro Canyon mudstone (Ekren and Houser, 1959, p. 194), and its surfaces weather puffy or frothy, owing to swelling of the clay, in contrast to the hackly weathering surfaces of the Burro Canyon mudstone.

Near McElmo Creek the uppermost part of the Burro Canyon Formation consists of about 90 feet of conglomeratic sandstone, which overlies 50 feet of shaly mudstone and, locally, a basal conglomeratic sandstone—the Karla Kay Conglomerate Member (Ekren and Houser, 1959, p. 195)—which is as much as 20 feet thick.

The Burro Canyon Formation is mapped from McElmo Creek at the Colorado State line westward to Montezuma Creek at the edge of the Navajo Indian Reservation, and southward nearly to the San Juan River. The proportion of sandstone in the Burro Canyon decreases southward, and the unit becomes increasingly difficult to distinguish from the underlying Brushy Basin Member of the Morrison Formation. Consequently, in the area south of the San Juan River, the Burro Canyon is mapped with the Brushy Basin Member of the Morrison.

The original areal extent of the Burro Canyon Formation is difficult to estimate, but there probably are equivalents in the northern Carrizo Mountains (Strobell, 1956), and a downdropped block of Burro Canyon and Dakota Sandstone is reportedly preserved in a volcanic vent (Mule Ear) about 1 mile south of the San Juan River along Comb Ridge (E. M. Shoemaker, oral commun., 1960). Thus, the Burro Canyon appears to have originally been present in an area northeast of a line running from about Ship Rock (the volcanic neck) to Mexican Hat. If it was ever deposited southwest of this line, it was removed by erosion prior to deposition of the Dakota Sandstone. The Burro Canyon (or genetic equivalent) is not recognized by the present authors in outcrops or in the subsurface eastward along the northeast or east side of the San Juan Basin. Its deposition appears to have been confined to a basin along the west side and perhaps around the north end of the Uncompahgre Plateau, and from there westward across southeastern Utah.

The Burro Canyon Formation is not a major aquifer in the Navajo Indian Reservation, although a few wells in the Four Corners area obtain some water from sandy beds within it.

AGE ASSIGNMENT AND CORRELATION

Simmons (1957, p. 2525–2527) outlined the evidence for the Early Cretaceous age of the Burro Canyon Formation in Disappointment basin, Colorado, about 45 miles north of Ismay. He stated that "no fossil evidence has been found to determine the age of the sandstone beds that form the lower part of the Burro Canyon formation in Disappointment basin and most of the formation away from the basin."

Fossils from two localities in the basal Karla Kay Conglomerate Member of the Burro Canyon Formation near Ismay and Hatch have been described (O'Sullivan, 1962). The fossils include pelecypods of the unioid type and a rootstock of a large monocotyledonous plant. The pelecypods, examined by D. W. Taylor (written commun., 1961), are of Cretaceous age, although they are more closely related to Late Cretaceous than Early Cretaceous forms. The monocotyledonous plant, examined by R. A. Scott (written commun., 1958), indicates only a lower age limit, inasmuch as such plants are not known to occur in rocks older than the Early Cretaceous. However, these fossils, together with more diagnostic fossils from the top of the Burro Canyon, as listed by Simmons (1957, p. 2528), indicate that the entire formation is of Early Cretaceous age.

The available fossils suggest that the Burro Canyon is middle Early Cretaceous (Aptian) age and equivalent to the Trinity Group of Texas and the Kootenai Formation of Montana. The fossils are fresh-water invertebrates, plants, and dinosaur bones; no marine beds are known in this unit.

LOWER(?) AND UPPER CRETACEOUS ROCKS

Outcrops of Cretaceous strata younger than the Lower Cretaceous Burro Canyon Formation cover nearly one-third of the Navajo and Hopi Indian Reservations. They have an aggregate thickness of about 6,500 feet in northern San Juan Basin and as much as 1,500 feet in the northern part of Black Mesa. Marine, marginal marine, and continental deposits are represented. These units document one of the most detailed histories of marine invasion and withdrawal in the interior of the North American continent. A stratigraphic fence diagram (pl. 2) shows the regional variations in thickness of the stratigraphic units, their complex interfingering, and their facies changes.

During the Cretaceous Period, two major marine transgressions occurred in the region of the San Juan Basin, but only the earlier of the two extended as far west as the Black Mesa area. The Dakota Sandstone and the Mancos Shale were deposited during the first transgression. Slow regression of the sea, interrupted by minor transgressions, left a thick series of intertonguing marine shale of the Mancos and marginal marine and continental sandstone of the lower part of the Mesaverde Group. During the second major transgression, the marginal marine and continental sandstone units of the upper part of the Mesaverde Group and the marine Lewis Shale were deposited. Withdrawal of the sea was more rapid after the second transgression than after the first, and during the second transgression, a relatively thin sequence of intertonguing marine beds of the Lewis Shale and marginal marine beds of the Pictured Cliffs Sandstone was deposited as the sea withdrew to the northeast. Continental beds of the Kirtland Shale, Fruitland Formation, and younger units were deposited across the region as the Cretaceous Period drew to a close.

The marine rocks are largely shale, and rocks of marginal marine or continental origin are of diverse lithologies, but are largely sandstone or sandy shale. In northern San Juan Basin, the latest Cretaceous continental deposits are in a nearly continuous sequence with overlying rocks of Tertiary age. The area of Black Mesa, on the other hand, appears to have been elevated and eroded in the latest Cretaceous and most of Tertiary time. As a result, equivalents of the younger rocks in the San Juan Basin are not preserved in the Black Mesa area.

As was pointed out in a general way by Lee (1915, p. 28–30) and more directly by Sears, Hunt, and Hendricks (1941, p. 102–105), continental and marine sediments were simultaneously deposited in different areas as the sea advanced or retreated and the depositional environments continuously shifted. Sears, Hunt, and Hendricks (1941, p. 105) emphasized that "the Mancos and Mesaverde are *lithologic* units—formations whose general rock characteristics persist over great areas but whose composition, thickness, boundaries, and age vary considerably from place to place."

The intertonguing relations produced a complex stratigraphy and a correspondingly complex nomenclature for the Cretaceous rocks. (See fig. 3.) This nomenclature has been reviewed by Beaumont, Dane, and Sears (1956). The nomenclature used herein is about the same as that adopted by those authors and by Repenning and Page (1956). As shown in figure 3 and on plate 2 the nomenclature used in the Black Mesa area differs from that used for correlative units in the San Juan Basin area.

The sandstone beds of Late Cretaceous age are important aquifers in the San Juan Basin and Black Mesa areas of the Navajo country because of their relatively high permeability and great lateral extent. Most ground water in Cretaceous rocks occurs in marine sandstone beds, but some occurs in the sandstone beds of the continental deposits. Generally, only very small amounts of water can be withdrawn from the marine shales.

DAKOTA SANDSTONE

The Dakota is the only Cretaceous formation in the Navajo country that was not named locally.

"Dakota" was first used by Meek and Hayden (1862) in northeastern Nebraska (for Dakota City, south of Sioux City, Iowa), and the name has since been applied throughout the Western Interior of the United States. For many years "Dakota(?)" was used by the U.S. Geological Survey in areas west of the Front Range of Colorado to indicate a questionable correlation with the type locality. To a large extent the question resulted from early attempts to restrict the name to Lower Cretaceous rocks.

The Dakota Sandstone of the Navajo country is characterized by three lithologic types that were deposited in response to changes in the environment marginal to the advancing Cretaceous sea. Under ideal transgressive conditions, deposits of each environment are overlapped in sequence by deposits of adjacent, seaward environment. The resulting sequence of strata consists of a lower member of fluvial sandstone overlying an erosional unconformity, a middle carbonaceous member largely of lagoonal origin that is characteristically gradational into the underlying unit, and an upper shallow marine sandstone member generally separated from the intermediate shaly unit by an erosional surface (fig. 5). For convenience, these three lithologies of the

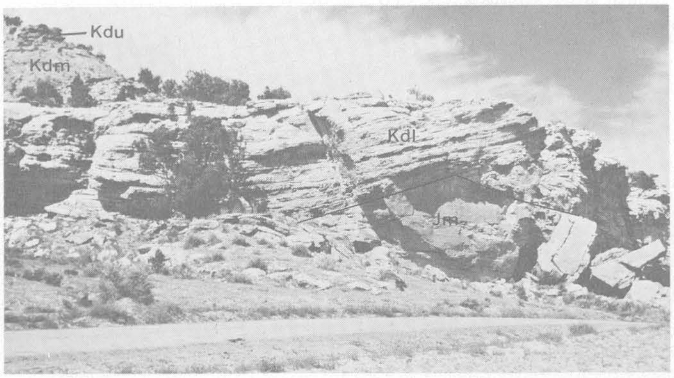

FIGURE 5.—Dakota Sandstone, near Steamboat, in southeastern Black Mesa. Upper sandstone member (Kdu) forms slight ledge at top of the slope-forming middle carbonaceous member (Kdm). Lower sandstone member (Kdl) channels into underlying Morrison Formation (Jm). Photograph by L. C. Craig, 1952.

Dakota Sandstone are described separately as the lower, middle, and upper members; however, deposition throughout the Navajo country was irregular, so that any one of these lithologic units may be either duplicated or absent at particular localities. Nevertheless, the threefold division of the Dakota is recognizable over wide areas, particularly in the Black Mesa area. In most of the other localities in the Navajo country, and throughout much of the southern Colorado Plateau, at least two of the three lithologic members are present.

The Dakota Sandstone (fig. 6) crops out in a narrow sinuous band along the west margin of the San Juan Basin from Lupton northward to Todilto Park. From there, it extends beneath the cover of younger rocks that make up the Chuska Mountains to a point near Toadlena, and it is continuous from there northward to the McElmo Creek area. Outliers are present around, and to the north of the Carrizo Mountains. The formation is exposed on the western and northern flanks of the Zuni Mountains and its outcrops also encircle Black Mesa, occurring well beyond the mesa to the southwest as far as Blue Point, and to the west as far as White Mesa. An isolated outcrop of Dakota apparently caps Navajo Mountain.

GENERAL DESCRIPTION AND FIELD RELATIONS

The lower sandstone member of the Dakota Sandstone is very pale orange (10*YR* 8/2) sandstone composed of medium- to fine-grained subrounded clear and stained quartz grains, intermixed with black accessory minerals. Iron-rich concretions are abundant in the unit at many localities. Typically, the bedding is very irregular and consists of a wide assortment of lenticular crossbed sets, in which the crossbedding is either tabular planar or the asymmetrical trough type, according to the cross-stratification classification of McKee and Weir (1953). Crossbeds are low to very low angle and small to medium scale. Plant fragments and flecks and chips of coal are locally common, and a few blebs of fossil resin are present. In many places the member has a basal conglomerate that is concentrated at the base of channels, and in some areas conglomeratic lenses are common throughout. Pebbles in the conglomeratic lenses are mainly chert and quartzite.

The lower sandstone member has an average thickness of about 20 feet, but it is as much as 60 feet thick in some exposures and is absent at a few places. In most of the Black Mesa area and along the southern part of the San Juan Basin, the lower member is well cemented and forms the upper part of a high cliff composed mostly of rocks of Jurassic age. From Toadlena northward to Bitlabito, it makes a ledge above a steep slope formed by shaly units of the Morrison. From Bitlabito northward to McElmo Creek, it either forms a ledge above shaly slopes of the Burro Canyon Formation or combines with conglomeratic units in the Burro Canyon to form a cliff. The basal contact of the lower sandstone member is the pre-Dakota unconformity.

The middle carbonaceous member of the Dakota Sandstone consists of dark-grayish-brown and black

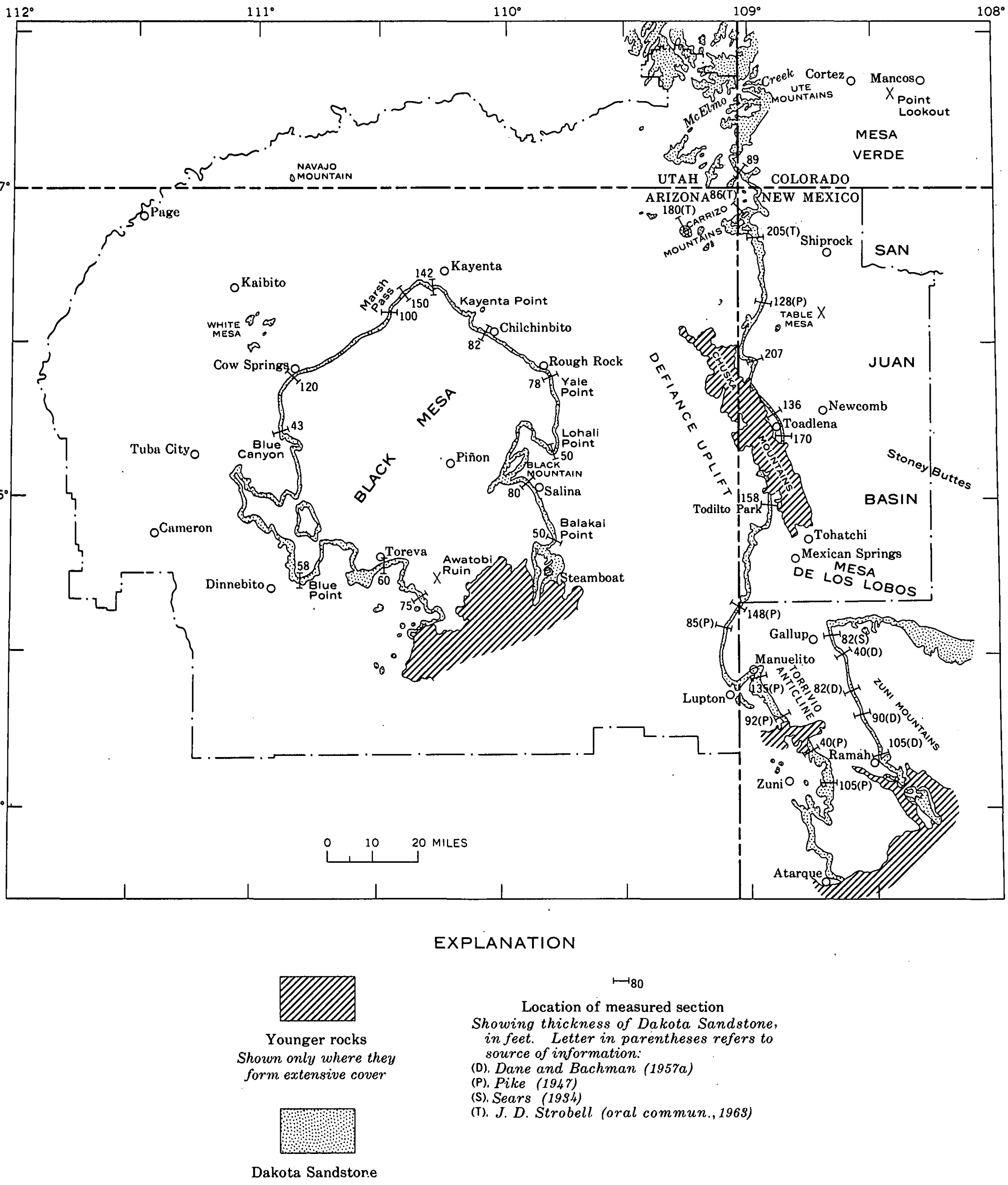

FIGURE 6.—Generalized distribution and thickness of the Dakota Sandstone in the Navajo country.

carbonaceous flat-bedded mudstone and siltstone, coal, and interbedded sandstone lenses. Gypsum is common as thin stringers and as isolated crystals throughout the member. The coal beds, which are several feet thick locally, are present at only a few places. Carbonized plant remains are present throughout the member. In the Black Mesa area lenses of fine-grained flat or crossbedded sandstone are locally common. In the San Juan Basin the middle carbonaceous member at many places contains a conspicuous medial sandstone.

The middle carbonaceous member is everywhere gradational downward into the lower sandstone member, and in many areas the two members intertongue laterally. In contrast, an erosional surface generally separates the middle carbonaceous shale member from the overlying upper sandstone member. Locally, however, the upper sandstone member is absent, and at these places there appears to have been uninterrupted deposition from the middle carbonaceous member into marine shale of the overlying Mancos. In much of the southern Black Mesa area, the carbonaceous shale member of the Dakota locally contains a marine fauna.

Generally, the middle carbonaceous member is 20–40 feet thick, weathers to a smooth slope above a cliff formed by the lower sandstone member, and is capped by a ledge or ledges formed by the upper sandstone member of the Dakota. The thickness is variable, however, and in many areas the middle member thickens at the expense of either or both the upper and lower sandstone members. In other areas the middle member is absent, and the upper and lower sandstone members coalesce to form a single cliff. Rarely, all the Dakota is shaly, and it combines with the Mancos to form a continuous shale slope.

The color and composition of the shallow marine upper sandstone member are generally the same as those of the lower member, except that the upper member contains more very fine sand and silt. Generally, the upper member consists of alternating thin sandstone ledges and intercalated shaly beds. The sandstone beds commonly are crossbedded at a very low angle and on a medium to large scale and are ripple marked and ripple cross-laminated. (See McKee, 1939, p. 74.) The upper member in most areas overlies a sharp, somewhat irregular surface of erosion cut on the middle carbonaceous member. The upper member of the Dakota forms prominent cliffs over much of the north half of the Black Mesa area, but it is absent in most of the area south of a line between Balakai Point and Cow Springs. It is present in nearly all areas where the Dakota is exposed in the San Juan Basin and is increasingly more conspicuous southeastward where it splits into two or more eastward-extending sandstone tongues that are separated by shale tongues of the Mancos Shale. This relation of the upper sandstone member of the Dakota and the Mancos can be seen in outcrops near Mariana Lake.

The thickness of the Dakota Sandstone in the Black Mesa area ranges (fig. 6) from an observed maximum of 150 feet to a minimum of 43 feet, and averages about 80 feet. Local differences in thickness appear to be random and unpredictable. Similar thickness relations exist in the San Juan Basin (fig. 6). J. D. Strobell (oral commun., 1963) measured 205 feet of Dakota about 2 miles southeast of Bitlabito, whereas Sears (1934, p. 13) reported an average thickness of 82 feet for the Dakota in the Gallup area. The Dakota is 207 feet thick 2 miles west of Sanostee, 140 feet thick at Toadlena, and 170 feet thick 5 miles south of Toadlena. The local changes in thickness are due in part to the irregularity of the pre-Dakota erosion surface and in part to intertonguing with the overlying Mancos Shale and to inconsistency in locating the arbitrary contacts in areas where the Dakota is gradational into the Mancos.

Regionally, the Dakota Sandstone shows a pronounced southward and southwestward thinning. It is 213 feet thick in the Durango, Colo., area (Zapp, 1949) and thins to 45–65 feet in the St. Johns, Ariz., area (Young, 1957, p. 1167). The Dakota Sandstone is generally thickest where it overlies the Lower Cretaceous Burro Canyon Formation, which suggests continued subsidence of the area along the western flank of the Uncompahgre Plateau, in Early to Late Cretaceous time.

Locally, the Dakota Sandstone is a major aquifer for ground water in the Navajo country. The lower sandstone member has relatively high permeability, as do some lenticular sandstone beds in the middle carbonaceous member. In most areas the upper sandstone member has low permeability because of a high silt content. In the Black Mesa area and in the southern part of the San Juan Basin, the Dakota and the immediately underlying sandstone of Jurassic age form a multiple aquifer. Water yield of the Dakota to most wells is less than 20 gallons per minute.

AGE ASSIGNMENT AND CORRELATION

The Dakota Sandstone is sparsely fossiliferous, and its age in most areas must be inferred from the fossils in the overlying Mancos Shale. Throughout the Navajo country, beds overlying the Dakota are of early Greenhorn age; older Upper Cretaceous beds are not represented in the basal Mancos Shale. Nowhere in the Navajo country have earliest Late Cretaceous fossils (correlative to the Belle Fourche Shale of the Western Interior reference sequence) been found. The Dakota is therefore assumed to be mostly Greenhorn in age.

In the Navajo country, the pelecypod *Gryphaea newberryi* was used by Repenning and Page (1956) as the index for the lowest of three faunal zones correlative to the Greenhorn Limestone of the reference sequence for the Western Interior of the United States. The zone of *G. newberryi* of Repenning and Page corresponds, in total or in part, to the lower two of four Greenhorn zones recognized by Cobban and Reeside (1952), for which they selected as zonal indices the ammonites *Dunveganoceras aff. D. albertense* and *Dunveganoceras pondi*. These ammonites are too poorly represented in the Navajo country to be used as zonal indices.

The *Gryphaea newberryi* zone is represented by fossils collected as low stratigraphically as 20 feet below the top of the Dakota Sandstone at Blue Point (Repenning and Page, 1956, p. 262) to as high stratigraphically as 190 feet above the top of the Dakota near McCarty (Pike, 1947, p. 72–73). Between these extremes in the Navajo country, *G. newberryi* occurs 20 feet above the Dakota near Shiprock and 80 feet above the Dakota near Gallup. There is a pronounced thickening of that part of the Mancos Shale containing the *Gryphaea newberryi* zone from Shiprock southward across the San Juan Basin to Gallup, and from there eastward to McCarty. The Dakota Sandstone thins in the same direction from 205 feet thick near Shiprock to 82 feet thick near Gallup to 25 feet thick near McCarty. This results in a nearly uniform thickness of rocks between the pre-Dakota unconformity and the top of the zone of *Gryphaea newberryi* and suggests that virtually the same time period but different depositional histories are represented. No such variations in deposition are found from the San Juan Basin to Black Mesa for the same stratigraphic interval; in this direction time-transgressive and depositional thinning trends are parallel.

East of the Navajo country, pre-Greenhorn fossils are present above the Dakota Sandstone. Near Acoma, in the south-central part of the San Juan Basin, basal beds of the Mancos Shale contain *Calycoceras* sp., a fossil assigned to the oldest Late Cretaceous. East of Mount Taylor, an ammonite that may be *Plesiacanthoceras amphibolum* (W. A. Cobban, written commun., 1966) occurs in the beds overlying the Dakota Sandstone. This ammonite lies in the zone of *Acanthoceras? amphibolum*, the middle faunal zone of the Belle Fourche Shale of the standard reference sequence. The presence of these pre-Greenhorn marine fossils in the southeastern part of the San Juan Basin indicates an early embayment of the Mancos Sea in that area. However, there is no fossil evidence to suggest that this early Late Cretaceous sea ever extended as far west as the Navajo country.

The intertonguing of the upper sandstone member of the Dakota with the Mancos—together with the local gradation of the middle carbonaceous shale member with the Mancos, where no intervening sandstone of the upper member is present—rules against any significant difference in age of the two members of the Dakota. The lower sandstone member is made up of many individual depositional sets, each bounded by an erosional diastem. The continuity of deposition was obviously broken, as it is in any fluvial deposit, and it would appear that this member could represent a considerable span of time. However, in Black Mesa the lower sandstone member grades upward into, and tongues laterally with, the medial carbonaceous shale, and locally it is entirely replaced by this unit. In this area, therefore, the time of deposition of the lower sandstone member seems to be only slightly older than that of the middle carbonaceous shale member. These relationships indicate that the lower sandstone represents a belt of fluvial deposits marginal to the sea that advanced on one side and to the lowlands that were actively eroded on the other.

In the Four Corners area of the Navajo country, however, subsidence may easily have initiated deposition of the Dakota, earlier than elsewhere, in lowlands that initially were far from the strand of the Cretaceous sea. Fragments of the plant *Tempskya*, of Early Cretaceous age (C. B. Read, oral commun., 1952) were found in the Carrizo Mountains area (Strobell, 1956) in a sandstone believed unequivocally to be the basal sandstone of the Dakota. Because of this, the lower part of the Dakota Sandstone is considered to be partly of Early (?) Cretaceous age in the San Juan Basin.

UPPER CRETACEOUS ROCKS

MANCOS SHALE

The Mancos Shale overlies the Dakota Sandstone and underlies the Mesaverde Group throughout the Navajo country and a considerable part of the surrounding region. The Mancos Shale was first named by Cross and Purington (1899) from exposures in Mancos Valley, near the town of Mancos, Colo., about 45 miles north-northeast of the town of Shiprock, N. Mex. Nearly continuous exposures (pl. 1) connect the type locality with outcrops along the southern and western parts of the San Juan Basin. A gap of about 45 miles separates the Mancos Shale in the Black Mesa area from the Mancos of the San Juan Basin.

The Mancos intertongues southwestward with units of the Mesaverde Group, and the upper beds of the Mancos Shale are progressively older in that direction (fig. 7). The Mancos Shale pinches out between the Dakota Sandstone and the Mesaverde

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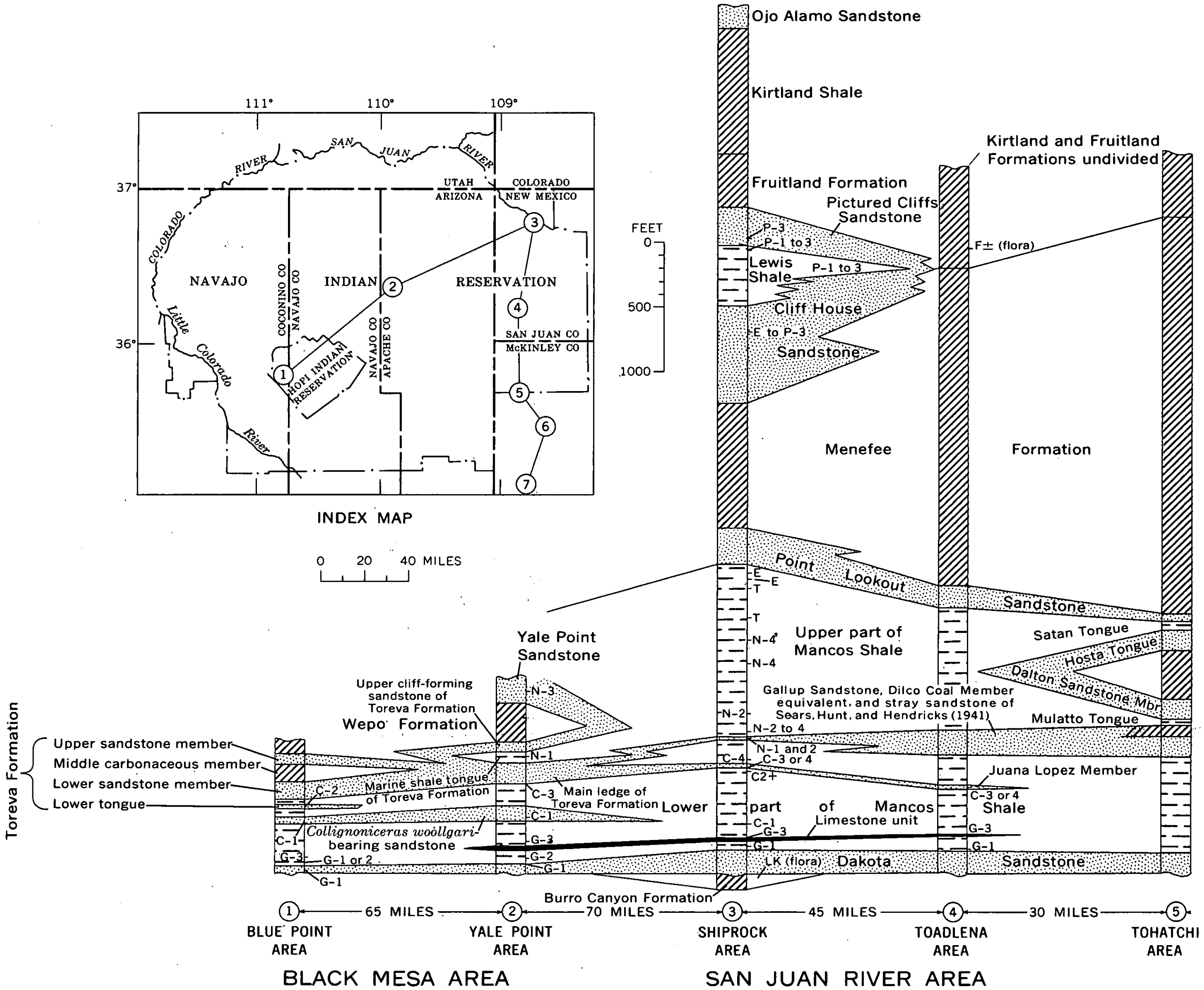
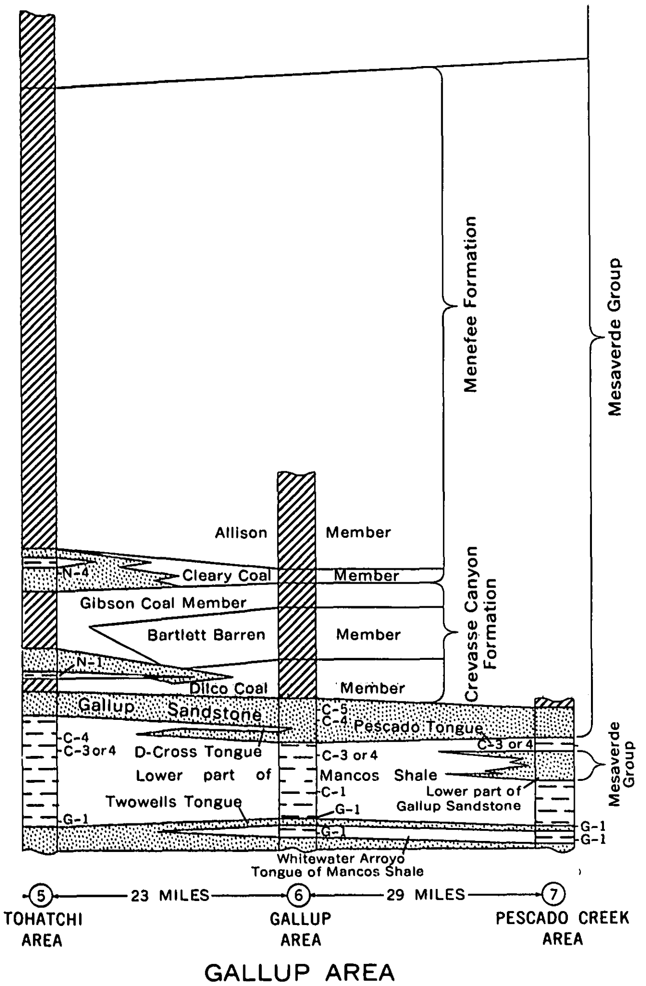


FIGURE 7.—Time-lithologic-correlation chart of the Cretaceous rocks in the Navajo country, Arizona and New Mexico. Part of (1924); Dane, Bachman, and Reeside (1957); Allen and Balk (1954); Sears (1925); Cobban and Reeside (1952);

Group in the Mogollon Rim area near Show Low, Ariz. Because of this relationship, the Mancos Shale of the Black Mesa and Gallup areas is correlative lithogenetically and temporally to only a small part of the Mancos in the Shiprock area.

