Stratigraphy of Slick Rock District and Vicinity San Miguel and Dolores Counties, Colorado

GEOLOGICAL SURVEY PROFESSIONAL PAPER 576-A

Prepared on behalf of the
U.S. Atomic Energy Commission

U.S. DEPARTMENT OF THE INTERIOR

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By DANIEL R. SHAWE, GEORGE C. SIMMONS, *and* NORBERT L. ARCHBOLD

GEOLOGICAL INVESTIGATIONS IN THE SLICK ROCK DISTRICT
SAN MIGUEL AND DOLORES COUNTIES, COLORADO

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A study of about 13,000 feet of strata of Paleozoic and Mesozoic age underlying the district forms the background for understanding the origin of uranium-vanadium deposits

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CONTENTS

ILLUSTRATIONS

[Plates are in separate map case]

TABLES

STRATIGRAPHY OF SLICK ROCK DISTRICT AND VICINITY, SAN MIGUEL AND DOLORES COUNTIES, COLORADO

By Daniel R. Shawe, George C. Simmons, and Norbert L. Archbold

ABSTRACT

The Slick Rock district covers about 570 square miles in western San Miguel and Dolores Counties, in southwestern Colorado. It is at the south edge of the salt-anticline region of southwestern Colorado and southeastern Utah and of the Uravan mineral belt.

Deposition of Paleozoic sedimentary rocks in the district and vicinity was principally controlled by development of the Paradox Basin, and of Mesozoic rocks by development of a depositional basin farther west. The Paleozoic rocks generally are thickest at the northeast side of the Paradox Basin in a northwest-trending trough which seems to be a wide graben in Precambrian igneous and metamorphic basement rocks; Mesozoic rocks generally thicken westward and southwestward from the district.

Sedimentary rocks rest on a Precambrian basement consisting of a variety of rocks, including granite and amphibolite. The surface of the Precambrian rocks is irregular and generally more than 2,000 feet below sea level and 7,000–11,000 feet below the ground surface. In the northern part of the district the Precambrian surface plunges abruptly northeastward into the trough occupying the northeast side of the Paradox Basin, and in the southern part it sags in a narrow northeasterly oriented trough. Deepening of both troughs, or crustal deformation in their vicinity, influenced sedimentation during much of late Paleozoic and Mesozoic time.

The maximum total thickness of sedimentary rocks underlying the district is 13,000 feet, and prior to extensive erosion in the late Tertiary and the Quaternary it may have been as much as about 18,000 feet. The lower 5,000 feet or more of the sequence of sedimentary rocks consists of arenaceous strata of early Paleozoic age overlain by dominantly marine carbonate rocks and evaporite beds interbedded with lesser amounts of clastic sediments of late Paleozoic age. Overlying these rocks is about 4,500 feet of terrestrial clastic sediments, dominantly sandstone with lesser amounts of shale, mudstone, siltstone, and conglomerate, of late Paleozoic and Mesozoic age. Above these rocks is as much as 2,300 feet of marine shale of late Mesozoic age. Perhaps about 5,000 feet of clastic sedimentary rocks, dominantly sandstone and in part shale, of late Mesozoic and early Cenozoic age, overlay the older rocks of the district prior to late Cenozoic erosion.

About 500–700 feet of dominantly marine clastic rocks of Cambrian age overlies Precambrian rocks. Light-gray to pinkish conglomeratic arkosic sandstone grades upward into interbedded shale, siltstone, dolomite, and sandstone, some of which is glauconitic.

From 250 to 550 feet of sandy thin-bedded dolomite and limestone with interbedded grayish-green and reddish sandy shale of Devonian age disconformably overlies Cambrian rocks.

Next higher strata consist of at least 240 feet of uniformly fine grained medium-gray limestone overlying dolomite of Early Mississippian (Kinderhook) age.

The Molas Formation of Pennsylvanian age consists of about 100 feet of interbedded reddish-brown, dark-gray, and greenish-gray shale and silty shale and gray fine-grained limestone.

Several thousand feet of marine strata consisting of a lower limestone member, Paradox Member (dominantly evaporites), and upper limestone member of the Hermosa Formation, Pennsylvanian age, disconformably overlies the Molas Formation. The lower limestone member consists of 100–150 feet of medium-gray very fine grained limestone containing some thin dark-gray shale interbeds. The lower unit of the Paradox Member consists of 50–200 feet of interbedded dark- to light-gray anhydrite, gray dolomite and limestone, dark-gray shale, gypsum, and halite. These strata are overlain by 2,900–4,150 feet of dominantly halite strata and minor interbedded gypsum, anhydrite, limestone, black shale, and sandstone composing the salt unit of the Paradox. The upper unit of the Paradox Member consists of 300–500 feet of interbedded gray limestone, dark-gray shale, gypsum, anhydrite, and halite. The upper limestone member of the Hermosa Formation is made up of 1,000–1,800 feet of thin- to thick-bedded light- to dark-gray fine- to medium-grained fossiliferous limestone interbedded with lesser amounts of dark-gray, gray, greenish-gray, and reddish-gray shale, and greenish-gray and reddish-gray very fine to fine-grained sandstone.

The Rico Formation of Pennsylvanian and Permian age consists of 130–240 feet of strata transitional between the underlying Hermosa Formation and overlying clastic beds. Because of its transitional nature the unit is poorly defined in the district.

Overlying the Rico Formation is as much as 3,000 feet of reddish-brown, orangish-brown, and light-brown arkosic terrestrial sandstone, siltstone, mudstone, and shale of the Cutler Formation of Permian age.

From 0 to 200 feet of chiefly light-reddish-brown micaceous siltstone and sandy siltstone of the Moenkopi Formation of Early and Middle(?) Triassic age disconformably overlies the Cutler Formation.

Next higher strata consist of several hundred feet of clastic terrestrial red beds of the Chinle Formation of Late Triassic age unconformably overlying the Cutler and Moenkopi Formations. The lowest, the Moss Back Member of the Chinle, consists of 20–75 feet of light-greenish-gray limy arkosic and quartzose sandstone and gray to greenish-gray limy sandstone (calcarenite) and conglomerate (calcirudite), with small amounts of

greenish-gray, and even less reddish-brown, mudstone, siltstone, and shale. The Petrified Forest(?) Member of the Chinle consists of 0–100 feet of greenish-gray mudstone, siltstone, and shale, with minor reddish-brown mudstone and greenish-gray sandstone and conglomerate. Unit 1, the so-called Black Ledge of the Church Rock Member, consists of 0–40 feet of chiefly light-reddish-brown to reddish-brown medium-fine, fine, and very fine grained sandstone and siltstone, in places interbedded with lenses of dark-reddish-brown and dark-greenish-gray sandstone and conglomerate. Unit 2 of the Church Rock consists of 200–275 feet of reddish-brown siltstone and sandstone, containing locally a few thin layers of dark-greenish-gray conglomerate. Unit 3 of the Church Rock Member, upper unit of the Chinle Formation, consists of 140–190 feet of reddish-brown, purplish-brown, and orangish-brown shaly siltstone and mudstone containing several thick beds of reddish-brown to orangish-brown generally structureless sandstone, silty sandstone, and siltstone.

From 200 to 400 feet of light-reddish-brown, light-orangish-brown, and light-buff fine grained to very fine grained eolian sandstone displaying large tangential crossbeds makes up the Wingate Sandstone of late Triassic age which disconformably overlies the Chinle Formation.

The Kayenta Formation of Late Triassic(?) age consists of 160–200 feet of largely reddish-brown to purplish-brown sandstone, shaly siltstone, shale, and conglomerate, showing sparse gray mottling in places.

Conformably overlying the Kayenta Formation is 0–420 feet of light-buff, locally light-reddish-brown, very fine grained to fine-grained sandstone with large-scale tangential eolian-type crossbeds which makes up the Navajo Sandstone of Triassic(?) and Jurassic age.

About 100–150 feet of tidal-flat siltstone and overlying eolian sandstone of the Entrada Sandstone of Late Jurassic age lies unconformably above the Navajo Sandstone. The lower unit, the Dewey Bridge Member, consists of 20–35 feet of reddish-brown clayey siltstone and very fine grained sandstone. The Slick Rock Member consists of 70–120 feet of light-brown or buff and light-reddish-brown chiefly very fine grained to fine-grained sandstone displaying large-scale tangential crossbeds truncated in places by horizontal beds.

From 80 to 160 feet of evenly bedded principally reddish-brown mudstone and siltstone, and some reddish-brown, brown, and light-greenish-gray very fine to fine-grained sandstone composing the Summerville Formation of Late Jurassic age conformably overlies the Entrada.

Sandstone beds laterally equivalent to the upper part of the Summerville Formation compose the Junction Creek Sandstone of Late Jurassic age at the southern end of the Slick Rock district. Light-buff medium- to fine-grained eolian sandstone about 150 feet thick displaying great sweeping tangential crossbeds changes facies northward, becoming light-reddish-brown and light-buff sandstone interbedded with reddish-brown mudstone and thinning to about 20 feet where it merges with the Summerville. The lower part of the Junction Creek is continuous with a thin medial sandstone bed in the Summerville.

Conformably overlying the Summerville Formation and the Junction Creek Sandstone are several hundred feet of interbedded fluvial sandstone and flood-plain mudstone strata of the Morrison Formation of Late Jurassic age. The Morrison Formation in the Colorado Plateau contains more than half of the known uranium reserves in the United States and hence is of prime economic importance. In the district the lower member, the Salt Wash Member, consists of three units aggregating 275–400 feet in thickness. The lower unit consists of 60–140 feet of light-reddish-brown and light-buff to light-gray fine-grained sandstone complexly divided by thin discontinuous reddish-brown mudstone layers. The middle unit is made up of 100–200 feet of chiefly reddish-brown mudstone containing discontinuous lenses of light-reddish-brown and light-buff to light-gray fine-grained sandstone as much as 60 feet thick. The upper unit of the Salt Wash Member, called the ore-bearing sandstone because it contains most of the uranium-vanadium deposits in the district, is a persistent layer 15–100 feet thick made up of numerous juxtaposed light-reddish-brown to light-buff and light-gray, fine-grained to very fine grained sandstone lenses locally separated by thin strata of reddish-brown and greenish-gray to gray mudstone. In places the unit contains abundant carbonized plant debris, with which the ore deposits are universally associated.

Above the Salt Wash Member is 300–700 feet of dominantly reddish-brown and greenish-gray bentonitic flood-plain mudstone interbedded with lesser amounts of light-reddish-brown, light-greenish-gray, and light-gray to light-buff sandstone and chert-rich conglomerate and minor thin limestone layers composing the Brushy Basin Member. The lower brown unit of the Brushy Basin consists of 50–200 feet of chiefly reddish-brown and light-reddish-brown mudstone, sandstone, and conglomerate. The middle green unit of the member is made up of 0–280 feet of dominantly greenish-gray or light-greenish-gray mudstone, parts of which are mottled or interlayered with different shades of reddish-gray, brownish-gray, purplish-brown, purplish-gray, and reddish-brown mudstone, and contains proportionately more sandstone and conglomerate, largely light greenish gray, than the rest of the Brushy Basin Member. A few thin limestone layers occur in the unit. The upper brown unit consists of 120–460 feet of reddish-brown mudstone with minor amounts of light-reddish-brown sandstone and conglomerate, and locally contains greenish-gray strata chiefly at the top of the unit.

Between 40 and 400 feet of clastic terrestrial strata making up the Burro Canyon Formation of Early Cretaceous age conformably overlies the Morrison Formation. The Burro Canyon is composed of dominantly light-gray to light-buff sandstone and conglomerate interbedded with thin layers of greenish-gray mudstone. In the vicinity of Disappointment Valley the formation has thin layers of interbedded mudstone, limestone, and chert at its top.

Unconformably overlying the Burro Canyon Formation is 120–180 feet of strata assigned to the Dakota Sandstone of Late Cretaceous age. The Dakota consists of chiefly fine- to medium-grained light-brown to dark-gray carbonaceous sandstone and minor conglomerate, dark-gray carbonaceous shale and mudstone, and impure coal. The lower arenaceous unit of the Dakota consists of fluvial lenticular sandstone and conglomerate. The middle argillaceous unit contains mostly mudstone, shale—including some thin layers of bentonitic shale—and coal. The upper arenaceous unit is mostly marine or marginal marine sandstone.

About 1,600–2,300 feet of dominantly dark-gray marine shale of the Mancos Shale conformably overlies the Dakota Sandstone; a complete section is not present in the district. The shale, or mudstone, contains abundant silt and sand grains, pyrite, biotite, and glauconite in many layers, a few percent carbonaceous material, and about 25 percent calcite. Minor limestone, siltstone, sandstone, and bentonitic shale or claystone make up some layers. The formation abounds in marine invertebrate fossils, and these have been the basis for dividing the Mancos into fossil zones of late middle Greenhorn, late Greenhorn, earlier Carlile, later Carlile, earlier Niobrara, and

later Niobrara age of the Western Interior of the United States, and Austin and Taylor age of the Gulf Coast.

Outside the Slick Rock district the Mancos Shale is overlain by dominantly terrestrial sandstone, mudstone, and coaly beds of the Mesaverde Group of Late Cretaceous age, and younger units such as the Wasatch and Green River Formations of Tertiary age, which once may have extended across the district. These units, totaling possibly 5,000 feet in thickness, were removed by erosion following middle Tertiary uplift of the Colorado Plateau.

Igneous rocks of Tertiary age crop out in only one small area in the district, but they are intruded extensively in the Mancos Shale east of the district, and, as shown by deep oil test wells, appear to be intruded widely in the Paradox Member of the Hermosa Formation in the southern part of the district and southeast of the district. Andesite porphyry occurs in a dike on Glade Mountain, microgranogabbro and microgranodiorite occur in thin sills east of the district, and rocks of similar composition form thick sills in the subsurface. All are similar chemically to igneous rocks in the San Juan Mountains southeast of the district and probably were the result of a specific igneous episode. They were intruded most likely during the Miocene.

Surficial deposits of Quaternary age include glacial till, terrace gravels, alluvial fans, landslide debris, loess, other soil, alluvium, colluvium, and talus. On Glade Mountain, glacial till of probable early Pleistocene age merges westward with terrace gravels that are correlative with terrace gravels which lie on an old weathered surface of Mancos Shale farther west on the rim of the Dolores River Canyon.

INTRODUCTION

Shortly after World War II the U.S. Geological Survey, on behalf of the Atomic Energy Commission, began a program to search for and appraise domestic uranium resources. In 1947 the Survey began geologic studies of, and exploration for, uranium deposits on the Colorado Plateau, the site of the largest and the most numerous deposits then known in the United States.

The earliest work in the Survey's Colorado Plateau program included extensive diamond drilling, largely of development nature. Drilling was concentrated in the Uravan mineral belt, then the most productive area in the Plateau, to locate as quickly as possible adequate reserves of uranium. Eventually the mineral belt was divided into districts, the Slick Rock district being the most southerly (fig. 1), in which exploratory drilling was integrated with general geological studies. A program was thus begun in the Slick Rock district in 1953 to evaluate previous diamond drilling, to extend exploratory drilling to areas where possible uranium deposits are deeply buried, to synthesize previous geologic studies that pertain to the district, and to undertake additional studies. The aim of the program was to gain a comprehensive understanding of the geology and ore deposits in the district.

Work in the Slick Rock uranium-vanadium district constitutes only a small part of the many hundreds of man-years of geologic studies by the Geological Survey of the uranium deposits in sedimentary rocks.

FIELDWORK AND EXPLORATORY AND DEVELOPMENT DRILLING

From the start of geologic investigations by the Geological Survey in the Slick Rock district, 12 separate drilling programs and more than 35 man-years of field and office work have been completed.

Between November 1947 and August 1953, the Survey completed nine exploratory and development diamond-drilling programs in the district. These were directed by A. L. Bush, R. D. Trace, Henry Bell III, C. C. Withington, L. S. Hilpert, W. L. Emerick, and J. L. Gualtieri. These geologists were assisted by D. O. Beehler, Leonid Bryner, J. J. Folger (geologic field assistant), R. B. Hall, H. M. Icke, H. L. Jicha, H. S. Johnson, J. A. MacKallor, R. L. McDonald, C. H. Meiss-

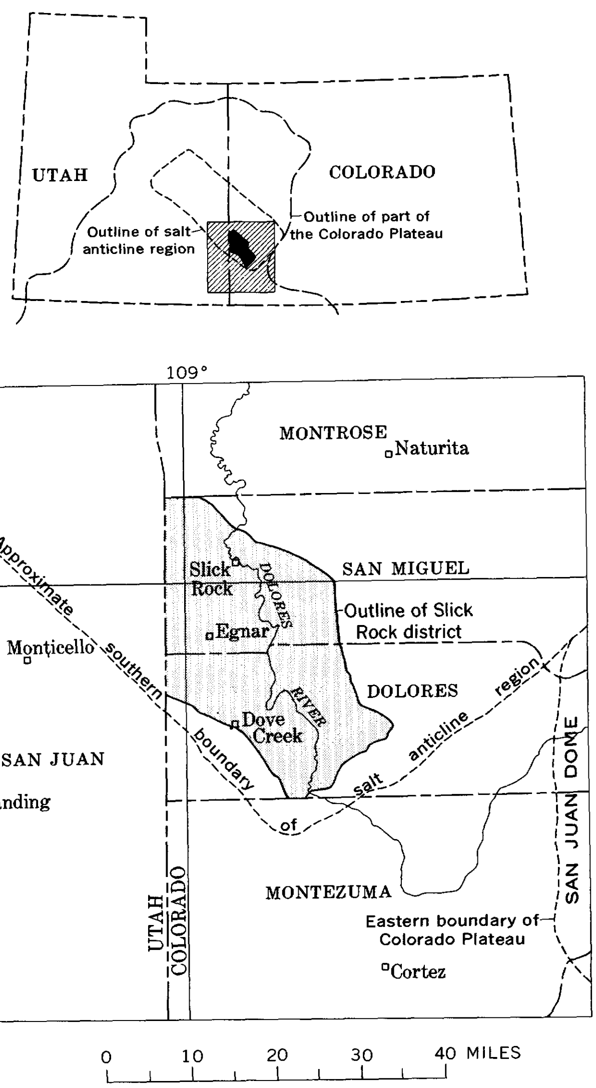

FIGURE 1.—Location of the Slick Rock district.

ner, F. B. Moore, R. W. Osterstock, B. K. Replogle, H. S. Samsel, C. L. Setzer, E. M. Shoemaker, H. K. Stager, L. R. Stieff, C. M. Tschanz, and J. D. Vogel, and by engineers M. F. Gilkey, W. T. Millar, T. W. Oster, E. V. Reinhardt, J. I. Schumacher, and J. E. Werner. Many of the results of the drilling programs and geologic studies undertaken by these persons are included in this report.

Geologic work in the district during 1947-53 consisted principally of examination and mapping of underground mine workings and surface areas in the vicinity of mines.