The Mancos Shale is banded mostly light gray (*N* 7) and medium dark gray (*N* 4) in alternating thick zones, and is yellowish gray (5*Y* 8/4) in the sandier parts. Upon weathering, the dark-gray parts have a bluish cast that accounts for such names as Blue Canyon, Blue Point, and Blue Hill, where the formation is conspicuously exposed. In many other places, debris from sandy yellowish-gray zones covers the hillsides and imparts a yellowish cast to large areas underlain by the Mancos. Plate 2 and figure 8 graphically present the interrelationship of the Mancos and Mesaverde.

Because of intertonguing with the partly equivalent Mesaverde Group, the Mancos thins from more than 2,000 feet thick along the San Juan River in the Shiprock area (fig. 9) to less than 300 feet thick 13 miles southeast of Zuni (Pike, 1947, p. 35). It is 1,887 feet thick at Toadlena, 635 feet thick at Yale Point on the northeastern part of Black Mesa, and 475 feet thick at Blue Point in the southwestern part of Black Mesa. A widespread sandstone tongue of the Mesaverde Group, present from the San Juan River southward, separates the Mancos Shale into two



Zone code[1]	Zonal indices (modified from Cobban and Reeside, 1952)	Reference sequence for Western Interior
	Triceratops	Hell Creek Formation
F	*Discoscaphites nebrascensis*	Fox Hills Sandstone
	Discoscaphites nicolletii	
	?	Pierre Shale
	Baculites grandis	
	Baculites baculus	
P–3	*Baculites compressus*	
P–2	*Baculites gregoryensis*	
P–1	*Baculites asperiformis*	
E	*Scaphites hippocrepis*	Eagle Sandstone
T	*Desmoscaphites bassleri*	Telegraph Creek Formation
N–5	*Desmoscaphites erdmanni*	Niobrara Formation
	Clioscaphites choteauensis	
N–4	*Clioscaphites vermiformis*	
N–3	*Scaphites depressus*	
N–2	*Scaphites ventricosus*	
N–1	*Inoceramus deformis*	
C–5	*Scaphites* species	Carlile Shale
C–4	*Prionocyclus wyomingensis*	
C–3	*Prionocyclus macombi*	
C–2	*Collignoniceras hyatti*	
C–1	*Collignoniceras woollgari*	
G–3	*Inoceramus labiatus*	Greenhorn Limestone
G–2	*Sciponoceras gracile*	
G–1	*Gryphaea newberryi*	
	(Not reported from this area)	Belle Fourche Shale
LK	Lower Cretaceous	

[1] A plus sign (+) following the zone code shown in the section indicates either that fauna or a younger fauna; a plus-or-minus sign (±) indicates either that fauna or a slightly younger or older fauna.

the faunal and lithologic information used to compile this figure was obtained from the following sources: Pike (1947); Reeside and Sabins and Bonham (1960). Table at right lists faunal zones shown in figure.

units that are shown on the geologic map (pl. 1) as the lower and upper parts. At places these two parts are further subdivided into several members, but on the geologic map (pl. 1), only the Satan and Mulatto Tongues of the Mancos are shown separately. In some areas the lower part of the Mancos can also be subdivided into members, but the small scale of the geologic map prevents showing these members separately. Only equivalents of the lower part of the Mancos Shale are present in the Gallup and Black Mesa areas.

The Mancos Shale forms a thick, relatively impermeable barrier between ground-water aquifers of the Dakota Sandstone and those of the Mesaverde Group. Within the Navajo and Hopi Indian Reservations, only a very small amount of ground water may be obtained directly from the Mancos Shale. However, the shale prevents downward percolation of ground water and, thus, increases the probability of obtaining water from any of the overlying alluvial, eolian, and landslide deposits. In general, the chemical quality of water in, or in contact with, the Mancos Shale is very poor.

LOWER PART OF MANCOS SHALE

The lower part of the Mancos can be subdivided into five units: a lower shale, a limestone, a medial shale, the Juana Lopez Member, and an upper shale.

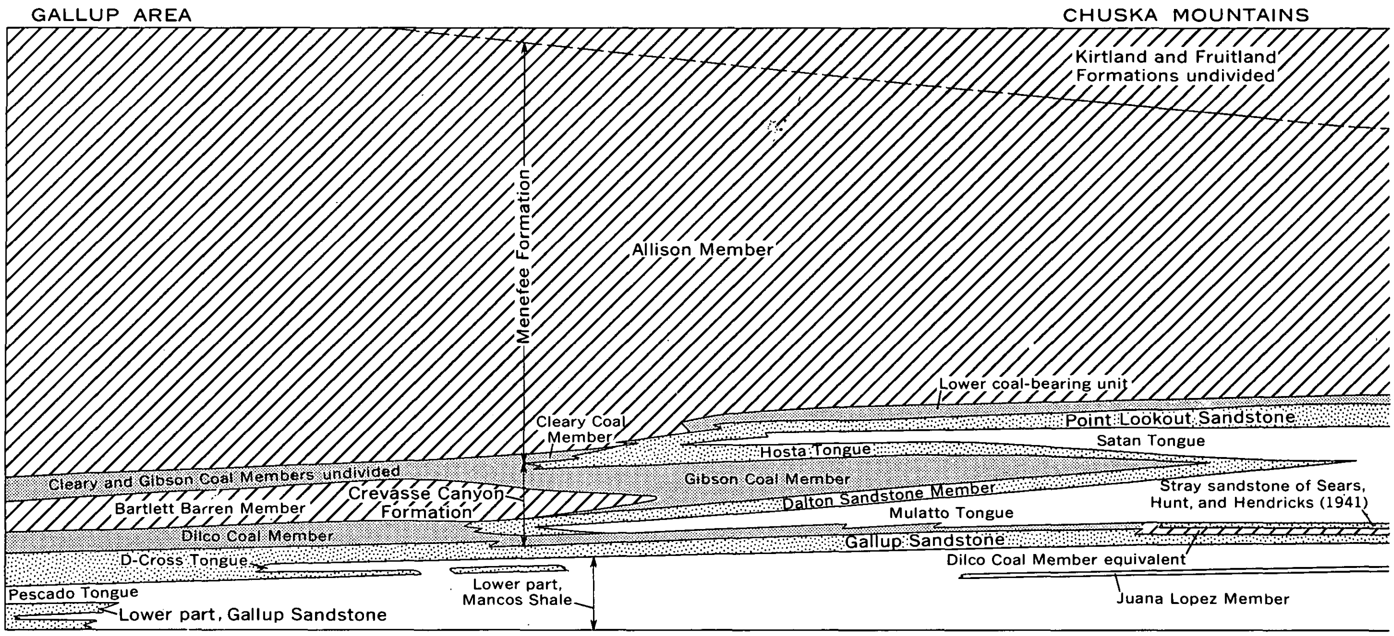


FIGURE 8.—Intertonguing relationships of the Mesaverde Group and related formations and the Mancos Shale in western San Juan Basin. Contacts are dashed where restored. From Allen and Balk (1954); Dane (1960a); Hayes and Zapp (1955); Sears (1925); and work by the present authors.

In the Navajo country these subdivisions are most distinct between Toadlena and the San Juan River.

The lower part of the Mancos Shale is 750–850 feet thick in the area between Toadlena and the San Juan River. From the Chuska Mountains southward, the lower part of the Mancos thins by intertonguing with progressively older tongues of the Mesaverde Group. In the vicinity of Manuelito, N. Mex., the Mancos is 480 feet thick (Pike, 1947, p. 9). About 13 miles southeast of Zuni, the Mancos is less than 300 feet thick (Pike, 1947, p. 35). In the Black Mesa area, the Mancos (equivalent to most of the lower part of the Mancos Shale in the San Juan Basin) ranges in thickness from 450 feet at Blue Point on the southwest to 669 feet near Rough Rock on the northeast.

LOWER SHALE UNIT

The lower shale unit ranges in thickness from 50 feet near the San Juan River to 100 feet in the northeastern Black Mesa area and near Toadlena. In the southwestern part of Black Mesa and in the Gallup area, this unit is not separable from the medial shale unit because the intervening limestone unit is absent. The lower shale is composed of medium-dark-gray to nearly black calcareous claystone, siltstone, and mudstone interbedded with thin beds of sandstone. The sequence is gradational into the underlying Dakota Sandstone. Thin beds of bentonitic clay are common in this unit. Marly beds are locally present near the base, and they commonly contain large quantities—so-called reefs—of *Gryphaea newberryi*. The upper part of this unit is increasingly calcareous upward and grades into the overlying limestone unit.

In the Gallup area, equivalents of the lower part of the Mancos Shale contain a prominent sandstone about 80 feet above the Dakota Sandstone. At a section measured by Dane and Bachman (1957a, p. 96) about 5 miles northeast of Gallup, this sandstone is fine to medium grained, contains brown concretionary masses, is 44 feet thick, and is capped by a coquina of *Gryphaea newberryi* 5 feet thick. This unit has been called the Tres Hermanos Sandstone Member of the Mancos Shale by Pike (1947, p. 32) and by Dane and Bachman (1957a, p. 97). The sandstone extends eastward along Mesa de los Lobos toward Mount Taylor and the McCarty area, where it has also been called Tres Hermanos (Pike, 1947, p. 66). The Tres Hermanos Sandstone Member (Herrick, 1900; Dane, 1959) was previously considered to be of Greenhorn age. Recent work by W. A. Cobban, C. H. Dane and E. R. Landis (E. R. Landis, oral commun., 1968), however, showed that the type Tres Hermanos is of Carlile age (thus, younger than Greenhorn age).

The *Gryphaea*-bearing sandstone east of Gallup, previously called Tres Hermanos, is probably the Twowells Sandstone Lentil of the Mancos Shale, as suggested by Dane (1960a, p. 50). Pike (1947, p. 35–36) named the Twowells Sandstone Lentil from

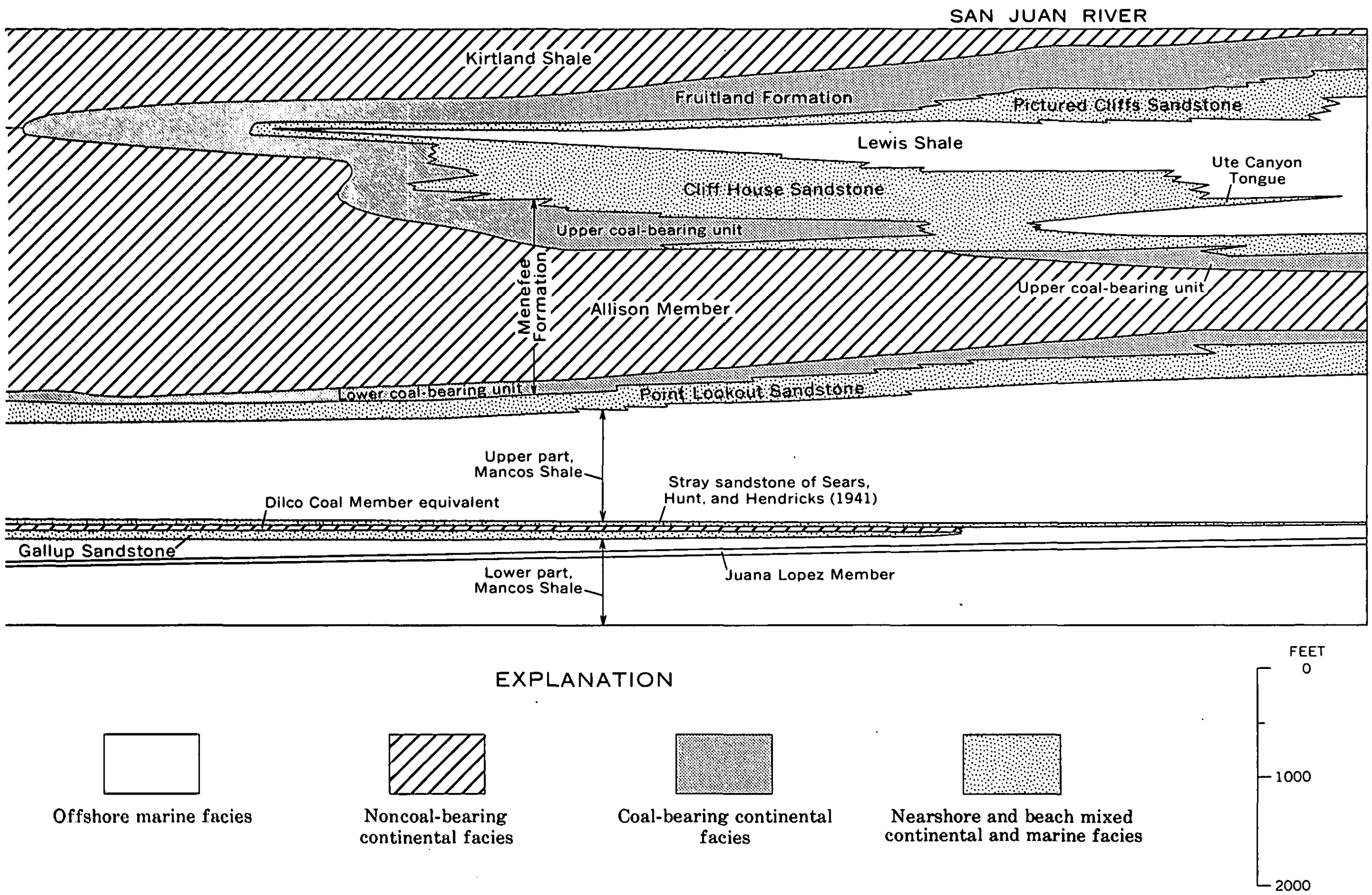


FIGURE 8.—Continued

a locality about 18 miles southwest of Gallup on the west side of the Gallup-Zuni basin, where the Twowells is separated from the Dakota Sandstone by 50 feet of Mancos Shale. The Twowells Sandstone Lentil merges with the Dakota Sandstone near the south boundary of the Navajo Indian Reservation (Dane, 1960a; Owen, 1966). The marine shale unit between the Twowells and the Dakota Sandstone has been called the Whitewater Arroyo Shale Member of the Dakota Sandstone (Owen, 1966, p. 1026). These two units are now recognized as the Twowells Tongue of the Dakota Sandstone and the Whitewater Arroyo Tongue of the Mancos Shale (Green and Pierson, 1971).

The lower shale unit contains fairly abundant fossils in nearly all areas. These fossils belong to four faunal zones that are common to the Greenhorn Limestone of the Western Interior reference sequence (Cobban and Reeside, 1952). The occurrence of the *Gryphaea newberryi* zone, as determined by Repenning and Page (1956), has already been discussed in connection with the age of the Dakota Sandstone. Ammonites were collected 32 feet above the base of the Mancos Shale along the road between Shiprock and Bitlabito. These include *Dunveganoceras* sp., *Calycoceras obrieni* Young? and *Metoicoceras defordi* Young, as identified by W. A. Cobban (written commun., 1966). These ammonites indicate a very late Cenomanian age and are probably in the zone of *Dunveganoceras conditum* (Cobban, 1961, p. 740).

Two younger fossil zones are recognized in the lower shale unit. The zone of *Sciponoceras gracile* is poorly represented in collections made thus far. Also, the zone appears to be confined to an interval of not more than about 40 feet thick near the middle of the lower shale unit. The zone overlaps part of the range of *Gryphaea newberryi* (Repenning and Page, 1956, p. 267). The upper 20 feet of the lower shale unit contains fossils belonging to the zone of *Inoceramus labiatus*.

In northern and eastern San Juan Basin, the lower shale unit has been called the "Graneros equivalent" (Wood and others, 1948) or "Graneros shale member of the Mancos" (Bozanic, 1955, p. 91; Dane, 1948; Silver, 1951, p. 109). The term "Graneros" was used in the San Juan Basin because of presumed lithologic continuity with the modified type Graneros Shale of

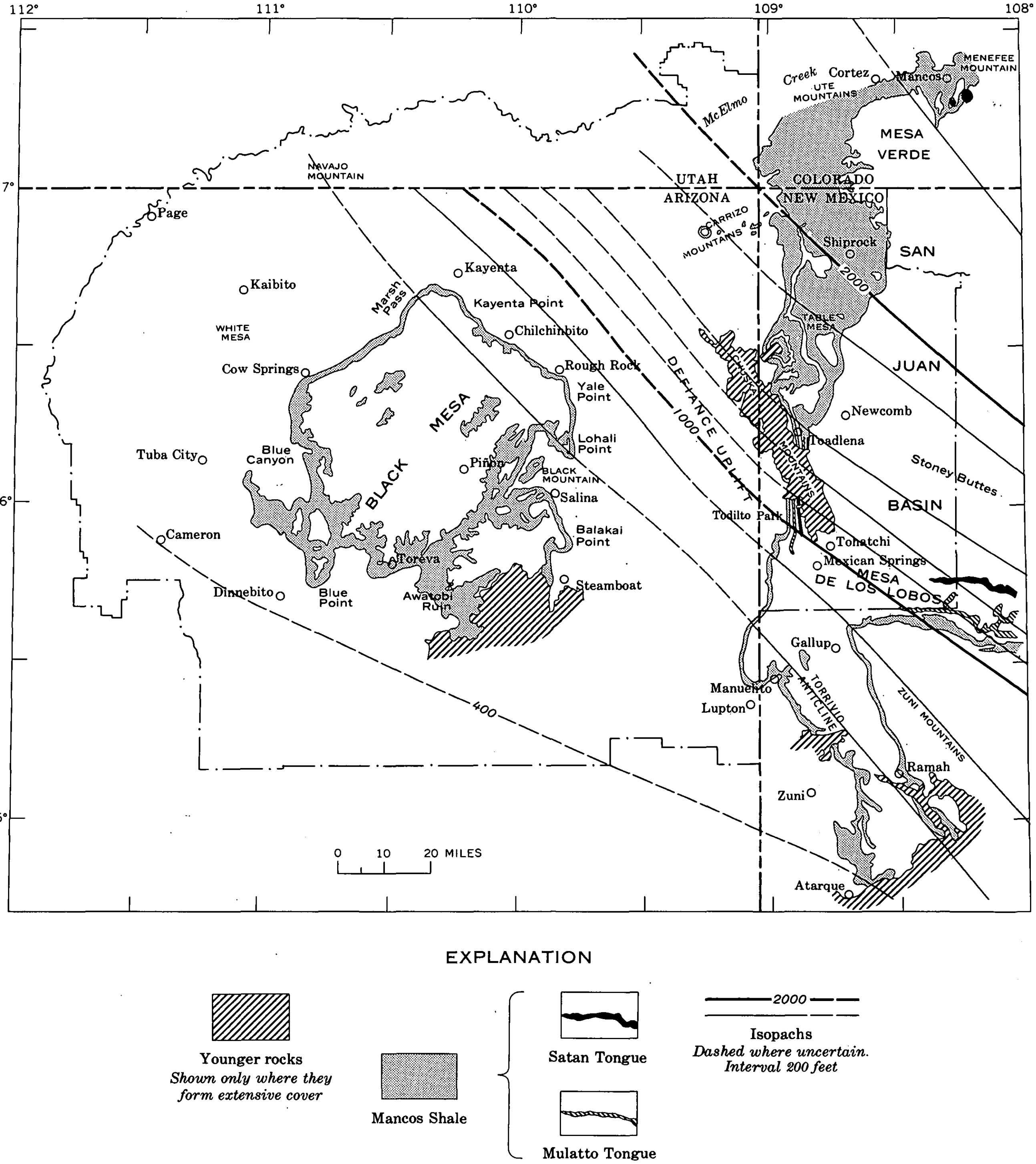


FIGURE 9.—Generalized distribution and thickness of Mancos Shale in the Navajo country.

the Front Range in southern Colorado, although the type Graneros is clearly older than the basal Mancos of the Four Corners area.

LIMESTONE UNIT

A very argillaceous greenish-black (5*GY* 2/1) limestone, weathering light bluish gray (5*B* 7/1) and interbedded with calcareous mudstone, is present in beds as much as 3 feet thick in the lower part of the Mancos Shale of northeastern Black Mesa and the area north of Toadlena. This unit is in gradational contact with the lower shale unit; the contact

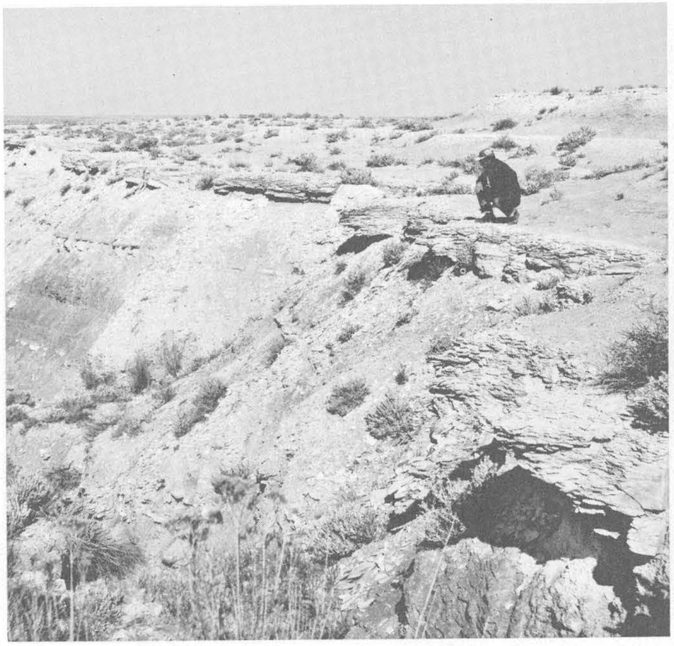


FIGURE 10.—Limestone unit of Greenhorn age near road between Shiprock and Bitlabito.

is everywhere selected arbitrarily within a sequence of shale and thin limestone beds that are increasingly calcareous upward. In general, the limestone unit is about 15 feet thick (fig. 10). It is not shown on the geologic map (pl. 1), but it has been mapped by Beaumont (1954, 1955) in the northwestern part of the San Juan Basin. It is recognizable only in the northeastern part of the Black Mesa area, from Lohali Point to Yale Point.

The limestone unit carries fossils belonging to the zone of *Inoceramus labiatus*, which is the highest faunal zone of the Greenhorn Limestone in the reference sequence of the Front Range. In most areas, fragments of the zonal index fossil are common. This unit has been referred to as the Greenhorn Limestone Member of the Mancos Shale by Dane (1948) in the northeastern part of the San Juan Basin.

MEDIAL SHALE UNIT

Gradationally overlying the limestone unit is the medial shale unit—a thick section of dark-gray fissile, slightly silty claystone that contains a few limestone concretions. Some bentonitic claystone beds are also present. The upper 50 feet of the medial shale unit is increasingly sandy, and the unit grades upward into the Juana Lopez Member where present in the San Juan Basin, and into the Toreva Formation of the Mesaverde Group in the Black Mesa area. The medial shale unit is about 520 feet thick near Shiprock and in the northeastern part of Black Mesa, and about 420 feet thick in the Toadlena area. To the south and southwest, the underlying limestone unit disappears, and the medial shale cannot be distinguished from the lower shale unit. In the Gallup area the Juana Lopez Member is not recognized, and the medial shale is therefore not distinguished from the overlying upper shale unit.

At most places the medial shale unit contains fossils belonging to the *Inoceramus labiatus* zone of the Greenhorn Limestone and the *Collignoniceras woollgari* and *C. hyatti* zones of the Carlile Shale. The last-named zone may be represented by the lower tongue of the Toreva Formation in the southwesternmost part of the Black Mesa area and by the lower tongue of the Gallup Sandstone in the area south of Gallup near Ramah.

The undifferentiated lower and medial shale units of the southwestern Black Mesa area contain about 50 feet of very thin bedded flaggy very fine grained sandstone and siltstone beds that form low cliffs 70–100 feet below the top of the Mancos Shale. (See fig. 18.) In most outcrops the sandstone contains impressions of juvenile *Collignoniceras woollgari*. A few recognizable fragments of adult ammonites are present, but the conditions of burial were such that the more fragile (or, perhaps, the more buoyant) adults were not preserved intact. In the northeastern part of the Black Mesa near Rough Rock, the rocks equivalent to this sandy interval consist of interbedded claystone and thin-bedded mudstone about 185 feet below the top of the Mancos. In the Shiprock area, flaggy sandstone beds are absent, and adult ammonites (*C. woollgari*), as well as juvenile ones, occur together in a shale sequence about 350 feet below the Juana Lopez Member of the Mancos Shale. Lithologically, the shale is indistinguishable from the rest of the medial shale unit.

The thin-bedded *Collignoniceras woollgari*-bearing sandstones in the Mancos Shale of the Black Mesa area are unique in the Navajo country. Although individual beds are almost everywhere less than 2 inches thick, each bed has a sharp basal contact and is gradational upward into the overlying shale. These sandstone beds were deposited on the surfaces of the underlying shale that were channeled, grooved, gouged, fluted, and scarred by drag marks from plants and other objects, such as tumbling ammonite shells. Although the grain size ranges only from that of very fine sand to silt, the beds are nonetheless graded through this size range. All evidence indicates that these beds were deposited from turbidity currents.

Current marks at the base of each turbid-water deposit indicate flow to the northeast and are re-

FIGURE 11.—Juana Lopez Member of the Mancos Shale along road between Shiprock and Bitlabito. Westward view, toward the Carrizo Mountains.

corded in rocks for a distance of about 50 miles across the Black Mesa area. The source of the dense and turbid water is unknown. However, the pattern of Cretaceous deposition in northeastern Arizona suggests the source may have been 50–100 miles to the southwest and that the dense turbid water flowed at least 100 miles from the source to area of dispersion. Furthermore, the gradient must have been very low, and the water shallow. These turbid-water deposits differ from most turbidity deposits that occur in very deep water and along, or at the foot of, a steep slope. Extensive shallow-water density flows, such as those recorded at Black Mesa, are either very rare or such flows have escaped much notice in the literature.

JUANA LOPEZ MEMBER

The Juana Lopez Member crops out about 500 feet above the top of the Dakota Sandstone. At most places the Juana Lopez is composed of shale containing many thin slabby arenaceous and silty limestone beds (fig. 11). The member is very fossiliferous (Pike, 1947, p. 22, 23; Reeside, 1924, loc. 10368 on pl. 3 and p. 12) and contains fauna belonging to the zones of *Prionocyclus macombi* and *P. wyomingensis*. These zones are common in the middle and upper parts of the Carlile Shale of the reference sequence for the Western Interior of the United States.