In the comprehensive study program in the Slick Rock district, which began in September 1953, geologic work was expanded and drilling programs were continued, under the supervision of D. R. Shawe. Field investigations continued virtually uninterrupted until April 1957, and a little fieldwork was done during December 1957 and June 1958. Exploratory drilling projects were conducted from April to November 1954 in the Disappointment Valley, Legin, and Spud Patch areas, and from January to November 1955 and from June 1955 to April 1956 in the Disappointment Valley area. The first two projects were supervised by Shawe; the third, by D. A. Phoenix. Geologists who worked in the district from 1953 to 1958, besides the authors of this report, are E. L. Boudette, W. B. Rogers, W. B. Gazdik, W. L. Emerick, J. A. Madsen, O. T. Marsh, R. L. McDonald, W. R. Barton, Jr., J. J. Connor, and O. B. Raup.

ACKNOWLEDGMENTS

Development and exploratory drilling in the Slick Rock district prior to 1954 was done under the general supervision of R. P. Fischer and L. S. Hilpert. Starting in 1954, it was done under the general supervision of A. L. Brokaw, Harold Kirkemo, and J. W. Hasler. Geologic studies during 1953–58 were under the general supervision of A. L. Brokaw. The authors benefitted from many informal discussions with these and other Geological Survey geologists, particularly D. G. Wyant, concerning the geology of the Slick Rock district and the Colorado Plateau as a whole. The ideas that are developed in this report originated in those discussions.

R. G. Coleman of the Geological Survey contributed much to the project by mineralogic studies and by valuable discussions in the field. W. D. Allan, also of the Survey, assisted in the compilation of geologic data for a few weeks in 1960.

Appreciation is extended to many individuals and companies engaged in mining and in mineral, oil, and gas exploration in the district for information, cooperation, or permission to publish data. Among the companies are Union Carbide Nuclear Co. (formerly United States Vanadium Corp.), Hunt Oil Co., Newmont Mining Co., and Marcey Exploration Co.

Development and exploratory drilling and geologic studies in the Slick Rock district were done by the Geological Survey on behalf of the Division of Raw Materials of the Atomic Energy Commission.

PREVIOUS WORK

The first publication on the geology of the area now known as the Slick Rock district, which also included what was probably the first published physiographic description of the area, was by Peale (1878, p. 163), who wrote that

> between Gypsum Valley and the Dolores River is [a] synclinal basin, the sides of which dip southwest and northeast. At the northwestern end there is a dip to the southeast, which gives a saucer-like shape to the valley. From this fact we called it Saucer Valley. [It is now known as Disappointment Valley.] Around the northwestern end or rim of this valley the Dolores flows in a cañon emerging from it into Gypsum Valley. Southwest of the Dolores the country rises into the northern border of the Sage Plain.

The first publication on uranium-vanadium deposits in the Slick Rock district was by Fleck and Haldane (1907), who summarized the brief history of the new district, then known as the McIntyre district, sketched the geology of the area, described the processing of the ores, and briefly described about 25 mining claims in the district.

Moore and Kithil (1913) described (apparently in part from Fleck and Haldane, 1907) uranium-vanadium ore deposits and mining activity in the McIntyre district and other districts in Colorado and Utah and briefly discussed the origin of the deposits, mining methods and costs, and transportation, prices, and concentration of the ores.

Coffin (1921) described the general geology and stratigraphy, the structural geology, the economic geology of carnotite and its related ores, the origin of the ores, and the geology of the McIntyre district and a large part of the larger present Slick Rock district.

Hess (1933) described the uranium-vanadium deposits in southwestern Colorado, but he made no specific mention of deposits in what is now the Slick Rock district, although much of his descriptive data is applicable to the district.

"In 1939 the Geological Survey * * * in cooperation with the State of Colorado and the Colorado Metal Mining Fund [now the Colorado State Mining Industrial Development Board], began a geologic study of [vanadium-uranium-radium] ores in the western part of Montrose County, Colo." and "other vanadium-producing areas in the region" including the Slick Rock district (Fischer, 1942). Although details of ore deposits described by Fischer pertain specifically to areas outside the Slick Rock district, general aspects apply to the district.

In 1942, the U.S. Geological Survey, as part of a national appraisal of vanadium resources, made a study of ore deposits and geology in the Slick Rock district (D. C. Duncan and W. L. Stokes, unpub. data, 1942).

In 1943, the U. S. Bureau of Mines did some development diamond drilling, under the direction of D. C. Duncan and W. L. Stokes of the Geological Survey, in parts of the Charles T., Ownbey, Radium, Lower, and Legin groups of claims. At that time Duncan, Stokes, and R. P. Fischer mapped some of the underground workings and surface areas in the vicinity of mines.

Fischer (1944) published a simplified geologic map of the vanadium region of southwestern Colorado and southeastern Utah on which is shown part of the Slick Rock district. The map shows the generalized distribution of sedimentary rocks in the district and the location of vanadium-uranium mines or groups of mines known at that time.

During 1944 the Union Mines Development Corp., under contract to the Manhattan Engineer District, which was developing the atomic bomb for the U.S. Government, undertook detailed studies and mapping of uranium-vanadium deposits in the Colorado Plateau. Areas studied included the Slick Rock district, which at that time corresponded approximately to the old McIntyre mining district, and the Dolores River district, which made up a large part of the south half of what is now known as the Slick Rock district. The old Slick Rock district was studied in the field in the summer of 1944 by R. K. Kirkpatrick, H. E. Vitz, J. H. Wells, J. W. Clark, and D. E. Cooper. The Dolores River district was studied in the field in the same summer by B. W. Van Voorhis, Jr., A. H. Lindley, Jr., J. W. Clark, N. B. Dodge, and J. R. Foster.

In addition to the Geological Survey geologists who worked on drilling projects in the district between 1947 and 1953 (listed in the section on fieldwork and drilling), other Survey geologists undertook topical studies, part of which were carried out in the district during this period. Some of these geologists and their studies are: L. C. Craig and his coworkers, measurement of many stratigraphic sections; R. A. Cadigan, petrology of sedimentary rocks; E. M. Shoemaker, A. T. Miesch, and W. L. Newman, distribution of elements in sedimentary rocks and ores; G. W. Weir, cross-stratification of the Morrison Formation in the Spud Patch area; D. A. Phoenix, sedimentary structures in the Morrison Formation in part of the district; and Phoenix, W. L. Stokes, and F. W. Cater, geologic mapping. Some of the results of these studies are incorporated in this report, although they are in part published, or in preparation for publication, elsewhere.

GEOGRAPHY

The Slick Rock district (fig. 1), which encompasses about 570 square miles, is in western San Miguel and Dolores Counties in southwest Colorado. The district is in the eastern part of the Canyon Lands section of the Colorado Plateaus province, just west of the westward extension of the Southern Rocky Mountains. Altitudes in the district range from 5,400 to 9,200 feet. Broadly, the district consists of a moderately high plain rising gradually from the southwest to the gently arched Dolores anticline, which trends northwest through the central part of the district. The land surface drops more abruptly northeastward on the northeast limb of the fold and is relatively low along the synclinal Disappointment Valley. Farther northeast, the surface rises rather steeply to the edge of the district, which is the crest along the southwest side of the collapsed Gypsum Valley salt anticline. (See pl. 1.)

The ground surface in the district corresponds roughly to the upper surface of folded Cretaceous sandstone strata; these and older strata are deeply incised by the antecedent generally north flowing Dolores River, whose canyon is deepest where the folded strata are highest on the Dolores anticline. The northwest quarter of the district has been dissected rather deeply by canyon streams that are tributary to the Dolores River, and a large amphitheater formed by this dissection lies across the northwestward-plunging Dolores anticline and opens eastward into the synclinal Disappointment Valley.

U.S. Highway 160 along the southwest edge of the district connects with Monticello, Utah, about 19 miles west of the district, and with Cortez, Colo., about 23 miles southeast of the district. Colorado Highway 80 extends about 30 miles through the district from a point 2 miles west of Dove Creek to Gypsum Gap. Numerous tributary roads extend from the main roads into most parts of the district and make nearly all mining properties accessible. Most of the secondary roads are not surfaced, and during the winter or after heavy summer rains some of them are impassable.

CLIMATE AND VEGETATION

The climate of the Slick Rock district is semiarid; annual precipitation averages 15–20 inches (Hunt, 1956, fig. 4). The U.S. Weather Bureau station at Northdale, Colo., at an altitude of about 6,700 feet, recorded an average annual rainfall of 14.20 inches for the period 1930–54, distributed as follows (in inches): January, 1.10; February, 1.16; March, 1.31; April, 1.18; May, 0.82; June, 0.63; July, 1.15; August, 1.45; September, 1.91; October, 1.52; November, 1.35; December, 1.19 (Phoenix, 1959, p. 57). Although no detailed records are available for other parts of the district, this average probably applies only to those areas that lie above altitudes of 6,500–7,000 feet. At lower altitudes, especially in Disappointment Valley at an altitude of about 5,700 feet, precipitation probably averages about 10 inches or less annually.

The Slick Rock district is in a transitional region characterized by desert shrubs (mostly sagebrush) scattered small cacti, and pinyon-juniper woodland (Hunt, 1956, fig. 5). By and large, woodland is dominant at higher altitudes and more open country is characteristic at lower levels. Large yellow pines grow generally at altitudes above 8,000 feet, but below 8,000 feet they grow only in the deep Dolores River Canyon and its tributaries, near springs, and where near-surface ground water is sufficient. Spruce and fir trees are sparse in the district and grow only at higher altitudes on north slopes. Small stands of aspen are scattered in the pine forests above 8,000 feet. Parts of the Sage Plain, which lies at an altitude of about 7,000 feet, are sagebrush covered and open.

Mancos Shale over the floor of Disappointment Valley prohibits the growth of pinyon and juniper trees where they might otherwise have established themselves. The shale holds so little ground water that trees have not been able to root themselves as they do in areas underlain by sandstones and siltstones that carry, at least during part of the year, ground water near the surface.

Pinyon and juniper trees grow to heights of 20 feet or more in places at higher altitudes and have been used sporadically for timbers in mining operations. Fairly dense stands of yellow pine near the southeast edge of the district have been logged periodically under U.S. Forest Service supervision.

WATER SUPPLY

Water in the Slick Rock district is derived chiefly from the Dolores River, but other sources for stock, agricultural, drilling, and drinking purposes include many spirings, some wells, numerous stock ponds and reservoirs, Disappointment Creek, and Glade Lake.

DOLORES RIVER

The Dolores River is a once-perennial stream which flows centrally through the district from south to north. From 1896 to 1927 its average flow was about 345,000 acre-feet annually; during the 1939 water year its runoff totaled only 134,700 acre-feet (table 1). Because of the upstream use of water for irrigation, including diversion of the water into Narraguinnep Reservoir about 10 miles west of the town of Dolores, the river is not now a reliable constant source of water. In most recent years the flow of water has been subsurface during the fall and early winter, and the river channel has been marked by a string of shallow pools.

TABLE 1.—*Dolores River flow from 1896 to 1927, and in 1939 water year*

[In acre-feet]

From 1896 to 1927: Annual discharge at Dolores, Colo., 20 miles upstream from south boundary of Slick Rock district [1]		1938–39 water year: Runoff at McPhee, Colo., 10 miles upstream from south boundary of Slick Rock district [2]	
1896	174,000	October 1938	2,460
1897	408,000	November	3,120
1898	328,000	December	3,000
1899	146,000	January 1939	1,740
1900	180,000	February	1,890
1901	303,000	March	21,690
1902	124,000	April	44,430
1903	354,000	May	46,840
1911	431,000	June	7,490
1912	402,000	July	275
1922	479,000	August	619
1923	494,000	September	1,150
1924	344,000		
1925	313,000	Total	134,700
1926	533,000		
1927	502,000		
Average	345,000		

[1] Follansbee (1929, p. 102).
[2] Paulsen and others (1940, p. 89).

The river is the source of municipal water for the town of Dove Creek. A pumping station on the river at the mouth of Big Canyon lifts water from a shallow well through a pipeline up the canyon to the town. The upgrading mill operated by Union Carbide Nuclear Co. at Poverty Flat used water from a well 30 feet deep that tapped the underflow in gravel at the river's edge. Most drilling contractors in the district have obtained drilling water from the river. Unless treated, the water is generally unfit for drinking.

SPRINGS

More than 30 springs, all small and some intermittent, are known in the district; they are at altitudes from about 5,600 to almost 8,300 feet.

Two springs are in alluvium in Disappointment Valley, about 4 miles east-southeast of Egnar. Six springs flow from the Dakota Sandstone; they are within 3 miles of the axis of the Dolores anticline and at altitudes above 7,500 feet. Nine springs are in the Burro Canyon Formation; they are more widely scattered and are at altitudes of 5,600–8,200 feet. Springs in the Brushy Basin Member of the Morrison Formation, which are also within 3 miles of the axis of the Dolores anticline, include two on Horse Range Mesa at an altitude of about 6,900 feet, one about 6 miles east of Egnar at 8,000 feet, and six which issue from the fault, at about 8,200 feet, northwest of Glade Mountain. Springs in the Salt Wash Member of the Morrison Formation, at altitudes of 5,–800–7,000 feet, are all within an area of about 30 square miles just north of Egnar, and, perhaps significantly, within the area of known uranium-vanadium deposits in the district. This fact suggests that the Salt Wash may be generally more permeable, either inherently or because of abundant fractures, in this area than elsewhere in the district.

WELLS

Wells in the district include a few shallow dug wells and several drilled wells a few feet to a few hundred feet deep. Water from these wells is used for irrigation, stock, milling, and domestic purposes.

In a well at the foot of Slick Rock hill, water is pumped from the Entrada Sandstone from a depth of about 200 feet. From 1954 to 1956 probably an average of 1,000 gallons a week was taken for use at the Government camp on Slick Rock hill. The water was pumped once or twice a week, on the average, at a rate of about 1,000 gallons per hour. Minor amounts of water were taken from the well by other users during this period, and some drawdown was apparent from the pumping. A well several hundred feet deep drilled on Poverty Flat in about 1956 by Union Carbide Nuclear Co. (John Motica, written commun., 1959) pumped water which flowed mostly from the Wingate Sandstone. This water was very hard, however, and was not potable.

Three deep holes in Disappointment Valley, diamond drilled in 1955 by the Geological Survey during a search for uranium-vanadium deposits, encountered water at a depth of about 200 feet in the Dakota Sandstone. This water was artesian and flowed from each hole at about 2–8 gallons per minute. This flow was ponded, and as late as 1958 it continued to feed ponds which were being used extensively for watering stock.

WATER ANALYSES

Analytical data on waters from two springs in the district, one flowing from sandy shale near the contact of the Brushy Basin Member of the Morrison Formation and the Burro Canyon Formation and the other from conglomeratic sandstone near the top of the Salt Wash Member of the Morrison Formation, are summarized in table 2. The dominant constituents of these waters are the sodium bicarbonate and sulfate radicals, but the amounts of calcium and chloride are also appreciable. These waters are unlike most of the spring waters listed by Clarke (1924, p. 68). They have uncommonly large amounts of dissolved solids, notably high chlorine, and unusual fluorine/chlorine and potassium/sodium ratios. The fluorine/chlorine ratios of the Slick Rock springs (0.016 and 0.003) approximate those of high-temperature thermal springs (0.0005–0.1) and are much higher than the ratios in oil-field brines and ocean water (0.00001–0.001) (White, 1957, p. 1666) and probably much higher than those in cold-water springs. The potassium/sodium ratios of the Slick Rock springs (0.024 and 0.022) are close to those

TABLE 2.—*Analyses of spring, well, and mine waters in the Slick Rock district, San Miguel County, Colo.*

[Data for samples 1–4, from Phoenix (1959, p. 6061); for 5, from Phoenix (written commun., 1958). Data in parts per million except as indicated. nd, not determined]

Sample No.	1	2	3	4	5
Laboratory No.	6318	6319	6320	4733	7237
Source of water	Spring	Spring	Dug well	Mine sump	Mine sump
Date sample collected	Mar. 24, 1951	Mar. 24, 1951	Mar. 24, 1951	June 26, 1950	Aug. 19, 1951
Silica (SiO_2)	9.9	16	20	17	8.6
Iron (Fe) (in solution)	.04	.05	.07	.04	.03
Iron (Fe) (total)	nd	nd	nd	nd	nd
Calcium (Ca)	41	88	98	64	66
Magnesium (Mg)	13	34	103	16	36
Sodium (Na)	360	203	118	27	160
Potassium (K)+manganese (Mn)[1]	8.8	4.4	[1] 6.6	4.8	3.2
Bicarbonate (HCO_3)	528	506	554	226	251
Sulfate (SO_4)	435	212	158	42	239
Chloride (Cl)	61	113	198	30	97
Fluoride (F)	1.0	.3	.3	.4	.5
Nitrate (NO_3)	.3	.1	14.0	1.7	[2] 74
Boron (B)	.07	.09	.03	.04	nd
Uranium (U)[3]	nd	.02	nd	<.01	nd
Vanadium (V)[4]	nd	.12	nd	<.01	nd
Copper (Cu)[4]	nd	.00	nd	.00	nd
Lead (Pb)[4]	nd	.00	nd	.33	nd
Selenium (Se)	nd	<.05	nd	.00	nd
Dissolved solids:					
Sum ppm	1,190	920	989	314	809
Sum—tons per acre-ft	1.62	1.25	1.35	.43	1.10
Hardness[5] as $CaCO_3$:					
Total	156	360	668	226	312
Noncarbonate	0	0	214	40	----------
Ratios:					
K/Na	.0244	.0216	.0533	.178	.0200
F/Cl	.0164	.0027	.0015	.0134	.0052
Specific conductance (micromhos at 25° C)	1,730	1,420	1,610	523	1,250
Percent sodium[6]	82	55	27	20	----------
Laboratory pH	8.1	7.9	7.7	7.7	7.6

[1] Manganese detected: 0.29 ppm in sample 3; 0.00 ppm in other samples.

[2] High NO_3 may have resulted from contamination by powder smoke (L. B. Riley, oral commun., 1955).

[3] Method of determination: fluorimetric.

[4] Method of determination: colorimetric.

[5] Total hardness is the sum of all constituents causing hardness; noncarbonate hardness is the sum of all the constituents except carbonate causing hardness. The two hardnesses are, by common practice, expressed as "hardness as $CaCO_3$."

[6] Percent sodium is obtained by dividing the total milligram equivalents into sodium milligram equivalents.

1. Joe Davis Canyon, SW¼ sec. 33, T. 44 N., R. 18 W. Sandy shale of Brushy Basin Member of Morrison Formation; field pH 7; temp 42° F.
2. Strawberry Spring, Bishop Canyon, SW¼ sec. 32, T. 43 N., R. 19 W. Conglomeratic sandstone near top of Salt Wash Member of Morrison Formation; field pH 7; temp 43° F.
3. Spud Patch, NE¼ sec. 6, T. 43 N., R. 18 W. Quaternary alluvium derived largely from Brushy Basin (?) Member of Morrison Formation; field pH 7.
4. May Day mine, Spud Patch, SW¼ sec. 29, T. 43 N., R. 18 W. Mineralized sandstone at top of Salt Wash Member of Morrison Formation; field pH 6; temp 44° F.
5. Cougar mine of Lower Group. Salt Wash Member of Morrison Formation.

of most oil-field brines (mean 0.02) and much lower than those of dilute ground waters (commonly 0.3–0.6) cited by White, 1957, p. 1668, from Schoeller, 1955, p. 136, 137.

These meager data certainly cannot be interpreted to mean that the Slick Rock spring waters are mixtures of thermal waters and oil-field brine, diluted by "ordinary" near-surface of meteoric ground water. But they possibly can be interpreted to mean that present-day ground water flowing from the rocks has been modified by the addition of elements that were deposited in the sedimentary rocks by thermal waters or oil-field brines, or both. This possible explanation is pertinent to the discussions, in later sections of this report, of the alteration of the sedimentary rocks and the origin and genesis of the uranium-vanadium ores.

In water from a shallow dug well in the Spud Patch area (table 2), content of dissolved solids is very similar to that in the analyzed spring waters. The well penetrates Quaternary alluvium derived from the Brushy Basin Member of the Morrison Formation and younger formations, but some of the water may come from the underlying sandstone of the Salt Wash Member of the Morrison Formation.

GEOLOGIC SETTING

The Slick Rock district is at the east edge of the high structural platform of the Colorado Plateau (fig. 1), which is a moderately thick sequence of sedimentary rocks lying upon a Precambrian basement. The district is 20 miles west of the San Juan Mountains, a domal pile of volcanic rocks that forms a westward extension of the Southern Rocky Mountains into the Plateau. The district is in the Paradox Basin and at the south edge of the salt anticline region. Northeast of the salt anticlines, about 35 miles from the district, lies an old structural high, the present Uncompahgre Plateau, which has long marked the east boundary of the Paradox Basin. About 25 miles northwest, west, and south of the district are three laccolithic igneous centers, respectively the La Sal, Abajo, and Ute Mountains, and at the east edge of the district are igneous dikes and sills in the Klondike, Disappointment Valley, and Glade Mountain areas.

Sedimentary rocks in the Slick Rock district and vicinity lie in a northwestward-trending trough which seems to be in essence a wide graben in Precambrian igneous and metamorphic basement rocks between the Uncompahgre Plateau and a Precambrian platform extending west and south from the district. Paleozoic and Mesozoic sedimentary rocks are thicker in the trough than on either side; perhaps depression of the trough played a prominent part in the formation of this part of the Paradox Basin.

The maximum total thickness of sedimentary rocks underlying the district is about 13,000 feet, and prior to extensive erosion in the late Tertiary and the Quaternary it may have been as much as about 18,000 feet. The lower 5,000 feet or more of the sequence of sedimentary rocks is composed of dominantly marine carbonate rocks and evaporite beds of late Paleozoic age interbedded with lesser amounts of clastic sedimentary rocks and overlying arenaceous strata of early Paleozoic age. Overlying these rocks is about 4,500 feet of terrestrial clastic sedimentary rocks, dominantly sandstone with lesser amounts of shale, mudstone, siltstone, and conglomerate, of late Paleozoic and Mesozoic age. Above these rocks is about 2,500 feet of marine shale of late Mesozoic age. Prior to erosion about 5,000 feet of clastic sedimentary rocks, dominantly sandstone and in part shale, of late Mesozoic and early Cenozoic age may have overlain the older rocks of the district.

Sedimentary rocks in the region are folded in a series of broad northwestward-trending anticlines and synclines which, because of their parallel orientation and proximity to the Uncompahgre Plateau, appear to be causally related to its formation. Nevertheless the folding was influenced to a considerable extent by flowage and intrusion of evaporite rocks of the Hermosa Formation into the axial parts of the anticlines. In addition, evaporites were extruded upward from, and moved laterally along, the axial regions of the anticlines or were removed by solution processes, so that the axial regions collapsed as grabens bounded by longitudinal faults or fault zones along the limbs of the anticlines. The Gypsum Valley anticline is such a collapsed anticline: faults on the southwest side of this graben form the northeast edge of the Slick Rock district. To the southwest the Dolores anticline extends the length of the district from northwest to southeast and is arched above a core of thickened evaporites of the Hermosa Formation. Collapse of this anticline may be incipient; it is suggested only by a zone of small en echelon grabens lying parallel to the anticline just northeast of its axis.

Faults bounding the en echelon grabens, which are part of the Dolores fault zone, are oriented more westerly than the zone and are parallel to faults in the Glade fault zone, which trends eastward across the south end of the district. The Dolores and Glade fault zones are merely segments of much longer regional fault zones, which in turn may be parts of a broad conjugate system whose two principal elements are oriented respectively northwest and between east and east-northeast.

Uranium-vanadium deposits, found principally in carbonaceous clastic terrestrial sedimentary rocks of Late Jurassic age, occur in a wide belt which is centered on the Dolores fault zone. In the vicinity of the faults, clastic sedimentary rocks were epigenetically altered as a result of the passage of aqueous solutions so that gross mineralogic changes occurred among the accessory minerals with accompanying redistribution of some elements in the rocks. Epigenetic alteration was most intense in the vicinity of the ore deposits. Some of the redistributed elements may have been concentrated in the uranium-vanadium deposits. Some other elements are most abundant in deposits close to faults and least abundant in deposits farther from faults, suggesting introduction by means of solutions moving outward from the faults. The coincidence of the belt of ore deposits with the fault zone and with alteration in the sediments, and the zoning of elements in the deposits relative to the faults may, therefore, have genetic significance. This and subsequent reports evaluate the geology of the district for the purpose of explaining the above facts, and thereby elucidating the origin and genesis of the uranium-vanadium deposits.

STRATIGRAPHY

Lithologic units that underlie the Slick Rock district include igneous and metamorphic basement rocks of Precambrian age, sedimentary rocks ranging in age from Cambrian to Cretaceous and totaling about 2½ miles in thickness, igneous rocks of Tertiary age, and unconsolidated sediments of Quaternary age. The older sedimentary and Precambrian rocks and some of the igneous rocks are known only from oil-well cuttings and cores.

Although probably no deep oil-test well in the district penetrates Precambrian basement rocks, drill holes in the region and geophysical data (Joesting and Byerly, 1958, p. 10) indicate that Paleozoic sedimentary rocks are underlain by an igneous and metamorphic basement complex, generally at about 2,000–4,000 feet below sea level.

The total thickness of sedimentary rocks underlying the Slick Rock district ranges from about 12,000 to 14,000 feet. Sedimentary rocks that crop out in the Slick Rock district have a maximum thickness of about 4,700 feet. Exposed rocks, dominantly clastic, include the upper part of the Cutler Formation of Permian age; the Chinle Formation and Wingate Sandstone of Triassic age; the Kayenta Formation of Triassic (?) age; the Navajo Sandstone of Triassic (?) and Jurassic age; the Entrada Sandstone, Summerville Formation, Junction Creek Sandstone, and Morrison Formation of Jurassic age; and the Burro Canyon Formation, Dakota Sandstone, and lower part of the marine Mancos Shale of Cretaceous age. Consolidated sedimentary rocks exposed in the district are described briefly on plate 1.

Older sedimentary rocks that do not crop out in the district total about 7,500–9,000 feet in thickness. They include arkosic sandstone and conglomerate of Cambrian age, carbonate and clastic rocks of the Elbert Formation of Devonian age, undifferentiated Devonian Ouray and Mississippian Leadville Limestones, carbonate and clastic rocks of the Molas Formation and carbonate and evaporite beds of the Hermosa Formation of Pennsylvanian age, limestone and arenaceous strata of the Rico Formation of Pennsylvanian and Permian age, the lower part of the clastic Cutler Formation of Permian age, and, in places, fine-grained clastic rocks of the Moenkopi Formation of Triassic age.

Igneous rocks occur in the southeast corner of the district on Glade Mountain as a poorly exposed dike (?) and near the district in the southeastern part of Disappointment Valley, and are known from oil-well cuttings as a thick sill in the salt unit of the Paradox Member of the Hermosa Formation, near sea level in the southern part of the district.

Unconsolidated sediments consist of glacial till, terrace gravels, mudflows, landslides, alluvial fans, loess, soil, alluvium, colluvium, and talus. None of the unconsolidated deposits has been studied in detail.

Throughout this report colors of sandstone are referred to chiefly as light reddish brown, light buff or light brown, and light gray, even though the rocks show various shades, values, and hues of these colors. For example, light reddish brown includes, in terms given in the "Rock-Color Chart of the National Research Council" (Goddard and others, 1948), colors such as pale red (10*R* 6/2), grayish orange pink (10*R* 8/2, 5 *YR* 7/2), pinkish gray (5*YR* 8/1), grayish red (10*R* 4/2), light brownish gray (5*YR* 6/1), and pale brown (5*YR* 5/2), as well as combinations of these. Light buff or light brown includes colors such as very pale orange (10*YR* 8/2) and yellowish gray (5*Y* 8/1). Light gray includes colors such as white (*N*9), very light gray (*N*8), light gray (*N*7), and light greenish gray (5*GY* 8/1, 5*G* 8/1), as well as combinations of these. Colors of mudstone, siltstone, and claystone are called mainly reddish brown, grayish brown, greenish gray, gray, and dark gray. Reddish brown, in "Rock-Color Chart" terms, includes moderate brown (5*YR* 4/4, 5*YR* 3/4), dark reddish brown (10*R* 3/4), grayish red (10*R* 4/2, 5*R* 4/2), and pale red (5*R* 6/2). Brownish gray includes colors such as brownish gray (5*YR* 4/1), pale red purple (5*RP* 6/2), grayish red purple (5*RP* 4/2), pale brown (5*YR* 5/2), and light brownish gray (5*YR* 6/1). Greenish gray includes light greenish gray (5*G* 8/1), greenish gray (5*GY* 6/1, 5*G* 6/1), pale green (10*G* 6/2), and grayish green (10*GY* 5/2, 5*G* 5/2). Gray includes medium light gray (*N*6), medium gray (*N*5), and medium dark gray (*N*4), whereas dark gray includes dark gray (*N*3) and grayish black (*N*2). A few additional color terms are used where none of the foregoing seems appropriate, and some of the foregoing terms are applied to rocks other than sandstone, mudstone, siltstone, and claystone.

The evolution of stratigraphic terminology for rocks exposed in the Slick Rock district is presented in table 3. Stratigraphic usage in this paper, as shown in the table, is largely that of Stokes and Phoenix (1948) and of Cater (1955a–f), but it includes subdivisions of the Mancos Shale, Dakota Sandstone, Salt Wash and Brushy Basin Members of the Morrison Formation, Entrada Sandstone, and Chinle Formation and considers strata they mapped as the Carmel Formation to be part of the Entrada Sandstone, following Wright, Shawe, and Lohman (1962). It designates their Junction Creek Sandstone Member of the Wanakah Formation as Junction Creek Sandstone and lowers slightly their basal contact of the Brushy Basin Member of the Morrison Formation.

No detailed accounts have been published of older rocks underlying the exposed sedimentary formations in the district. Brief and incomplete descriptions of the formations given here incorporate terminology currently in use for subsurface rocks in surrounding areas.

PRECAMBRIAN ROCKS

Precambrian rocks in the Slick Rock district have not been penetrated by deep oil test wells, but their general nature is inferred from drill holes that penetrate Precambrian rocks in the vicinity of the district, from exposures in the Uncompahgre Plateau about 35 miles northeast of the district, from presumed Precambrian rock inclusions in the North La Sal stock of the La Sal Mountains about 30 miles northwest of the district, and from geophysical data.

Lithology

Rock presumed to be Precambrian was penetrated by the Gulf Oil Corp. Fulks 1 14 miles south of the district (fig. 2). According to an American Stratigraphic Co. log, the rock consists of light-colored granite, weathered in part near the top. Similar rocks have been found in wells southwest of the Fulks 1 in the vicinity of the Ute Mountains, Colo. (E. B. Ekren, oral commun., 1959). Hunt (1958, p. 311) summarized the Precambrian in the Uncompahgre as described by Dane (1935, p. 20–24) as follows: The rocks include

> strongly foliated biotite gneiss, hornblende and biotite schist, and coarsely crystalline biotite granite with associated pegmatitic phases. The coarsely crystalline granite is cut by stringers and dikes of finer grained granite. Pegmatite veins cutting the granite consist mostly of pink feldspar and a smaller proportion of quartz in masses almost as large as the feldspar. The granite contains microcline but no plagioclase, less quartz than feldspar, and less than 10 percent of biotite, chlorite, and muscovite. Fine-grained biotite gneiss, locally containing small garnet porphyroblasts, is interlayered with hornblende-quartz schist. Also present is a garnetiferous biotite-hornblende gneiss, abundantly injected with quartz and pegmatite, the latter locally containing considerable black tourmaline.

In soda syenite of the North La Sal stock in the La Sal Mountains, Utah, Hunt and Waters (Hunt, 1958, p. 330) described large blocks of Precambrian rocks brought up from the basement during irruption, includ-

TABLE 3.—*Evolution of current stratigraphic terminology for rocks exposed in the Slick Rock district, San Miguel and Dolores Counties Colo.*

Coffin (1921)	Stokes and Phoenix (1948) and Cater (1955a–f)	This paper		
Mancos shale	Mancos shale	Mancos Shale	Strata of:	post-Niobrara age
				later Niobrara age
				earlier Niobrara age
				later Carlile age
				earlier Carlile age
				late Greenhorn age
				late middle Greenhorn age
Dakota sandstone	Dakota sandstone	Dakota Sandstone	upper arenaceous unit	
			middle (carbonaceous shale) unit	
			lower arenaceous unit	

TABLE 3.—*Evolution of current stratigraphic terminology for rocks exposed in the Slick Rock district, San Miguel and Dolores Counties, Colo.*—Continued

Coffin (1921)			Stokes and Phoenix (1948) and Cater (1955a-f)		This paper		
"post-McElmo"			Burro Canyon formation		Burro Canyon Formation		
McElmo formation			Morrison formation	Brushy Basin member	Morrison Formation	Brushy Basin Member	upper brown unit
							middle green unit
							lower brown unit
				Salt Wash member		Salt Wash Member	top unit (ore-bearing sandstone)
							middle unit
							bottom unit
			San Rafael group	Junction Creek sandstone member of Wanakah formation	San Rafael Group	Junction Creek Sandstone	
				Summerville formation		Summerville formation	
La Plata group	Upper La Plata	Upper La Plata sandstone		Entrada sandstone		Entrada Sandstone, Slick Rock Member[1]	horizontally bedded unit
							crossbedded unit
							massive unit
		(not named)		Carmel formation		Entrada Sandstone, Dewey Bridge Member[1]	
	Lower La Plata sandstone		Glen Canyon group	Navajo sandstone	Glen Canyon Group	Navajo Sandstone	
Dolores formation				Kayenta formation		Kayenta Formation	
				Wingate sandstone		Wingate Sandstone	
			Chinle formation		Chinle Formation	Church Rock Member	unit 3
							unit 2
							unit 1
						Petrified Forest (?) Member	
						Moss Back Member	
Cutler formation			Cutler formation		Cutler Formation		

[1] Wright, Shawe, and Lohman (1962).

282-180 O—68——2

ing "amphibolite schist, biotite schist, hornblende gneiss, schistose garnetiferous amphibolite, and banded epidote amphibolite."

Joesting and Byerly (1958, p. 12–13) suggested that some gravity anomalies in the southeastern part of the salt anticline region are due to intrabasement density contrasts. Perhaps where anomalously high gravity is indicated, denser rocks such as amphibolite may displace more granitic rocks in the basement.

Configuration of the upper surface

The configuration of the upper surface of Precambrian rocks in and near the district is shown in figure 2. The surface was determined on the basis of the estimated thickness of sedimentary rocks below the deepest recognizable horizon (top of Mississippian rocks or deeper) in nine deep oil test wells drilled in and around the district, as well as one hole that penetrated the Precambrian south of the district. The inferred surface of the Precambrian southwest of the district is generally about 2,500 feet below sea level, and thence slopes downward to the northeast, abruptly near the northeast boundary of the district, to about 5,500 feet below sea level. Superimposed on this generally sloping surface is a southwesterly alined trough, at the south end of the district, which lies about 500–1,000 feet deeper than the surrounding surface. As proposed in later sections of this report, the northeasterly slope represents a drop from a Precambrian platform underlying the Sage Plain into a wide northwesterly alined graben bounded on the northeast by the Uncompahgre Plateau. The wide graben apparently localized the salt anticlines. The trough probably reflects a major structural zone in the basement, most likely a fault-bounded graben.

CAMBRIAN ROCKS

Lithofacies and isopach maps prepared by Baars (1958, p. 94–98) from deep oil-test wells in the district and vicinity, such as the Gulf Oil Corp. Coalbed Canyon 2 and the Gulf Oil Corp. Fulks 1 (locations shown in fig. 2), suggest that clastic sedimentary rocks of Cambrian age underlie the district.

Lithology

About 140 feet of conglomeratic arkosic sandstone lies directly upon weathered granitic rock of the Precambrian basement, according to the American Stratigraphic Co. log of the Fulks 1 south of the district. The unit consists of whitish to pinkish coarse-grained sandstone whose constituent grains are in part pink feldspar and which contains pebbles. Hematite stains the rock near the base of the unit. About 100 feet of light-gray and gray to grayish-red medium-grained to very coarse grained quartzitic sandstone with some shale partings lies above the conglomeratic sandstone unit. Traces of pink feldspar are found in the sandstone. Overlying the quartzitic sandstone unit is about 100 feet of light-gray fine- to coarse-grained partly quartzitic sandstone, which in places is conglomeratic. The unit contains some shale, dolomite, glauconite, pyrite, and rounded quartz grains. The upper 130 feet of sedimentary rocks of presumed Cambrian age consists of interbedded shale, siltstone, dolomite, and fine- to coarse-grained sandstone, which in places is glauconitic. The unit is varicolored—olive, gray, grayish red, and reddish brown.

According to Baars (1958, p. 95–97) only the lower part of the rocks here described as of Cambrian age, about 140 feet of conglomeratic sandstone, is correlative with Cambrian rocks to the east—the Ignacio Quartzite of Late Cambrian age. Baars suggested that the upper part may be equivalent to the McCracken Sandstone Member (Knight and Cooper, 1955) of the Elbert Formation of Late Devonian age in the Four Corners region and that an unconformity represents an appreciable hiatus between the upper and lower units. The upper part of the rocks described here contains shale and dolomite in addition to sandstone and is possibly in part equivalent to one or more Cambrian formations in surrounding regions, such as the Middle Cambrian Bright Angel Shale and Muav Limestone of the Grand Canyon in Arizona, the Middle and Lower Cambrian Ophir Shale and Middle Cambrian Maxfield Limestone in the Oquirrh range in Utah, or the Middle(?) and Upper Cambrian Lynch Dolomite of the Four Corners region. In view of the meager data, these younger rocks, totaling more than 300 feet in thickness, are described merely as rocks of Cambrian age.

Configuration

These sedimentary rocks are probably about 500–700 feet thick within the district; they are thinnest in the southeastern part and thicken northwestward (Baars, 1958, fig. 1).