Rankin (1944, p. 12, 22) extended the name Juana Lopez Sandstone Member of the Carlile Shale into the San Juan Basin from its type locality in Mesita de Juana Lopez Grant, east of the Rio Grande, about 17 miles southwest of Santa Fe, N. Mex. In the Shiprock area, Rankin (1944, p. 22) applied the name Juana Lopez to 10 feet of thin-layered very calcareous sandstone or sandy limestone, interbedded with black shale 217 feet below the Gallup Sandstone. Pike (1947, p. 23) referred to this unit as the "late Carlile zone" of the Mancos and correlated it with the Ferron Sandstone Member of the Mancos Shale in eastern Utah.

The name Sanastee (or Sanostee) Sandstone Member has been applied to this same unit by several geologists (Di Giambattista, 1952, p. 6; Lilly, 1952, p. 101; Budd, 1957, p. 122; Reese, 1957, p. 38; and others). The first reference to the Sanastee Sandstone Member (spelled "Sanostee" on the U.S. Geol. Survey topographic map of the Sanostee quadrangle, 1953, 15-minute series; and fig. 1, no. 50, present report) appeared in a roadlog of the New Mexico Geological Society (1951, p. 46), which stated: "The unit has not been named except informally and W. B. Hoover of the Humble Oil and Refining Company suggests 'Sanastee sandstone member' because of the prominent development of this unit around Sanastee Trading Post."

Although the name has been used by geologists in the San Juan Basin since 1951, the type Sanastee has never been formally defined. Furthermore, the name was applied to a unit that already had been given a different name 7 years before. Therefore, in the present report the name Sanastee is rejected, and the name Juana Lopez is recognized in the western San Juan Basin of New Mexico.

The Juana Lopez Member has generally been called a sandstone, but from Toadlena northward along the west side of San Juan Basin, the member consists dominantly of shale and a few thin beds of limestone. Inasmuch as the member is not a sandstone, the lithologic designation is also dropped.

As shown in the following measured section, near Sanostee, the Juana Lopez Member is about 35 feet thick and consists of slope-forming shale beds ranging in thickness from 4 to 18 feet and intercalated ledge-forming limestone beds ranging in thickness from 3 inches to about 1 foot. The insoluble residues in the limestone range from 7½ to 44 percent, and average 26 percent. The insoluble residues consist of grains that range in size from medium sand to silt and clay, but that are primarily of the very fine sand size and smaller.

Section of the Juana Lopez Member and adjacent units

[Measured by R. B. O'Sullivan and E. C. Beaumont. Section is on the east side of the Beautiful Mountain anticline, about 200 ft south of the main road to the Sanostee Indian School, in the SE¼ sec. 3, T. 24 N., R. 19 W., San Juan County, N. Mex.]

	Feet
Gallup Sandstone:	
Sandstone, fine- to medium-grained; base transitional into underlying Mancos Shale	Not measured.
Mancos Shale, lower part:	
Upper shale unit:	
Shale, dark-gray (*N* 3), gypsiferous; contains numerous beds of calcareous sandstone 1–2 in. thick; in part arenaceous or silty; forms long gentle slope that steepens near top	240.0
Juana Lopez Member:	
Limestone, arenaceous or silty, pale-yellowish-brown (10*YR* 6/2); weathers dark yellowish orange (10*YR* 6/6); finely crystalline, fossiliferous, petroliferous; contains numerous bits of carbonaceous material; very thin bedded; forms slight ledge	0.5
Shale, dark-gray (*N* 5); forms gentle slope; contains a 1-in.-thick arenaceous limestone bed, 4.5 ft above base of unit, that forms a slight ledge	17.6
Limestone, very arenaceous, nearly yellowish-gray (5*Y* 7/2); weathers nearly pale yellowish orange (10*YR* 8/6); very finely crystalline, petroliferous, fossiliferous, carbonaceous; forms slight ledge	.7
Shale, dark-gray; forms slope	4.3
Limestone, arenaceous and silty, grayish-orange (10*YR* 7/4); weathers yellowish gray (5*Y* 7/2); finely crystalline, fossiliferous, petroliferous; contains worm trails	.9
Shale, dark-gray; forms slope	6.0
Limestone, very arenaceous and silty, pale-yellowish-brown (10*YR* 6/2); weathers grayish orange (10*YR* 7/4); finely crystalline; forms prominent ledge	.2
Shale, gray; forms steep slope	4.0
Limestone, very slightly arenaceous or silty, medium-gray (*N* 5); weathers pale brown (5*YR* 5/2) to grayish orange (10*YR* 7/4); fine to medium crystalline, gypsiferous, petroliferous, fossiliferous, very thin bedded; forms prominent ledge	1.1
Total Juana Lopez Member	35.3
Medial shale unit:	
Shale, medium-light-gray (*N* 6) to dark-gray (*N* 3); fissile clay shale with very small amounts of silty material; contains a few scattered beds of concretionary limestone	440.0
Limestone unit (of Greenhorn age):	
Limestone, argillaceous, light-gray (*N* 7) to dark-gray (*N* 3); forms ledge	Not measured.

The Juana Lopez Member of the Mancos is exposed in outcrops from Toadlena northward into Colorado (Pike, 1947, pl. 10 ["late Carlile zone"]; Beaumont, 1954 ["contact line a"], 1955 ["Juana Lopez sandstone member of Rankin"]). Bozanic (1955, p. 91–92) reported that it is exposed east of Gallup and near Cuba, N. Mex., on the east side of the San Juan Basin, and that it is also recognizable in the subsurface throughout most of the basin. Dane, Cobban, and Kauffman (1966) established a reference section and discussed regional relationship of the Juana Lopez in the San Juan Basin. However, within the Navajo country, the Juana Lopez was not recognized in any outcrops south of Toadlena by the present authors.

The Juana Lopez Member is the same age as the lower part of the Toreva Formation of Black Mesa. It is also equivalent to the lower part of the Gallup Sandstone in the area south of Gallup (Dane, Bachman, and Reeside, 1957, p. 112). The Juana Lopez appears to be an offshore deposit contemporaneous with, but genetically distinct from, these sandstones, which are marginal marine units of the Mesaverde Group.

UPPER SHALE UNIT

The Juana Lopez Member grades upward into the upper shale unit—the highest subdivision of the lower part of the Mancos Shale. This unit is very similar to, but somewhat sandier than, the medial shale unit and is 200–250 feet thick in the Shiprock area. South of Toadlena, the upper shale unit is indistinguishable from the underlying shale beds because the Juana Lopez Member is absent. In the upper shale unit are found in the Mesaverde Group.

Black Mesa area, beds the same age as those in the For the most part, the upper shale unit is barren of fossils. Cobban (in Dane, 1960a, p. 52) collected a species of *Inoceramus,* which he considered to be of latest Carlile age, from the top of this unit in the Shiprock area. The faunas of the overlying units of the Mesaverde Group and of the underlying Juana Lopez Member indicate that the upper shale unit of the Mancos probably contains beds equivalent in age to the middle to late Carlile faunal zones of *Prionocyclus wyomingensis, Scaphites nigricollensis,* and *S. corvensis.*

The boundary between the upper shale unit of the lower part of the Mancos Shale and the overlying Gallup Sandstone of the Mesaverde Group is within a gradational sequence that is as much as 50 feet thick. In mapping, the contact was selected at the break in slope beneath the cliffs, or ledges, formed by the basal Mesaverde sandstone.

TONGUES OF THE LOWER PART OF THE MANCOS SHALE

In the Gallup and Black Mesa areas, the contact relations of the lower part of the Mancos Shale with the basal sandstone of the Mesaverde Group is particularly complicated because of intertonguing between the two units. To the east and to the south of Gallup, three named tongues of the lower part of the Mancos interfinger with the lower part of the Mesaverde. These tongues are, in ascending order, the Horsehead and Pescado Tongues, which are locally as much as 50 feet thick and which were named by Pike (1947, p. 34–35), and the D–Cross Tongue, which is as much as 150 feet thick (Dane, Bachman, and Reeside, 1957, p. 108) and which was named by Dane, Wanek, and Reeside (1957, p. 187). The tongues consist of dark-gray sandy marine shale that is locally fossiliferous. The Horsehead Tongue is present southeast of Zuni. The Pescado Tongue occurs east of Zuni on both sides of the Gallup-Zuni basin (Dane, Bachman, and Reeside, 1957, fig. 3). The D–Cross Tongue is thickest along the south side of Mesa de los Lobos and grades into the Gallup Sandstone in the hogback east of Gallup.

The lower part of the Mancos Shale in the Gallup area is no younger than middle Carlile age (Dane, 1960a, p. 52); the youngest faunas collected represent the zone of *Prionocyclus wyomingensis*. In contrast, the lower part of the Mancos in the Shiprock area is as young as latest Carlile.

In the Black Mesa area, Repenning and Page (1956, p. 286–287) described extensive intertonguing between the Mancos Shale and the Toreva Formation, believed to be the result of a southeastward-projecting sand spit that extended across the northeast (or seaward) side of a large lagoon in the position of the modern structural Black Mesa basin. The spit and the lagoonal deposits it partly surrounds are approximately contemporaneous with the lower part of the Gallup Sandstone south of Gallup.

UPPER PART OF MANCOS SHALE

The upper part of the Mancos shale—above the Gallup Sandstone—is a sequence of gray and light-brownish-gray shale broken by several thin sandy zones and many limestone concretions. Near Shiprock, the upper part of the Mancos is 1,300–1,400 feet thick; however, it thins southward, and near Toadlena, it is about 1,000 feet thick.

North of the Chuska Mountains the upper part of the Mancos is overlain by the Point Lookout Sandstone of the Mesaverde Group. The contact between the Mancos and the Point Lookout is gradational, and the transitional zone ranges in thickness from a few feet to more than 50 feet. The top of the Mancos is placed at the base of the first prominent sandstone ledge, which consists in most localities of a sandstone bed 2–3 feet thick. In southern Colorado and adjacent parts of New Mexico, Zapp (1949), Wanek (1954), and Hayes and Zapp (1955) included the transitional shale and sandstone interval with the Point Lookout because in southern Colorado, such as on Mesa Verde, near Mancos, and in the Durango area, the upper part of the Mancos is generally clearly exposed in steep cliffs and hills. In the area south of the San Juan River, however, the shale and soft sandstone beds of the transitional interval are, for the most part, covered in low slopes below cuestas that are held up by the Point Lookout, and the contact commonly is placed arbitrarily near the top of the transitional interval.

From Toadlena southward, the entire upper part of the Mancos Shale intertongues with, and is replaced by, rocks assigned to the Mesaverde Group (Allen and Balk, 1954). For information in this area we have drawn freely from the report of Allen and Balk, as well as from that of Pike (1947). The Mancos is completely replaced within a distance of about 25 miles in the area between Toadlena and Todilto Park, and is replaced within a distance of about 70 miles in the Mesa de los Lobos area. The distances differ because the outcrops along the west side of the basin are nearly normal to the ancient shoreline.

In the southern part of the San Juan Basin, south of the area between Mesa de los Lobos and Toadlena, the Mancos Shale was recognized by earlier investigators (Schrader, 1906; Shaler, 1907; Gardner, 1909); however, the intertonguing between the

Mesaverde Group and the Mancos Shale was not studied in detail until the series of investigations initiated by Sears in 1919 from the Gallup area eastward to Mount Taylor (Sears, 1925, 1934; Hunt, 1936; Dane, 1936; Sears and others, 1941). In summarizing the stratigraphic results of these studies, Sears, Hunt, and Hendricks (1941) showed that the strandlines of the Cretaceous sea were nearly straight and parallel, and they predicted a similar stratigraphic succession and similar intertonguing west of the Gallup-Zuni basin. Pike (1947), in the course of his detailed investigation of the Mesaverde rocks between Atarque, N. Mex., and Mesa Verde, Colo., confirmed this conclusion, and the zone of intertonguing is now known to extend to the Black Mesa area with only minor differences, due to irregularities of the shorelines.

Near Toadlena the upper part of the Mancos is split by a tongue of Mesaverde rocks that extends northward for a distance of about 5 miles from beneath the cover of Tertiary rocks forming the Chuska Mountains (Zieglar, 1955). This sandstone bed is the northernmost extension of the Hosta Tongue of the Point Lookout Sandstone, possibly combined with the Dalton Sandstone Member of the Crevasse Canyon Formation of the Mesaverde Group. The part of the Mancos below the Hosta and Dalton unit and above the Gallup Sandstone is the Mulatto Tongue of the Mancos Shale, as described by Hunt (1936, p. 44) in the southern San Juan Basin. The part of the Mancos above the Hosta and Dalton and below the Point Lookout Sandstone is the Satan Tongue of the Mancos Shale, as described by Sears (1934, p. 14). The area near Toadlena is the only place in the Navajo country where the Satan and Mulatto Tongues of the Mancos can be traced northward into the upper part of the Mancos Shale.

MULATTO TONGUE

The Mulatto Tongue, as originally described by Hunt (1936, p. 44) for exposures at the south end of Canyon Mulatto, in the area near Mount Taylor, lies between the Dilco Coal Member and Dalton Sandstone Member of the Crevasse Canyon Formation. The Mulatto Tongue consists principally of dark-gray sandy marine shale and numerous thin beds of fine-grained calcareous sandstone. The unit becomes increasingly sandy southward toward its pinchout.

The Mulatto Tongue was traced westward in the Mesa de los Lobos area by Sears (1934, pl. 1) to a vanishing point in the northwestern part of T. 16 N., R. 16 W. In this township, the Mulatto splits into two parts. The upper tongue, about 45 feet thick, lies between the main body of the Dalton and the lower tongue of the Dalton. The lower tongue of the Mulatto Tongue, about 20 feet thick, pinches out between the lower tongue of the Dalton and the Dilco Coal Member. Both tongues of the Mulatto wedge out at approximately the same lateral position in this area. The maximum thickness of the Mulatto Tongue in the Mesa de los Lobos area is about 220 feet (Sears and others, 1941, pl. 26).

The Mulatto Tongue was studied by Pike (1947) and Allen and Balk (1954) along the west side of the San Juan Basin in the Tohatchi area. Allen and Balk (1954, p. 90) stated that the Mulatto Tongue was not recognized in the Tohatchi quadrangle, but in a section measured near Todilto Park, Pike (1947, p. 30) assigned 144 feet of nonresistant, mostly covered material to the Mulatto Tongue. D. L. Zieglar (written commun., 1953), assigned more than 200 feet of sandy shale to the Mulatto at about this same locality. Part of this interval might be the Dilco Coal Member of the Crevasse Canyon Formation, but the presence of the Mulatto at this locality seems more probable. The exposures are poor, and the rocks assigned by Pike and Zieglar to the Mulatto Tongue are very sandy as compared with the main body of the Mancos. A soft shaly interval persists from Todilto Park southward to a point about 6 miles north of the south boundary of the Navajo Indian Reservation in New Mexico. This interval is assigned to the Mulatto Tongue in the present report. According to D. L. Zieglar (written commun., 1953), the Mulatto Tongue has a maximum thickness of 525 feet near Toadlena.

SATAN TONGUE

The Satan Tongue is the uppermost named unit of the Mancos Shale. Named by Sears (1934), it was first described for exposures in Satan Pass (Sears, 1934, p. 14), near Crownpoint. Where present, the Satan Tongue lies between the Point Lookout Sandstone and the Hosta Tongue of the Point Lookout (fig. 24). The Satan Tongue, like the Mulatto Tongue, is considerably sandier than the main body of the Mancos Shale. It, too, intertongues southwestward with units of the Mesaverde Group, but it does not extend as far southwestward as does the Mulatto. The Satan Tongue has a maximum thickness of 330 feet near Toadlena and thins to about 70 feet at Todilto Park (D. L. Zieglar, written commun., 1953). Allen and Balk (1954, p. 94) assigned as much as 120 feet of sandy shale to the Satan Tongue; however, they did not delineate the Satan on their map nor in their stratigraphic sections (Allen and Balk, 1954, pls. 1, 11). Hence, considerable doubt remains as to both the vertical and the lateral limits of the Satan Tongue in the Tohatchi quadrangle. In the Mesa de los Lobos area, the Satan Tongue has a maximum thickness of about 120 feet.

AGE ASSIGNMENT AND CORRELATION

The entire upper part of the Mancos Shale is nowhere older than the Niobrara Formation, although its uppermost beds vary in age. The upper beds are oldest in the southwestern part of the region, and youngest in the northeastern part. The Mancos Shale in the type locality was reported (Cross and others, 1899, p. 5) to be of Colorado age (Niobrara age and older) in the lower part, and reported to be of Montana age (Telegraph Creek age of the standard reference sequence) in the "upper few hundred feet." Pike (1947, p. 23) indicated that the boundary between rocks of Niobrara and Telegraph Creek ages is 400 feet below the Point Lookout Sandstone at Point Lookout, in Mesa Verde, Colo. Reeside (1924, pl. 3) placed this boundary between 435 and 500 feet below the Point Lookout along the San Juan River. Pike (1947, p. 24) found no further evidence south of the San Juan River for establishing the Niobrara-Telegraph Creek age boundary, but Hunt (1936, p. 45) indicated that on the south side of the San Juan Basin, near Mount Taylor, the boundary may be no lower than in the upper part of the Satan Tongue. In the Mesa de los Lobos area, the Hosta Tongue of the Point Lookout Sandstone contains a marine fauna belonging to the zone of *Clioscaphites vermiformis* (Sabins and Bonham, 1960) and is correlative to the upper part of the Niobrara Formation of the reference sequence for the Western Interior of the United States. The overlying Satan Tongue in this area is therefore considered to be at least of late Niobrara age and may be partly equivalent in age to the Telegraph Creek Formation.

In the Black Mesa area, the upper part of the Mancos is represented only by a shale unit within the Toreva Formation that crops out along the northeastern face of the mesa between Yale Point and Kayenta Point. The stratigraphic position and the fauna of this shale indicate a correlation with the Mulatto Tongue of the upper part of the Mancos (Repenning and Page, 1956, p. 282); however, the shale unit is mapped and discussed with the Toreva Formation because its distribution is limited. The Satan Tongue has not been recognized in the Black Mesa area; however, the Yale Point Sandstone may contain its temporal equivalents.

MESAVERDE GROUP

Outcrops of the Mesaverde Group in the Navajo country provide one of the world's finest displays of intertonguing continental, marginal marine, and marine deposits. In general, the group forms a broad wedge that tapers to the northeast between the younger, Lewis Shale and the older, Mancos Shale.

The Mesaverde Group has the maximum known range in age in the southern part of the San Juan Basin. The oldest rocks in the group crop out 30 miles south of Gallup, and the youngest, near Tohatchi. The range in age is from the age of the Blue Hill Shale Member of the Carlile Shale to the Fox Hills Sandstone—a time span which represents about half of the Late Cretaceous. Only a small part of this time span is represented by deposits of the group at the type locality on Mesa Verde in southwestern Colorado.

Because of the great regional variation in age and nomenclature, the Mesaverde Group is divided, in the present report, into lower and upper parts. The lower sequence of Mesaverde rocks, exposed mainly in the southern part of the San Juan Basin and in the Black Mesa area, are discussed first. The stratigraphic and intertonguing relations of the formations are shown graphically on plate 2 and in figure 8.

Perennial supplies of ground water are withdrawn from the sandstone beds of the Mesaverde Group. The principal aquifers are the Toreva Formation, the Gallup Sandstone, the Point Lookout Sandstone, the sandstone beds in the Menefee Formation, and the Cliff House Sandstone. These units furnish water for stock and for a large number of trading posts and schools throughout the Navajo and Hopi Indian Reservations. Because of small yields, wells in many areas tap ground water from several units. Some of these wells are as much as 1,500 feet deep. Lateral wedging of the sandy units of the Mesaverde Group controls the occurrence, amount, and, to some extent, the chemical quality of the ground water.

Throughout its area of distribution in the San Juan Basin, the Gallup Sandstone is a water-bearing unit. Although yields are not high, a dependable supply of ground water for both domestic and stock purposes is obtained from wells penetrating this formation. Because the Gallup Sandstone thins laterally and increases its content of argillaceous material northward, it becomes progressively less important as an aquifer in the Ship Rock area.

Most wells in the Gallup-Tohatchi area of the San Juan Basin withdraw water from the Crevasse Canyon Formation, as well as from the underlying Gallup Sandstone and the overlying Point Lookout Sandstone. The only extensive water-producing unit in the formation is the Dalton Sandstone Member. Generally, however, the Dalton yields less than 5 gallons per minute, and in many places the Dalton does not produce usable quantities of water because of a high silt content. Because the sandstone units of the Crevasse Canyon Formation are lenticular, both the depth to water-bearing strata and the amount of water available to wells are difficult to predict.

In the Navajo Indian Reservation, the Point Lookout Sandstone is not utilized extensively for water supplies because it generally lies at great depth and is overlain by other aquifers. Most wells that tap the Point Lookout are east of Tohatchi and north of Mesa de los Lobos, and many of these wells also withdraw water from the Menefee or the Crevasse Canyon Formation. In most places, the water in these formations is under artesian head. Locally, some of the wells tapping these formations flow at the land surface.

The Menefee Formation yields variable amounts of water to a large number of wells ranging in depth from about 200 to 1,000 feet. Logs of the wells show that sandstone beds are randomly distributed throughout the formation. The aquifers have a wide range in permeability; some silty zones are apparently fairly permeable. Chemical quality of the water is generally uniform, which suggests that the Menefee Formation is flushed by migrating ground water, and that the formation acts as a hydrologic unit. However, because of the high sulfate content of the ground water, its chemical quality is not considered to be very good.

The Mesaverde Group in the Black Mesa area yields water primarily from the Toreva Formation and secondarily from the Wepo Formation, but no water is obtained from the Yale Point Sandstone. The Toreva Formation contains sandstone units that transmit water easily so that springs are present in the formation along many of the mesa and canyon rims. In the central part of Black Mesa, the ground water is under artesian heads. Although the Toreva is the principal aquifer in the central and southern parts of Black Mesa, its yields are low. Some of the sandstone units of the Wepo Formation discharge ground water as springs and to a few wells in the central part of Black Mesa. The Yale Point Sandstone apparently is very permeable; nonetheless, it is not used for water supply because of the limited areal distribution and the topographic position of its remnants prevent the unit from accumulating, or retaining, much water.

LOWER PART OF THE MESAVERDE GROUP IN THE SAN JUAN BASIN

In the area south and southeast of the Chuska Mountains, along the northern flank of the Zuni Mountains, the lower part of the Mesaverde Group is temporally equivalent to much of the upper part of the Mancos Shale of the San Juan River area. In the northern and northeastern parts of this area, the lower part of the Mesaverde Group consists of intertongued marine and nonmarine rocks, but to the south and southwest it is almost wholly nonmarine.

The lower part of the Mesaverde Group is made up of the Gallup Sandstone, which extends northward almost to the San Juan River, and the overlying Crevasse Canyon Formation, which is present only south of the latitude of the Chuska Mountains.

GALLUP SANDSTONE

The name Gallup Sandstone was applied by Sears (1925, p. 17) to a sequence of rocks at the base of the Mesaverde Group in the southern San Juan Basin. Although the Gallup was described by Sears (1934), Hunt (1936), and Pike (1947), the most detailed descriptions of its lithology, facies, and regional correlation in recent years are by Beaumont (1957), Budd (1957), and Dane, Bachman, and Reeside (1957).

The Gallup Sandstone crops out in a nearly continuous band along the west margin of the San Juan Basin from the Zuni area northward to the San Juan River, a distance of about 150 miles. The formation is completely obscured for 11½ miles by the Tertiary rocks that form the Chuska Mountains, and precise correlation of the units on the north and south sides of the mountains is uncertain. Dane (1960a) suggested that one or more units may be included in the assemblage of rocks that were mapped during the present investigation as Gallup Sandstone in the area north of the Chuska Mountains. Hence, this break in the outcrop belt affords a convenient place to divide the following discussion of the Gallup Sandstone into two parts. The Gallup exposed south of the mountains is discussed first.

GALLUP SANDSTONE SOUTH OF THE CHUSKA MOUNTAINS

South of the Chuska Mountains, the Gallup is exposed in a narrow sinuous belt along the west side of the Gallup-Zuni basin and from there southward into the Zuni Mountains area, where it forms extensive outcrops south of Ramah (fig. 13). The outcrop in the first 10 miles south of the Chuska Mountains in the timbered area near Todilto Park is poorly exposed. A somewhat greater area of outcrop is present east of the steeply dipping monoclinal fold in the vicinity of Mexican Springs and also on either side of the Puerco River near the Arizona–New Mexico State line. The Gallup is also displayed in the Torrivio anticline near Mentmore, and in the town of

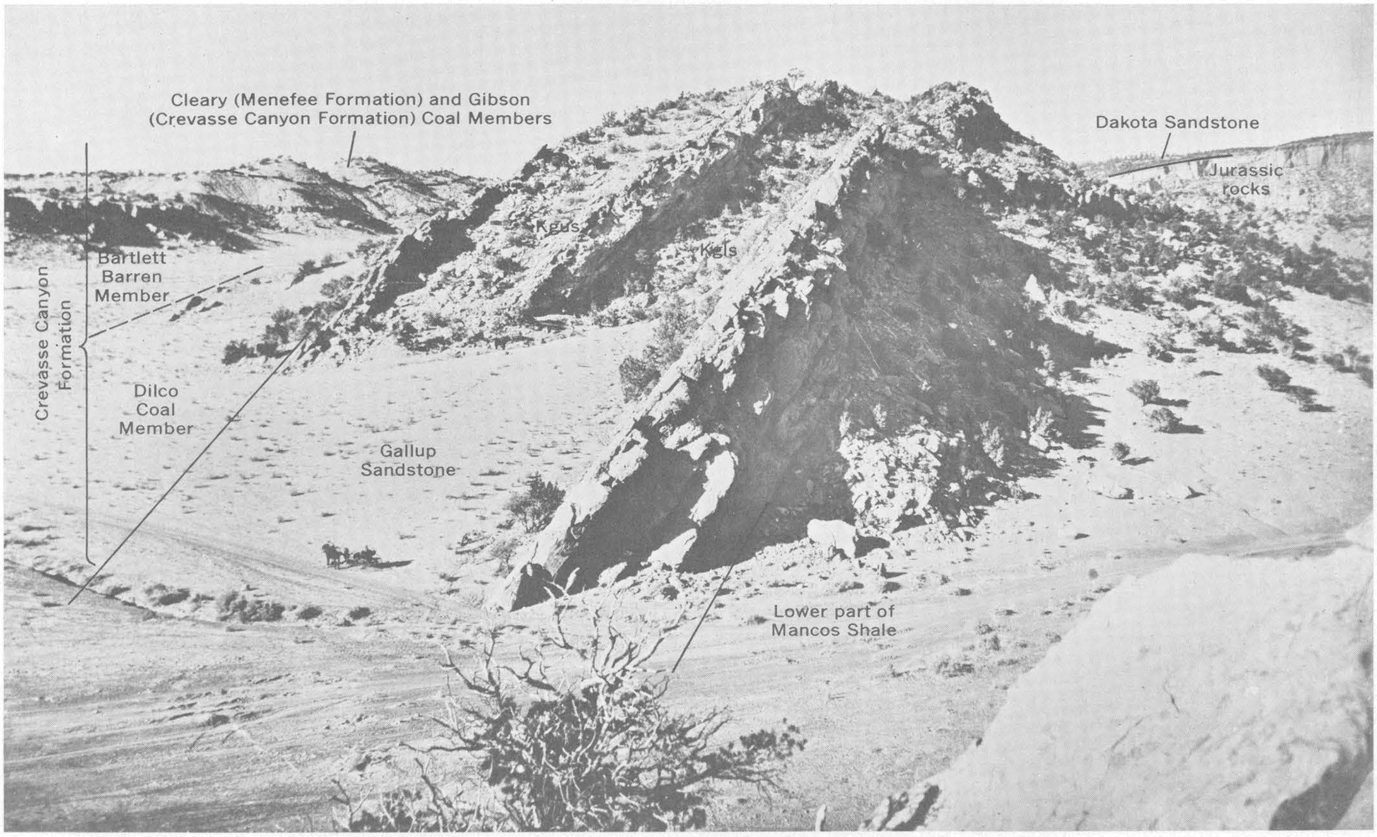


FIGURE 12.—Gallup Sandstone at The Hogback 2½ miles northeast of Gallup. Northward view, along Nutria monocline about 1½ miles north of Puerco Gap. Note three prominent sandstone beds (ridges). Eastward, lower shale (Kgls) grades into D–Cross Tongue of Mancos Shale. Upper shale (Kgus) contains Myers (Richards) coal beds. Photograph by N. H. Darton, 1901.

Gallup on the Gallup anticline. The Gallup crops out as a narrow band along the Nutria monocline, on the west side of the Zuni Mountains, from Ramah northward to Gallup and then eastward along the south face of Mesa de los Lobos, where the beds dip gently northward, and the Gallup Sandstone forms a series of ledges and benches.