DEVONIAN ROCKS

Lithology

South and southwest of the Slick Rock district, probable Devonian rocks cut by the Fulks 1 and the Coalbed Canyon 2 consist of, respectively, about 250 and 550 feet of sandy thin-bedded dolomite and limestone with interbedded grayish-green and reddish sandy shale. Other test wells in the region penetrate but do not pass through presumed Devonian rocks. Neff and Brown (1958) described the rocks penetrated by the Coalbed Canyon 2 as about 200 feet of argillaceous dark limestone and dolomite and calcareous grayish-green and brown shale of the Aneth Formation (Knight and Cooper, 1955), less than 100 feet of light-colored sandstone of the McCracken Sandstone Member (Knight and Cooper, 1955) of the Elbert Formation, about 150 feet of dolomite of the upper member of the Elbert, and less than 100 feet of limestone of the Ouray Limestone, all of Late Devonian age.

Regardless of the terminology chosen to designate the strata of supposed Devonian age, contacts are apparently difficult to locate and correlations are tenuous. Uncertainty still exists as to whether the unconformity representing the Ordovician, Silurian, and Early Devonian hiatus is just above the basal sandstone unit of Ignacio Quartzite as proposed by Baars (1958), just below the Aneth Formation as indicated by Neff and Brown (1958), or at a different horizon. Similarly, the

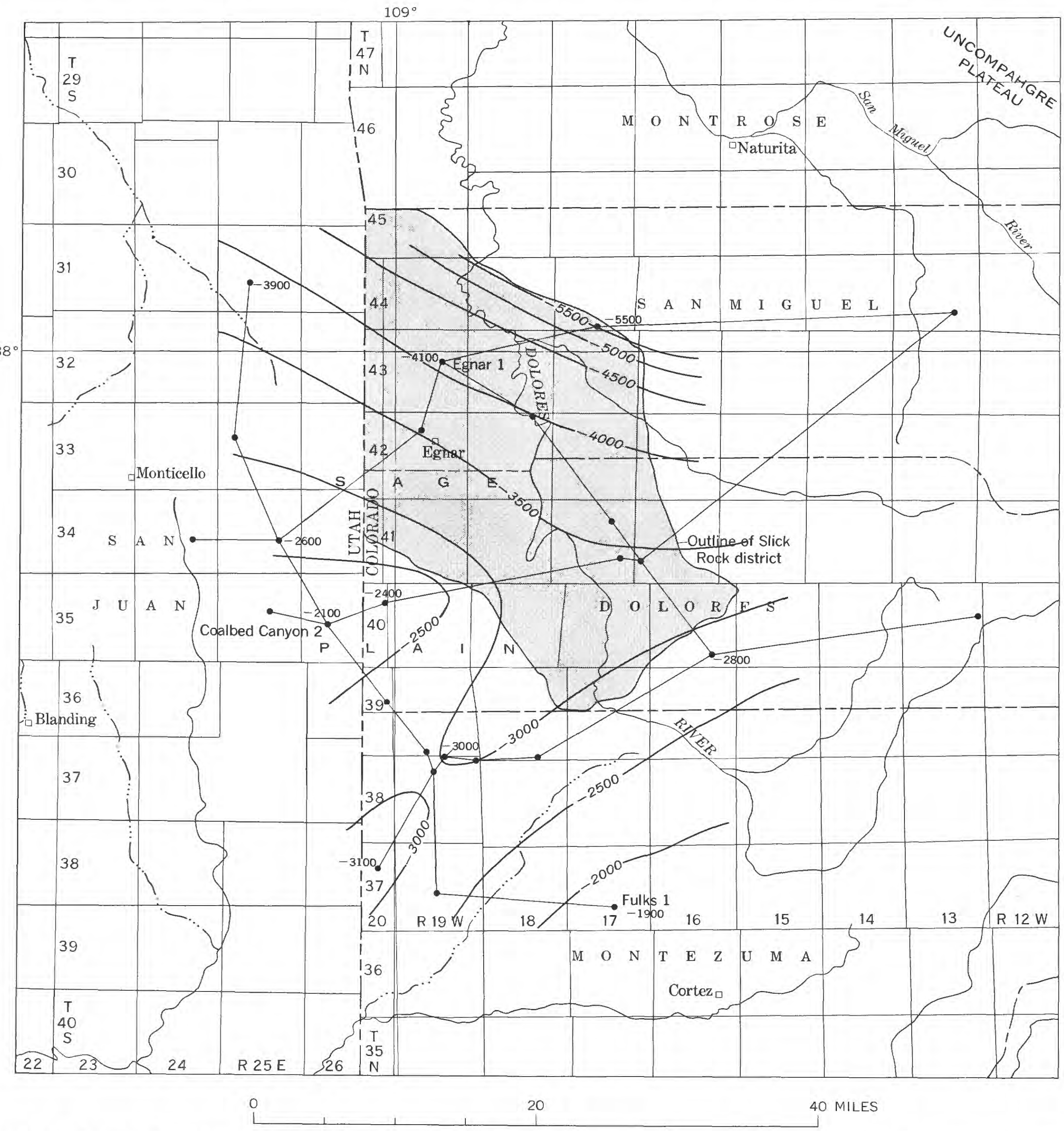

FIGURE 2.—Inferred upper surface of Precambrian rocks, Slick Rock district. Contours based on altitudes shown at oil-test wells (dots). Datum is mean sea level. Correlation diagrams betweens oil-test wells shown on plate 3.

contact at the top of Devonian rocks is uncertain, since the Ouray Limestone is similar to, and grades imperceptibly into, the overlying Leadville Limestone of Mississippian age. The absence of Ouray Limestone in the Fulks 1 south of the Slick Rock district may indicate an unconformity at the top of Devonian rocks in the region. J. D. Strobell suggested (oral commun., 1959), however, that in places in the Four Corners region Ouray Limestone is dolomitic, and dolomite at the horizon of the Ouray in the Fulks 1 may be the Ouray.

Configuration

Not enough data are available to show variations in thickness of Devonian rocks in the Slick Rock district. These strata range in thickness from 250 to 550 feet south and southwest of the district. According to Neff and Brown (1958, p. 106), Devonian rocks in the Paradox basin are thickest along a line extending from a point near the Four Corners northwesterly into Utah and are generally thinner to the north, east, and south. A locally thinner part of the Devonian rocks lies along another northwestward-trending line that passes through the southern part of the Slick Rock district.

MISSISSIPPIAN ROCKS

Numerous deep oil-test wells drilled in the district and nearby penetrate carbonate rocks of supposed Missisipian age, and some cut completely through these rocks. Mississippian rocks do not crop out in the district. Those found in the subsurface in the Four Corners area are generally called Leadville Limestone; fossils suggest an age of Early Mississippian (Kinderhook), which is the age of the Madison Limestone of central Utah (Neff and Brown, 1958, p. 102).

Lithology

The supposed Leadville Limestone penetrated in the Reynolds Mining Co. Egnar 1 (fig. 3) consists of a minimum of about 240 feet of uniformly fine-grained medium-gray limestone. The absence of any beds of greenish-gray shale suggests that none of this interval is part of the Ouray Limestone, which typically contains such shale (J. D. Strobell, oral commun., 1959). Neff and Brown (1958) indicated that the Leadville Limestone just south of the district, penetrated in the Coalbed Canyon 2 and the Fulks 1, consists of an upper limestone member about 60–120 feet thick and a lower dolomite member about 140–260 feet thick.

Configuration

In the Slick Rock district the thickness of the interval of Mississippian rocks ranges from about 250 to 500 feet. According to Neff and Brown (1958, p. 103) the dolomite member of the Leadville Limestone thickens from a zero isopach in San Juan County, N. Mex., and Montezuma County, Colo., northwestward to over 800 feet in Utah northwest of the Colorado River. The dolomite member is locally thinner along a northwestward-trending line that passes through the Slick Rock district.

PENNSYLVANIAN ROCKS

No rocks of Pennsylvanian age are exposed in the Slick Rock district; however, some details of these rocks are known from carbonate strata assigned to the Pennsylvanian System that crop out along the Lisbon Valley anticline about 10 miles west of the north end of the district, from gypsum and black shales of the Hermosa Formation that crop out in Gypsum Valley adjacent to the district, and from many deep oil-test wells in and near the district that penetrate or pass through Pennsylvanian strata. Formations underlying the district include, successively, the Molas Formation of Pennsylvanian (Morrow and Atoka) age, the lower limestone member of the Hermosa Formation of Middle Pennsylvanian (Atoka and early Des Moines) age, the Paradox Member of the Hermosa Formation of Middle Pennsylvanian (early Des Moines or Cherokee) age, the upper limestone member of the Hermosa Formation of Pennsylvanian (late Des Moines, Missouri, and Virgil) age, and the lower part of the Rico Formation of Pennsylvanian and Permian (Virgil and Wolfcamp) age (Wengerd, 1958, p. 119).

MOLAS FORMATION

The Molas Formation is cut through by at least two deep oil-test wells in the district—the Reynolds Mining Co. Egnar 1 and the Three States Natural Gas Gypsum Valley 1 (fig. 3)—and by several other test wells near the district. The formation is absent, however, from three wells that bottom below the horizon of the Molas—the Skelly Oil Co. Summit Point 1, the Gulf Oil Corp. Coalbed Canyon 2, and the Gulf Oil Corp. Fulks 1 (fig. 3).

Lithology

In the district the Molas Formation consists of about 100 feet of interbedded reddish-brown, dark-gray, and greenish-gray silty shale and shale and gray fine-grained limestone. According to Wengerd (1958, p. 118) "The Molas formation is predominantly a clastic red-bed sequence comprising reddish-brown to variegated siltstone, red silty shale, calcareous sandstone, and some gray to reddish-buff limestone lentils. The basal part of the formation comprises boulders and cobbles of Leadville limestone and dolomite both in situ and transported."

Configuration

The Molas Formation is thickest along a line trending northwest through the district and along a line trending almost southwest from the southeast edge of the district into Utah; it is absent in three areas near the district (fig. 3).

HERMOSA FORMATION

Earlier writers (for example, Stokes and Phoenix, 1948; Cater, 1955a, e, f) considered the Hermosa rocks as a formation consisting of a lower (Paradox) member composed of salt, gypsum, and anhydrite, and minor amounts of limestone, black shale, and sandstone, and

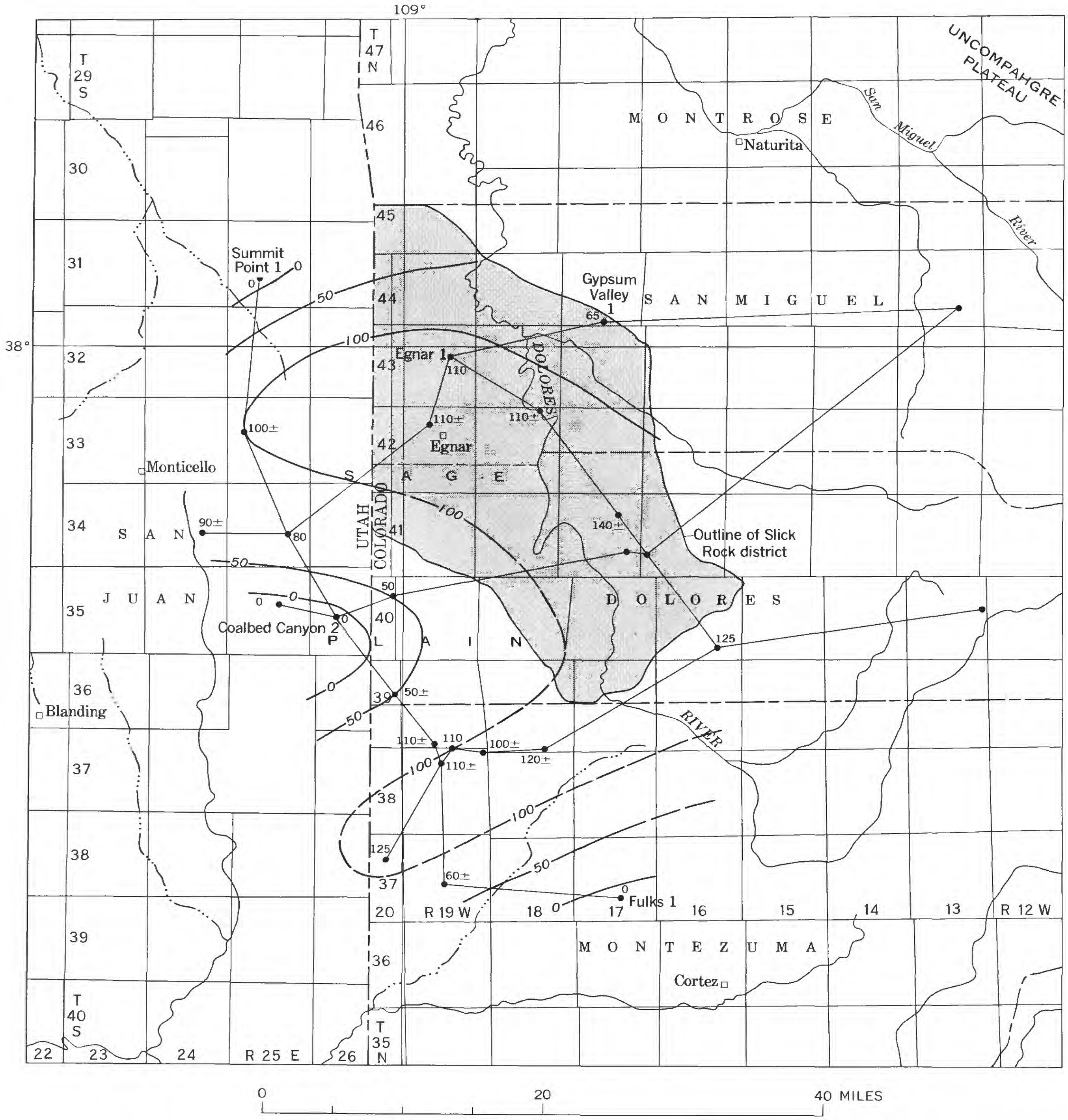

FIGURE 3.—Thickness of the Molas Formation. Isopachs dashed where approximately located; interval 50 feet. Number by oil-test well (dot) is measured thickness, in feet, of stratigraphic unit. Correlation diagrams between oil-test wells shown on plate 3.

an upper member composed largely of fossiliferous thick-bedded gray limestone with some thin shale beds. Many writers (for example, Wengerd, 1958; Picard, 1958; Carter, 1958) consider the Hermosa rocks as a group which is divided into three formations, a lower limestone formation, a middle (Paradox) formation, and an upper limestone formation. The Paradox Formation has in turn been divided into three members; a lower member, the salt member, and an upper member. Hermosa rocks will be described here as a formation made up of three members of the lower limestone, Paradox, and upper limestone.

Although no rocks of the Hermosa Formation crop out in the Slick Rock district, strata assigned to this interval are exposed a short distance northeast of the district, in Gypsum Valley. Here rocks of the salt unit of the Paradox Member have been intruded into the axial part of the Gypsum Valley anticline and have been exposed by erosion; they are not in normal contact with younger limestone rocks of the Hermosa that overlie them. Concerning the Hermosa rocks in Gypsum Valley, Stokes wrote (Stokes and Phoenix, 1948):

> The salt- and gypsum-bearing Paradox member of the Hermosa formation is exposed as several masses of gypsum in the Gypsum Valley trough, the largest of which is at the southeastern end of Big Gypsum Valley. It is probable that gypsum buried under shallow alluvial cover is present over most of the floor of Big Gypsum Valley. Overlying the gypsum of the Paradox member, but nowhere showing a clear-cut undisturbed contact with it, is a sequence of limestones and shales also assigned to the Hermosa formation. This sequence is exposed in steeply dipping and disturbed outcrops at several places about the margins of the Gypsum Valley trough. A thickness of 300 feet was measured on Klondyke Ridge, but this is almost surely an incomplete section as the contact with the Paradox member is probably intrusive. Fossils collected at several points have been examined by J. S. Williams and Lloyd G. Henbest and identified as being of Des Moines age and typical of the Hermosa of other areas.

LOWER LIMESTONE MEMBER

The lower limestone member of the Hermosa Formation of Pennsylvanian age, probably stratigraphically equivalent to the Pinkerton Trail Limestone of Middle Pennsylvanian age of Wengerd and Stickland (1954), is known only from deep oil-test well cores and cuttings. At least two test wells in the district and about eight nearby cut through the member. Within the district the member consists of medium-gray very fine grained limestone containing some thin dark-gray shale interbeds that are most abundant near the top. It is about 100–150 feet thick and is thinnest along a line trending northwest approximately along the southwest boundary of the district (fig. 4).

PARADOX MEMBER

The Paradox Member of the Hermosa Formation, generally a few thousand feet thick, is divided into three units—a lower unit consisting of carbonate, dark-gray shale, anhydrite, gypsum, and salt strata; a middle or salt unit which in the region surrounding the district consists predominantly of massive beds of halite; and an upper unit similar to the lower unit.

The Paradox Member underlies large parts of southeastern Utah and southwestern Colorado and smaller parts of northeastern Arizona and northwestern New Mexico. Its distribution defines the Paradox structural basin, and it represents a major phenomenon of the basin which probably had its inception prior to Paradox time and which was active long after Paradox time. The basin itself is roughly oval shaped, about 150 miles wide and 250 miles long; the long axis trends northwest and the northeast boundary of the basin lies against the northwestward-trending Uncompahgre uplift.

LOWER UNIT

The sedimentary rocks that constitute the lower unit of the Paradox Member underlying the district are known only from deep oil-test wells, only two of which cut through the unit. However, about 8 test wells nearby bottom in lower formations, and the 10 wells provide sufficient data from which to construct an isopach map showing the general thickness of the member (fig. 5). Rocks that are stratigraphically equivalent have been widely recognized in the Paradox Basin and are generally called the lower member of the Paradox Formation (Wengerd, 1958). The age of the unit is early Middle Pennsylvanian (early Cherokee or earliest Des Moines) (Welsh, 1958, p. 153).

Lithology

The lower unit of the Paradox Member consists of interbedded dark- to light-gray anhydrite, gray dolomite and limestone, dark-gray shale, gypsum, and halite strata, each generally a few feet to a few tens of feet thick. The rocks are transitional with those in the underlying lower limestone member and in the overlying salt unit of the Paradox.

Configuration

In the district the thickness of the lower unit (fig. 5) ranges from 30 feet in the south end to 200 feet in the Three States Natural Gas Co. Gypsum Valley 1, at the northeast edge. South of the district, in the Fulks 1, it is about 300 feet.

SALT UNIT

Strata of the salt unit of the Paradox Member are exposed a short distance northeast of the boundary of the Slick Rock district, in Gypsum Valley. Data on lithology are derived chiefly from three deep oil-test wells drilled in or near the district (fig. 6).