The Gallup Sandstone is underlain by the Mancos Shale, with which it intertongues on a large scale. In detail, however, the contact of the two is gradational. The upper contact with the Dilco Coal Member—lowest part of the overlying Crevasse Canyon Formation—is also gradational. This upper contact is somewhat arbitrarily chosen in most areas, and in the Todilto Park area, the Gallup intertongues with the Dilco Coal Member. Both the Gallup and Dilco contain economically valuable coal beds, and the most reliable criterion for identifying the contact between these two units south of the Chuska Mountains is the prevalence of coarse-grained to granular sandstone in the upper beds of the Gallup.

The composition of the Gallup Sandstone is dominantly sandstone interbedded with some shale, carbonaceous shale, and conglomerate. The beds are pale red (10*R* 6/2) with rusty stains to light gray (*N* 7); they are well cemented, blocky weathering, and thin to very thick bedded. Most are trough crossbedded, with medium-scale medium- to low-angle crossbeds. The sandstone beds in most places form prominent cliffs or ledges that are separated by mostly thinner siltstone, shale, and friable silty sandstone beds.

A striking and characteristic lithologic feature of the Gallup Sandstone is coarse-grained sandstone that is present in all sections examined. Almost everywhere the coarse-grained material is merely a component of a poorly sorted, very fine or fine-grained to very coarse grained sandstone. This coarse-grained material is more abundant in the upper part of the formation, where it occurs typically as pods and stringers oriented along planes of cross-lamination. The largest grains are principally subangular and angular quartz of a distinct smoky type. Feldspar, both weathered and fresh, was observed as coarse grains and granules at most localities south of the Chuska Mountains. Although the abundance of fresh feldspar grains varies considerably, it was estimated to be as much as 20 percent locally. The coarser grained sandstone appears to be relatively free of dark minerals.

The Gallup Sandstone is well exposed in the area of the Puerco Gap, east of Gallup, through which pass the railroad and U.S. Highway 66. Dane, Bachman, and Reeside (1957) described the Gallup Sandstone in this area as consisting of three conspicuous sandstone ledges separated by two soft zones of shale and siltstone (fig. 12). A lower pink or buff fine- to medium-grained sandstone is 50–70 feet thick. The overlying nonresistant unit is gray or tan siltstone, shale, and friable sandstone about 40–50 feet thick. The middle sandstone is gray and white, fine to medium grained, and about 30 feet thick. Overlying the middle sandstone is a nonresistant unit of shale and carbonaceous shale about 25 feet thick that contains one or more coal beds, including the Myers (Richards) coal beds that have been mined in the Gallup area. The uppermost sandstone is pink, coarse grained, arkosic, and 30–60 feet thick.

Changes in the Gallup Sandstone north of Puerco Gap and east of the gap along the south face of Mesa de los Lobos were described by Dane, Bachman, and Reeside (1957). In general, the upper coarse-grained sandstone grades laterally into shale about 5 miles north of Puerco Gap on the south face of Mesa de los Lobos. Less than 2 miles farther east, a fine- to medium-grained sandstone replaces the stratigraphic interval that at Puerco Gap includes the upper coarse-grained sandstone and the underlying shale unit that contains the Myers (Richards) coal beds (fig. 3; Dane, Bachman, and Reeside, 1957, p. 102–103). This fine- to medium-grained sandstone is as much as 150 feet thick and forms the main ledge of the Gallup Sandstone far to the east almost to Mount Taylor. The shale unit lying between the lower and middle sandstones at Puerco Gap is partly marine and grades eastward into the D–Cross Tongue of the Mancos Shale. The lower and middle sandstone units pinch out eastward into the D–Cross Tongue and are represented along the south face of Mesa de los Lobos by apparently disconnected sandstone lentils.

The sequence of beds seen at Puerco Gap is maintained from the gap southward along the Nutria monocline and westward to the Zuni area (Dane, Bachman, and Reeside, 1957, p. 108). The uppermost pink coarse sandstone conspicuously marks the top of the Gallup Sandstone over large areas of the Gallup-Zuni basin.

In the Rio Pescado area, about 10 miles east of Zuni, a 50-foot-thick bed of marine shale, named the Pescado Tongue of the Mancos Shale (Pike, 1947, p. 9), separates the Gallup Sandstone from an underlying sandstone unit, about 220–280 feet thick, which Pike named the lower part of the Gallup Sandstone. The lower part consists dominantly of sandstone and of lesser amounts of interbedded shale and siltstone, and it tongues northward into the Mancos Shale. The upper part of the Gallup Sandstone of the Rio Pescado area represents the entire formation as exposed at Puerco Gap, and it is similar in lithology and in sequence of beds. The Pescado Tongue is believed to be equivalent to the youngest beds of the Mancos Shale underlying the Gallup Sandstone at Puerco Gap (Dane, Bachman, and Reeside, 1957, p. 108).

The base of the Mesaverde Group is progressively older from the Rio Pescado southward. Pike (1947, p. 11) described the "Atarque member of the Mesaverde formation" 6–12 miles south of the Rio Pescado, separated from the lower part of the Gallup Sandstone by the Horsehead Tongue of the Mancos, and O'Brien (in Young, 1957, p. 1167) called a still lower sandstone unit east of St. Johns, Ariz., the lower part of the Mesaverde. The sandstone unit described by O'Brien lies 100 feet above the base of the Mancos Shale and is 90 feet thick. According to Young (1957, p. 1167), the unit contains a Greenhorn fauna, and, therefore, it is the oldest rock yet assigned to the Mesaverde Group.

West of Puerco Gap, the Gallup Sandstone dips below the surface to the west, but the upper, pink coarse-grained sandstone reappears in a small area in the town of Gallup. About 7 miles farther west, on the Torrivio anticline near Mentmore, the entire Gallup Sandstone is again exposed. Here, the basal unit is a cliff-forming light-brown-weathering very fine to medium-grained sandstone that is distinct and continuous, and is equivalent to the basal sandstone of the Gallup at Puerco Gap. The middle part of the Gallup Sandstone consists of fine-grained to very coarse grained and granular sandstone in beds, as much as 25 feet thick, that are separated by intervals of softer carbonaceous shale, claystone, and coal. An interval of carbonaceous shale at the top of the middle part of the Gallup contains the Myers (Richards) coal beds. The uppermost part of the Gallup Sandstone on the Torrivio anticline consists, in ascending order, of a 30-foot-thick coarse-grained sandstone, a 10- to 12-foot-thick coaly shale and coal sequence, and a 7-foot-thick bed of very coarse grained sandstone. This three-part unit is equivalent to the upper, pink coarse-grained sandstone at Gallup and at Puerco Gap.

The basal sandstone at the Torrivio anticline is correlated with the basal sandstone of the Gallup between Manuelito and Window Rock. At Todilto

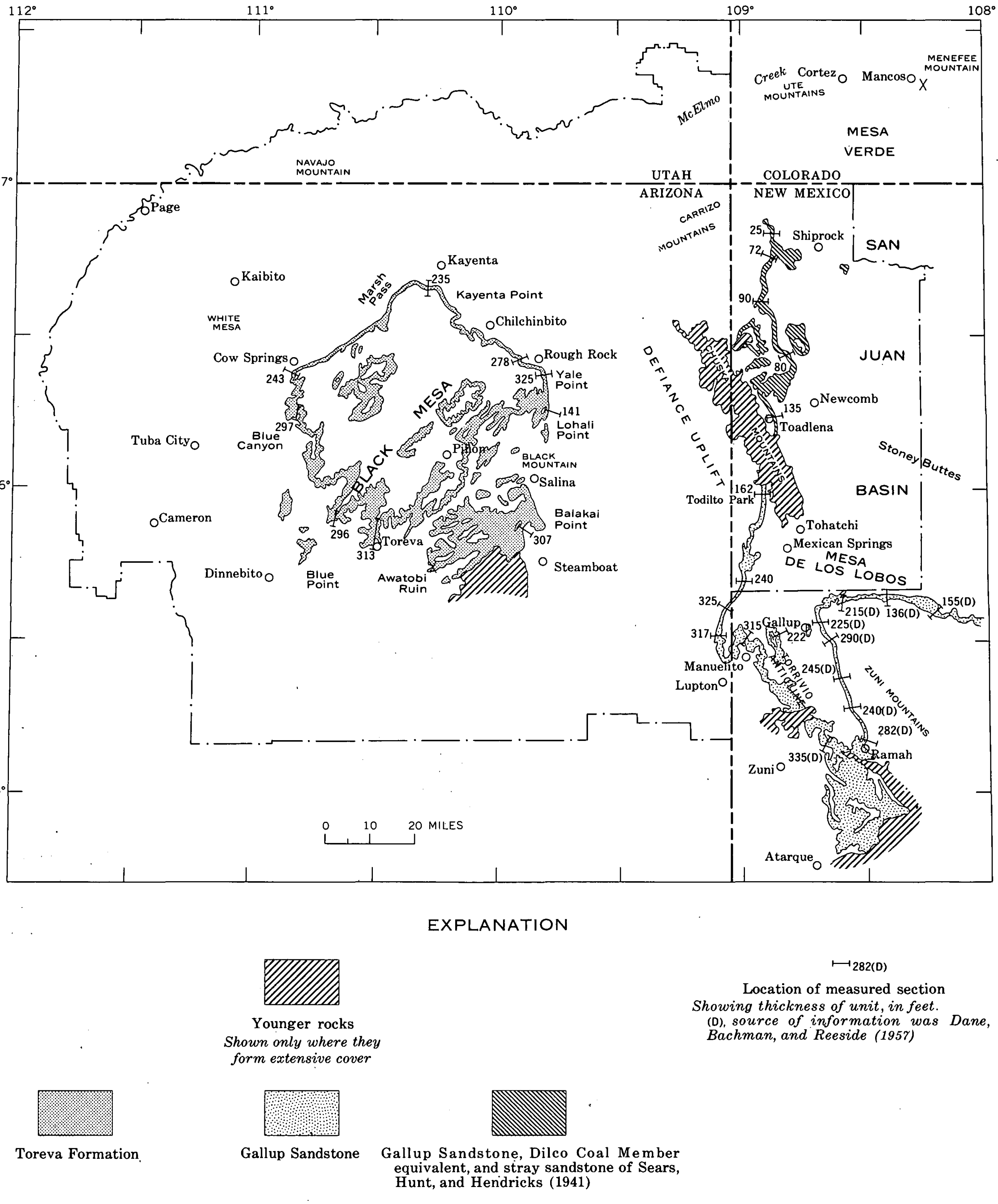


FIGURE 13.—Generalized distribution and thickness of the Toreva Formation and the Gallup Sandstone and related units in the Navajo country.

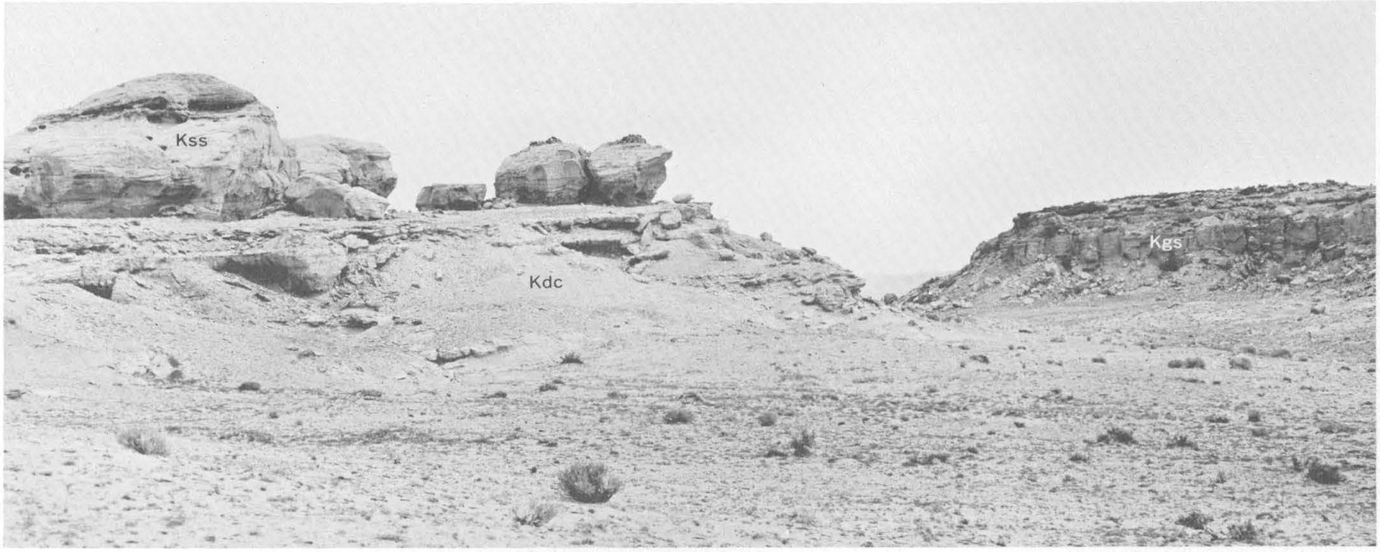


FIGURE 14.—Gallup Sandstone along road to Sanostee. Southward view, on eastern flank of the Beautiful Mountain anticline. Gallup Sandstone (Kgs), Dilco Coal Member equivalent (Kdc), and stray sandstone (Kss) of Sears, Hunt, and Hendricks (1941).

Park the basal sandstone merges with a higher sandstone, and the two units form a continuous 100-foot-thick sequence. Sandstone and shale overlying the basal sandstone are in a variable sequence from Todilto Park northward to a point near the Chuska Mountains. The upper sandstone at the Torrivio anticline above the Myers (Richards) coal beds thins northward because of intertonguing with the overlying Dilco Coal Member of the Crevasse Canyon Formation, but the addition of thinner sandstone beds to the base of this unit results in a 50-foot-thick sequence of slabby sandstone in the top of the Gallup at Todilto Park. The upper and lower sandstones are separated by only 10 feet of coaly and carbonaceous shale at Todilto Park.

South of the Chuska Mountains, the Gallup Sandstone ranges in thickness (fig. 13) from 160 to 450 feet (Sears, 1925; Dane, Bachman, and Reeside, 1957; Pike, 1947). At Puerco Gap (east of Gallup) the formation is about 220 feet thick, and at the Torrivio anticline it is 225 feet thick. Along Mesa de los Lobos the main, upper ledge of the Gallup is about 120 feet thick, and the lower part of the formation, below the D–Cross Tongue of the Mancos Shale, is as much as 80 feet thick. Near Zuni the Gallup Sandstone is about 335 feet thick.

GALLUP SANDSTONE, DILCO COAL MEMBER EQUIVALENT, AND STRAY SANDSTONE OF SEARS, HUNT, AND HENDRICKS (1941)

About 800 feet above the Dakota Sandstone, in the area north of Toadlena, there is a sequence of fine- to coarse-grained sandstone and some interbedded shale, siltstone, and carbonaceous shale. These rocks form conspicuous cliffs and hogbacks along the western flank of the San Juan Basin and are also exposed on the Tocito and Rattlesnake anticlines.

The sequence is well exposed in the dissected area on the Beautiful Mountain anticline near Sanostee. There, it has a well-defined threefold division (fig. 14): a lower massive fine-grained sandstone, about 22 feet thick; an upper slabby coarse-grained sandstone, about 45 feet thick; and a distinctly less resistant middle unit that contains coal and carbonaceous shale.

Reeside (1924, p. 9) first applied the name Tocito Sandstone Lentil of the Mancos Shale to this entire sequence. He noted that this name was in common use by the petroleum geologists familiar with the area, but that it was also informally known to some as the "Frontier sandstone." Later, Pike (1947, p. 28, pl. 11) referred the lower unit to the Gallup Sandstone, the middle carbonaceous shale to the Dilco Coal Member, and the upper unit to the stray sandstone of Sears, Hunt, and Hendricks (1941). Still later, the Gallup Sandstone was extended into the Shiprock area to include the three units (Harshbarger and Repenning, 1954; Beaumont, 1955; Beaumont and O'Sullivan, 1955; Zieglar, 1955) and the name Tocito Sandstone Lentil was abandoned (Beaumont and others, 1956). Subsequent study in the area tended to confirm Pike's interpretation and the names used by Pike are used in this report, with one minor revision: inasmuch as the middle unit contains no economically important coal beds, the term Dilco Coal Member equivalent is used.

The Gallup Sandstone, as mapped (pl. 1) in the area north of the Chuska Mountains, includes not only Gallup, but also the Dilco Coal Member equivalent and the stray sandstone of Sears, Hunt, and Hendricks. The Gallup Sandstone and Dilco Coal Member equivalent terminate south of the San Juan River, but the stray sandstone of Sears, Hunt, and Hendricks can be traced across the San Juan River (Dane 1960a, p. 53) and into Colorado, where it rests on beds of the Mancos Shale that are considerably older than those of the Gallup Sandstone. Where the Gallup Sandstone is absent, the stray sandstone of Sears, Hunt, and Hendricks is included with the Mancos Shale.

The Gallup Sandstone in the Ship Rock area is a light-brown fine- to medium-grained crossbedded sandstone. Both the lower contact with the Mancos Shale and the upper contact with the Dilco Coal Member equivalent are transitional. A single massive sandstone bed constitutes almost the entire formation and forms prominent steep cliffs in the Sanostee–Ship Rock area. The Gallup Sandstone is 41 feet thick at Toadlena and 55 feet thick near the road between Shiprock and Redrock. The Gallup Sandstone thins northward, but can be traced through the Rattlesnake oil field to a point about 1½ miles south of the San Juan River, where the sandstone becomes too shaly and silty to trace separately.

The Dilco Coal Member equivalent overlies the Gallup Sandstone and, in the vicinity of Beautiful Mountain, consists predominantly of grayish-brown carbonaceous shale containing some thin lenses of coal. In the Toadlena–Ship Rock area the unit is 15 to 25 feet thick. Northward, it grades into marine shale.

Sears, Hunt, and Hendricks (1941, p. 113) applied the field designation stray sandstone to a conspicuous bed of sandstone that crops out in the southern part of the San Juan Basin in the Crownpoint-Grants area. The stray sandstone attains a maximum thickness of 75 feet in this area (Sears and others, 1941, p. 113) and lies between the Dilco Coal Member of the Crevasse Canyon Formation and the Mulatto Tongue of the Mancos Shale. The uppermost part of the stray sandstone in the Crownpoint-Grants area contains a striking zone of pebbles and cobbles as much as 3 inches across. The pebbles are composed principally of quartzite and are generally well rounded.

In the Shiprock area, the bed considered to be the stray sandstone of Sears, Hunt, and Hendricks (1941) unconformably overlies the Dilco Coal Member equivalent and is transitional into the overlying Mancos Shale. The lower contact is a channeled surface of erosion. The stray sandstone is crossbedded and is noticeably coarser grained than the other sandstone units of the Mesaverde. Most of the grains are granule size, but many are pebbles as much as 1 inch cross. The pebbles are composed principally of mafic igneous rocks that seem to be of extrusive igneous origin and are characteristically subangular and somewhat altered on the surface. Dane (1960a, p. 53) also reported that the stray sandstone in this area is markedly glauconitic. The stray sandstone, 10–40 feet thick, is present over large areas north of the Chuska Mountains (Dane, 1960b) and can be traced northward—beyond the pinchout of the Gallup Sandstone and Dilco Coal Member equivalent—into Colorado.

Northward from the pinchout of the Gallup Sandstone and the Dilco Coal Member equivalent, increasingly older parts of the underlying Mancos Shale are present immediately below the stray sandstone of Sears, Hunt, and Hendricks (1941). Dane (1960a, p. 53) postulated an unconformity in this area. In the Shiprock area, the interval that includes the upper shale unit of the lower part of the Mancos, lying between the Juana Lopez and stray sandstone of Sears, Hunt, and Hendricks, is about 250 feet thick. At a point 3 miles south of the Colorado State line, shale in this same interval is 60 feet thick, and near Towaoc, Colo., about 14 miles north of the Colorado State line, the shale is absent, and the stray sandstone rests directly on the Juana Lopez Member of the Mancos Shale (Dane, 1960a, p. 53; Penttila, 1964).

Age Assignment and Correlation

The lower part of the Gallup Sandstone, below the Pescado Tongue of the Mancos Shale in the Zuni Mountains area and in areas to the east, contains fauna of the *Collignoniceras hyatti* zone of the lower part of the Carlile Shale (Dane, Wanek, and Reeside, 1957, p. 192–195; Dane, Bachman, and Reeside, 1957, p. 109–113) and may also include equivalents of the zones of *Prionocyclus macombi* and *P. wyomingensis*, which are faunas present in intertonguing marine shale south of Grants, N. Mex., as shown by Dane, Wanek, and Reeside (1957, fig. 2, section 6). The two younger faunal zones—equal in age to the middle of the Carlile Shale—are also represented locally in the overlying Pescado Tongue of the Mancos (Dane, Bachman, and Reeside, 1957, p. 109). The lower part of the Gallup Sandstone, therefore, appears to be approximately equal in age to much of the Toreva Formation of Black Mesa. It is also the temporal equivalent of the Juana Lopez Member of the Mancos and some of the underlying shale in the Shiprock area.

The Pescado Tongue of the Mancos Shale, separating the lower and upper parts of the Gallup Sandstone, appears to be of mid-Carlile age, as stated above. Although faunal evidence is inconclusive, the Pescado Tongue probably correlates with a marine and lagoonal medial carbonaceous member of the Toreva Formation in the southern part of Black Mesa. The Pescado Tongue may represent the same transgressive episodes as that represented by the D-Cross Tongue of the Mancos in the Puertocito area. However, if this is so, the sea transgressed southeastward, for Dane, Wanek, and Reeside (1957, fig. 2) indicated that the D-Cross Tongue contains a fauna correlative to the youngest zone of the Carlile Shale—that shown in figure 7 as the zone of "*Scaphites* species." This zone is equivalent to the zones of *Scaphites nigricollensis* and *S. corvensis* of Cobban and Reeside (1952). The deposition of the D-Cross Tongue of the Mancos was thus contemporaneous with the deposition of parts of the upper part of the Gallup Sandstone of the Gallup area (Dane, Bachman, and Reeside, 1957, p. 112) and with some of the unfossiliferous upper part of the Toreva Formation in the southern Black Mesa area. In addition to being latest Carlile in age, the upper part of the Gallup Sandstone may be, in part, earliest Niobrara in age—the age of the upper part of the Toreva Formation in northeastern Black Mesa. The marine shale tongue of the Toreva Formation in northeastern Black Mesa (of early Niobrara age) appears to be genetically correlative to the "Dilco-to-Mulatto transgressive stage" of Sears, Hunt, and Hendricks (1941, p. 116, 117).

In the area of the San Juan River, the Dilco Coal Member equivalent and the stray sandstone of Sears, Hunt, and Hendricks (1941) contain faunas assignable to the zone of *Inoceramus deformis*, an early faunal zone in the Niobrara Formation of the Western Interior reference sequence. This age assignment is in some doubt, however, for the fauna of the threefold sequence of rocks in the Shiprock area is largely unstudied. Reeside (1924, pl. 3) showed *Inoceramus umbonatous* Meek and Hayden from the top of the stray sandstone west of The Hogback near the San Juan River (loc. 12002). This fossil occurs in the middle Niobrara zone of *Scaphites ventricosus*. In the same report, however, Reeside also reported finding *Inoceramus deformis* Meek 50 feet above the stray sandstone in the same area (loc. 12003). Fossils have been identified by W. A. Cobban (in Dane, 1960a, p. 52–53) from the Gallup Sandstone and related rocks in the Shiprock area. The list of forms includes *Ostrea sannionis* White from the Dilco Coal Member equivalent south of the road to Bitlabito and *Inoceramus deformis* from a unit presumably correlative to the stray sandstone west of Towaoc, Colo. However, Dane (1960a) also reported *Inoceramus platinus* (*Inoceramus grandis* of previous authors) in the shale immediately overlying the stray sandstone in the Shiprock area and, also, reported *Inoceramus involutus* (equals *I. umbonatus*) to be near the top of the stray sandstone in the same area. These fossils occur in the middle Niobrara *Scaphites ventricosus* zone and in younger faunas. Thus, it appears from the fossil data that the stray sandstone of Sears, Hunt, and Hendricks is correlative to the basal part of the Niobrara Formation, and, further, that its uppermost part near the San Juan River probably approximates the boundary between the faunal zone of *Inoceramus deformis* and the middle Niobrara zone of *Scaphites ventricosus*.

CREVASSE CANYON FORMATION

Sears (1925, p. 17, 18) divided the Cretaceous rocks overlying the Mancos Shale in the Gallup area into five members and assigned them all to the Mesaverde Formation. In ascending order, these members were the Gallup Sandstone Member, Dilco Coal Member, Bartlett Barren Member, Gibson Coal Member, and Allison Barren Member. Later, Sears (1934, p. 18) found that, in the Mesa de los Lobos area, the Point Lookout Sandstone (Hosta Sandstone Member) appeared in the midst of the Gibson Coal Member, thus dividing it into upper and lower parts. In the same report, Sears also recognized the Dalton Sandstone Member as the unit that laterally replaced the upper part of the Dilco in a northward direction.

Subsequently, the Mesaverde Formation in southern San Juan Basin was raised to group status by Allen and Balk (1954, p. 90). The Gallup Sandstone was also elevated to formational status at that time, and a new formation, the Crevasse Canyon, was introduced.

The Crevasse Canyon Formation was defined by Allen and Balk (1954, p. 91, 92) to include "the sedimentary units which lie between the top of the Gallup sandstone and the base of the Point Lookout sandstone," and the type locality, west of Mexican Springs, was given as "the area of excellent exposures which lie on a north fork of Catron Creek about 3 miles southwest of the mouth of Crevasse Canyon." The Crevasse Canyon Formation, in the Tohatchi area, ranges in thickness from 420 to about 700 feet, and Allen and Balk (1954, p. 92) recognized the presence of three members in ascending order: "the Dilco, the Dalton sandstone tongue, and the lower Gibson." The writers of the present report, in addition, recognize the Bartlett Barren Member above the Dilco Coal Member (and prefer to retain the term "coal," as used in the original definition).

The name Gibson Coal Member is now restricted (Beaumont and others, 1956, p. 2157) to the lower part of the Gibson Coal Member of Sears (1934, p. 18) and Allen and Balk (1954, p. 93). The upper part of the Gibson Coal Member of Sears (1934, p. 18), which overlies the Point Lookout Sandstone, was recently renamed the Cleary Coal Member and assigned to the Menefee Formation (Beaumont and others, 1956, p. 2157). The Point Lookout, where present, forms a sharp, easily recognizable upper limit to the Crevasse Canyon Formation, but the Point Lookout is absent in the Gallup area south of the latitude of Mexican Springs. Where the Point Lookout is absent, the Cleary Coal Member of the Menefee rests on the Gibson Coal Member, and the upper boundary of the Crevasse Canyon Formation falls within an undivided coal-bearing unit (the Cleary and Gibson Coal Members undivided) that is treated with the Crevasse Canyon Formation in this report.

The uppermost member of the Mesaverde in the Gallup area, called the Allison Barren Member (Sears, 1925, p. 18), is now considered to be a member of the Menefee Formation, and the descriptive term "barren" has been dropped (Beaumont and others, 1956, p. 2157).

The Crevasse Canyon Formation is not recognized north of the Chuska Mountains (fig. 15). In the Todilto Park area—west of the southern part of the Chuska Mountains—the Crevasse Canyon forms a relatively narrow band of poorly exposed outcrops along the east side of the Defiance uplift. In the Mesa de los Lobos area the dip is low, and the formation presents a series of gentle to steep slopes interspersed with steep cliffs. In the Gallup area the Crevasse Canyon Formation is exposed as a drab sequence of lenticular sandstone and shale. The area is hilly and is marked by narrow ridges, high buttes, and numerous sandstone cliffs and ledges.

General Description and Field Relations

The nonmarine part of the Crevasse Canyon Formation consists of a highly variable sequence of interbedded sandstone, siltstone, and mudstone. Thick sandstone ledges disappear abruptly to be replaced by mudstone or siltstone units which, in turn, thicken and thin rapidly. The coal-bearing members and the barren member of the Crevasse Canyon do not differ markedly in lithology, except for the presence or absence of commercially valuable coal.

Sandstone beds are light gray (*N* 7) and light olive gray (5*Y* 6/1), and are very fine to fine grained. Locally, very coarse grained sandstones are present. The grains are mostly poorly to fairly well sorted, and consist dominantly of clear and stained subround to subangular quartz. At places, mica and dark accessory minerals are common. The sandstone beds are generally calcareous and silty, and they range in thickness from 5 to 25 feet, although most are about 10 feet thick.

The siltstone interbeds are light olive gray (5*Y* 6/1), light brownish gray (5*YR* 6/1), or light gray (*N* 7). The beds range in thickness from 5 to 90 feet, but most are 10–15 feet thick. Mudstone beds are very light gray (*N* 8) to medium dark gray (*N* 4), olive gray (5*Y* 4/1), or light brownish gray (5*YR* 6/1). These beds range in thickness from 5 to 50 feet, although most are 5–20 feet thick.

Lenticular coal beds as much as 10 feet thick occur in the Crevasse Canyon Formation. Although coal beds are present throughout the formation, the thicker beds (those more than 14 in.) are found in the Dilco Coal Member and in the Cleary and Gibson Coal Members undivided. Based on the figures of Sears (1925, p. 44) and the figures cited by Read, Duffner, Wood, and Zapp (1950, p. 22), the total amount of coal produced in the Gallup area—primarily from the Crevasse Canyon and the Gallup Sandstone—for the years 1882–1948 is about 30 million tons, or roughly one-fourth of the total coal output of the State of New Mexico for those years.

In the Gallup area the Dilco is separated from the Cleary and Gibson Coal Members undivided by the Bartlett Barren Member (fig. 8), which has much the same composition as the overlying and underlying coal members, with the exception that the Bartlett contains less carbonaceous shale, more sandstone, and only thin, uneconomic coal beds. The upper and lower limits of the Bartlett vary from place to place, owing to the local occurrences of the thicker coal lenses (more than 14 in.) in the overlying and underlying members. Near Dalton Pass and Crevasse Canyon, rocks equivalent to the Bartlett Barren Member become coaly and grade laterally into the Gibson Coal Member. Future detailed coal investigations in the Tohatchi area may somewhat alter the interpreted distribution of the Bartlett in this area.

In the Gallup area the Dilco Coal Member is 240–300 feet thick, the Bartlett Barren Member is 330–440 feet thick, and the Cleary and Gibson Coal Members undivided is 150–175 feet thick (Sears, 1925, p. 17). Along Mesa de los Lobos the Dilco Coal Member is about 200 feet thick, and the Gibson Coal Member is 180–280 feet thick. In the Tohatchi

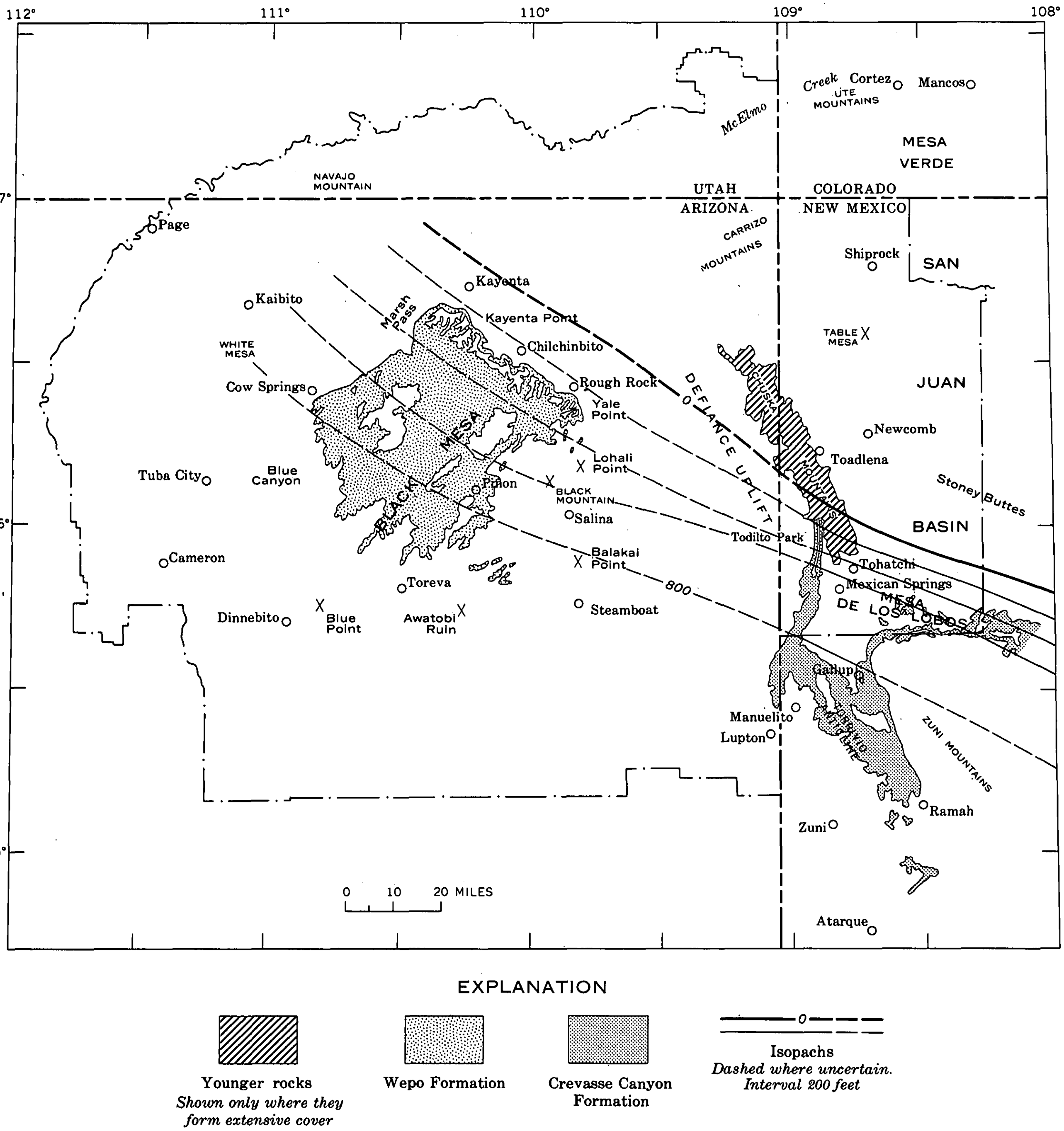


FIGURE 15.—Generalized distribution and thickness of the Crevasse Canyon and Wepo Formations in the Navajo country.

area the Dilco is 40–100 feet thick (Pike, 1947, pl. 11), and the Gibson is 135–550 feet thick (Allen and Balk, 1954, p. 93).

The Dalton Sandstone Member (Sears, 1934, p. 17) of the Crevasse Canyon Formation is not recognized near the town of Gallup. Beginning at a point about 4½ miles northeast of Gallup, a thin persistent sandstone bed in the upper part of the Dilco Coal Member thickens eastward to about 180 feet, in sec. 13, T. 16 N., R. 18 W., by replacing the upper part of the Dilco. This sandstone, named the Dalton Sandstone Member (Sears, 1934, p. 17) for exposures at Dalton Pass, forms a conspicuous cliff (fig. 16) and bench in the Mesa de los Lobos area. Northwest of Gallup the Dalton is thick enough to recognize separately, about 3 miles north of the south boundary

FIGURE 16.—Dalton Sandstone Member and related rocks. Westward view, on the south side of Mesa de los Lobos, about 14 miles northeast of Gallup. Units overlying the Gallup Sandstone (Kg) include Dilco Coal Member (Kdc) and Dalton Sandstone Member (Kda) of the Crevasse Canyon Formation and Mulatto Tongue (Kmm) of the Mancos Shale.

of the Navajo Indian Reservation, and from there northward to the Chuska Mountains, where it is concealed by the overlying Tertiary rocks.

Sandstone in the Dalton Sandstone Member (fig. 16) is grayish orange (10*YR* 7/4) and grayish yellow (5*Y* 8/4) and is fine to medium grained. The upper part of the Dalton is massive, whereas the lower part is thin bedded and contains some intercalated sandy shale. Also, the sandstone at some places in the uppermost part of the Dalton is crossbedded. The Dalton in most of the area is 100–125 feet thick.

For a distance of 4½ miles along the outcrop in the Tohatchi area and a distance of 7½ miles in the Mesa de los Lobos area, the Dalton Sandstone Member is divided into two distinct cliff-forming sandstones by the Mulatto Tongue of the Mancos Shale (fig. 8), which is as much as 80 feet thick. The lower sandstone is similar to the upper sandstone, but of limited distribution. It ranges in thickness from 0 to about 80 feet. In the Mesa de los Lobos area the lower sandstone intertongues with the lower part of the Mulatto Tongue, but in the Tohatchi area the lower sandstone is underlain (fig. 8) by the Dilco Coal Member. The main part of the Dalton Sandstone Member, above the Mulatto, is overlain by either the Gibson Coal Member or the Bartlett Barren Member.

Beyond the study area east of Gallup, the Dalton Sandstone Member thins, rises stratigraphically at the expense of the overlying nonmarine strata, and joins the Hosta Tongue of the Point Lookout Sandstone in the eastern part of McKinley County (Sears and others, 1941, p. 115, pl. 26). North of the Chuska Mountains, near Toadlena, a sandstone lying between the Satan and Mulatto Tongues of the Mancos Shale is thought to be the coalesced Hosta Tongue of the Point Lookout Sandstone and the Dalton Sandstone Member of the Crevasse Canyon Formation. However, the stratigraphic relations are concealed by the Tertiary rocks that form the Chuska Mountains; hence, this sandstone is shown only as Hosta Tongue on plate 1.

AGE ASSIGNMENT AND CORRELATION

Fossils have not been collected from the nonmarine beds of the Crevasse Canyon Formation, but the stratigraphic relations indicate that the formation is all older than the type Mesaverde. The underlying Gallup Sandstone in the southern part of the San Juan Basin is considered to be of latest Carlile age. The marine units of the upper part of the Mancos Shale, which intertongue with the Crevasse Canyon, span most of Niobrara time. The Gibson Coal Member and Cleary and Gibson Coal Members undivided are stratigraphically equivalent to much of the Satan Tongue of the Mancos Shale, which is of middle to late Niobrara age.

LOWER PART OF THE MESAVERDE GROUP IN THE BLACK MESA AREA

The Mesaverde Group of Black Mesa, in large part, is equivalent in age to the Gallup Sandstone and

Crevasse Canyon Formation, and all of it is older than any part of the Mesaverde at the type locality in southwestern Colorado. Repenning and Page (1956) subdivided the Mesaverde Group in the Black Mesa area into three formations—the Toreva Formation, at the base; the Wepo Formation; and the Yale Point Sandstone, which is the youngest Cretaceous unit in the area. Subdivision into homotaxial units is possible in the Toreva Formation in the northern part of the area and also in the Wepo Formation in most of the area. Such additional subdivisions may be desirable at a later date, particularly in the central part of Black Mesa, where their recognition would aid materially in structural mapping and in coal and ground-water studies. At present, subdivision of the Yale Point Sandstone appears to be impractical.

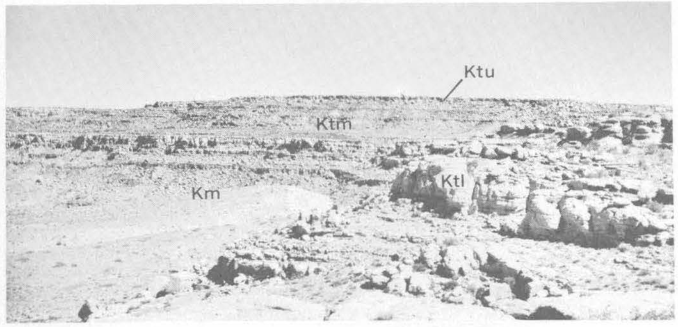


FIGURE 17.—Toreva Formation at the south end of Third Mesa. Westward view, about 3 miles northwest of Oraibi along old road between Hotevilla and Oraibi. Uppermost Mancos Shale (Km) is overlain by Toreva Formation, including lower sandstone member (Ktl), middle carbonaceous member (Ktm), and upper sandstone member (Ktu). Toreva Formation here is 296 feet thick.

TOREVA FORMATION

The Toreva Formation of the Mesaverde Group is named after a small settlement in the Hopi Indian Reservation, Navajo County, Ariz. (Repenning and Page, 1956, p. 271). The Toreva was traced around the entire margin of Black Mesa and is present either in the subsurface or on the surface of an area of about 3,600 square miles (fig. 13).

In approximately the south half of Black Mesa, the Toreva Formation consists of three distinct members; in the north half of the mesa, three other subdivisions are recognized. Both the upper and the lower contacts of the formation are gradational.

GENERAL DESCRIPTION AND FIELD RELATIONS

In about the south half of Black Mesa, the Toreva Formation consists of three members—a basal cliff-forming sandstone member, as much as 130 feet thick; a middle slope-forming carbonaceous member, as much as 106 feet thick; and an upper cliff-forming sandstone member, 20–80 feet thick (fig. 17).

Throughout the southern part of Black Mesa, the lower sandstone member of the Toreva Formation (fig. 17) is a light-brown (5*YR* 5/6) to pale-yellowish-gray (5*Y* 8/1) fine- to medium-grained quartz sandstone containing accessory mica. The lower part of the member, which is transitional into the Mancos Shale, contains several thin beds of mudstone and some sandstone that is finer grained than the sandstone in the upper part of the member. Sandstone in the lower part contains medium- and large-scale planar crossbeds, inclined at low to very low angles. The upper part of the lower sandstone member contains no mudstone, is fine to medium grained, and is crossbedded on a medium scale in irregular to lenticular sets, in which the beds are inclined at high angles. The lower sandstone member of the Toreva forms a single, almost vertical blocky cliff.

The lower sandstone member is absent locally (pl. 2) in a small area in the southeastern part of Black Mesa, where the middle carbonaceous member rests on the Mancos Shale.

The middle, carbonaceous member of the Toreva is in gradational contact with the lower sandstone member in the southern part of Black Mesa. In general, the middle member consists of alternating thin-bedded carbonaceous mudstone, varicolored siltstone, some coal, and thick lenses of yellowish-gray (5*Y* 8/1) fine- to coarse-grained, poorly sorted quartz sandstone that is trough crossbedded at a medium angle and of medium scale. Mica is common in its sandstone and siltstone beds. At some places, as in Keams Canyon, the member consists almost entirely of sandstone, except for shale and coal in the lower part only. In other places, the member is mostly shale, siltstone, or mudstone—especially in the southeastern part of the area, where the member locally overlies the Mancos Shale. The middle member pinches out northward in Black Mesa along a line roughly connecting Black Mountain on the east with Cow Springs on the west.

The upper sandstone member is a yellowish-gray (5*Y* 8/1) to grayish-orange-pink (5*YR* 7/2) sandstone composed of fine-grained to very coarse grained subrounded to subangular poorly sorted quartz sand. Mica is present as an accessory mineral, as in other parts of the Toreva Formation, but the upper member contains also a large amount of altered feldspar, especially near the top. The upper part of the upper sandstone member is conglomeratic in the southern part of Black Mesa, where it contains pebbles and cobbles as much as 3 inches across com-

FIGURE 18.—Lower tongue of the Toreva Formation near Blue Point. Northward view, toward Padilla Mesa. Mancos Shale (Km) and tongue of Mancos Shale (Kmt); *Collignoniceras woollgari*-bearing sandstone beds (Kmc), Toreva Formation proper (Kt) and lower tongue (Ktlt). Tongue of Mancos Shale is 23 feet thick at locality marked X.

posed of silicified limestone in which Paleozoic fossils are common.

Bedding in the upper sandstone member consists of irregular and lenticular sets of trough-type crossbeds that are from 6 inches to 4 feet thick, inclined at medium to low angles, and of a medium scale. Within and between the sets of crossbeds (particuarly toward the top of the member) are mudstone pellets and lenses as much as 3 feet thick. A few units within the upper member are slumped and folded at some localities.

Although thicknesses of the separate members of the Toreva Formation vary considerably (pl. 2) from locality to locality in the southern part of Black Mesa, the overall thickness of the formation is approximately constant (fig. 13). It is 313 feet at the type locality, 307 feet at Balakai Point, and 297 feet at Blue Canyon.

In the southwestern part of Black Mesa, a lower sandstone tongue of the Toreva Formation is present. The tongue is 13 feet thick and consists of very fine to fine-grained sandstone. At Blue Point the tongue is only 75 feet above the *Collignoniceras woollgari*-bearing beds of the Mancos Shale, where it is separated from the Toreva proper by a tongue of the Mancos as much as 23 feet thick. (See figs. 7, 18.) A fauna belonging to the zone of *Collignoniceras hyatti* is present at the top of the lower tongue of the Toreva.

In approximately the north half of Black Mesa, the Toreva Formation consists of three subdivisions (fig. 19) that are different from the members recognized in the south half of the mesa. These are a widespread basal sandstone unit, as much as 275 feet thick, referred to for convenience herein as the main ledge of the Toreva; an overlying locally present marine shale tongue, as much as 90 feet thick; and a locally present upper cliff-forming sandstone, as much as 80 feet thick. The main ledge is, for the most part, correlative with all three members of the Toreva in the southern part of Black Mesa; the marine shale tongue and the upper cliff-forming sandstone are stratigraphically higher than most of the Toreva that extends to the southwest toward the type locality.

The main ledge of the Toreva Formation, which is recognized above the Mancos Shale throughout the northern part of Black Mesa, consists mostly of fine- to medium-grained sandstone. In addition, the upper part contains abundant lenses of coarse-grained to very coarse grained sandstone locally containing fragments of granite. A small amount of coal, carbonaceous shale, and siltstone occurs in thin beds, particularly in the area between Marsh Pass and Yale Point.

The main ledge of the Toreva Formation differs considerably in thickness: it is 120 feet thick at Kayenta Point, 141 feet thick at Lohali Point, 142 feet thick north of Pinon, 167 feet thick at Yale Point, 243 feet thick near Cow Springs, and 275 feet thick at Marsh Pass.

The marine tongue that overlies the main ledge of the Toreva is confined to an area extending a few miles southwest of the northeast face of Black Mesa, roughly between Kayenta Point and Yale

FIGURE 19.—Toreva Formation and related rocks at Yale Point. Northward view shows the Toreva Formation, here 325 feet thick, including the main ledge (Ktml), a slope-forming marine shale tongue (Ktms), and an upper cliff-forming sandstone (Ktus). The Toreva Formation is underlain by the Mancos Shale (Km) and is overlain by the Wepo Formation (Kw) and the Yale Point Sandstone (Ky).

Point (pl. 2). The marine shale tongue consists primarily of a slope-forming medium-gray (*N* 6) siltstone containing a few ledges of sandstone and a few of light-gray (*N* 7), firmly cemented siltstone.

A cliff-forming sandstone overlies the marine shale tongue and constitutes the stratigraphically highest part of the Toreva in the northeastern part of Black Mesa. The upper cliff-forming sandstone is yellowish gray (5*Y* 8/1) and is composed of very coarse to medium-grained, poorly sorted sandstone. It contains altered feldspar, as an accessory mineral, but no mica was noted. The bedding is flat and very irregular; individual beds are 2–4 feet thick and are crossbedded. Crossbedding is of the trough type, and the crossbeds are inclined at a low angle and are of small scale.

Near the pinchout of the marine shale tongue, the base of the upper cliff-forming sandstone coalesces with the underlying main ledge of the Toreva. The combined sandstone unit is split by a nonmarine shale tongue of the Wepo Formation that stratigraphically is slightly lower than the marine tongue just described. This nonmarine tongue thickens southwestward and joins the main body of the Wepo Formation; the overlying sandstone of the Toreva Formation thins and wedges out in the same direction (pl. 2). The sandstone above the Wepo Tongue is recognized over a wide area in the northeastern part of Black Mesa. It consists, in part, of a conspicuously crossbedded conglomeratic sandstone in which the crossbeds are of trough type and of both medium angle and medium scale. Fragmental remains of marine vertebrates were found in it, but no invertebrates were noted.

Age Assignment and Correlation

Fossils are rare in the Toreva Formation of the Mesaverde Group in the northern part of Black Mesa. In the lower part of the formation, no fossils of significance in age assignment were collected, with the exception of *Inoceramus dimidius*, found at the base of the formation near Marsh Pass. In the upper part of the formation, the marine shale tongue contains an early Niobrara fauna that belongs to the zone of *Inoceramus deformis* (Reeside and Baker, 1929, p. 34). On the basis of these two occurrences, the writers conclude that the Toreva Formation in the northern part of Black Mesa, near Kayenta, includes rocks as old as the zone of *Prionocyclus macombi* of the upper part of the Carlile Shale, and as young as the zone of *Inoceramus deformis* at the base of the Niobrara Formation of the Front Range.

The type locality of the Toreva Formation in the southern part of Black Mesa is entirely of Carlile age; *Collignoniceras woollgari* was found 20 feet below the base of the Toreva, 14 miles southeast of the type locality, at Awatobi Ruin. A collection from the top of the lower tongue of the Toreva on Blue Point (shipment F–54–33, loc. 25239) was identified by J. B. Reeside, Jr., and included *Pugnellus fusiformis* (Meek). This fauna was considered by Reeside to be "at about the level of the Blue Hill" Shale Member of the Carlile Shale in the faunal zone of *Collignoniceras hyatti*. Thus, it appears that rocks younger than the lower part of the Carlile Shale are absent in the Mancos Shale in this southwesternmost part of the Black Mesa area. Because of these relationships, the writers believe that the Toreva Formation, at its type locality, is equivalent in age to all but the basal part of the Carlile Shale, and that it does not contain any beds as young as the Niobrara Formation.

Other fossils, not diagnostic of age, include sharks' teeth and bones, and scales and teeth of other fish found at many localities and at most horizons throughout the Black Mesa area. Several types of mollusks were collected at different localities, but were not identified. Plant remains, identified by R. W. Brown, found in the upper part of the Toreva 5 miles northwest of Lohali Point, include *Brachyphylum macrocarpum* Newberry, *Gleichenites repenningi* Brown, *Nelumbium* sp., *Cinnamomum* sp., and unidentified ferns, dicotyledonous leaves, a flower cluster, and an insect (Brown, 1956; Repenning and Page, 1956, p. 277).

The main part of the Toreva Formation is considered to be correlative to the Juana Lopez Member of the Mancos Shale in the Shiprock area, to the lower part of the Gallup Sandstone in the area south of Gallup, to the Ferron Sandstone Member of the Mancos Shale in east-central Utah, and to an unknown amount of the basal part of the Funk Valley Formation in central Utah. The main ledge of the Toreva Formation is equivalent to the Tibbet Canyon and Smoky Hollow Members of the Straight Cliffs Formation in the Kaiparowits Plateau of southern Utah—the marine shale tongue and the upper cliff-forming sandstone of the Toreva correlate, respectively, with the lower marine mudstone tongue and the A sandstone of the John Henry Member of the Straight Cliffs Formation (Fred Peterson, oral commun., 1970). (See Peterson, 1969, fig. 5.) In the northern part of Black Mesa, the upper part of the Toreva appears to be generally correlative to the Gallup Sandstone of the Shiprock area, and to the Dilco Coal Member of the Crevasse Canyon Formation, the Mulatto Tongue of the Mancos, and the Dalton Sandstone Member of the Crevasse Canyon Formation in the Gallup area.

WEPO FORMATION

The name Wepo Formation was applied by Repenning and Page (1956, p. 277) to a sequence of continental shale and sandstone interbedded with some marine sandstone exposed 8 miles northeast of the town of Pinon on the west side of Wepo Wash. At this locality, 142 feet of the cliff-forming Toreva Formation is overlain gradationally by 656 feet of the slope- and ledge-forming Wepo Formation, including the upper tongue of the Toreva which occupies the interval that lies between 67 and 134 feet above the base of the Wepo. In the type locality the Wepo Formation is capped by 50 feet of sandstone that may be correlative to the Yale Point Sandstone of the Mesaverde Group.

General Description and Field Relations

The Wepo Formation comprises a thick series of intercalated siltstone, mudstone, sandstone, and coal. The siltstone and mudstone units range in color from dark olive gray (5*Y* 3/2), through light olive brown (5*Y* 5/6), to medium light gray (*N* 6). In many places the units are carbonaceous, and throughout the area they contain sandy zones and sandstone lenses. At most localities the bedding in the siltstone and mudstone units is flat and is laminated to very thin. Locally, the units contain very low angle trough crossbedding. In most places the bedding is masked by the shaly weathering of these units (fig. 20).

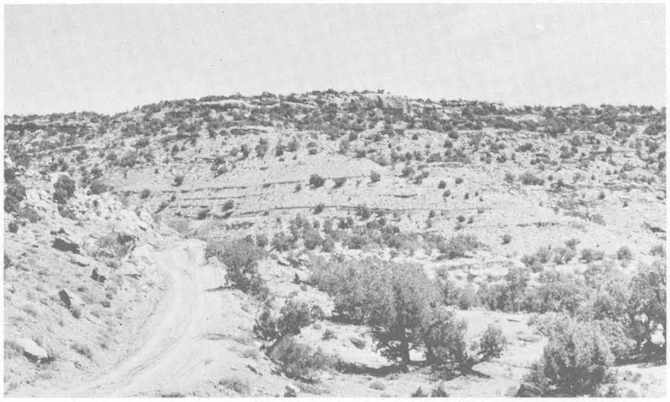


FIGURE 20.—Wepo Formation near the Cow Springs coal mine, showing typical exposures of the formation on the west side of Black Mesa along road to coal mine, about 7 miles east of Cow Springs.

Sandstone in the Wepo is generally yellowish gray (5*Y* 8/1) and is crossbedded. Some beds are weakly cemented and very argillaceous and weather into slopes similar to those formed by the mudstone and siltstone units, whereas other beds are firmly cemented and form cliffs as much as 40 feet high. The sandstone is poorly sorted and is composed of very coarse to fine subrounded to subangular clear and frosted grains of quartz. Altered feldspar, mica, and black minerals are present as accessory minerals at most localities. The thicker sandstone units are in part conglomeratic and have a concentration of granules and pebbles of gray to white chert and silicified limestone near their base. Iron-rich concretions, mud pellets, silty lenses, and carbonized plant remains are common.

Coal beds are commonly interbedded with siltstone near major sandstone units. Some of the coal is being mined. Hard red baked shale, resulting from burned coal beds, is typical of the formation throughout the Black Mesa area; in an area about 20 miles northwest of Pinon, coal beds were burning in 1955.

The Wepo Formation thins to the northeast (fig. 15) across Black Mesa as a result of tonguing in that direction into the underlying Toreva Formation and into the overlying Yale Point Sandstone. The entire formation is preserved in only the north half of the area, where the formation ranges in thickness from 743 feet east of Cow Springs to 304 feet at Yale Point. In the south half of Black Mesa, the upper part of the Wepo Formation has been removed by recent erosion.

AGE ASSIGNMENT AND CORRELATION

With the exception of plant remains, none of which have been identified, fossils have not been found in the Wepo Formation in the present study. Reagan (1925, 1926) listed *Ostrea glabra, O. soleniscus,* and *Modiola laticostata* from a unit in the area west of Pinon that he refers to in different places as the Zilhlejini Coal Formation, Zilhlejini Formation, or Zilhlejini Shales. Without much question, these fossils were collected from the lower part of the Wepo Formation. Reeside and Baker (1929, p. 36) discussed Reagan's fossils and suggested that his *Modiola laticostata* is *M. multilinigera,* and they classed the entire collection as being of Niobrara age.

The early Niobrara fauna in the marine shale tongue of the Toreva Formation in the northeastern part of Black Mesa has already been discussed, as well as the equivalence of this unit to strata in the basal part of the Wepo Formation farther to the southwest. Reeside and Baker (1929, p. 36) listed the fossils in a collection made by H. E. Gregory, (but not published by him) which was labeled "Chilchinbito (14½ miles northwest of Rough Rock toward Kayenta), massive sandstone capping Black Mesa." From this description, it appears that the collection (USGS loc. 11642) was made in the Yale Point Sandstone. It contained *Inoceramus stantoni, Ostrea* sp., *Mactra* sp., and *Volutoderma* sp., which Reeside and Baker stated are of Niobrara age. It may be added that *I. stantoni* is typical of the fauna in the middle of the Niobrara Formation and does not occur in the youngest beds and, also, that the long-ranged *Ostrea soleniscus*—though found somewhat higher stratigraphically than *Inoceramus stantoni*—is not found in beds as young as the highest parts of the Niobrara.

The fossils indicate that the Wepo Formation is equivalent in age to the lower part of the Niobrara Formation of eastern Colorado. In the northeastern part of Black Mesa, units beneath the Wepo are of earliest Niobrara age, but in the southern part of the area the lower part of the Wepo Formation probably includes beds as old as earliest Niobrara and possibly contains beds equivalent in age to the upper part of the Carlile Shale.

The Wepo Formation is considered to be correlative to the Crevasse Canyon Formation of the southwestern part of the San Juan Basin in the vicinity of Gallup, N. Mex. However, some of the Wepo is possibly equivalent to some of the upper part of the Gallup Sandstone in that area, and certainly the Gallup Sandstone and part of the Mancos Shale overlying the Gallup in the Shiprock area are the same age as the Wepo Formation on the southern part of Black Mesa.