Lithology

Cater (1955a, e, f) has described the Paradox strata at the surface in Gypsum Valley as follows: * * *

largely of cellular and earthy gypsum and minor amounts of limestone, black shale, and sandstone. At depth more than half the formation is rock salt. All known surface occurrences of the Paradox are intrusive, and the beds are complexly folded and contorted. The undisturbed thickness of the member is not known, but a well drilled in Paradox Valley penetrated more than 10,800 feet of intrusive beds without reaching pre-Paradox

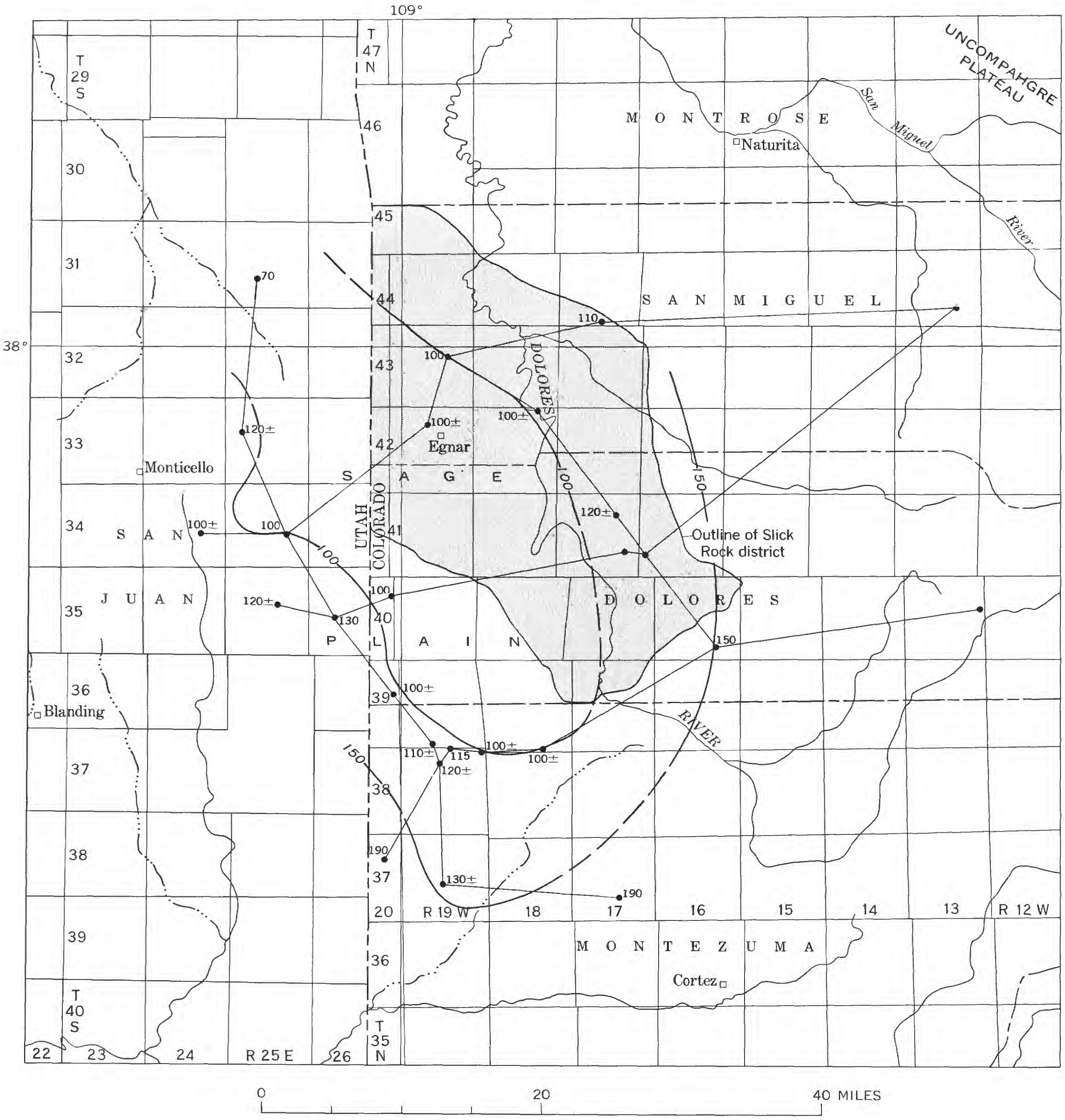

FIGURE 4.—Thickness of the lower limestone member of the Hermosa Formation. Isopachs dashed where approximately located; interval 50 feet. Number of oil-test well (dot) is measured thickness in feet of stratigraphic unit. Correlation diagrams between oil-test wells shown on plate 3.

strata, and there is little reason to believe that the intrusive beds underlying Gypsum Valley are appreciably thinner.

Halite clearly has been removed by solution from the rocks at or near the surface, and anhydrite has been almost completely hydrated to gypsum. The exceptional abundance of gypsum in the Paradox strata has given Gypsum Valley its name. The Three States Natural Gas Co. Gypsum Valley 1 penetrated several thousand feet of the salt unit which chiefly consists of halite. Logs of drill cuttings from the Reynolds Mining Co. Egnar 1 and the Continental Oil Co. Lone Dome 1, just southeast of the district where the salt unit is thickened be-

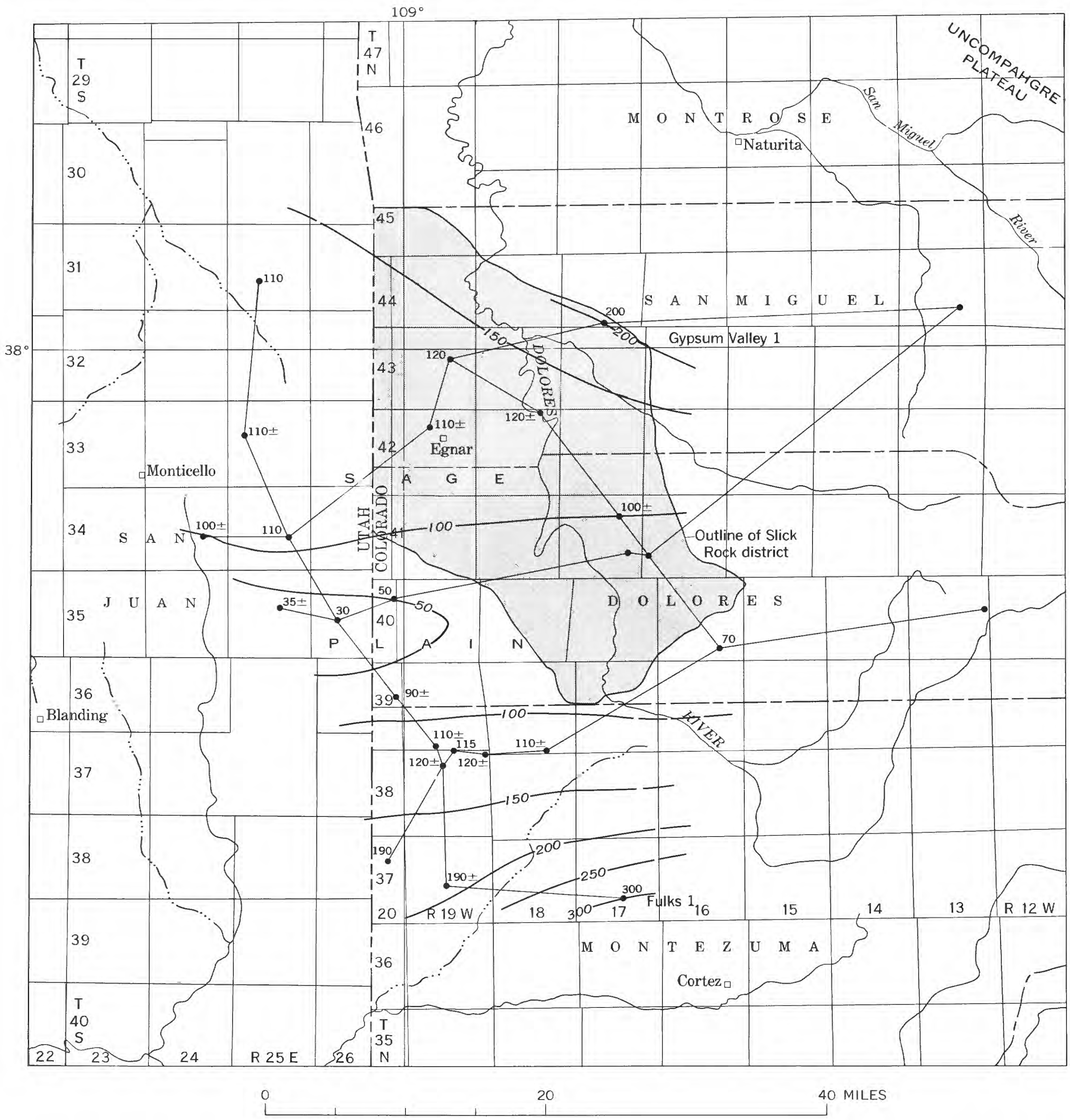

Figure 5.—Thickness of the lower unit of the Paradox Member. Isopachs dashed where approximately located; interval 50 feet. Number by oil-test well (dot) is measured thickness, in feet, of stratigraphic unit. Correlation diagrams between oil-test wells shown on plate 3.

neath the Dolores anticline, show that these sections are each several thousand feet thick and contain respectively about 75 and 72 percent halite in massive beds more than 10 feet thick. Locations of the drill holes are shown in figure 6. Clear colorless to light-gray halite occurs in massive beds as much as 400 feet thick and commonly more than 200 feet thick, although many halite beds are a few tens of feet or less thick. Interbedded with the halite are units of alternating black shale, containing traces of silt grains, mica, and pyrite, carbonate, white to gray dense to punky anhydrite, light-gray gypsum, and minor sylvite and carnallite. These units are as much as 100 feet thick but commonly only a few tens of feet or less thick.

Configuration

The salt unit of the Paradox Member underlies a large part of the Paradox structural basin in Utah and Colorado, but it is absent along the southwest edge of the basin. The unit ranges in thickness from several hundred feet in southeastern Utah and southwesternmost Colorado to several thousand feet on the northeast side of the basin, in the Paradox fold and fault belt of Kelley (1958).

Data from oil test wells that cut through the unit, two within the district and eight nearby, were used to construct an isopach map showing the general thickness of the unit (fig. 6). The thickest salt in the region is penetrated in three holes in and near the district—4,140 feet in the Egnar 1; 3,590 feet in the Gypsum Valley 1; and 3,210 feet in the Lone Dome 1. Evidence that the salt has undergone considerable thickening and thinning because of postdepositional flowage prohibits the use of the map to indicate the configuration of the unit at the time of its deposition. Nevertheless the "normal" thickness of the salt unit after deposition was probably about 1,500–2,000 feet in the vicinity of the district, as suggested by the present thickness of the unit in the area southwest of the district, where post-Paradox deformation has been slight.

UPPER UNIT

The stratigraphy of the upper unit of the Paradox Member is known from logs of 5 deep oil-test wells in the district and about 15 nearby. Stratigraphically equivalent rocks throughout the Paradox Basin are widely known and have been studied intensively because they constitute the most important gas-and-oil-producing interval in the basin.

No oil has been produced from the unit in the Slick Rock district, but shows of gas are reported in the Prestige-Allison Long 1 and in the Carter Oil Co. Glade 1 (Oil and Gas News, Dec. 28, 1957). Just outside the district, about 9 miles southwest of Cahone, initial oil and gas production in the area was from the Byrd-Frost Driscoll 1 (Finley, 1951). Oil well locations are shown in figure 7. Discovery, in February 1956, of the important Aneth oil field in southeastern Utah, whose production comes from the Desert Creek (lower) zone and the Ismay (upper) zone of the upper member of the Paradox (Carter, 1958), has emphasized the importance of this interval in petroleum exploration.

The age of the upper unit of the Paradox Member is early Des Moines or Cherokee (Welsh, 1958, p. 153).

Lithology

In the Slick Rock district the upper unit of the Paradox Member consists of interbedded gray limestone, dark-gray shale, gypsum, anhydrite, and halite. Throughout the region the abundance of gypsum together with salt casts in shale is suggestive of weathering and ablation of the member prior to deposition of the overlying upper limestone member of the Hermosa Formation (D. P. Elston, oral commun., 1959).

Configuration

In the district the upper unit is about 300–500 feet thick; a zero-thickness contour is shown around its outcrop areas in Gypsum Valley (fig. 7). A thick part of the unit lies along a line extending from the southern part of the district northwestward into Utah. Between this thick part and a thicker section recorded in the Fred H. Turner Buss 1 (fig. 7), a thin part of the upper unit lies along a northwestward trending line. Southeast of the district the upper unit thins appreciably.

UPPER LIMESTONE MEMBER

The stratigraphy of the upper limestone member of the Hermosa Formation is inferred from logs of 7 deep oil-test wells drilled in the district and 19 drilled nearby. Thickness data from these holes are shown in figure 8. The upper limestone member in the district is stratigraphically equivalent to rocks of similar lithology recognized throughout the Paradox Basin—the Honaker Trail Formation of Wengerd and Matheny (1958) in San Juan County, Utah. The age of the member in the vicinity of Slick Rock was given by Wengerd (1958, p. 119) as Middle to Late Pennsylvanian to earliest Permian (Des Moines to Missouri to Virgil, and including Wolfcamp in places). He correlated the unit with part of the Oquirrh Formation in north-central Utah, the upper part of the Madera Limestone of the Magdalena Group in central New Mexico, the lower and middle parts of the Supai Formation in north-central Arizona, the upper part of the Gothic Formation of Langenheim (1952), and the lower part of the Maroon Formation in the vicinity of Eagle and Gypsum in Colorado (Wengerd, 1958, p. 115).

Lithology

In the Slick Rock district and vicinity the upper limestone member of the Hermosa consists generally of interbedded limestone, shale, siltstone, and standstone. The limestone, which is light to dark gray, fine to medium grained, and fossiliferous, forms beds as much as 100 feet thick (but commonly much thinner) that are in part silty and shaly and in places contain abundant gray and reddish-gray chert and traces of pyrite. The shale, which is dark gray, gray, greenish gray, and reddish gray, forms beds as much as 20 feet thick that are in part calcareous and in places contain abundant

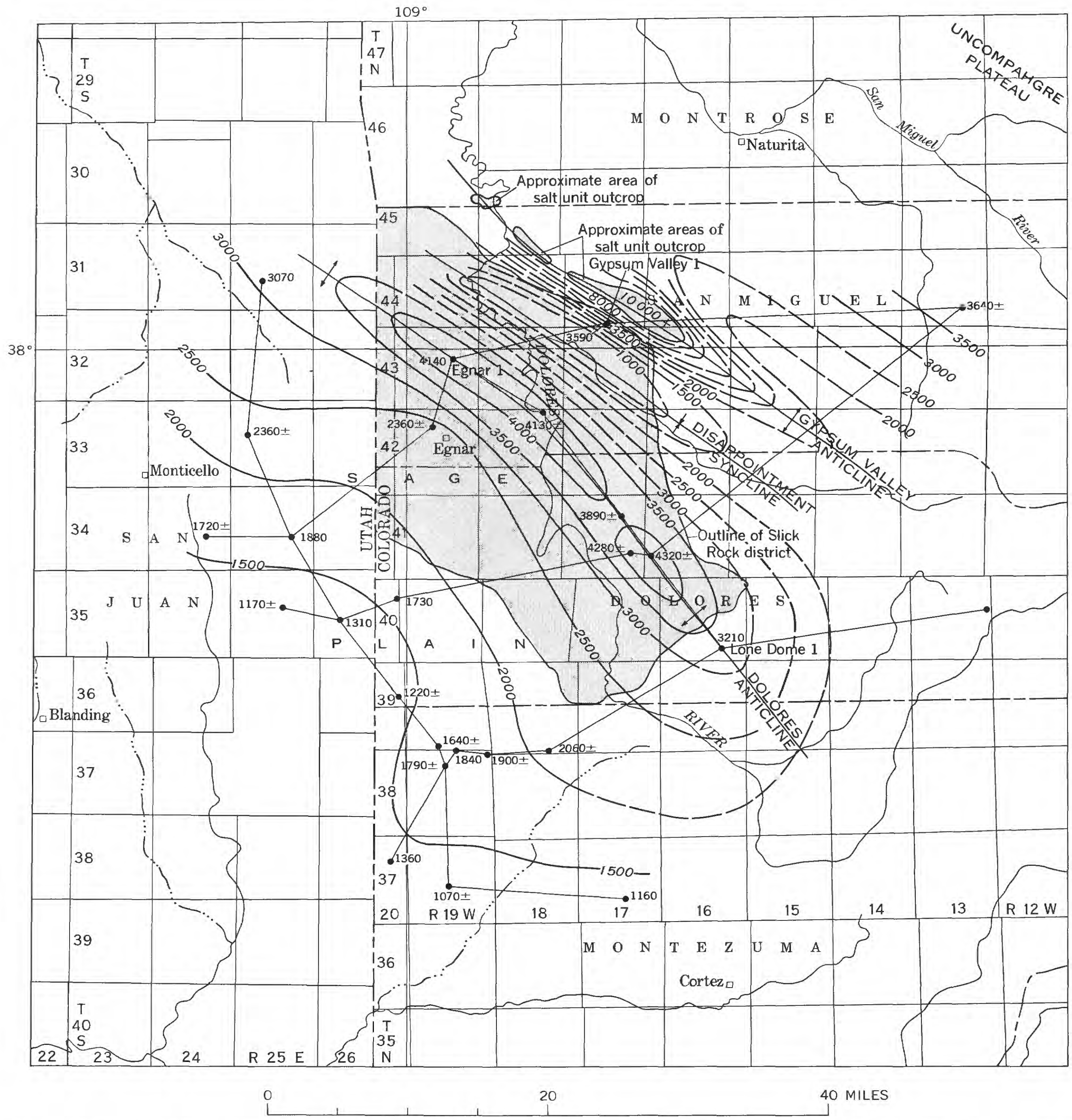

FIGURE 6.—Thickness of the salt unit of the Paradox Member. Isopachs dashed where approximately located; interval 500 feet. Number by oil-test well (dot) is measured thickness, in feet, of stratigraphic unit. Correlation diagrams between oil-test wells shown on plate 3.

muscovite and some pyrite. The siltstone, which is greenish gray and reddish gray, forms beds as much as 20 feet thick that are in part calcareous and in places contain abundant muscovite and some pyrite. The sandstone, which is greenish gray and reddish gray and very fine to fine grained, forms beds as much as 30 feet thick that are in part calcareous and arkosic and in places contain some muscovite, biotite, and pyrite. In the Egnar 1 (fig. 8) the upper 700 feet of the member contains considerable reddish-brown shale, siltstone, and sandstone.

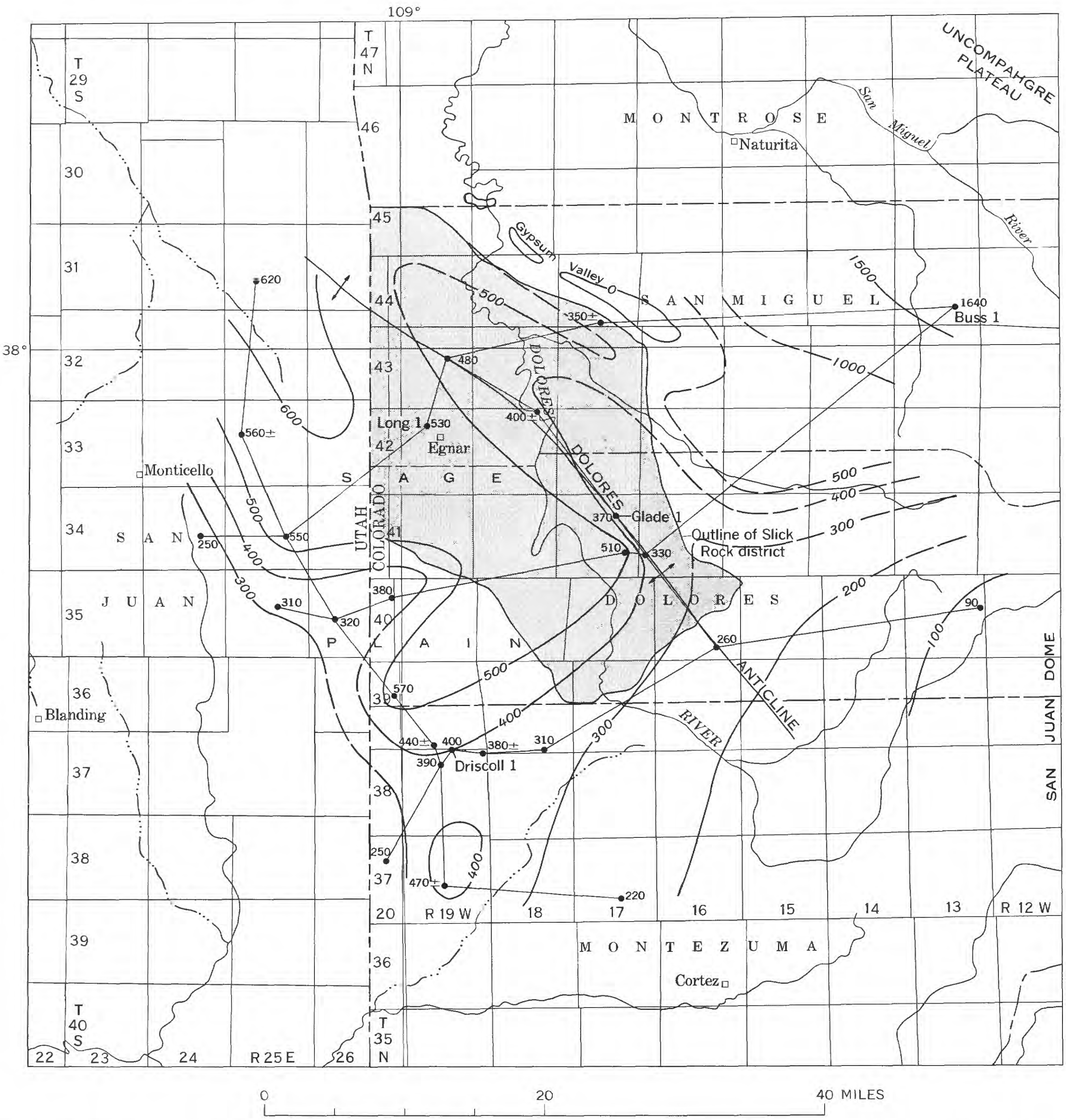

FIGURE 7.—Thickness of the upper unit of the Paradox Member. Isopachs dashed where approximately located; intervals 100 and 500 feet. Number by oil-test well (dot) is measured thickness, in feet, of stratigraphic unit. Correlation diagrams between oil-test wells shown on plate 3.

The upper part of the member which has a higher proportion of clastic material than the lower part, seems to be a transitional unit between dominantly carbonate and evaporite rocks below and detrital rocks above. Both upper and lower contacts of the upper limestone member appear to be gradational because abrupt changes in lithology are not discernible in most test well logs.

Configuration

In the Slick Rock district the upper limestone member of the Hermosa generally ranges in thickness from a little more than 1,000 feet to 1,800 feet (fig. 8). Along the northeast edge of the district the member thins out completely around the outcrop of the salt unit of the underlying Paradox Member. How much of the thinning is a result of nondeposition and how much a result of truncation by intrusion of the underlying salt is not known. Probably both are responsible for the thickness variations. The thickest part of the upper limestone member lies along a line extending northwestward through the northern part of the district. The member thins to the southwest and is thinnest just outside of the district along a north-northwest line extending from Montezuma County into Utah.

PENNSYLVANIAN AND PERMIAN ROCKS—RICO FORMATION

The Rico Formation in the Slick Rock district and vicinity is not everywhere clearly recognizable on the basis of available subsurface data. Nevertheless, in places strata of distinct lithology have been assigned to the Rico, and these are described here. Rocks of the Rico Formation have been recognized in cuttings from about nine deep oil-test wells drilled in and near the district, and their presence is inferred in nearby holes. The occurrence of fossiliferous limestone strata about 10 feet or more thick has generally been the criterion for distinguishing the Rico Formation from the principally arkosic sandstone of the overlying Cutler Formation, and dominant reds and yellows rather than drab grays and greenish grays has been the basis for distinguishing the Rico from the underlying Hermosa rocks. Nevertheless, what has been called the upper part of the Hermosa in places contains abundant reddish rocks, so the contact between the Rico and the Hermosa in the district must be considered indefinite.

According to Kunkel (1958, p. 163) the Rico Formation is of Middle Pennsylvanian (Des Moines) age in the Rico quadrangle of Colorado (Herman and Sharps, 1956) and of Late Pennsylvanian age near Moab, Utah (Henbest, 1948). Similar beds west of Moab are early Permian (Wolfcamp). Kunkel stated that George Herman (oral commun., 1958) reported that rocks mapped as the Rico Formation in Monument Valley (Baker, 1936) are Late Pennsylvanian (Missouri) in age. Details of the relationships of the Rico to adjacent formations in the Four Corners area and the manner in which lithologies of different ages change from place to place are imperfectly known. For example, that the Rico of Middle Pennsylvanian age at Rico, Colo., is continuous with the Rico of Early Permian age west of Moab is not certain. Wengerd (1958, p. 119) suggested that the Rico is in part stratigraphically equivalent to the upper part of the Pennsylvanian and Permian Supai Formation in southern Utah and in Arizona and to the Pennsylvanian Red Tanks Member of the Madera Limestone in southeastern New Mexico.

Lithology

In the Slick Rock district rocks that are probably equivalents of the Rico Formation are brownish to brownish-red and brownish-gray very fine to medium-grained sandstone, siltstone, and shale, and gray very fine to fine-grained fossiliferous limestone, in beds ranging in thickness from a few feet to about 50 feet. The lithology of the presumed Rico in the vicinity of the Slick Rock district is clearly transitional between that of the underlying Hermosa Formation and that of the overlying Cutler Formation.

In the area south of the district near the Four Corners, Strobell (1958, p. 67) showed the Rico Formation to be separated from Hermosa and Cutler rocks on the basis of key beds that can be correlated in well logs. He indicated, however, that the base of the orange-red beds that characterize the Cutler and the base of the varicolored shale beds that characterize the Rico do not coincide in stratigraphic position with the key beds that bound the Rico Formation. He further pointed out (p. 68) that the transitional nature of the Rico makes definition of the formation arbitrary locally.

Configuration

The Rico Formation is recorded in less than half of the logs of deep oil-test wells drilled in and around the Slick Rock district. However, the Rico was reported in most of the wells drilled within a northwesterly alined area of about 20 by 40 miles, centered on the southwest boundary of the district. The thickness of the presumed Rico in wells in this area generally ranges from 130 to 240 feet.

PERMIAN ROCKS—CUTLER FORMATION

Only the upper 240 feet of the Cutler Formation is exposed in the Slick Rock district; data on the lower part are derived from 7 deep oil-test wells drilled in the district and about 20 drilled nearby. The Cutler in the surrounding area is transitional between an arkosic facies adjacent to the Uncompahgre highland to the east and finer grained clastic rocks and chemical sediments of the Cutler in Utah to the west (Kunkel, 1958).

At its type locality on Cutler Creek near Ouray, Colo., the Cutler Formation (named by C. W. Cross, Ernest Howe, and F. L. Ransome, in Cross and others, 1905, and Cross and Ransome, 1905) consists of about 1,000 feet of bright-red sandstone, lighter red or pinkish grits and conglomerates alternating with sandy shales, and earthy or sandy limestones of various shades of red. Near Gateway, northeast of the district and adjacent to the Uncompahgre Plateau, the Cutler is about 8,000 feet thick (Mallory, 1960, fig. 8).

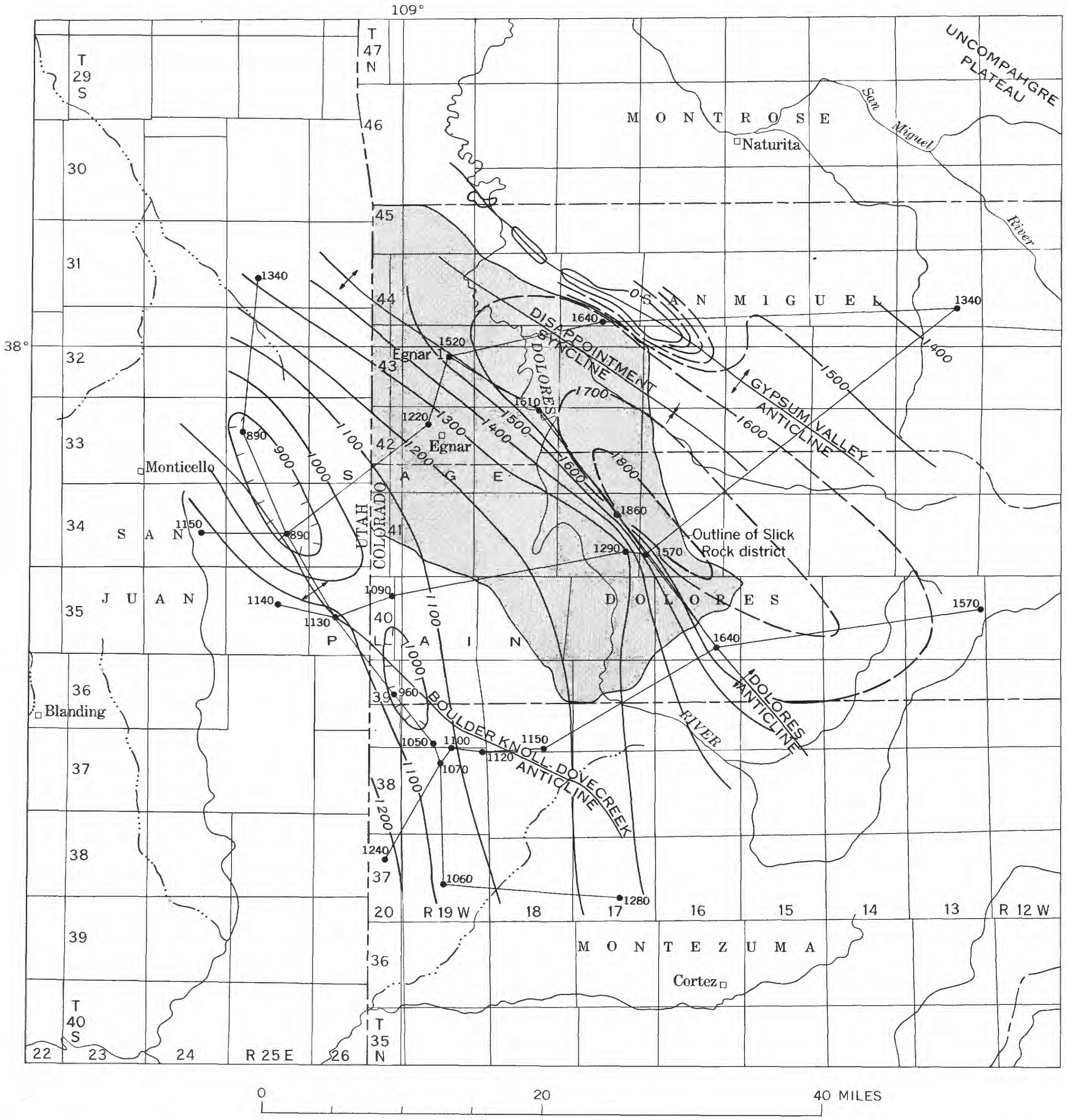

FIGURE 8.—Thickness of the upper limestone member of the Hermosa Formation. Isopachs dashed where approximately located; interval 100 feet. Number by oil-test well is measured thickness, in feet, of stratigraphic unit. Correlation diagrams between oil-test wells shown on plate 3.

Carbonate rock units that are interbedded with fine-grained clastic rocks of the Cutler Formation in Utah are fossiliferous, yielding fossils of Early Permian (Wolfcamp and Leonard) age; this indicates that the Cutler in the Slick Rock district and vicinity also is likely of Permian age.

Lithology

Northeast of the district, in the eastern part of the Paradox structural basin and adjacent to the Uncompahgre highland, the Cutler Formation is a complex assemblage of "interbedded coarse red and pink arkosic granite wash, black, purple, red, maroon, green, and brown micaceous silty shale, tan finely crystalline limestone, orange-red [and] maroon micaceous sandy arkosic calcareous siltstone, and orange, red, brown, maroon, and pink, conglomeratic to fine-grained arkosic sandstone" (Kunkel, 1958, p. 164). To the west, in Utah, the Cutler according to Kunkel consists of a basal carbonate unit (probably Rico equivalent) in places, and in other places of fine-grained clastic rocks of the Halgaito Tongue of the Cutler. Above these lies fine-grained well-sorted sandstone called either "Coconino Sandstone" or the Cedar Mesa Sandstone Member of the Cutler Formation. Fine-grained clastic rocks of the Organ Tongue of the Cutler lie above the Cedar Mesa Sandstone Member and farther west, in the vicinity of Escalante, Utah, carbonate and clastic rocks of the Toroweap Formation overlie "Coconino Sandstone." The De Chelly Sandstone Member of the Cutler overlies the Organ Rock Tongue and in turn is overlain by shale, sandstone, and siltstone of the Hoskinnini Tongue of the Moenkopi Formation. The Kaibab Limestone lies above rocks equivalent to the Cutler in the vicinity of Escalante. West of Slick Rock near Comb Wash, Utah, the Cedar Mesa Sandstone Member grades along bedding abruptly into "predominantly reddish to purple gypsiferous or anhydritic shales, brownish-red to gray medium- to fine grained crossbedded friable gypsiferous sandstone, conglomeratic and evenly bedded cherty fine- to medium-crystalline gray to purple limestone, and much sandy pink to white gypsum or anhydrite" (Kunkel, 1958, p. 166). These rocks compose the Cedar

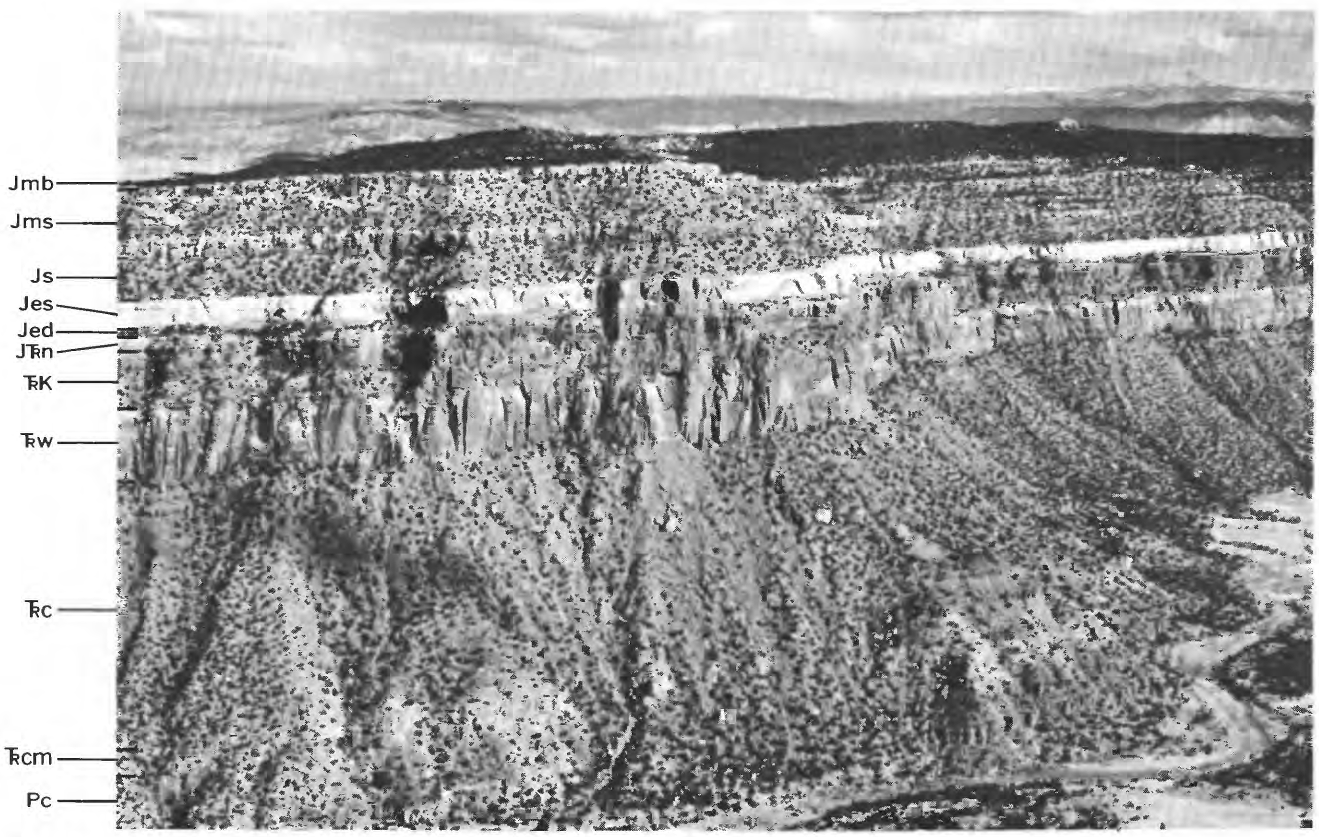

FIGURE 9.—East wall of the Dolores River Canyon, T. 43 N., R. 18 W., showing most of the sedimentary formations exposed in the Slick Rock district. Disappointment Valley lies beyond heavily wooded Joe Davis Hill; Lone Cone peak is visible in the distance, upper right. Pc, Cutler Formation; TRcm, Moss Back Member of Chinle Formation; TRc, Chinle Formation, undifferentiated; TRw, Wingate Sandstone; TRk, Kayenta Formation; JTRn, Navajo Sandstone; Jed, Dewey Bridge Member of Entrada Sandstone; Jes, Slick Rock Member of Entrada Sandstone; Js, Summerville Formation; Jms, Salt Wash Member of Morrison Formation; Jmb, Brushy Basin Member of Morrison Formation. Photograph by E. L. Boudette.

Mesa evaporite facies. To the east the evaporite facies grades into arkosic red beds of the Cutler south of the district. According to Kunkel (1958, p. 166) the De Chelly Sandstone Member above the Cedar Mesa and Organ Rock "merges into undifferentiated Cutler beds" near Dove Creek, Colo.