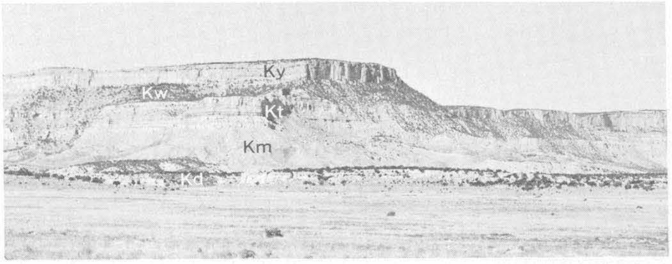


FIGURE 21.—Northeast wall of Black Mesa. Southwestward view of Cretaceous exposures west of Rough Rock. Dakota Sandstone (Kd), Mancos Shale (Km), Toreva Formation (Kt), Wepo Formation (Kw), and Yale Point Sandstone (Ky). Slope in foreground is formed by the Morrison Formation.

YALE POINT SANDSTONE

A massive sandstone forms a nearly continuous vertical escarpment above the Wepo Formation at Yale Point and elsewhere along the northeast edge of Black Mesa. The sheer cliff is 200 feet high at Yale Point, and the cliff-forming sandstone maintains that thickness for a distance of more than 40 miles (fig. 21). This unit of the Mesaverde Group is the Yale Point Sandstone (Repenning and Page, 1956, p. 280), named after the prominent physiographic feature it forms. The type locality is three-quarters of a mile west of Yale Point.

The Yale Point Sandstone crops out in only a small area. Although its 40-mile-long scarp is spectacular, in many places the formation is present as only a very narrow, almost knife-edged ridge. Its width is nowhere more than about 6 miles, except for an isolated outcrop near the Cow Springs coal mine, about 7 miles east of Cow Springs (pl. 1). The narrowness of the outcrop band is due principally to recent erosion but is also due in part to the southward intertonguing of the Yale Point with the partly equivalent, partly underlying Wepo Formation.

The lower contact of the Yale Point Sandstone in the type locality is a sharp surface of minor erosion; regionally, however, the Yale Point intertongues with underlying rocks. No younger rocks overlie the formation, and its upper limit is the surface of recent erosion.

General Description and Field Relations

The Yale Point Sandstone is yellowish gray (5*Y* 8/1), weathers grayish orange (10*YR* 7/4), and is composed of coarse- to fine-grained subrounded to subangular clear quartz. It is fairly well sorted and contains large amounts of altered feldspar and mica as accessory minerals. Bedding in the formation is lenticular, and individual units are crossbedded. Crossbedding is of the trough type, with medium-scale crossbeds deposited at medium to low angles. At widely spaced intervals, the Yale Point contains thin silty units which are not apparent in cliff faces, but which permit the formation to weather into a series of ledges and minor slopes on the less precipitous exposures. South of the escarpment along the north side of Black Mesa, intertonguing with the Wepo Formation introduces many finer grained units into the Yale Point Sandstone, and its outcrop is decidedly ledgy. The slope-forming units contain minor amounts of coal in the area of Marsh Pass and near the Cow Springs coal mine.

The Yale Point Sandstone is 204 feet thick at Yale Point. Its differences in thickness along the northern escarpment of Black Mesa are controlled entirely by erosion at the top. The maximum observed thickness was slightly more than 380 feet about 6½ miles west of Chilchinbito. From Chilchinbito southward, the Yale Point rapidly decreases in thickness because of intertonguing with the Wepo Formation.

Age Assignment and Correlation

Fossils collected by H. E. Gregory from the Yale Point Sandstone near Chilchinbito have been discussed in connection with the age of the Wepo Formation. The fossils from this collection, identified by Reeside and Baker (1929), are typical of the middle of the Niobrara Formation. Therefore, rocks of the Yale Point Sandstone are believed to be no younger than Niobrara age.

Other diagnostic fossils were not collected from the Yale Point Sandstone during the present study, although sharks' teeth are common throughout the unit, and poorly preserved mollusks are common at the base of the unit. In areas where the Yale Point Sandstone intertongues with the Wepo Formation, plant remains and coal are fairly common in the zone of intertonguing.

The Yale Point Sandstone is considered to be correlative with the Hosta Tongue of the Point Lookout Sandstone in the southwestern part of the San Juan Basin in New Mexico, which is of middle to late Niobrara age. This correlation is based primarily upon the similarity in lithology and in stratigraphic position. According to Fred Peterson (oral commun., 1970) the Yale Point Sandstone is equivalent to the D, E, F, and G sandstones of the John Henry Member of the Straight Cliffs Formation in the Kaiparowits Plateau of southern Utah (Peterson, 1969, fig. 5).

UPPER PART OF THE MESAVERDE GROUP

The upper part of the Mesaverde Group is entirely confined (fig. 22) to the San Juan Basin part of the

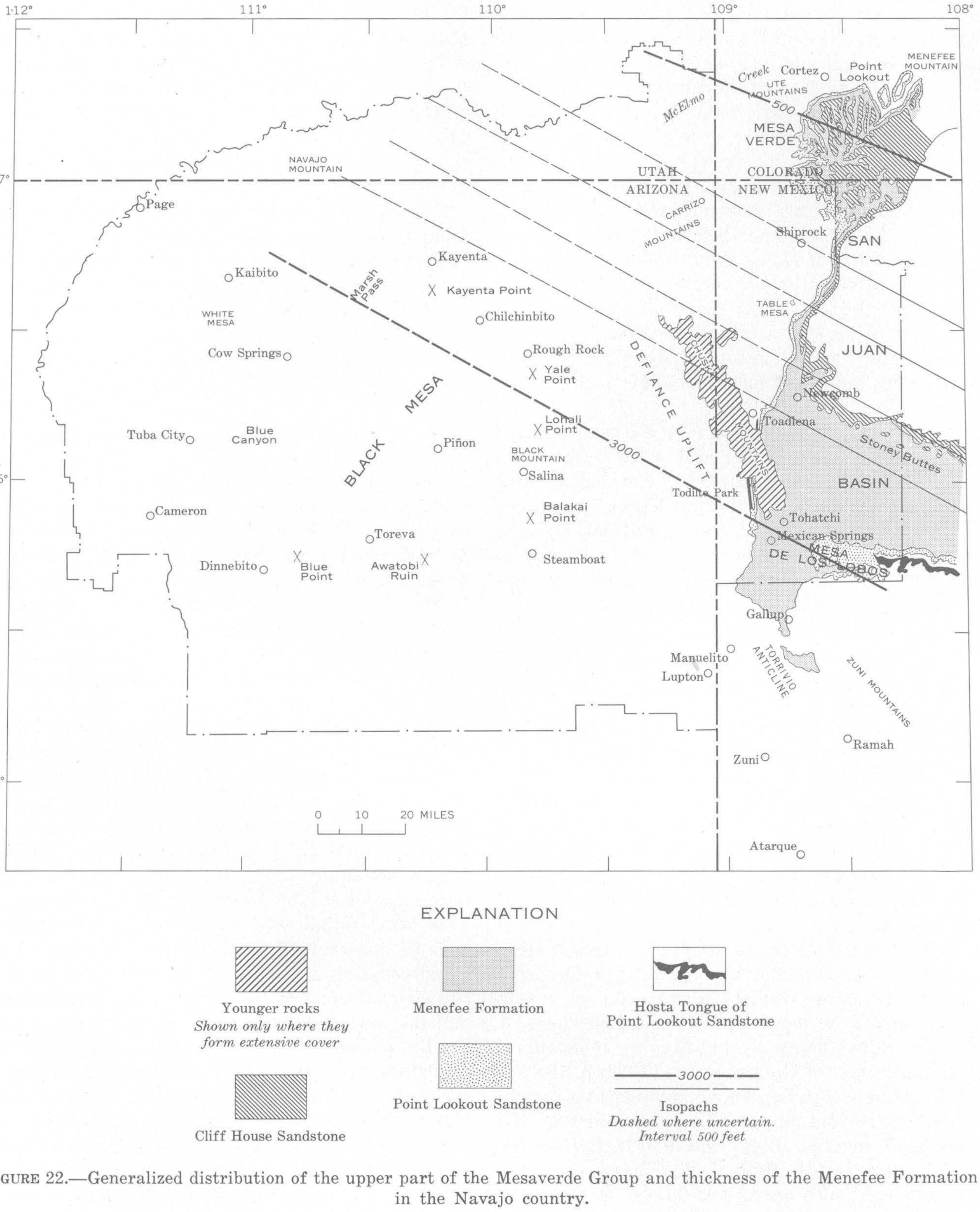


FIGURE 22.—Generalized distribution of the upper part of the Mesaverde Group and thickness of the Menefee Formation in the Navajo country.

Navajo country. A few miles north of the San Juan River, the formations of the Mesaverde Group are nearly horizontal and are exposed in mesas and buttes that form the southernmost part of Mesa Verde. This is the type locality of the Mesaverde Group, described by Holmes (1877), where, in ascending order, the group consists of the Point Lookout Sandstone, Menefee Formation, and Cliff House Sandstone. The Point Lookout Sandstone was deposited during a major northeastward regression of the sea, and the Cliff House Sandstone was laid down in a transgressional movement of the sea, at the beginning of the last major marine invasion of this area. Intervening strata of the Menefee Formation were deposited in lagoonal and flood-plain environments during the time that the sea lay to the northeast.

In the transgressional movement, the sea advanced to the southwest only as far as the Newcomb area, and the Cliff House, therefore, was not deposited at the site of the Chuska Mountains. There, a younger unit directly overlies the Menefee Formation. This unit was called the Kirtland and Fruitland Formations undivided, by Zieglar (1955) and, for convenience, is here mapped with the Menefee (pl. 1) and assigned to the Mesaverde Group.

POINT LOOKOUT SANDSTONE

The name Point Lookout Sandstone was applied to a massive sandstone overlying the Mancos Shale at Point Lookout, about 7½ miles southwest of Mancos, Colo. (Collier, 1919, p. 296). From the type locality at Mesa Verde, the Point Lookout can be traced in continuous outcrops (pl. 1) southward to the Toadlena area, where the sandstone is covered by Tertiary rocks of the Chuska Mountains. The Point Lookout is exposed in the Todilto Park area and is widely displayed in the Mesa de los Lobos area. In the Mesa Verde area, near Tohatchi, and in the area northeast of Gallup, the Point Lookout forms a flat or gently dipping caprock on mesas or benches. Elsewhere, it forms low ridges along steeply dipping monoclines.

In the area east of Gallup, Sears (1934, p. 18) applied the name Hosta Sandstone Member to a prominent sandstone that appeared in the midst of the Gibson Coal Member of his Mesaverde Formation. He noted that in the Mesa de los Lobos area, the Hosta was split into upper and lower parts by the Satan Tongue of the Mancos Shale. Sears (1934, p. 19) and Hunt (1936, p. 48, 49) noted that the upper sandstone persisted along the south and east margins of the San Juan Basin as the basal sandstone of their Mesaverde Formation and that the lower sandstone of the Hosta eventually merged into an expanded Mancos Shale. Sears and Hunt, in the papers here cited, did not attempt to correlate the Hosta beyond the area of investigation, but in the summary paper of the area Sears, Hunt, and Hendricks (1941, p. 115) acknowledged the correlation of the Hosta with the Point Lookout Sandstone reported by W. S. Pike, Jr. (oral commun., no date).

Subsequently (Allen and Balk, 1954, p. 90; Beaumont and others, 1956, p. 2156), the name Point Lookout was extended into the Gallup area and replaced the name Hosta or, where the Hosta was subdivided, replaced the upper part of the Hosta. The name Hosta Tongue of the Point Lookout Sandstone was given to the unit formerly known as the lower part of the Hosta Sandstone.

General Description and Field Relations

The Point Lookout Sandstone consists of two or more massive sandstone units separated by thin beds of gray sandy shale. From Toadlena northward, the Point Lookout is grayish orange (10*YR* 7/4) to very pale orange (10*YR* 8/2); it is generally evenly bedded and, at places, crossbedded and is composed of fine- to medium-grained quartzose sand. The sandstone is moderately well sorted and contains relatively few dark accessory minerals. Locally, the beds contain ironstone concretions, and weathered surfaces tend to be pitted and honeycomblike.

North of Toadlena the Point Lookout Sandstone conformably overlies the undivided upper part of the Mancos Shale. The contact is gradational and, thus, somewhat arbitrary. North of the San Juan River, the contact (fig. 23), is the same as that defined by Hayes and Zapp (1955), and the basal Point Lookout here includes 50–150 feet of the gradational sequence. This transitional zone consists of alternating thin beds of fine-grained sandstone and gray and brown gypsiferous shale. South of the San Juan River, the transitional zone is assigned to the Mancos Shale, and the lower contact of the Point Lookout is arbitrarily placed at the base of the lowermost thick sandstone. The contact of the Point Lookout with the overlying Menefee Formation is conformable and generally is sharp. Locally, the upper 3–5 feet of the Point Lookout contains thin stringers and beds of carbonaceous shale.

North of the San Juan River, the upper part of the Point Lookout is massive sandstone 200–250 feet thick, and the underlying transitional zone is 50–150 feet thick (P. T. Hayes, written commun., 1951). In the vicinity of Table Mesa south of the San Juan River, the Point Lookout is about 180 feet thick, but

FIGURE 23.—Point Lookout Sandstone on Chimney Rock, Montezuma County, southwestern Colorado. Pedestal is formed by Mancos Shale (Km). The transitional shale and sandstone unit of the Point Lookout (Kplt), here, is about 100 feet thick. The butte is capped by the massive part of the Point Lookout Sandstone (Kplm). Photograph by J. H. Irwin (1966, p. G40).

at one locality near there, it is only 110 feet thick. Near Toadlena the thickness increases to about 200 feet.

The Hosta Tongue of the Point Lookout Sandstone is present for a distance of about 25 miles, south of Toadlena and in the Mesa de los Lobos area. In these areas the Hosta Tongue is separated from the Point Lookout by the Satan Tongue of the Mancos Shale, which is 330 feet thick near Toadlena and which thins gradually until it pinches out near Crevasse Canyon, south of the Chuska Mountains, and also near Dalton Pass, in the Mesa de los Lobos area. Where the Satan Tongue pinches out, the Hosta Tongue merges with the Point Lookout Sandstone (fig. 24), and the two cannot be distinguished from each other.

The Hosta Tongue ranges in thickness from 0 to about 120 feet. It is mostly sandstone that is thick bedded, grayish orange (10*YR* 7/4) to yellowish gray (5*Y* 8/1), fine grained, calcareous, and well sorted. Near Toadlena, the Hosta Tongue—possibly in combination with the Dalton Sandstone Member of the Crevasse Canyon Formation (fig. 8)—contains interbedded gray shale, and about 3 miles southeast of Toadlena, the Hosta Tongue grades laterally into the upper part of the Mancos Shale.

In the Mesa de los Lobos area, the Hosta Tongue merges with the overlying Point Lookout and forms prominent ledgy cliffs. The combined unit is as much as 250 feet thick and is noticeably coarser grained than either the Point Lookout or the Hosta Tongue where the two can be distinguished. The basal contact with the underlying Gibson Coal Member of the Crevasse Canyon Formation is locally gradational. Although the Point Lookout in this area is dominantly sandstone, near Dalton Pass the lower 25–50 feet locally contains thin lenticular coal and shale beds (Sears and others, 1941, p. 114). West of Dalton Pass, the lower part passes laterally into the Gibson Coal Member of the Crevasse Canyon Formation, and the upper part of the Point Lookout thins to 150 feet 10 miles west of Dalton Pass, and thins to a featheredge 17 miles west of Dalton Pass.

South of Crevasse Canyon on the west side of the

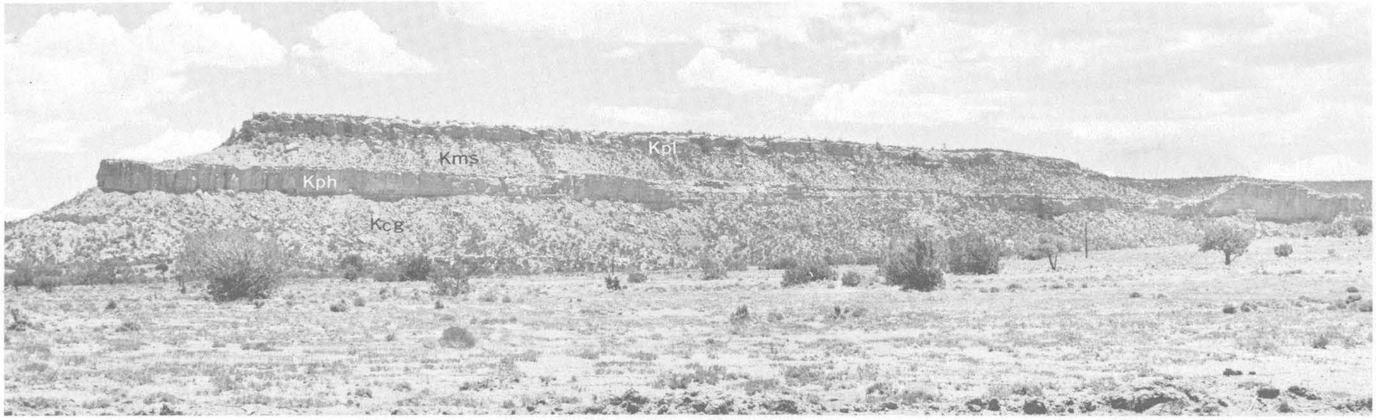


FIGURE 24.—Hosta Tongue of the Point Lookout Sandstone and related rocks on Mesa de los Lobos. Eastward view, in Mariana Pass. Point Lookout Sandstone (Kpl) and Hosta Tongue (Kph); Gibson Coal Member of Crevasse Canyon Formation (Kcg) and Satan Tongue of Mancos Shale (Kms). Satan Tongue is about 100 feet thick at the north (left) side of mesa and pinches out to the south (right).

Gallup-Zuni basin, the Point Lookout is about 320 feet thick; within 1 mile it thins abruptly to 25 feet, and within 2 miles it is absent (Allen and Balk, 1954, p. 94).

AGE ASSIGNMENT AND CORRELATION

Along the San Juan River, Reeside (1924, USGS loc. 12004) collected a fauna from 75 feet below the base of the Point Lookout Sandstone that is most reasonably assigned to the zone of *Scaphites hippocrepis* of the Eagle Sandstone of the reference sequence. Pike (1947, p. 24) stated that the Point Lookout Sandstone in the vicinity of the Chuska Mountains is probably the same age as the lower part of the Telegraph Creek Formation of the reference sequence. His opinion is based on a comparison of the sequence near the Chuska Mountains with the more fossiliferous rocks at Mesa Verde and in the southeastern part of the San Juan Basin.

MENEFEE FORMATION

About 2 miles southeast of Mancos, Colo., on the slopes of Menefee Mountain, the Point Lookout Sandstone is overlain by a highly variable nonmarine sequence of sandstone, shale, and coal about 400 feet thick. The name Menefee Formation is applied to this sequence which, in the type locality, is estimated to be about 55 percent shale, 42 percent sandstone, and 2–3 percent coal (Collier, 1919, p. 296).

The lower contact with the Point Lookout is gradational; the upper contact with the overlying Cliff House Sandstone is locally sharp, but regionally, the upper contact is marked by striking large-scale intertonguing of the two formations.

The formation crops out continuously from Menefee Mountain to the Gallup area (pl. 1). North of Newcomb, the Menefee Formation is exposed in a relatively narrow band along the Hogback monocline. North of the San Juan River, the formation crops out in steep slopes between the flat-lying Point Lookout and Cliff House Sandstones. In the area between Stoney Buttes and Gallup, the Menefee is 2,500–3,000 feet thick and is widely exposed. In general, this area is one of low relief, but, locally the Menefee contains a large proportion of sandstone beds that crop out in high cliffs on a few isolated buttes.

The Menefee Formation is coal-bearing at both the base and the top but is virtually barren of coal in the middle part (fig. 8). The lower and upper coal-bearing units contain brown and gray carbonaceous mudstone and shale and lenticular beds of sandstone and coal. The middle unit, which makes up by far the largest part of the Menefee, differs in that it contains only a few thin, economically unimportant coal beds, less carbonaceous mudstone and shale, and a greater proportion of sandstone beds. Individual beds in the formation are characteristically lenticular and discontinuous.

The middle, noncoal-bearing part of the Menefee Formation is called the Allison Member, and the underlying coal-bearing unit is locally called the Cleary Coal Member (Beaumont and others, 1956, p. 2156, 2157). These two units were formerly known as the Allison Barren Member and upper part of the Gibson Coal Member, respectively. The upper coal-bearing part of the Menefee is unnamed.

GENERAL DESCRIPTION AND FIELD RELATIONS

The Cleary Coal Member is present immediately above the Point Lookout Sandstone at the crest of

Mesa de los Lobos and in the area to the north, where the beds dip into the San Juan Basin. The Cleary, which is generally poorly exposed, is about 150 feet thick and consists of brown lenticular fine- to medium-grained sandstone, brown carbonaceous shale and silty shale, ferruginous concretionary beds, and a few coal beds. The contact with the overlying Allison Member is so placed as to include in the Cleary all the potentially valuable coal beds.

Where the Point Lookout Sandstone is absent, south of a point about 12 miles north-northeast of Gallup, the Cleary rests on the Gibson Coal Member of the underlying Crevasse Canyon Formation, and the base of the Menefee was mapped at the top of the Cleary and Gibson Coal Members undivided, which is included in the Crevasse Canyon Formation for convenience in mapping (fig. 8). In the outcrop area within the Gallup–Zuni basin where the Point Lookout is absent, the Cleary and Gibson Coal Members undivided forms a mappable unit that has been included with the Crevasse Canyon Formation.

In the western San Juan Basin between Tohatchi and the San Juan River, the Point Lookout is present, but the Cleary Coal Member was not recognized separately. However, the basal part of the Menefee contains some coal throughout this area and, in this report, is informally referred to as the lower coal-bearing unit.

The Menefee Formation was not subdivided into members by Allen and Balk in the Tohatchi quadrangle. Regarding the Menefee, however, they stated (Allen and Balk, 1954, p. 95), "The lower 500 feet of the unit contain carbonaceous shales and thin coals, and are the equivalent environmentally of the upper Gibson coal member of Sears (1934)." Coal beds described by Allen and Balk (1954, p. 27) are as much as 6 feet thick, and all occur in the lower 100 feet of the Menefee Formation.

Near Two Grey Hills, the lower coal-bearing unit is 125–150 feet thick. It consists of coal beds, as much as 2 feet thick, and of interbedded grayish-yellow (5*Y* 8/4) fine-grained sandstone and dusky-yellow (5*Y* 6/4) to olive-gray (5*Y* 3/2) carbonaceous shale. Locally, moderate-yellowish-brown (10*YR* 5/4) arenaceous limestone beds, as much as 4 feet thick, form dip slopes on low cuestas that are held up by sandstone beds.

Northward, between Two Grey Hills and the place where the Chaco River crosses the outcrop of the Point Lookout, the lower coal-bearing unit of the Menefee decreases in thickness, but one or two beds of coal persist. From the vicinity of the San Juan River northward to the Colorado–New Mexico State line, both the number and the thickness of coal beds in the lower part of the Menefee increase, and this lower part was designated as the lower coal-bearing member by Hayes and Zapp (1955).

The Allison Member conformably lies on either the Cleary Coal Member or the lower coal-bearing unit in most areas. In the Gallup-Zuni basin, where the Point Lookout Sandstone is absent, the Allison arbitrarily forms the base of the Menefee and rests on the Cleary and Gibson Coal Members undivided. Near Gallup, the Allison is at least 800 feet thick (Sears, 1925, p. 18), but its upper part has been removed by erosion.

Near Newcomb, the Allison Member is more than 2,000 feet thick. In the lower 300 feet there are at least six grayish-yellow (5*Y* 8/4) fine- to medium-grained sandstone beds that range in thickness from 15 to 30 feet. These sandstone beds are lenticular and crossbedded, and rarely persist for more than half a mile. The sandstones are interbedded with dusky-yellow (5*Y* 6/4) to olive gray (5*Y* 3/2) sandy shale and mudstone in beds 5–60 feet thick. These sandstones form a prominent stratigraphic zone in the area between Ford Butte and Toadlena but were not observed in the same stratigraphic position between Ford Butte and the San Juan River.

Overlying this sandy sequence at the base of the Allison Member is about 1,200 feet of dusky-yellow (5*Y* 6/4), olive-gray (5*Y* 3/2), and dark-gray (*N* 3) to black (*N* 1) shale and mudstone containing thin lenticular beds of carbonaceous shale, shaly coal, and, in some places, yellowish-gray (5*Y* 7/2) fine-grained sandstone. Sandstone beds are not so conspicuous in the middle part of the Allison Member as they are at the base and at the top.

Sandstone beds are prominent in the upper 600 feet of the Allison Member, where they are lenticular, crossbedded, grayish orange (10*YR* 7/4), and fine to medium grained. They are extremely discontinuous. Individual beds, 20–30 feet thick, thin and disappear within lateral distances of 100 feet or less. Carbonaceous shale, dusky-yellow (5*Y* 6/4) to dark-gray (*N* 3) shale, and siltstone are interbedded with the sandstone.

The Allison Member thins northward and is about 600 feet thick at the San Juan River. North of the San Juan River, equivalent beds were designated as the "middle barren member" of the Menefee by Hayes and Zapp (1955).

At the top of the Menefee and overlying the Allison Member is the upper coal-bearing unit, in which thickness and distribution of coal beds are more erratic than in the lower coal-bearing unit. Coal is present in the upper 250 feet of the Menefee north of the San Juan River, where the coal-bearing sequence was called the upper coal-bearing member by Hayes and Zapp (1955). They stated that "nearly two-thirds of the calculated coal reserves in the Menefee Formation [north of the San Juan River in New Mexico] are contained in the upper coal-bearing member." However, from the San Juan River southward to about the vicinity of Hogback Mountain, the coal beds thin to near nonexistence. Near Hogback Mountain, in an area of pronounced intertonguing with the overlying Cliff House Sandstone, coal beds are abundant in the upper 250 feet of the Menefee, and the upper coal-bearing unit can be distinguished, from Hogback Mountain southward and eastward along the Chaco River to the east border of the report area. Coal beds are especially numerous and thick in the vicinity of Sanostee Wash. Near Newcomb and for a few miles to the east, the upper coal-bearing unit contains a few coal beds (some as much as 8 ft thick) that almost everywhere have been burned at the outcrop.

Stratigraphically, the top of the Menefee rises about 1,200 feet, between the San Juan River and the Newcomb area, by intertonguing with the overlying Cliff House. A conspicuous stratigraphic rise of about 250 feet occurs near Hogback Mountain. A thinning tongue of Menefee extends northward, east of the ridge line of Hogback Mountain, for a distance of 7 miles above a corresponding tongue of the Cliff House. The top of the Menefee continues to rise southward across a series of lesser tongues. Near Sanostee Wash, three separate tongues abruptly raise the top of the Menefee about 600 feet. Another conspicuous tongue of Menefee is present east of Newcomb along the Chaco River and Coal Creek. The tongue of Menefee, isolated by erosion from the main body of Menefee, is 8–10 feet thick and overlies a tongue of Cliff House that is 100–120 feet thick.

As a result of the large-scale intertonguing, the Menefee Formation thickens rapidly to the southwest (fig. 22). It is approximately 400 feet thick at the type locality (Collier, 1919, p. 296) and almost 1,000 feet thick at the San Juan River. Between the San Juan River and the vicinity of Newcomb, a distance of 33 miles, the Menefee more than doubles its thickness to about 2,500 feet. According to Allen and Balk (1954, p. 95), the Menefee Formation in the Tohatchi area is 2,290 feet thick. To this should be added about 850 feet of beds of the lower carbonaceous member of the Tohatchi Formation, as used by Allen Menefee Formation. (See p. E47.) This, then, makes (1953, p. 2570), which is here included with the the Menefee Formation in the Tohatchi area more than 3,000 feet thick.

Age Assignment and Correlation

Fossils are not numerous in the Menefee Formation, and the ones found are generally not diagnostic as to age. Fossils collected by D. L. Zieglar from a thin limy bed near the top of the Menefee about 5 miles northwest of Sheep Springs (USGS Mesozoic loc. 24128) include the following (J. B. Reeside, Jr., written commun., 1952): *Unio sp.; Corbicula sp.; Corbula chacoensis* Stanton; *Corbula* cf. *C. perundata* Meek and Hayden; *Neritina* cf. *N. bauri* Stanton; *Neritina*? n. sp.; *Goniobasis*? sp. The fossils are of late Late Cretaceous age and, except for the *Unio*, represent a brackish-water fauna, in contrast to the fresh-water forms found in the overlying Kirtland and Fruitland Formations undivided.