In the Slick Rock district the Cutler Formation consists of reddish-brown, orange-brown, and light-brown sandstone, siltstone, mudstone, and shale, probably of terrestrial deposition. Well cuttings from Egnar 1 (fig. 8) indicate that here the Cutler consists of about 85 percent reddish-brown siltstone, mudstone, and shale, and about 15 percent very fine to medium-grained poorly sorted light-reddish-brown and orangish-brown sandstone. The lower half of the formation has little sandstone, but the upper half contains several sandstone units about 10–70 feet thick. Cores of the upper part of the Cutler Formation taken from diamond-drill holes in Summit Canyon (pl. 1) consist of fine- to coarse-grained arkosic sandstone. In places the sandstone contains angular granules of feldspar and moderately to poorly rounded light-greenish-gray to dark-gray granules of chert. Logs of the drill holes show that in one place a sandstone unit at the top of the Cutler Formation is directly overlain by the Moss Back Member of the Chinle Formation. Here the Cutler dips more steeply southwest than the Moss Back, and downdip the Moss Back and the sandstone unit of the Cutler are separated by several feet of mudstone and siltstone (plate 2). A similar unit in the top part of the Cutler, which is crossbedded and horizontally bedded fine- to coarse-grained sandstone about 10–70 feet thick, is exposed at the bottom of the Dolores River canyon, T. 42 and 43 N., R. 18 W., where the sandstone unit in the Cutler forms a prominent ledge beneath the Moss Back Member of the Chinle Formation (fig. 9). In places the unit is in direct contact with the Moss Back and in other places it is separated from the Moss Back by as much as 200 feet of reddish-brown siltstone, mudstone, and shale (pls. 1, 2).

Configuration and surface distribution

Because of difficulty in determining a consistent contact between the Rico and Cutler Formations as well as the apparent absence, in places, of Rico as shown in logs from deep oil-test wells in and around the district, the Rico Formation is included with the Cutler for the purpose of determining the total thickness of the unit (fig. 10). The minimum thickness of the Cutler in the area is about 1,550 feet (in Utah), except where the formation is completely pinched out around the Gypsum Valley salt anticline at the northeast edge of the district. It is much thicker, 3,640 feet, farther east in the Fred H. Turner Buss 1, sec. 26, T. 44 N., R. 13 W., San Miguel County. The maximum recorded thickness of the interval in the district is about 2,120 feet, in the Byrd-Frost J. A. Uhl–Govt. 1 in sec. 26, T. 41 N., R. 17 W., Dolores County. A maximum interpreted thickness of more than 3,000 feet is shown in figure 10, and in correlation diagram A, plate 3, along Disappointment syncline. Such a thickness of the Cutler along the syncline is commensurate with the known increased thicknesses of younger formations in the syncline and accords with gravity data for the northern part of the Slick Rock district (Joesting and Byerly, 1958, p. 12; and P. E. Byerly, oral commun., 1960).

A second elongate area of fairly thick Cutler lies oriented approximately at right angles to the northwesterly area in the Disappointment syncline and extends southwestward through the south end of the district. Perhaps the isopachs as shown in figure 10 could have been closed around the wells in T. 38 N., R. 19 W., Montezuma County. This would subdue the apparent southwesterly elongation of thicker Cutler Formation but would still show a generally thicker section along the southwesterly line.

In the Slick Rock district the Cutler Formation is exposed only in the bottom of the Dolores River Canyon, in Tps. 42 and 43 N., R. 18 W.

TRIASSIC ROCKS

MOENKOPI FORMATION

No rocks of the Moenkopi Formation are known at the surface in the Slick Rock district and vicinity. Nevertheless, numerous logs of deep oil-test wells record Moenkopi in the vicinity, and possibly the formation is present in places in the district. However, because the lithology of the Moenkopi of eastern Utah is similar to that of the underlying Cutler (Stewart and others, 1959, p. 497–498), the Moenkopi may have been incorrectly identified in well cuttings, and the contacts, where the formation is present, may be incorrectly located. The Moenkopi may have been incorrectly located in the Three States Natural Gas White 2 and the Byrd-Frost White 1, Montezuma County (pl. 3, diagram E, wells 17 and 19). The White 1 shows no Moenkopi (although the base of the Moenkopi is projected in the diagram), whereas the White 2 shows more than 200 feet of Moenkopi. The thickening of the Cutler as shown in figure 10 extending southwesterly through the southern part of the district and to the vicinity of these wells thus may be illusory, and incorrect location of the upper contact of the Cutler Formation results in apparent differences in thickness which are shown on the isopach map. However, if the thickness of the Moenkopi as recorded in well logs is added to the thickness of the Rico and

Cutler undivided, which was used to construct figure 10, the isopachs of this thicker interval enhance, rather than subdue, the area of southwesterly alined thicker Cutler.

Stewart, Williams, Albee, and Raup (1959) showed Moenkopi in southeastern Utah pinching out eastward along the Colorado-Utah line but suggest that further study of drill-hole information may show that Moenkopi extends farther east (p. 496).

The age of the Moenkopi is Early and Middle (?) Triassic, according to Stewart, Williams, Albee, and Raup (1959, p. 496).

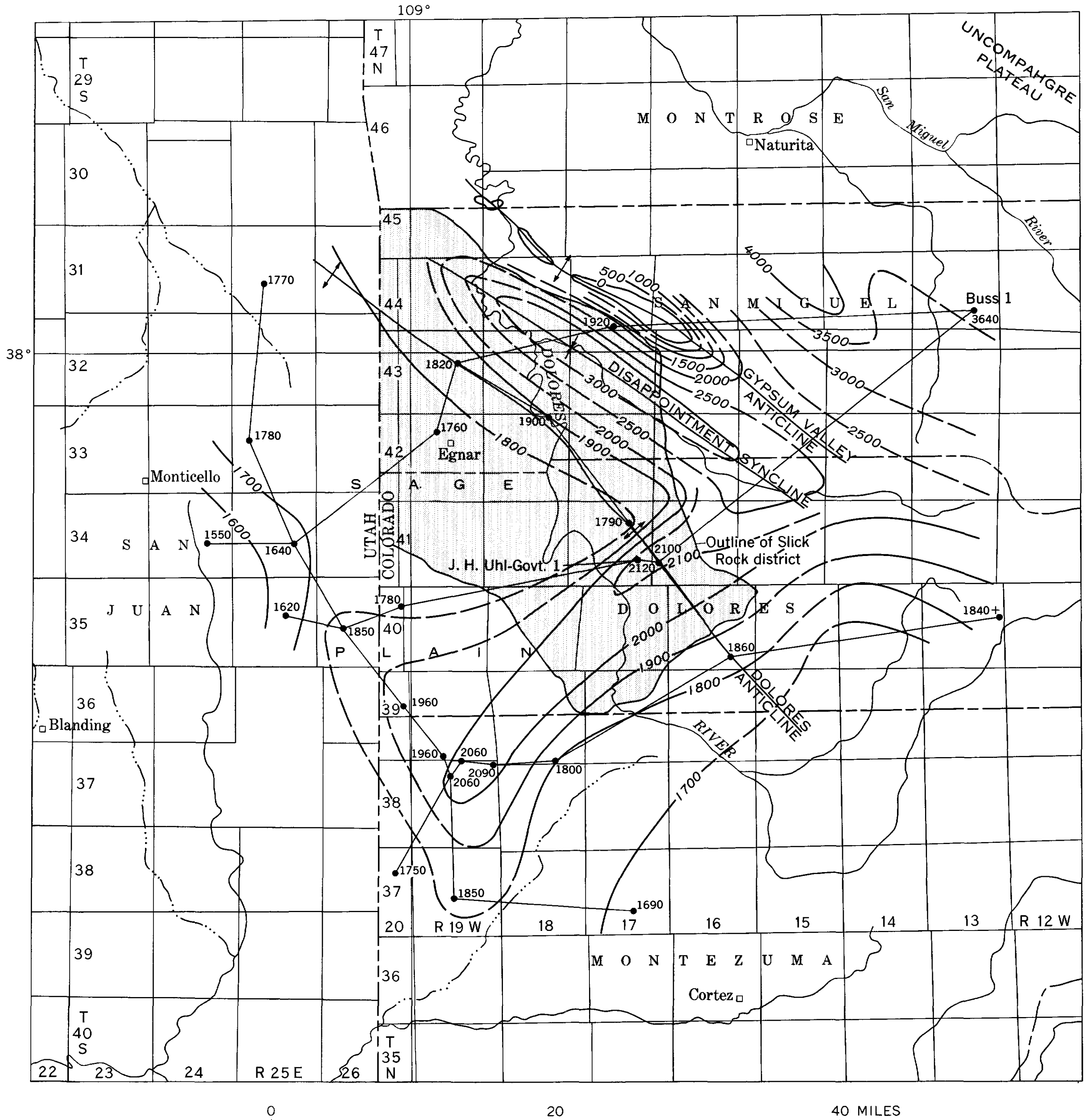

FIGURE 10.—Thickness of the Rico and Cutler Formations undivided. Isopachs dashed where approximately located; intervals 100 and 500 feet. Number by oil-test (dot) is thickness, in feet, of stratigraphic unit. Correlation diagrams between oil-test wells shown on plate 3.

Lithology

Rocks called Moenkopi Formation in drill holes in the vicinity of the district, and Moenkopi described by Stewart, Williams, Albee, and Raup (1959, p. 496–497) in southeastern Utah, consist chiefly of light-reddish-brown micaceous siltstone and sandy siltstone.

Configuration

An isopach map of the Moenkopi (fig. 11) was drawn using thicknesses recorded on logs of deep oil-test wells in the district and vicinity, even though some of the data are of doubtful accuracy. Much of the district and vicinity, including possible outcrop areas, has no Moenkopi, but two areas are indicated where the formation is about 200 feet or more thick. One southwesterly alined area extends across the west boundary of the district, partly in Utah and partly in Colorado. Southeastward from this area the formation thins and in places pinches out.

CHINLE FORMATION

The Chinle Formation in the Slick Rock district is important as a potential uranium- and vanadium-producing horizon. What is probably the Moss Back Member of the Chinle in the Lisbon Valley area, Utah, 5–10 miles west of the northwest corner of the district, has produced commercially important amounts of uranium-vanadium ore. The similarity of the Moss Back lithology and structural setting in the Slick Rock district to that in Lisbon Valley favors the likelihood of undiscovered ore in the district.

The Chinle Formation was named and described by Gregory (1917, p. 42–50), who considered the formation to lie between the Shinarump Conglomerate and the Wingate Sandstone; the type locality is in northeastern Arizona. The Shinarump is now a member of the Chinle (Stewart, 1957), and Gregory's nomenclature for the Chinle (A, B, C, and D members) has been revised and refined throughout the Colorado Plateau, and formal member names have been given to the Chinle (R. C. Robeck, 1956; Stewart, 1957; Stewart and others, 1959). Lower members of the Chinle Formation recognized elsewhere but probably not present in the Slick Rock district are the Temple Mountain, Shinarump, Monitor Butte, and Owl Rock Members. In the district five units are recognized. The first and lowest is the Moss Back Member, the next higher unit is possibly a facies of the Petrified Forest Member or part of the Church Rock Member, and the three highest units are equivalents of the Church Rock Member.

The Chinle was deposited upon an erosional surface of the Cutler and Moenkopi Formations. The oldest members of the formation were deposited in western and southern Utah and in northern Arizona, and in a general way successively younger members were spread to the northeast, or their deposition was localized to the northeast, so that younger members are in contact with the underlying Cutler and Moenkopi in that direction (Stewart and others, 1959, figs. 73, 81). Northeasterly and easterly pinchout of the Temple Mountain, Shinarump, Monitor Butte, and Owl Rock Members thus accounts for their absence in the district.

The Chinle Formation was first mapped in the Slick Rock district by Coffin (1962) as the lower part of the Dolores Formation, and was not recognized here as a separate formation until Stokes and Phoenix mapped in the area in the 1940's.

On the basis of vertebrate fossils, Stewart, Williams, Albee, and Raup (1959, p. 522) assigned the Chinle Formation to the Upper Triassic.

LITHOLOGY

The Chinle Formation in the district is composed dominantly of siltstone, shale, conglomerate, and sandstone. It crops out as a steep slope broken by a few ledges of siltstone and sandstone, and where exposed in the lower part, a few ledges and cliffs of sandstone and conglomerate. The siltstone is generally orangish brown to reddish brown, has a high clay content, and is indistinctly bedded. Where clay content is low the siltstone forms resistant ledges. The shale is not markedly fissile, is greenish gray and reddish brown, has a variable content of sand and silt and hence grades into mudstone, and is probably in part bentonitic, especially where greenish gray. The conglomerate is dark gray to greenish gray and is typically composed mainly of limestone clasts and a small number of shale, quartzite, and chert clasts that range up to pebble size, in a calcareous clay matrix. Thicker conglomerate lenses in most places are associated with lenses of greenish-gray sandstone. The sandstone is generally light reddish brown and light gray to greenish gray. In light-reddish-brown sandstone (generally fine grained) and conglomerate units, quartz and chert clasts are more numerous than limestone and calcite clasts, and micas are abundant. Reddish-brown units are colored by abundant hematite films on detrital grains. Light-greenish-gray sandstone is very fine to coarse grained; the clasts commonly are comprised chiefly of quartz, but in places they consist of about 75 percent limestone and calcite, 10 percent quartz, 10 percent feldspar, and minor amounts of mica. Clasts are well rounded to angular; limestone and calcite grains tend to be well rounded, whereas quartz and feldspar are generally angular. Sorting in the sandstone is variable; generally poor, but good in local lenses. Bedding in the sandstone is also variable, ranging from massive to thin bedded and crossbedded to horizontal. The matrix is generally calcareous clay.

Light-gray and light-greenish-gray sandstone and conglomerate in the Chinle commonly contain sparse to abundant pyrite and marcasite. Carbonized plant fragments and other carbonaceous material are common in light-gray and greenish-gray sandstone and conglomerate, especially near the base of the formation.

MOSS BACK MEMBER

The lowest unit of the Chinle Formation is the Moss Back Member. It typically consists of light-greenish-gray limy arkosic and quartzose sandstone and gray to greenish-gray limy sandstone (calcarenite) and conglomerate (calcirudite), with small amounts of green-

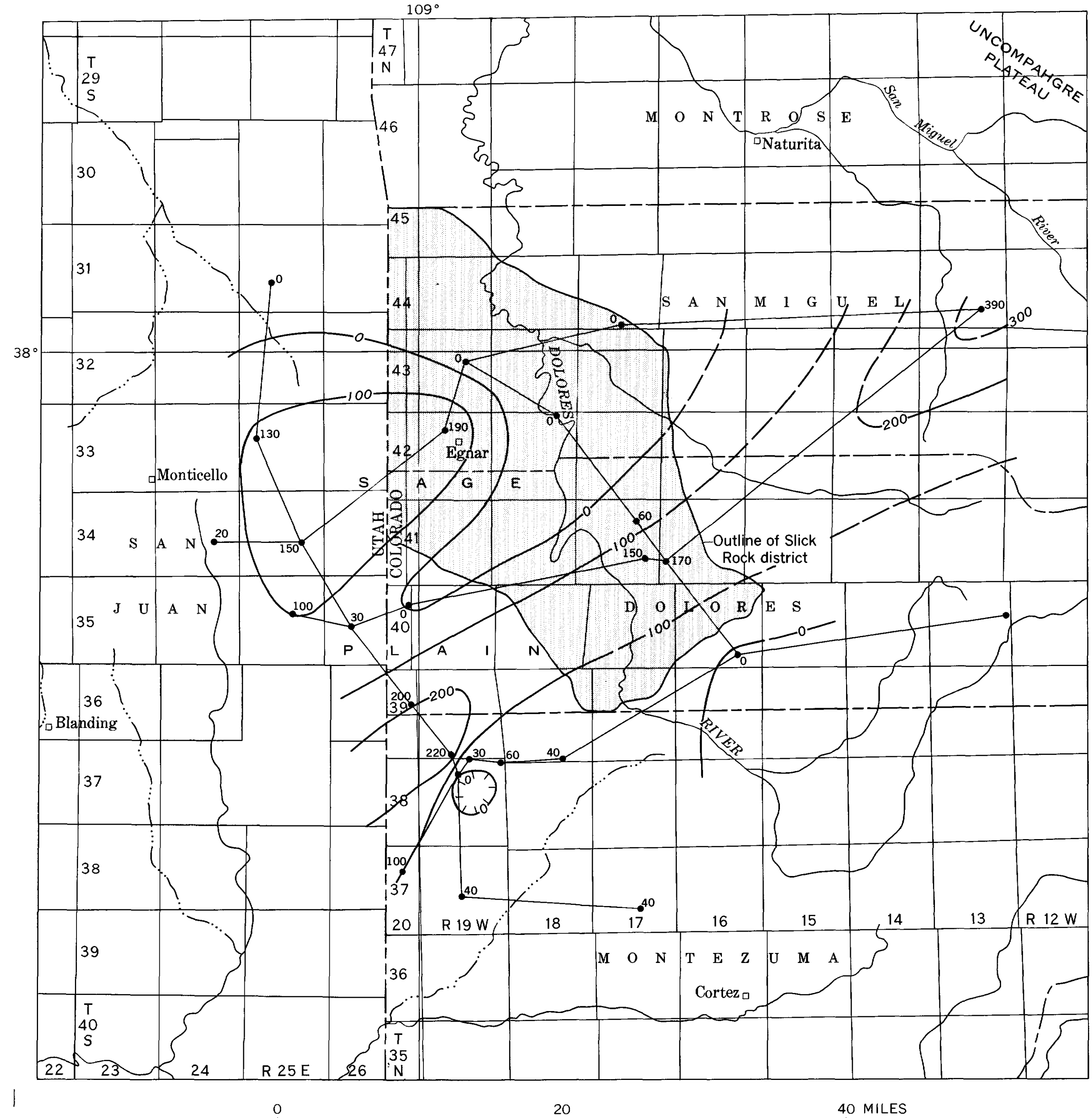

FIGURE 11.—Thickness of the Moenkopi Formation. Isopachs dashed where approximately located; interval 100 feet. Number by oil-test well (dot) is measured thickness, in feet, of stratigraphic unit. Correlation diagrams between oil-test wells shown on plate 3.

ish-gray, and even less reddish-brown, mudstone, siltstone, and shale. Carbonized and silicified plant fragments are locally abundant in greenish-gray sandstone, conglomerate, and mudstone. The unit contains fossil bones, according to Coffin (1921, p. 55).

In places in the Slick Rock district, siltstone, shale, and mudstone make up a large part of the Moss Back Member, as shown in the correlation of measured sections in the Dolores River Canyon (pl. 4).

Crossbeds, current ripple marks, and scour and fill characters are typical of the Moss Back and suggest terrestrial stream deposition of most of the unit.

Parts of the Moss Back Member show evidence of preconsolidation deformation. A small vertical clastic dike about a quarter of an inch thick in very fine grained light-brownish-gray thin-bedded clayey sandstone was observed in a drill core from Summit Canyon. Locally, bedding in fine-grained facies of the Moss Back is strongly contorted. These features may have formed during slumping of water-saturated sediment shortly after deposition, or by tectonic disturbance before the rocks become well cemented.