Plants of Late Cretaceous age from the upper part of the Menefee 1.8 miles northwest of Tohatchi (USGS Mesozoic loc. 5313) were identified by R. W. Brown (written commun., 1953) and include the following: *Anemia hesperia* Knowlton; *Sequoia reichenbachi* (Geinitz) Heer; *Sabalites montanus* (Knowlton) Dorf; *Ficus planicostata* Lesquereux.

Because of the lack of critical dating fossils, the time interval included in the Menefee must be inferred from the age of the overlying and underlying rocks and from the lateral equivalents in the marine rocks to the northeast. According to W. A. Cobban (written commun., 1966), the entire Mesaverde Group at the type locality, in Colorado, occupies roughly the four recently defined faunal zones from *Baculites* sp. (smooth) to *Baculites mc learni* inclusive of the Western Interior ammonite zone (Gill and Cobban, 1965, fig. 3). These ammonite zones correlate, in general, with the upper part of the Eagle Sandstone and the basal part of the Pierre Shale of the Western Interior reference sequence (Cobban and Reeside, 1952). Southwestward, the Menefee Formation spans progressively more time (fig. 7). Near Toadlena, the Point Lookout is probably equal in age to the early part of the Telegraph Creek (Pike, 1947, p. 24). Younger fresh-water beds in the Toadlena area that conformably overlie the Menefee are probably as young as the Fox Hills Sandstone. Hence, the Menefee Formation in the Toadlena area is possibly equal in age to part of the Telegraph Creek Formation and all of the Eagle Sandstone and Pierre Shale of the standard reference sequence. Farther south, basal beds of the Menefee may be as old as the upper part of the Niobrara Formation.

POST-MENEFEE ROCKS IN THE CHUSKA MOUNTAINS AREA

On the flanks of the Chuska Mountains, near Toadlena, the Menefee Formation is conformably overlain by a sequence of rocks mapped by Zieglar (1955) as the Kirtland and Fruitland Formations undivided. This sequence of post-Menefee rocks is equivalent in age to the Fruitland Formation and Kirtland Shale east of the Chaco River, where they are separated from the Menefee Formation by the Cliff House Sandstone, Lewis Shale, and Pictured Cliffs Sandstone (fig. 8).

At the south end of the Chuska Mountains, near Tohatchi, Allen and Balk (1954) mapped and redefined a unit overlying the Menefee, so that the unit would approximately equal the Tohachi Shale as used by Gregory (1917, p. 80). On the basis of new paleontologic evidence, lithology, and general stratigraphic relations, Allen and Balk assigned their Tohatchi Formation (spelling modified by Allen, 1953) to the Upper Cretaceous and placed it conformably above the Menefee Formation and in the Mesaverde Group of that area. The Tohachi was originally assigned by Gregory (1917, p. 80) to the Tertiary, but with the notation that his conclusions were subject to radical revision.

The initial announcement of the redefinition of the Tohachi Shale by Allen (1953) was followed by considerable discussion (Silver, 1954; Allen, 1954; Wright, 1954; Repenning, 1954). Most of the dispute was the result of differences in interpretation of Gregory's somewhat tenuous description of the rock units, which he based on an admitted cursory field examination. One point of conflict is the presence (or absence) of an angular unconformity reported by Gregory (1917, p. 15, 80, pl. 3) to be present at the base of the Tohachi Shale. The unconformity in question was not found during three independent surveys in the area (Allen and Balk, 1954; Repenning, 1954; Wright, 1954); thus, it can be presumed that Gregory's observations probably were in error.

Near Tohatchi, Allen (1953) recognized a lower carbonaceous member and an upper bentonitic member in his Tohatchi Formation. The lower carbonaceous member is cliff forming and consists of 400–850 feet of interbedded sandstone, silty claystone, carbonaceous shale, and lignite. Allen (1953, p. 2570) reported the lower member to be overlain "by upward of 500 feet (top not exposed) of uniform, light olive-gray to yellowish-gray, indistinctly thin-bedded, highly bentonitic shales which are carbonaceous near the base."

Allen (1953, p. 2571) correlated the upper bentonitic member with the Fruitland Formation and Kirtland Shale of the northern San Juan Basin. Allen's upper bentonitic member also seems to correspond in thickness and lithology to the Kirtland and Fruitland Formations undivided, as used by Zieglar (1955): both are bentonitic, and both have a carbonaceous zone at the base. The stratal relations, however, are masked by a heavy cover of landslide debris along the east side of the Chuska Mountains. Allen's lower carbonaceous member of the Tohatchi Formation is here included with the upper part of the Menefee Formation. Allen (1953, p. 2571) tentatively correlated it with the Cliff House and Pictured Cliffs Sandstones, a correlation that is most plausible, in view of the northward intertonguing of the Menefee in these units. If Allen's lower carbonaceous member of the Tohatchi is included with the Menefee, the thickness of the Menefee, then, is about 3,000 feet (Allen and Balk, 1954, pl. 11, sections 5, 11), and this thickness agrees well with regional trends of the Menefee (fig. 22) expanding uniformly southwestward.

In the present report, the local outcrops of the Kirtland and Fruitland Formations undivided—along the flank of the Chuska Mountains between Tohatchi and Toadlena—are arbitrarily mapped as part of the Menefee Formation (pl. 1). It is recognized, however, that this is an expansion of the usage of Menefee that is not defendable except as a local convenience in mapping, for, in this area, the Kirtland and Fruitland Formations undivided forms a distinct unit, as mapped by Zieglar (1955).

General Description and Field Relations

The Kirtland and Fruitland Formations undivided is about 800 feet thick near Toadlena. The following description of the rocks was given by D. L. Zieglar (written commun., 1953). The lower 75–100 feet of the Kirtland and Fruitland Formations undivided is dark-gray (*N* 3) to black (*N* 1) carbonaceous shale, siltstone, and shaly coal beds. The overlying upper part of the formations consists of a sequence of grayish-yellow-green (5*GY* 7/2) to olive-gray (5*Y* 3/2) shale and clay containing lenticular beds of light-gray (*N* 7) to white (*N* 9) crossbedded sandstone and thin beds of carbonaceous shale. The sandstone lenses, which are fine to medium grained and are cemented with calcite or kaolinite, range in thickness from 0 to 30 feet and generally do not extend more than 200 feet laterally. Neither the shale nor the sandstone is resistant, and the formation weathers to badlands (fig. 25). The clays swell upon exposure to form a puffy surface, suggesting that they are bentonitic. Fragments of petrified wood are fairly abundant, and in many places they litter the weathered surfaces.

Age Assignment and Correlation

Fossils were collected from the Kirtland and Fruitland Formations undivided at two localities by D. L.

FIGURE 25.—Post-Menefee rocks 3 miles west of Sheep Springs, showing beds included in the Kirtland and Fruitland Formations undivided (Zieglar, 1955). Rubble is landslide debris. Vertebrates and invertebrates were collected at this locality. Photograph by D. L. Zieglar, 1953.

Zieglar. The fossil identifications were made by J. B. Reeside, Jr. One collection, from a place 5 miles northwest of Sheep Springs (USGS Mesozoic loc. 24125), contains: *Unio* aff. *U. reesidei* Stanton; *Sphaerium* sp.; *Corbula* aff. *C. chacoensis* Stanton; *Viviparus* sp.; *Campeloma*? sp.; *Goniobasis*? *subtortuosa* (Meek and Hayden); *Goniobasis*? sp.; *Physa* sp.; *Mesolanistes reesidei* (Stanton). The other collection, from a place 2 miles west of Sheep Springs (USGS Mesozoic loc. 24126), contains: *Unio amarillensis* Stanton; *Unio* aff. *U. brachyopisthus* White; *Unio* aff. *U. brimhallensis* Stanton; *Unio* n. sp.?; *Corbula chacoensis* Stanton; *Campeloma amarillensis* Stanton; *Viviparous* sp; *Tulotomops* n. sp. A plant from this last locality was identified by R. W. Brown as *Sequoia reichenbachi* (Geinitz). J. B. Reeside, Jr. (written commun., 1952) stated that the fossils "are of late Late Cretaceous age; nothing like them is known from the Tertiary of the Rocky Mountain region," and that they are similar "to the Fruitland-Kirtland fauna described by Stanton and the species in them are normally fresh-water forms, except for the *Corbula*, which is a brackish-water form."

Other fossils were collected by J. B. Reeside, Jr., 3.5 miles southwest of Sheep Springs (USGS Mesozoic loc. 5310) and were identified by R. W. Brown as: *Anemia hesperia* Knowlton; *Metasequoia cuneata* (Newberry) Chaney; *Sequoia reichenbachi* (Geinitz) Herr; *Ficus planicostata* Lesquereux; *Rhamus cleburni* Lesquereux; and *Dombeyopsis obtusa* Lesquereux. According to Brown (written commun., 1953) the plants are of Late Cretaceous age and are "probably as late as Vermejo," an age comparable to that of the Kirtland Shale. Invertebrates and vertebrates were also found at this locality but were not studied.

CLIFF HOUSE SANDSTONE

The Cliff House Sandstone is the uppermost formation of the Mesaverde Group in the type locality. The name is derived from outcrops at Mesa Verde, where ancient Indian cliff houses are found along the niches and caves in the formation (Collier, 1919, p. 297). From the type locality, the Cliff House Sandstone can be traced (pl. 1) southward into the Navajo country.

Near the Colorado–New Mexico State line, the Cliff House Sandstone forms spectacular cliffs that cap Mesa Verde. A few miles north of the San Juan River, the Cliff House is tilted into a prominent ridge along The Hogback monocline. This ridge continues southward toward Bennett Peak, where The Hogback monocline fades into the low, easterly regional dip of western San Juan Basin. The Cliff House Sandstone is more widely exposed in the area between Bennett Peak and Newcomb than it is along the monocline. South of Captain Tom Wash, the outcrop trends to the east toward Stoney Buttes.

The Cliff House Sandstone is absent in the Chuska Mountains, and, although erosion has removed much of the record between Newcomb and Gallup, the Cliff House Sandstone probably did not extend much farther south than its present-day outcrop.

GENERAL DESCRIPTION AND FIELD RELATIONS

The Cliff House Sandstone is white (N 9) to dark yellowish orange (10YR 6/6) and is composed of fine-grained subround to subangular quartz. Rare pink quartz and very fine grained accessory minerals are present in some places. The Cliff House beds range in thickness from thin to very thick, and individual beds are lenticular and crossbedded. At places, particularly near Hunter Wash, the weathered surface of the formation is covered by small, raised concretionary pellets. Although dominantly a resistant sandstone, at some localities the Cliff House also contains prominent silty and shaly units. These shaly units represent tongues of the overlying Lewis Shale or of the underlying Menefee Formation which laterally project into the Cliff House Sandstone.

The lower contact of the Cliff House with the Menefee Formation was previously described (p. E46). The upper contact with the Lewis Shale is transitional and intertonguing. The formation becomes increasingly shaly upward, where it grades into the overlying Lewis Shale. The contact is placed at the highest conspicuous sandstone in the transition zone.

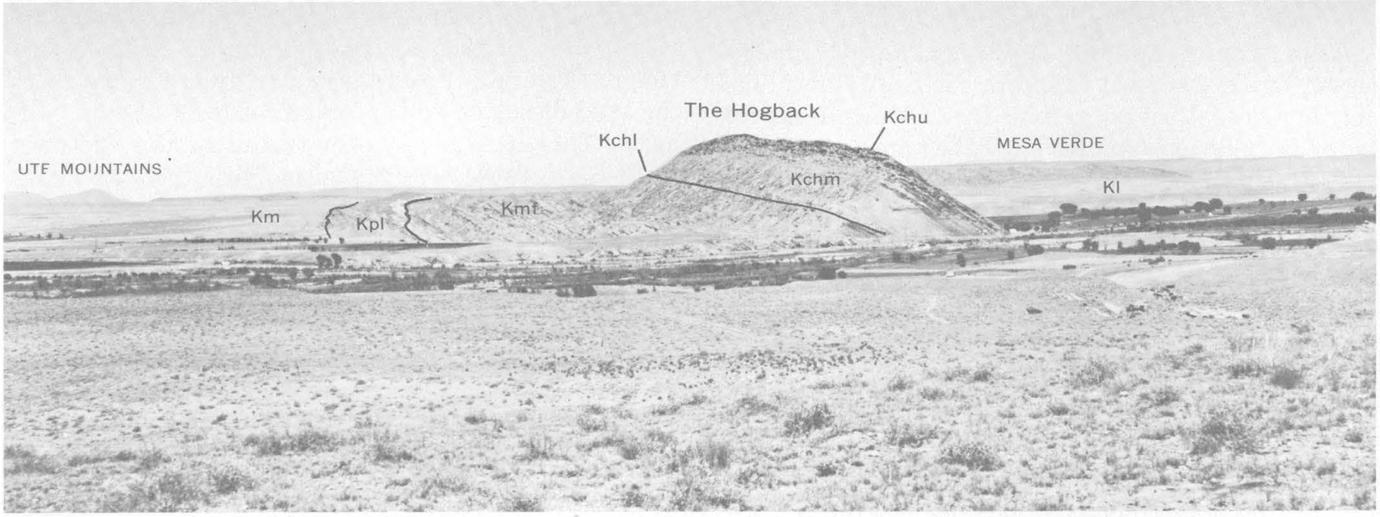


FIGURE 26.—Northward view of the Mesaverde Group in The Hogback at the San Juan River; Mancos Shale (Km), Point Lookout Sandstone (Kpl), Menefee Formation (Kmf), and Lewis Shale (Kl). Above the Menefee Formation, the three units of the Cliff House Sandstone include the lower massive sandstone (Kchl), here, 35 feet thick; a middle shaly unit (Kchm), about 190 feet thick; and the upper sandstone, the Ute Canyon Tongue (Kchu), about 330 feet thick.

At the San Juan River, the Cliff House Sandstone (fig. 26) has a threefold division: a lower massive sandstone bed, about 35 feet thick; a middle soft shaly zone, about 190 feet thick; and an upper sandstone unit, about 330 feet thick, that forms the dip slope of The Hogback monocline in this area. The upper sandstone is the Ute Canyon Tongue of the Cliff House Sandstone (Hayes and Zapp, 1955). Within 3½ miles northward, the Ute Canyon Tongue thins to 15 feet, and farther northward it pinches out. The middle shaly zone present at the river below the Ute Canyon Tongue grades northward into the Lewis Shale (fig. 8). North of the San Juan River where the Ute Canyon Tongue and the underlying soft shaly zone are replaced by Lewis Shale, the lower sandstone unit (which, there, represents the entire Cliff House) thickens to about 120 feet. Southward from the San Juan River, the middle shaly unit pinches out near Hogback Mountain, and the Ute Canyon Tongue merges with the lower sandstone to form a Cliff House Sandstone that is almost 800 feet thick.

Southward from Hogback Mountain, intertonguing of the Cliff House and underlying Menefee results in a rapid stratigraphic rise in the base of the formation. The top of the Cliff House also rises southward because of lateral gradation with the partly equivalent and partly overlying Lewis Shale. The top rises stratigraphically (fig. 8) much less than the base, and as a consequence, the Cliff House thins southward to less than 100 feet, east of Newcomb. Between the San Juan River and Sanostee Wash, the Cliff House ranges in thickness from about 450 to nearly 800 feet, but it is generally about 600 feet thick. When one considers the amount of intertonguing with both the underlying Menefee and the overlying Lewis Shale, this variation in thickness seems slight.

In a small area on the north side of Captain Tom Wash, the Cliff House Sandstone is absent, and the Lewis Shale rests on the Menefee Formation. In the bluffs south of Captain Tom Wash, massive sandstone beds that probably represent the Cliff House reappear. Outcrops of sandstone do not connect across the wash, and the beds on the south could not be traced positively into those on the north; therefore, the correlation is tentative. South of Captain Tom Wash, the writers traced the sandstone interval eastward and believe it to be identical with the Chacra Sandstone Member of the Mesaverde Formation, as defined by Dane (1936, p. 101). As a result, the name Cliff House Sandstone replaces the name Chacra Sandstone Member (a name abandoned by Beaumont, Dane, and Sears, 1956, p. 2159).

Between Newcomb and Coal Creek, the Cliff House ranges in thickness from 80 to 175 feet. Locally, a tongue of the Menefee separates the Cliff House into two parts. At Coal Creek the upper part is 30–75 feet thick, and the lower part is 114 feet thick.

In an area near Hunter Wash, the Lewis Shale pinches out, and the overlying Pictured Cliffs Sandstone rests directly on the Cliff House Sandstone. The two sandstones are undivided in a very small area about 8 miles east of Newcomb.

Age Assignment and Correlation

Aside from ubiquitous *Ophiomorpha* and sharks' teeth, fossils were not found in the Cliff House during the present investigation. Fossils have been collected for previous studies from the upper part of the Cliff House Sandstone near the east border of the Navajo Indian Reservation and near the southernmost limit of the formation (Reeside, 1924, p. 15, locs. 9743, 9744) but are not diagnostic as to the age of the Cliff House. In the absence of diagnostic fossils in the Navajo country, the age of the Cliff House must be based on an estimate of the rate of transgression, as determined from the regional age relations. At the type locality, in Colorado, the Cliff House Sandstone contains fossils of early Pierre age (W. A. Cobban, written commun., 1966). The Cliff House is progressively younger to the southwest; hence, in the Captain Tom Wash area, the Cliff House may be as young as middle Pierre.

LEWIS SHALE

Throughout most of the San Juan Basin, the distinctive Lewis Shale separates the transgressive deposits of the upper part of the Mesaverde Group from the Pictured Cliffs Sandstone, which was deposited during the final major marine regression from the Navajo country. In general, the Lewis is a wedge of marine shale tapering to a featheredge toward the southwest. Like the Mancos, the Lewis Shale is an offshore facies that is equivalent to rocks of nearshore and continental facies deposited to the southwest. The nearshore and continental deposits, partly equivalent to the upper part of the Lewis, are in the Pictured Cliffs Sandstone and in the overlying nonmarine coal-bearing Fruitland Formation and barren Kirtland Shale.

The Lewis Shale was named by Cross, Spencer, and Purington (1899, p. 5) from exposures at Fort Lewis, an old Army post in the La Plata River valley of southwestern Colorado, about 8 miles southeast of Mancos. These above-mentioned authors described the formation as a "body of more or less sandy shales and clays with occasional thin layers of impure limestone, or of concretionary masses at several different horizons" and assigned to it a thickness of 2,000 feet.

The Lewis crops out in an arcuate band that extends from the northeastern part of the Navajo Indian Reservation at the San Juan River to the east boundary of the mapped area near Coal Creek (pl. 1). Throughout much of its extent, shaly beds of the Lewis are poorly exposed and, in part, lie within the broad valley of the Chaco River.

Where present in the Navajo Indian Reservation, the Lewis Shale forms a barrier that prevents mixing of the ground water in the underlying Cliff House and in the overlying Pictured Cliffs Sandstone. There is a progressive northward increase in the total dissolved-solids content of the water in both units. This increase is pronounced in the Pictured Cliffs Sandstone; near Moncisco Mesa the water contains more than 10,000 parts per million of total dissolved solids and is unfit for watering stock. However, water of suitable chemical quality may be obtained locally by drilling deeper through the impermeable Lewis Shale and into the Cliff House Sandstone.

GENERAL DESCRIPTION AND FIELD RELATIONS

In the Navajo country, the Lewis Shale ranges in thickness from about 500 feet in the vicinity of the San Juan River to zero in the vicinity of Hunter Wash. Where the outcrop band of the Upper Cretaceous rocks swings eastward from the Hunter Wash area, the formation reappears, and its thickness increases eastward from a wedge edge to 67 feet at Coal Creek.

The Lewis is transitional downward with the Cliff House Sandstone. In the vicinity of the San Juan River, the basal transitional zone is 50–100 feet thick and consists of thinly interbedded shale and very fine grained sandstone. Above this zone is an interval 350–450 feet thick in which the rocks are predominantly light-gray (*N* 7) to dark-olive (*N* 3) and olive-gray (5*Y* 4/1) claystone and siltstone that contain a few thin sandy zones and scattered beds of impure concretionary limestone. The upper 100–150 feet of the formation is mostly shale that contains an increasing abundance upward of thin, platy tan fine-grained bench-forming sandstone beds. These are more massively bedded near the top of the formation and in the basal part of the overlying Pictured Cliffs Sandstone. Where sandstone predominates, the interbedded sandstone and shale is mapped with the Pictured Cliffs Sandstone. Where the Lewis becomes thinner to the south, it consists entirely of interbedded shale and sandstone, and the formation contains enough shale to be identified as far south as Hunter Wash.

AGE ASSIGNMENT AND CORRELATION

The Lewis Shale is entirely of Montana age. According to W. A. Cobban (written commun., 1966), the age span of the Lewis Shale in the Durango, Colo., area (near the type locality) is from the zone of *Baculites mc learni* up into the zone of *Didymoceras cheyennense* (Gill and Cobban, 1965, fig. 3). This age span correlates roughly with the lower half of the Pierre Shale of the Western Interior reference

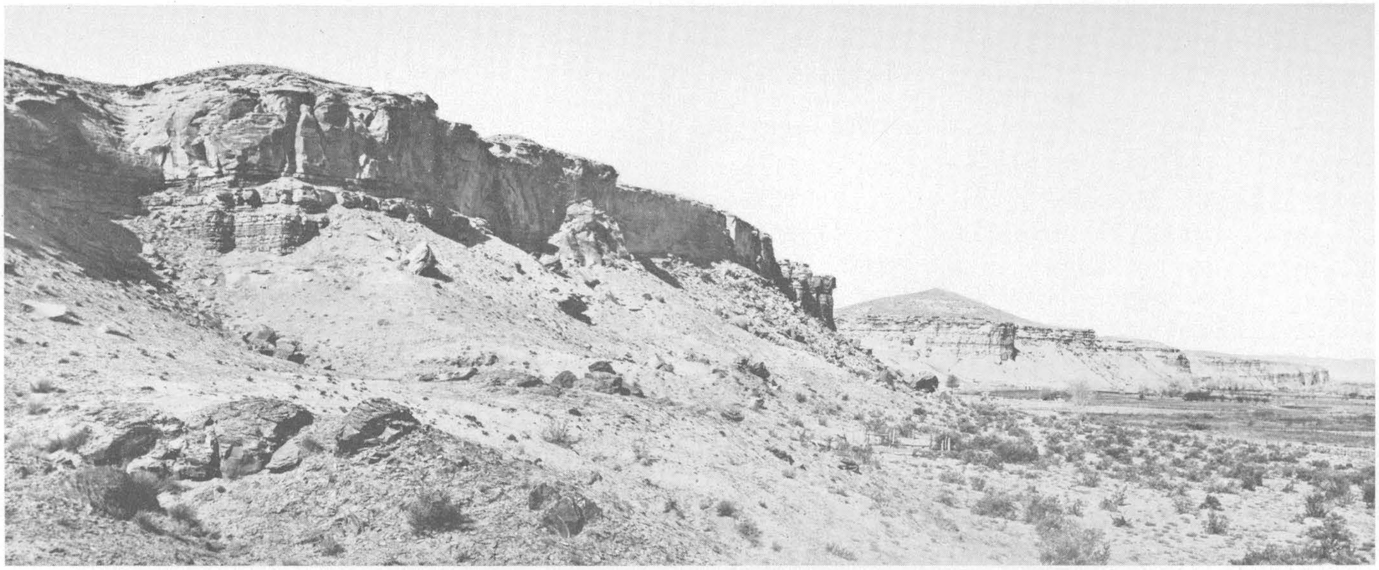


FIGURE 27.—Pictured Cliffs Sandstone along the south side of the San Juan River about 5 miles below Fruitland, N. Mex. Westward view, showing interbedded sandstone and shale of lower transition zone overlain by the massive cliff-forming unit. The Pictured Cliffs in this area is 320 feet thick.

sequence. Where the formation pinches out near Hunter Wash, it is probably middle Pierre in age, although this has not been confirmed by fossils.

PICTURED CLIFFS SANDSTONE

The Pictured Cliffs Sandstone was first described and named by Holmes (1877, pl. 35) for exposures 1 mile west of Fruitland, N. Mex., and north of the San Juan River. Holmes, according to Reeside (1924, p. 18), evidently included only the massive sandstone ledges and he excluded the underlying interbedded shale and sandstone. Consequently, he assigned only 140 feet of rocks to the formation. Reeside (1924, p. 18) included part of the underlying transitional zone in the Pictured Cliffs, and his definition is used in this report.

South of the San Juan River, the Pictured Cliffs Sandstone is nearly horizontal, and it crops out across the area in an irregular arcuate band that is open to the northeast. The Pictured Cliffs Sandstone is only moderately resistant to erosion; in most places, it is exposed in a line of low cliffs between the more nearly level land formed on the underlying Lewis Shale and the overlying Fruitland Formation.

GENERAL DESCRIPTION AND FIELD RELATIONS

When the Cretaceous sea began its final retreat, nearshore and beach deposits of the Pictured Cliffs Sandstone were deposited along its margin. This unit is similar in character and origin to the Point Lookout Sandstone of the Mesaverde Group. Within the report area the lithology of the Pictured Cliffs Sandstone differs only in detail. Near the San Juan River (fig. 27), the Pictured Cliffs is about 300 feet thick; the lower two-thirds of the formation consists of alternating thin beds of yellowish-gray (5*Y* 8/1) to moderate-brown (5*YR* 3/4) fine-grained to very fine grained sandstone and light-gray (*N* 7) to dark-gray (*N* 3) silty shale. The sandstone beds increase in number and thickness upward and in the uppermost 80–90 feet, they are as much as 15 feet thick. The upper cliff-forming part of the Pictured Cliffs consists of yellowish-gray (5*Y* 7/2) to grayish-orange (10*YR* 7/4) sandstone that weathers tan and is fine to medium grained, thick bedded, and cross-bedded.

The Pictured Cliffs thins rapidly southward from the San Juan River because of intertonguing of part of the massive cliff-forming upper sandstone with the overlying Fruitland Formation. About 7 miles south of the San Juan River, the formation is 132 feet thick (Reeside, 1924, p. 65, 66); the lower 32 feet consists mainly of shale and thin sandstone beds that might well be included in the Lewis Shale. About 1 mile north of Sanostee Wash and west of the Chaco River, an outlier of Pictured Cliffs that is exposed in a small low butte consists of only 20 feet of interbedded sandstone and shale and of 19 feet of soft, very light gray fine-grained sandstone. The top of the butte is capped by red, clinkered shale, presumably part of the Fruitland Formation. Bauer (1917, pl. 65) reported 49 feet of Pictured Cliffs at Brimhall Wash, in the vicinity of Burnham. Eastward from Brimhall Wash, the formation thickens and is 66 feet thick along Coal Creek at the east border of the Navajo Indian Reservation.

AGE ASSIGNMENT AND CORRELATION

The Pictured Cliffs Sandstone in the San Juan Basin is middle Montana in age. Reeside (1924, p. 19) stated that the Pictured Cliffs "includes species of *Inoceramus* not known in the latest Montana fauna of other regions, such as that of the typical Fox Hills sandstone and it completely lacks, so far as now known, the typical Fox Hills forms." In the Durango area, the youngest fossils from the underlying Lewis Shale lie in the zone of *Didymoceras cheyennense,* and, therefore, the Pictured Cliffs Sandstone in the same area might be as young as the zone of *Baculites compressus* (Gill and Cobban, 1965, fig. 3). Fauna listed by Reeside (1924, pl. 3) from the middle part of the formation south of Durango (loc. 10502) and along the San Juan River (loc. 9278) contain *Inoceramus barabini* and *Inoceramus sagensis,* and this association also suggests the zone of *Baculites compressus* from the middle of the Pierre Shale of the standard reference sequence.

Sometime during the depositional period of the Lewis Shale it appears that landmasses began to rise to the north of the present San Juan Basin (Dane, 1946) in the initial stage of the Laramide Revolution. As these highlands developed, they became new sources of sediments, and their influence is progressively greater in the younger deposits of the San Juan Basin. However, the intertonguing relationships of the Pictured Cliffs with both the underlying Lewis and the overlying Fruitland Formation (Hayes and Zapp, 1955) suggest that the Pictured Cliffs within the report area and in nearby areas was derived from southwestern sources, which was also the direction to the source areas for the Mesaverde Group. The intertonguing relationships also indicate that the Pictured Cliffs in the Navajo Indian Reservation is increasingly younger in a northeasterly direction, although the difference in age across the area does not seem to be large.

FRUITLAND FORMATION

The Fruitland Formation conformably overlies the Pictured Cliffs Sandstone. The formation was named by Bauer (1917, p. 274) for the town of Fruitland, N. Mex., which is located on the outcrop at the San Juan River.

Because of low dips, the outcrop band of the Fruitland Formation is as much as 4 miles wide. The lower contact is gradational through a thin carbonaceous mudstone or carbonaceous sandstone, about 1–2 feet thick, that rests on the Pictured Cliffs Sandstone. The upper contact with the Kirtland Shale is gradational and arbitrary. The Fruitland Formation does not contain enough water to make it useful as a supply for stock wells.

GENERAL DESCRIPTION AND FIELD RELATIONS

The Fruitland Formation consists of a highly variable sequence of intercalated sandstone, siltstone, mudstone, and coal. The siltstone and mudstone are dusky yellow (*5Y* 6/4) to moderate brown (*5YR* 3/4). Mudstone units may be as much as 50 feet thick, but most are 5–20 feet thick. Carbonaceous mudstone and siltstone, carbonized plant remains, and iron-rich concretions, some with veins of barite, are common in places.

Sandstone beds are generally very light gray (*N* 8) to moderate brown (*5YR* 4/4) and composed of very fine to medium subround to subangular quartz grains. Dark ferromagnesian minerals and weathered feldspars are present in minor amounts. In general, bedding is irregularly flat, although some crossbedding is present. The beds are lenticular and grade both laterally and vertically into siltstone or mudstone. Some sandstone beds are well cemented by calcium carbonate or limonite and stand up as ledges; other beds are friable and weather into a maze of pillars, knobs, and other badland forms (fig. 28).

Coal is present throughout the Fruitland Formation, but the thickest, most persistent beds are in the lower part of the formation. Coal beds as much as 15 feet thick are present within the lower 50 feet of the formation. The formation contains almost one-third of New Mexico's total estimated coal reserves (Read and others, 1950, table 14).

FIGURE 28.—Fruitland Formation, west of Bisti, at Hunter Wash, showing unequal weathering characteristics of sandstone beds in the lower part of the formation.

The upper part of the formation is appreciably more shaly than the lower part. The upper part of the formation grades, in turn, into the Kirtland Shale. The top of the formation is arbitrarily placed at the highest persistent sandstone bed. Some local differences in thickness of the formation reflect differences in horizons selected for the upper contact; nevertheless, the formation thins generally southward from 420 feet at the San Juan River to 275 feet at Hunter Wash.

KIRTLAND SHALE

The Kirtland Shale conformably overlies the Fruitland Formation. It was named by Bauer (1917, p. 274) for the town of Kirtland, N. Mex., located on the outcrop at the San Juan River. The Kirtland Shale contains lower and upper shale members and a middle sandy part which Bauer (1917, p. 274) named the Farmington Sandstone Member, for the town of Farmington, N. Mex. Locally, a small amount of water of poor chemical quality is produced from the Farmington Sandstone Member between the San Juan River and Moncisco Mesa.

Throughout the area the Kirtland Shale is almost flat lying and is exposed in a broad band as much as 12 miles wide. Soft, easily eroded shale members that make up parts of the formation weather into extensive, intricately dissected badlands. The middle, or Farmington Sandstone Member, however, is resistant and forms prominent bluffs and isolated buttes.

GENERAL DESCRIPTION AND FIELD RELATIONS

The lower shale member of the Kirtland Shale consists of silty and sandy mudstone and a few thin sandstone beds. The mudstone units are light olive gray (5*Y* 5/2) to greenish gray (5*GY* 6/1). Fine-grained to very fine grained sandstone beds about 1–2 feet thick occur throughout the lower shale member. These beds are lenticular and of small lateral extent, and most are covered by slope wash from the overlying shale units.

The lower shale member is 310 feet thick at the San Juan River, 550 feet thick at Brimhall Wash, and more than 1,000 feet thick at Hunter Wash. Most of the increase in thickness occurs at the expense of the overlying Farmington Sandstone Member. The contacts of the lower shale member with adjacent units are transitional.

The Farmington Sandstone Member, which is the middle member of the formation, consists of interbedded sandstone, siltstone, and mudstone. The sandstone beds are ledge and cliff forming, and are dusky-yellow (5*Y* 6/4), yellowish-gray (5*Y* 7/2), and dark-yellowish-orange (10*YR* 6/6), fine- to medium-grained quartz sandstone containing minor amounts of weathered feldspar and dark ferromagnesian minerals. The grains are poorly sorted and subangular to angular. Sandstone beds are well indurated and cemented by calcium carbonate or limonite. The beds are medium to thick, irregular and crossbedded, and very lenticular. Interbeds are made up of greenish-gray (5*G* 6/1) and yellowish-gray (5*Y* 7/2) mudstone lenses that thin or thicken rapidly along the outcrop.

The Farmington Sandstone Member is 580 feet thick at the San Juan River, 450 feet at Brimhall Wash, and 90 feet thick on the divide between Hunter Wash and Ojo Alamo Arroyo, about 10 miles northeast of Bisti.

The upper shale member of the Kirtland consists of various proportions of sandstone and mudstone that commonly form a slope between the top of the Farmington Sandstone Member to the base of the Ojo Alamo Sandstone. The mudstone is similar to the mudstone of the lower shale member of the Kirtland Shale and is commonly greenish gray (5*GY* 6/1), although it locally contains minor bands of mudstone that are purple and dark gray. The sandstone is very fine to fine grained and is similar to sandstone beds of the Farmington Sandstone Member, but with less argillaceous matrix. The beds also have much less cement than sandstone beds in the Farmington Sandstone Member and tend to be friable and to weather in much the same manner as the intercalated mudstone beds, especially in cliffs capped by the overlying Ojo Alamo Sandstone. A thin layer of siliceous pebbles was found 35 feet below the top of the upper member of the Kirtland Shale at a locality 1 mile south of the San Juan River, in sec. 20, T. 29 N., R. 13 W; however, no other such pebbles were noted elsewhere on the Navajo Indian Reservation. This is in contrast to the area north of the San Juan River, where abundant siliceous pebbles occur in the uppermost part of the Kirtland Shale (Hayes and Zapp, 1955; Barnes and others, 1954).

Reeside (1924, pl. 2) reported 475 feet in the upper shale member of the Kirtland at the Colorado–New Mexico State line. The member is 92 feet thick at the San Juan River. This indicates thinning of 383 feet from the State line to the San Juan River. Most of this apparent thinning is the result of placing the base of the upper member at different stratigraphic horizons in the two areas. Along the road between Farmington and Bisti, just south of the river, as much as 200 feet of slope-forming shale and sandstone might well be included in the upper shale member; however, they were included in the

Farmington because westward along the San Juan River and within the mapped area, sandstone beds in the lower part of the upper shale member equivalent become ledge formers and are, therefore, part of the Farmington of this report. The upper shale member of the Kirtland is 67 feet thick on Moncisco Mesa near the head of Brimhall Wash.

Until about 1960 the available stratigraphic information, particularly the fossil evidence, indicated that the Kirtland Shale was entirely of fluviatile origin. In 1960, however, Dilworth (1960) found a small collection of foraminifera in the middle of the Farmington Sandstone Member on the south side of the San Juan River southwest of Farmington and on the Navajo Indian Reservation. The foraminifera, although poorly preserved, were identified as a shallow-marine or marine-brackish-water assemblage. Although the main Cretaceous sea stood far to the east, these fossils suggest that there may have been a temporary but rapid incursion of an arm of the sea into the Navajo country for a short time during the deposition of the Farmington Sandstone Member.

The contact between the Fruitland Formation and the Kirtland Shale varies in its stratigraphic position in short distances because of the intergradational relations of the two formations. As a result, the combined Kirtland and Fruitland thickness gives a more reliable indication of regional thickness trends than do the measurements of the formations individually. Reeside (1924, pl. 2) reported a total thickness of 1,051 feet along the San Juan River for the combined Kirtland and Fruitland. During the present investigation, the section was remeasured with the aid of detailed river survey maps and well information, which were unavailable to Reeside. The thickness of the combined Kirtland and Fruitland was found to total about 1,400 feet. Reeside (1924, pl. 2) reported 1,595 feet for the combined Kirtland and Fruitland at the State line. This agrees reasonably well with the 1,635 feet measured for the same interval about 3 miles southwest of Bridge Timber Mountain in the Red Mesa area, just north of the Colorado–New Mexico State line (Barnes and others, 1954). Hence, there is a lateral thinning of about 200 feet in 20 miles for the total Kirtland and Fruitland from the State line to the San Juan River. The combined Kirtland and Fruitland thins slightly south of the river, and Reeside (1924, pl. 2) reported a total thickness of 1,314 feet at Brimhall Wash—or an additional thinning of about 100 feet in 20 miles.

Bauer (1917) and Bauer and Reeside (1921) defined the Kirtland Shale as being overlain by the Ojo Alamo Sandstone in the area south of the San Juan River. Subsequent work by Reeside (1924, p. 24), to the north, established the presence of an intervening unit he named the McDermott Formation for exposures along McDermott Arroyo in La Plata County, Colo. The McDermott, now a member of the Animas Formation (Barnes and others, 1954), at the type locality in Colorado consists of a sequence of sandstone; purple, yellow, and bluish-gray tuffaceous shale; andesite cobble conglomerate; and conglomeratic beds composed of quartz, quartzite, and chert pebbles. According to Reeside (1924, p. 25), the McDermott south of the San Juan River is equivalent to the uppermost part of the Kirtland Shale, as used by Bauer (1917) and Bauer and Reeside (1921). In the area south of the San Juan River, it is 30–50 feet thick and does not greatly resemble the McDermott of the type locality, except for the presence of andesitic debris (Reeside, 1924, p. 25). It was, apparently, on the basis of this andesitic debris that Reeside traced his McDermott Formation from the Farmington area southward to a point about 8 miles southeast of Ojo Alamo Arroyo. Reeside (1924, p. 51) assumed that andesitic debris appeared suddenly in the succession of rocks only after the deposition of the Kirtland Shale and that it was, therefore, a reliable criterion for identification of his McDermott Formation. Recent studies, however, have disclosed that andesitic debris at least 300 feet below the top of the Kirtland Shale is present in the area immediately north of the San Juan River, and that the McDermott Member of the Animas Formation, as now defined, is not present south of the San Juan River. Accordingly, in this report, all the rocks from the top of the Farmington Sandstone Member to the base of the Ojo Alamo Sandstone throughout the Navajo Indian Reservation are included in the upper member of the Kirtland Shale.

AGE ASSIGNMENT AND CORRELATION

Extensive paleontological collections were made from the Fruitland Formation and the Kirtland Shale in the area south of the San Juan River by field parties of the U.S. Geological Survey in the years 1915–16. The flora and fauna were described, and the correlation of the Kirtland and Fruitland sequence was discussed by Stanton (1917), Gilmore (1917, 1919), and Knowlton (1917, 1924). Reeside (1924, p. 24) summarized all information concerning the paleontology of the Kirtland and Fruitland sequence and considered the Fruitland Formation and the Kirtland Shale to be of late Montana age.

Cobban and Reeside (1952) considered the Fruitland Formation and Kirtland Shale south of the San Juan River to be of Montana age and to be equivalent to the upper part of the Pierre Shale and the lower part of the Fox Hills Sandstone of their standard reference sequence for the Western Interior. They noted (1952, p. 1028), however, that some vertebrate paleontologists consider the Kirtland and Fruitland sequence to be older.

Plants identified by R. W. Brown (in Repenning, 1954) from the Kirtland and Fruitland sequence along the eastern flank of the Chuska Mountains (J. B. Reeside, Jr., field No. 5310) confirm the age assignment made by Cobban and Reeside (1952).

TERTIARY OJO ALAMO SANDSTONE

The name Ojo Alamo Sandstone has been applied in various ways to a sequence of sandstone, shale, and conglomerate that crops out along Ojo Alamo Arroyo east of the Navajo Indian Reservation. The strata along the arroyo that have been included by some workers in the Ojo Alamo Sandstone contain numerous fossils of Cretaceous age. For many years the Ojo Alamo has been assigned to the Cretaceous, and this age designation was accepted at the time the fieldwork for this report was done. Consequently, the unit is discussed in this section of the report on the hydrogeology of the Navajo and Hopi Indian Reservations, despite the fact that the Ojo Alamo Sandstone has since been redefined and assigned to the Tertiary (Baltz and others, 1966).

The type locality of the Ojo Alamo Sandstone is about 12 miles southeast of Moncisco Mesa (pl. 1). There, along Ojo Alamo Arroyo, a tributary to Coal Creek, the strata have the following arrangement:

Generalized section of rocks exposed along Ojo Alamo Arroyo

Top.

Unit 5. Shale and siltstone, predominantly various shades of gray, but locally banded buff, brown, and red; contains tan and white lenticular, generally friable sandstone beds. Unit forms extensive slopes and badlands.

Unit 4. Sandstone, tan, fine- to coarse-grained and conglomeratic; contains numerous silicified logs. Unit is about 45 ft thick; forms rounded bluffs. Several springs issue from the unit, and ruins of an old store, called Ojo Alamo, stand on it.

Unit 3. Shale, banded gray and purple, and lenticular friable grayish-white sandstone beds. Unit is 0–50 ft thick; forms a slope.

Unit 2. Sandstone, buff, fine- to coarse-grained and conglomeratic. Unit is as much as 15 ft thick; forms a slight ledge.

Unit 1. Shale, greenish-gray, and some buff lenticular sandstone beds. Uppermost part, at places, is banded gray and purple. Unit forms a slope.

Base.

Barnum Brown, of the American Museum of Natural History, investigated this area while looking for fossils, and he described the strata in the following manner (Brown, 1910, p. 268):

> Less than a mile south of the store at Ojo Alamo the Puerco formation rests unconformably on a conglomerate that is composed of red, gray, yellow and white pebbles. * * * Below the conglomerate there is a series of shales and sandstones evenly stratified and usually horizontal. * * * The shales below the conglomerate that contain numerous dinosaur and turtle remains I shall designate as the Ojo Alamo beds.

The store at Ojo Alamo (now in ruins) was built on unit 4, and the conglomerate "less than a mile south of the store" would be unit 2. The "shales below the conglomerate," which Brown termed "Ojo Alamo beds," is unit 1. A lower limit was not given to the "Ojo Alamo beds," but Brown (1910, p. 268) stated that they "were estimated to be about 200 feet thick, but owing to lack of time was unable to determine their relation to the underlying formations." Brown's "Puerco formation" included units 5, 4, and 3. The lower conglomerate, unit 2, was unnamed by Brown and, apparently, was assigned to neither the Puerco nor the Ojo Alamo.

Shortly after Brown's work, Sinclair and Granger (1914), of the American Museum of Natural History, made a more extensive study of these rocks. In the Ojo Alamo area they (Sinclair and Granger, 1914, p. 300–302, fig. 2) recognized (with reference to the generalized section) "Shales with Dinosaurs, Lower Horizon" (unit 1); a "Lower Conglomerate" (unit 2); "Shales with Dinosaur, Upper Horizon" (unit 3); a "Conglomeratic Sandstone with Fossil Logs" (unit 4), all unconformably overlain by "the Puerco formation" (unit 5). The "Conglomeratic Sandstone with Fossil Logs" is clearly unit 4, as a photograph (Sinclair and Granger, 1914, pl. 21) shows the old store at Ojo Alamo on this unit. Sinclair and Granger (1914, fig. 3) therefore included in their "Ojo Alamo beds of Brown" units 1, 2, 3, and 4, whereas Brown originally recognized only unit 1 as his "Ojo Alamo beds." Sinclair and Granger, like Brown, gave no lower limit to the "Ojo Alamo beds."

Subsequently, Bauer (1917) concluded that the Ojo Alamo should be redefined because of discrepancies in descriptions of the unit and because of failure of previous investigators to assign a lower limit to it. Regarding the Ojo Alamo, Bauer (1917, p. 276) stated that as he found the formation "to be essentially a sandstone including lenses of shale and conglomerate, it seems desirable to call it Ojo Alamo sandstone and to define it as consisting on Ojo Alamo Arroyo of two conglomeratic beds [units 2 and 4 of generalized section] and the shale lenses [unit 3] which they include." Bauer further defined the Ojo

Alamo to be unconformably overlain by the "Puerco formation" (unit 5), to be conformably underlain by Kirtland Shale (unit 1), and to be assigned to the Cretaceous.

Subsequent workers (Reeside, 1924; Dane, 1936) who mapped these rocks followed Bauer's usage of Ojo Alamo Sandstone. Reeside (1924, p. 32), however, assigned the Ojo Alamo to the Tertiary (?), and Dane (1936, p. 121) reassigned it to the Cretaceous. Dane (1946) applied the name Nacimiento Formation to the beds overlying the Ojo Alamo Sandstone, following Gardner's (1910) usage.

Recent work by Anderson (1960) and Baltz (1962) on the east side of the San Juan Basin near Cuba reopened the question of the age of the Ojo Alamo Sandstone. Anderson (1960, fig. 1, p. 13) assigned the Ojo Alamo to both the Cretaceous and the Tertiary; Baltz (1962, p. 108) assigned it to the Tertiary(?). Baltz (1962, p. 101–108) summarized all the information on the age of the Ojo Alamo Sandstone and concluded that the differences in the age assignment have been the result of inclusion in the Ojo Alamo of lithologically similar rocks that actually are of different ages.

Baltz, Ash, and Anderson (1966) reexamined the type locality of the Ojo Alamo Sandstone to reconcile the discrepancies. They found that the upper conglomerate (unit 4) rests with erosional unconformity on the beds below, and that it grades upward by intertonguing with the overlying Nacimiento Formation. In addition, apparently only the upper conglomeratic sandstone (unit 4) is equivalent to that previously mapped as Ojo Alamo Sandstone in other parts of the San Juan Basin. The paleontological and physical evidence (Baltz and others, 1966) indicates that unit 4 is of Paleocene age, in contrast to the Cretaceous age of the underlying beds (units 2 and 3).

Consequently, Baltz, Ash, and Anderson (1966) restricted and redefined the Ojo Alamo Sandstone at the type locality to include only the upper conglomerate (unit 4). Underlying units 2 and 3, previously assigned to the Ojo Alamo Sandstone, were redefined (Baltz and others, 1966) as the Naashoibito Member of the Kirtland Shale. In the Ojo Alamo Arroyo area the Naashoibito Member is mapped with the upper shale member of the Kirtland Shale (pl. 1).

From the Ojo Alamo Arroyo, the beds can be traced westward about 6 miles to the head of Hunter Wash. There, the beds have the same stratigraphic arrangement as at Ojo Alamo Arroyo. The Naashoibito Member of the Kirtland Shale consists of a lower, sparsely conglomeratic sandstone, 10 feet thick, overlain by a shale unit about 20 feet thick. The Naashoibito Member is overlain by the Ojo Alamo Sandstone, which, there, is at least 25 feet thick, but the top is not exposed. Westward, the Ojo Alamo Sandstone and underlying beds are poorly exposed for about 6 miles, from the head of Hunter Wash to the outcrops at the south end of Moncisco Mesa. The Ojo Alamo Sandstone rests on the upper shale member of the Kirtland Shale at Moncisco Mesa, and the Naashoibito Member apparently is absent.

GENERAL DESCRIPTION AND FIELD RELATIONS

In the mapped area the Ojo Alamo Sandstone, where exposed, is well indurated and forms prominent cliffs along the San Juan River and along Moncisco Mesa. It consists of predominantly light-brown (5*YR* 6/4) fine- to coarse-grained conglomeratic (fig. 29) crossbedded sandstone. Thin lenses of light-olive-gray (5*Y* 6/1) mudstone occur sparsely throughout the sandstone. Pebbles and cobbles in the Ojo Alamo Sandstone are subround and are as much as 6 inches across. Reeside (1924, p. 29) found that two-thirds of the pebbles were quartz or chert and the other one-third were silicified igneous rocks of various kinds. Numerous silicified limestone pebbles, some containing late Paleozoic fossils, were found during the present investigation. Pebbles are very common throughout the mapped area, which contrasts with their rarity along the southeast side of the San Juan Basin (Dane, 1936, p. 117). The base of the Ojo Alamo is a sharp wavy surface of erosion; the coarse conglomeratic Ojo Alamo contrasts distinctly with the mudstones and soft sandstones of the underlying Kirtland Shale.

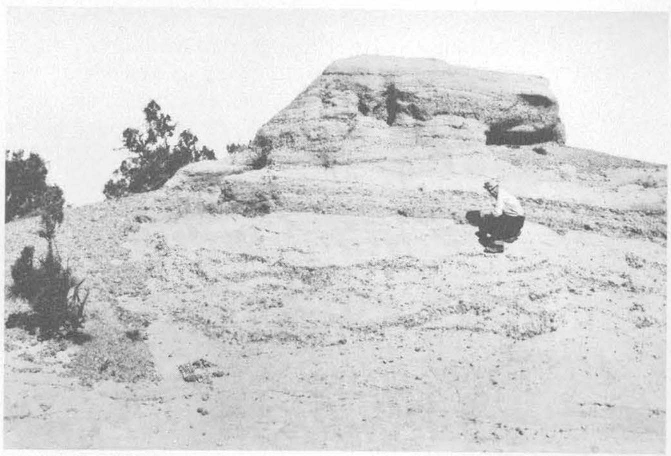


FIGURE 29.—Lower conglomeratic part of the Ojo Alamo Sandstone in cliffs south of Farmington, near the road between Farmington and Bisti.

The Ojo Alamo Sandstone is about 110 feet thick at Moncisco Mesa. The lower part is well exposed along the steep west face of the mesa; the upper part weathers back at the top of the mesa, and the top is mostly concealed. The Ojo Alamo Sandstone is poorly exposed between Moncisco Mesa and the San Juan River along the line of outcrops that mark the present western limit of the sandstone. East of this line of outcrops, however, the Ojo Alamo Sandstone crops out continuously (pl. 1) from along Gallego Arroyo to the line of cliffs along the San Juan River.

At the San Juan River, the Ojo Alamo Sandstone overlies the Kirtland Shale and consists of a lower cliff-forming conglomeratic sandstone 110 feet thick that is equivalent to the Ojo Alamo at Moncisco Mesa and at the type locality. Just south of Farmington along the road between Farmington and Bisti, the lower cliff-forming sandstone is overlain by a mudstone unit 10 feet thick that in turn is overlain by an upper conglomeratic sandstone, 90 feet thick. The mudstone unit between the upper and lower conglomeratic sandstones thickens to the south and west and merges with the Nacimiento Formation, and thus is a tongue of that formation; the upper conglomerate also grades laterally into the Nacimiento Formation in the same direction, and about 5 miles southwest of Farmington in the NE¼ sec. 36, T. 29 N., R. 14 W., where rocks assigned to the Ojo Alamo Sandstone are 120 feet thick, the upper conglomeratic sandstone is no longer recognizable.

Traced eastward about 3 miles from the road between Farmington and Bisti, the mudstone unit between the upper and lower conglomeratic sandstones thins and pinches out, and the upper and lower conglomeratic sandstones merge to form an unbroken sequence about 200 feet thick. In the same area along the San Juan River, Reeside considered the Ojo Alamo to be 400 feet thick. In this report, only the lower 220 feet of rocks described by Reeside (1924, p. 62) are included in the Ojo Alamo Sandstone. The rest is assigned to the Nacimiento Formation.

AGE ASSIGNMENT AND CORRELATION

On the Navajo Indian Reservation, the Ojo Alamo Sandstone has yielded a few fragmentary plant remains at one fossil locality (Bauer, 1917, No. 44, pl. 64) on Moncisco Mesa. These were examined by Knowlton (1917, p. 329), who reported as follows:

> The material in the single collection from the Ojo Alamo beds [Ojo Alamo Sandstone of this report] is so fragmentary that it cannot be identified with satisfaction. It includes portions of a large leaf of unknown affinity, a small willow-like leaf, and a large leaf that appears to be an Aralia of the type or *Aralia notata* Lesquereux, a species very abundant and widely distributed in the Fort Union formation. Nothing like this has been noted in the underlying beds, and to a certain extent it argues for the Tertiary age of the Ojo Alamo beds, though obviously the evidence is not strong. For the present, therefore, the dictum based on the evidence of the fossil vertebrates that these beds cannot be separated from the underlying beds must be accepted, though the writer cannot escape the impression that they may ultimately be shown to be of Tertiary age.

The vertebrate remains, mentioned by Knowlton, were all collected from the vicinity of Ojo Alamo Arroyo and described in several reports (Brown, 1910; Sinclair and Granger, 1914; Gilmore, 1917, 1919). It is now clear (Baltz and others, 1966) that all the vertebrate material, with one exception, was collected from the Naashoibito Member of the Kirtland Shale or underlying rocks and not from the redefined (restricted) Ojo Alamo Sandstone. The one exception was a fossil that was found on the surface of the Ojo Alamo Sandstone (restricted) and was described by Sinclair and Granger (1914, p. 301) as "the centrum of a dinosaurian caudal vertebra * * * found, loose on the surface * * *. It was not in place * * *. Some may question its value as an index fossil."

Baltz, Ash, and Anderson (1966) showed that the known dinosaurian-bearing beds at Ojo Alamo Arroyo are separated by an erosional unconformity from the overlying conglomeratic sandstone that now constitutes the restricted Ojo Alamo Sandstone. At the type locality, the Ojo Alamo Sandstone intertongues with the Nacimiento Formation in an area where the Nacimiento Formation carries the classical Puerco fauna of Paleocene age. There is, in addition, microflorule evidence (Baltz and others, 1966) which, together with the interfingering stratigraphic relations, indicates that the Ojo Alamo Sandstone (restricted) is of Paleocene age.

Similar interfingering relations between the Ojo Alamo Sandstone and the Nacimiento Formation are also well displayed in the Farmington area, where, heretofore, the relationship of the two formations has been poorly understood (Hayes and Zapp, 1955). The Ojo Alamo thins gradually northward along the La Plata River and pinches out into the Nacimiento about 9 miles north of Farmington. Near the pinchout, the Ojo Alamo is overlain and underlain by the Nacimiento Formation (O'Sullivan and Beikman, 1963).

In the area about 2 miles south of Farmington, two significant lots of fragmentary plants have been collected from the Ojo Alamo Sandstone east of the Navajo Indian Reservation. One of these lots was found by Bauer at a fossil locality (Bauer, 1917, No. 9, pl. 64) about 100 feet above the base of the Ojo Alamo (mistakenly called the Wasatch Formation by Bauer, 1917, pl. 64). The plants were examined by F. H. Knowlton (in Bauer, 1917, p. 278), who reported:

> This material is very fragmentary. It includes, apparently, two ferns, one Pteris-like and the other Anemia-like, but neither is sufficiently well preserved to be identified. There is also a monocotyledon that may be a palm ray or a large leaf of a sedge. The only dicotyledon present is a Sapindus not unlike a large leaflet of *S. angustifolia* Lesquereux, a Green River species.
>
> This lot appears to be Tertiary, but is too fragmentary to place positively.

Another collection was made by J. B. Reeside, Jr., at a locality very close to the one just described. It was examined by Knowlton (in Reeside, 1924, p. 31, 32), who reported that:

> 2 miles south of Farmington, N. Mex.; horizon 25 feet above the base of the Ojo Alamo sandstone, * * * I note the presence of a peculiar fern that is probably an *Anemia*, but it can not be fixed with certainty. There are also at least two types of dicotyledonous leaves, a small one that seems to be a *Sapindus* of the type of *Sapindus affinis* Newberry (a Fort Union species) and a larger one that strongly suggests an undescribed species of *Ficus* from the Dawson arkose of Colorado.

The flora examined by Knowlton from the localities south of Farmington and in the Moncisco Mesa area have previously only suggested a Tertiary age. The presence of *Sapindus* now appears to be especially significant, for Anderson (1960, p. 9) noted that it is highly probable that *Sapindus* is an index fossil of Paleocene age in the Rocky Mountain area. *Sapindus* apparently has nowhere been found in beds known to be Cretaceous. Anderson (1960, p. 9) reported that "*Sapindus* has been found in such Paleocene beds as the Tullock-Ludlow, Fort Union, Raton, Denver, and the upper part of the Animas formation. Its presence in the Ojo Alamo sandstone certainly favors Paleocene age for that unit."

The paleontological evidence and the interfingering relations with the Nacimiento Formation indicate that the Ojo Alamo Sandstone on the west side of the San Juan Basin is Paleocene in age. The Kirtland Shale underlying the Ojo Alamo is of late, but not latest, Cretaceous age; it is apparently no younger than the lower part of the Fox Hills Sandstone of the standard reference sequence for the Western Interior. The entire *Triceratops* zone of latest Cretaceous age is not known to occur in the San Juan Basin, and the unconformity beneath the Ojo Alamo Sandstone apparently represents an important hiatus.

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