The Moss Back in the district is similar to the northern facies of the Moss Back in the vicinity of the junction of the Green and Colorado Rivers in Utah, described by Stewart, Williams, Albee, and Raup (1959, p. 512). There the Moss Back consists of fine- to medium-grained sandstone, largely subround clear quartz, that contains abundant interstitial greenish silt and clay and interstratified thin lenses of greenish siltstone and claystone. Conglomeratic parts of the northern facies of the Moss Back contain largely limestone pebbles and very few quartzose pebbles. Conglomerate lenses in the Slick Rock district probably contain more abundant quartzite pebbles, although limestone pebbles predominate. Many of the quartzite pebbles are flat, and their shape parallels the faint schistosity that resulted from alinement of muscovite flakes during metamorphism in the source area.

According to Weir, Puffett, and Kennedy (1957) and Isachsen and Evensen (1956, p. 274) the Moss Back in the Lisbon Valley area northwest of Slick Rock is a quartzose sandstone unit. It is the principal ore-bearing unit of the area. The unit is typically a "light-colored, well-cemented fine- to medium-grained quartzose and feldspathic sandstone. Silt and clay occur as interstitial material in sandstone and as thin layers of grayish mudstone. Gray mudstone overlies the basal sandstone unit." (Weir and others, 1957, p. 37.) H. L. Gibbs and E. G. Irwin (in Steen and others, 1953, p. 8–9) describe the rock in which ore occurs as poorly sorted fine-grained sandstone containing about 70 percent sand grains and 30 percent matrix material. The sand grains are rounded and comprise about 85 percent quartz and about 10 percent microcline.

Above-background radioactivity was detected with a scintillation counter in many places at the base of the Moss Back Member in the Dolores River Canyon, and with a Geiger counter in some drill holes in Summit Canyon near the base of the member.

In most places in the district, sandstone or conglomerate of the Moss Back Member appear to overlie the Cutler Formation unconformably (pls. 2 and 4). But at one place in Summit Canyon where this contact is not exposed, shown at the southwest end of the cross section in plate 2, greenish-gray and reddish-brown mudstone, siltstone, and shale, and light-greenish-gray sandstone lie between the Cutler and the sandstone and conglomerate of the Moss Back. There the base of the Chinle Formation consists of several inches to several feet of orange chert containing some irregular blebs and septa of gray calcareous clay, which probably indicates an old weathered surface on the Cutler Formation. Possibly the thin wedge of chiefly argillaceous rock between the Cutler and Moss Back represents a featheredge of the Monitor Butte Member, known in eastern Utah (Stewart and others, 1959, p. 508–512), but not enough details of lithology are known nor is direct correlation possible to make this certain.

A typical measured section of the Moss Back Member follows.

Section in Dolores River Canyon, sec. 3, T. 42 N., R. 18 W.

[Measured by D. R. Shawe, December 1953]

Moss Back Member:	*Thickness (feet)*
8. Sandstone, light-greenish-gray, fine-grained, thin, platy	10
7. Conglomerate, greenish-gray	2
6. Sandstone, greenish-gray, thin, platy	4
5. Sandstone, light-greenish-gray, fine-grained, massive	5
4. Sandstone, light-greenish-gray, fine-grained, thin-bedded platy and crossbedded	20
3. Conglomerate, greenish-gray	1
2. Sandstone, light-greenish-gray, thinly crossbedded	10
1. Conglomerate, greenish-gray	5
Total Moss Back Member	57

The Moss Back Member was penetrated by a diamond-drill hole in Bush Canyon, sec. 23, T. 43 N., R. 19 W., San Miguel County (location shown in fig. 12), where the Chinle is not exposed. Here the Moss Back consists of about 55 feet of light-gray to light-greenish-gray very fine to coarse-grained limy quartzose sandstone that contains abundant muscovite, biotite, interstitial greenish-gray clay and pebbles, thin layers of greenish-gray mudstone and siltstone, and flakes, films, and pebbles of carbonaceous material, especially in the lower 15 feet of the unit. The lower 5 feet of the unit contains very abundant calcite.

PETRIFIED FOREST(?) MEMBER

The unit of the Chinle Formation above the Moss Back Member in the Slick Rock district is most likely a facies of the Petrified Forest Member of the Chinle of Gregory (1950, p. 57), but it may be correlative with the lower part of the Church Rock Member of I. J. Witkind and R. E. Thaden (in Stewart and others, 1959, p. 517). It is composed mostly of greenish-gray mudstone, siltstone, and shale, with minor reddish-brown mudstone and greenish-gray sandstone and conglomerate.

In the Dolores River Canyon the Petrified Forest(?) Member contains a few thin layers, a foot or more thick, of greenish-gray to dark-gray medium- to very coarse grained conglomeratic sandstone and conglomerate, in places crossbedded, in which most of the pebbles are limestone and mudstone.

Throughout the district the base of the Petrified Forest(?) Member is a transitional contact with the Moss Back Member (pls. 2 and 4). The upper contact of the member is generally conformable with overlying strata and in most places is sharp (pls. 2 and 4). However, in the northeastern part of Summit Canyon unit 1 of the overlying Church Rock Member appears to pinch out to the northeast (pl. 2), and the Petrified Forest(?) Member is gradational, by intertonguing and change in lithology, with unit 2 of the Church Rock Member. At the extreme northeast end of the section shown in plate 2, the Petrified Forest(?) Member may merge laterally through facies change with unit 2 of the Church Rock Member.

A typical section of the unit where the Chinle is subsurface follows.

Drill core section in Bush Canyon, sec. 23, T. 43 N., R. 19 W.

[Measured by D. R. Shawe, August 1955]

	Thickness (feet)
Petrified Forest(?) Member:	
7. Mudstone; reddish-brown and greenish-gray in alternating layers; mottled with light purplish brown in places	70
6. Mudstone and siltstone, light- to medium-greenish-gray; mottled with purplish brown near the base; in alternating thin layers that contain abundant calcite and moderate amounts of carbonaceous material; siltstone contains moderate amounts of black opaque minerals; mudstone contains moderate amounts of micas	20
5. Sandstone, light-gray, fine- to medium-grained; contains very abundant calcite, abundant small fragments of carbonaceous material, and abundant granules and pebbles of light-greenish-gray mudstone	1
4. Mudstone and siltstone, purplish-brown; in alternating thin layers that contain sparse to moderate calcite	5

Drill core section in Bush Canyon, sec. 23, T. 43 N., R. 19 W.—Continued

	Thickness (feet)
Petrified Forest(?) Member—Continued	
3. Sandstone, light-brownish-gray, fine-grained, quartzose; contains abundant calcite	2
2. Mudstone and siltstone, purplish-brown; in alternating thin layers that contain sparse to moderate calcite	7
1. Mudstone and siltstone, light- to medium-greenish-gray; shaly in part; in alternating thin layers that contain abundant calcite and moderate amounts of carbonaceous material	5
Total Petrified Forest(?) Member	110

UNIT 1, OR THE SO-CALLED BLACK LEDGE OF THE CHURCH ROCK MEMBER

The unit of the Chinle Formation above the Petrified Forest(?) Member in the Slick Rock district is stratigraphically equivalent to the so-called Black Ledge of the Church Rock Member in the San Rafael Swell area and near the junction of the Green and Colorado Rivers in Utah, described by Stewart, Williams, Albee, and Raup (1959, p. 518). In the district it has variable lithology and consists chiefly of light-reddish-brown to reddish-brown medium-fine, to very fine grained sandstone and siltstone, in places interbedded with lenses of dark-reddish-brown and dark-greenish-gray sandstone and conglomerate (pl. 4). In other places the so-called Black Ledge or unit 1 of the Church Rock Member consists of light-gray and light-greenish-gray sandstone and conglomerate (pl. 2). Reddish-brown and greenish-gray mudstone are interbedded in the unit in places (pl. 4). Some carbonized and silicified plant fragments are present locally. In places detritus in the unit is quite angular to flakelike, suggesting a possible volcanic source of airborne material. The so-called Black Ledge pinches out to the northeast in the northeastern part of Summit Canyon (pl. 2).

The unit is generally conformable (locally unconformable in channel scours) with the underlying Petrified Forest(?) Member.

A typical section of the so-called Black Ledge unit follows.

Section on northeast side of Dolores River Canyon, NW¼SE¼ sec. 34, T. 43 N., R. 18 W.

[Measured by G. C. Simmons, September 1955]

	Thickness (feet)
So-called Black Ledge (unit 1):	
5. Sandstone, reddish-brown (5*YR* 6/1 to 5*R* 6/2), very fine grained to fine-grained	10
4. Conglomerate, reddish-brown; abundant pebbles	7
3. Mudstone, reddish-brown	3
2. Sandstone, reddish-brown, fine-grained	3
1. Conglomerate, reddish-brown; abundant pebbles	4
Total so-called Black Ledge (unit 1)	27

UNIT 2 OF THE CHURCH ROCK MEMBER

Unit 2 of the Church Rock Member in the Slick Rock district is probably the middle part of the Church Rock Member above the so-called Black Ledge and below the upper sandy part of the Church Rock as described by Stewart, Williams, Albee, and Raup (1959, p. 517–519). It differs from the typical Church Rock of Stewart, Williams, Albee, and Raup, which is reddish-brown siltstone and sandstone, in that it locally contains a few layers of dark-greenish-gray conglomerate as much as 3 feet but generally about 6 inches thick.

In parts of the district the shaly siltstone of unit 2 is, besides reddish brown, also orangish brown, purplish brown, purplish gray, and brownish gray. Most of the siltstone of the unit is structureless or horizontally laminated. Sandstone and conglomerate both are crossbedded and horizontally layered.

Unit 2 is abruptly gradational with unit 1—the so-called Black Ledge—below. Where unit 1 is absent, unit 2 appears to be transitional with the Petrified Forest (?) Member below, by intertonguing and by intergrading lithology. In the northeastern part of Summit Canyon where the Chinle is subsurface, drill-hole data indicate that unit 2 merges laterally with the Petrified Forest(?) Member by facies change and intertonguing; there unit 1 is absent (pl. 2). The upper contact of unit 2 is considered to be the top of the highest conglomerate layer. Probably one continuous bed does not form the boundary, so the contact undoubtedly is stratigraphically different from place to place (pl. 4). Because no thin conglomerate beds were recognized in drill cuttings of unit 2 in the northeast part of Summit Canyon, the upper contact of unit 2 is arbitrarily placed at the top of a thick sandstone bed in the upper part of the Church Rock Member (pl. 2), slightly below the stratigraphic level of the highest conglomerate beds in the Dolores River Canyon. Lithologically the bed is akin to beds in the overlying unit 3, or upper part of the Church Rock Member, in the district. The bed lies approximately at the horizon of, and perhaps it is equivalent to, the so-called Bowknot bed in the area near the junction of the Green and Colorado Rivers, described by Stewart, Williams, Albee, and Raup (1959, p. 518, and fig. 73).

A typical section of unit 2 follows.

Section in Dolores River Canyon, SE¼SW¼ sec. 13 T. 42 N., R. 18 W.

[Measured by G. C. Simmons, June 1955]

Unit 2:	Thickness (feet)
11. Conglomerate, greenish-gray; abundant pebbles	1
10. Siltstone, reddish-brown; contains about 5 percent interbedded reddish-brown fine-grained sandstone in beds less than 3 ft. thick	58
9. Sandstone, reddish-brown, medium-fine-grained; contains about 10 percent thin shale layers	14
8. Siltstone, reddish-brown, shaly; contains about 10 percent interbedded reddish-brown fine-grained sandstone in beds less than 3 ft. thick	34
7. Sandstone, reddish-brown, medium-fine-grained; in beds less than 3 ft. thick; contains about 35 percent interbedded reddish-brown shaly siltstone; forms upper part of a cliff	13
6. Sandstone, greenish-gray and reddish-brown interlayered, medium-grained; interbedded with greenish-gray and reddish-brown interlayered pebble conglomerate; forms lower part of cliff	9
5. Siltstone, reddish-brown, shaly	44
4. Conglomerate, gray; abundant pebbles	1
3. Shale, reddish-brown, sandy	8
2. Sandstone, reddish-brown, medium-fine-grained; in beds less than 3 ft. thick; contains about 20 percent interbedded reddish-brown shaly siltstone; forms ledges	11
1. Siltstone, reddish-brown, shaly	45
Total unit 2	238

UNIT 3, OR UPPER PART OF THE CHURCH ROCK MEMBER

Unit 3 of the Church Rock Member in the Slick Rock district is probably continuous with the sandy facies of the Church Rock Member in east-central Utah as described by Stewart, Williams, Albee, and Raup (1959, p. 518). It consists of reddish-brown, purplish-brown, and orangish-brown shaly siltstone and mudstone containing several thick beds of reddish-brown to orangish-brown generally structureless standstone, silty sandstone, and cliff-forming siltstone (pls. 2 and 4) conformably overlying unit 2. Sandstone near the top of the unit is commonly crossbedded. In the vicinity of Glade Canyon in the Dolores River Canyon, beds in the top part of unit 3 have been tilted and truncated by erosion, and the overlying Wingate lies unconformably on the Chinle.

A typical section of the unit follows.

Section on northeast side of Dolores River Canyon, SE¼NE¼ sec. 2, T. 42 N., R. 18 W.

[Measured by G. C. Simmons, June 1955]

Unit 3:	Thickness (feet)
5. Mudstone and shaly siltstone, reddish-brown	28
4. Sandstone, reddish-brown, very fine grained	16
3. Mudstone and shaly siltstone, reddish-brown	10
2. Sandstone, reddish-brown, very fine grained	18
1. Mudstone and shaly siltstone, reddish-brown; contains about 10 percent interbedded reddish-brown very fine grained sandstone in beds less than 3 ft thick	82
Total unit 3	154

A similar thickness of unit 3 of the Church Rock Member of the Chinle Formation, recorded in more detail, follows.

Section on west side of Summit Canyon, NE¼SE¼ sec. 4, T. 43 N., R. 19 W.

[Measured by D. R. Shawe and W. L. Emerick, Feb. 24, 1954]

Unit 3:	Thickness (feet)
20. Sandstone, light-reddish-brown, fine-grained	4
19. Sandstone, light-reddish-brown, fine-grained, thin, platy	4
18. Sandstone, light-reddish-brown, fine-grained, evenly bedded, blocky	3
17. Mudstone, reddish-brown	9
16. Sandstone, light-reddish-brown, very fine grained, massive	6
15. Sandstone, light-reddish-brown, very fine grained, massive, friable	5
14. Sandstone, light-reddish-brown, very fine grained, massive	28
13. Siltstone to very fine grained sandstone, light-reddish-brown, thin, platy	2
12. Siltstone to very fine grained sandstone, reddish-brown; buff at base; buff part contains hematite pseudomorphs of magnetite on joint surfaces	8
11. Sandstone, greenish-gray, very fine grained	1
10. Mudstone, reddish-brown	17
9. Siltstone, reddish-brown	6
8. Mudstone, purplish-brown	6
7. Siltstone, purplish-brown	2
6. Mudstone, purplish-brown	8
5. Siltstone; purplish-brown with sparse spots of greenish-gray; in three beds each 3 ft. thick	9
4. Mudstone, dark-purplish-brown; massive near the top, shaly near the base	16
3. Mudstone and siltstone interbedded, purplish-brown; some greenish-gray laminations; thin, platy	9
2. Mudstone, light-purplish-brown; some greenish-gray spots	12
1. Mudstone, dark-reddish-brown to purplish-brown with sparse ½-inch greenish-gray spots. Mudstone in the section is in part shaly siltstone and silty shale	8
Total unit 3	163

SURFACE DISTRIBUTION AND CONFIGURATION

The Chinle Formation is exposed in the Slick Rock district only in Summit Canyon, for a linear distance of about 3 miles, and in the Dolores River Canyon, for a distance of about 20 miles. The entire thickness of the formation is exposed only in the Dolores River Canyon.

An isopach map of the Chinle Formation was prepared on the basis of data from logs of about 20 deep oil-test wells drilled in and near the district, 5 diamond drill holes put down in the district, and 4 sections measured in the district (fig. 12). In general the formation thickens from about 400 feet in the northeastern part of the district to more than 1,200 feet southwest of the district. The Chinle thins abruptly or is pinched out across the Gypsum Valley anticline northeast of the district (Cater, 1955a, e, f). The thicknesses shown in figure 12 are in accord with those shown on an isopach map of the Chinle in southwestern Utah prepared by Stewart, Williams, Albee, and Raup (1959, fig. 80). According to figure 12 the Chinle thickens more rapidly to the southwest in southwestern Colorado than Stewart, Williams Albee, and Raup (1959) suggested it does in southeastern Utah. An area of thinner Chinle centered in T. 41 N., R. 17 W., modifies the regional configuration of the formation.

The units within the Chinle in the district vary in thickness locally, but lack of data prohibits showing isopachs of any unit on a district scale. The thickness of the Moss Back Member averages about 50 feet but is as much as about 75 feet in places in Summit Canyon and in the Dolores River Canyon where the base is channeled into the underlying Cutler, or where sandstone layers build up at the top; in places it is as little as 20 feet. In the Dolores River Canyon a locally thicker part of the Moss Back, more than 50 feet thick, appears to extend from the SW cor. sec. 13, T. 42 N., R. 18 W., north-northwesterly to the SW cor. sec. 27, T. 43 N., R. 18 W. (fig. 13). Perhaps this thicker part of the member extends as far northwest as Summit Canyon; it is shown on the left side of the section in plate 2 as a channel filling. This projection of thicker Moss Back and nearby areas of thicker Moss Back may represent old channels in the northwesterly flowing stream system that brought Chinle detritus into the area.

The Petrified Forest(?) Member has an average thickness of 70 feet, but in the northeast part of Summit Canyon it appears to pinch out, and in other places it is as much as 100 feet thick. The so-called Black Ledge, unit 1 of the Church Rock Member, probably averages 20 feet in thickness but is absent in the northeastern part of Summit Canyon and is as much as 40 feet thick in other places. The thickness of unit 2 of the Church Rock Member is 200–275 feet and averages 240 feet; the thickness of unit 3 of the Church Rock is 140–190 feet and averages 165 feet.

WINGATE SANDSTONE

The Wingate Sandstone is the lowest formation of the Glen Canyon Group. The Glen Canyon was formally named by Gregory and Moore (1931, p. 61), but was first published by Baker, Dobbin, McKnight, and Reeside (1927). The Glen Canyon Group consists of rocks which form the walls of Glen Canyon of the Colorado River in southern Utah and northern Arizona and includes also the Kayenta Formation above the Wingate and the

Navajo Sandstone above the Kayenta. The Wingate Sandstone was named by Dutton (1885, p. 136–127) for exposures near Fort Wingate, N. Mex. The upper 300 feet of Dutton's type Wingate (most of the unit) is now recognized as Entrada Sandstone (Baker and others, 1947, p. 1667), and Wingate is restricted to the lower part of Dutton's type section (Harshbarger and others, 1957, p. 8).

The Wingate Sandstone in what is now the Slick Rock district was first described by Coffin (1921, p. 58) as "massive Dolores sandstone" in the upper part of the Dolores Formation. Stokes and Phoenix (1948) and

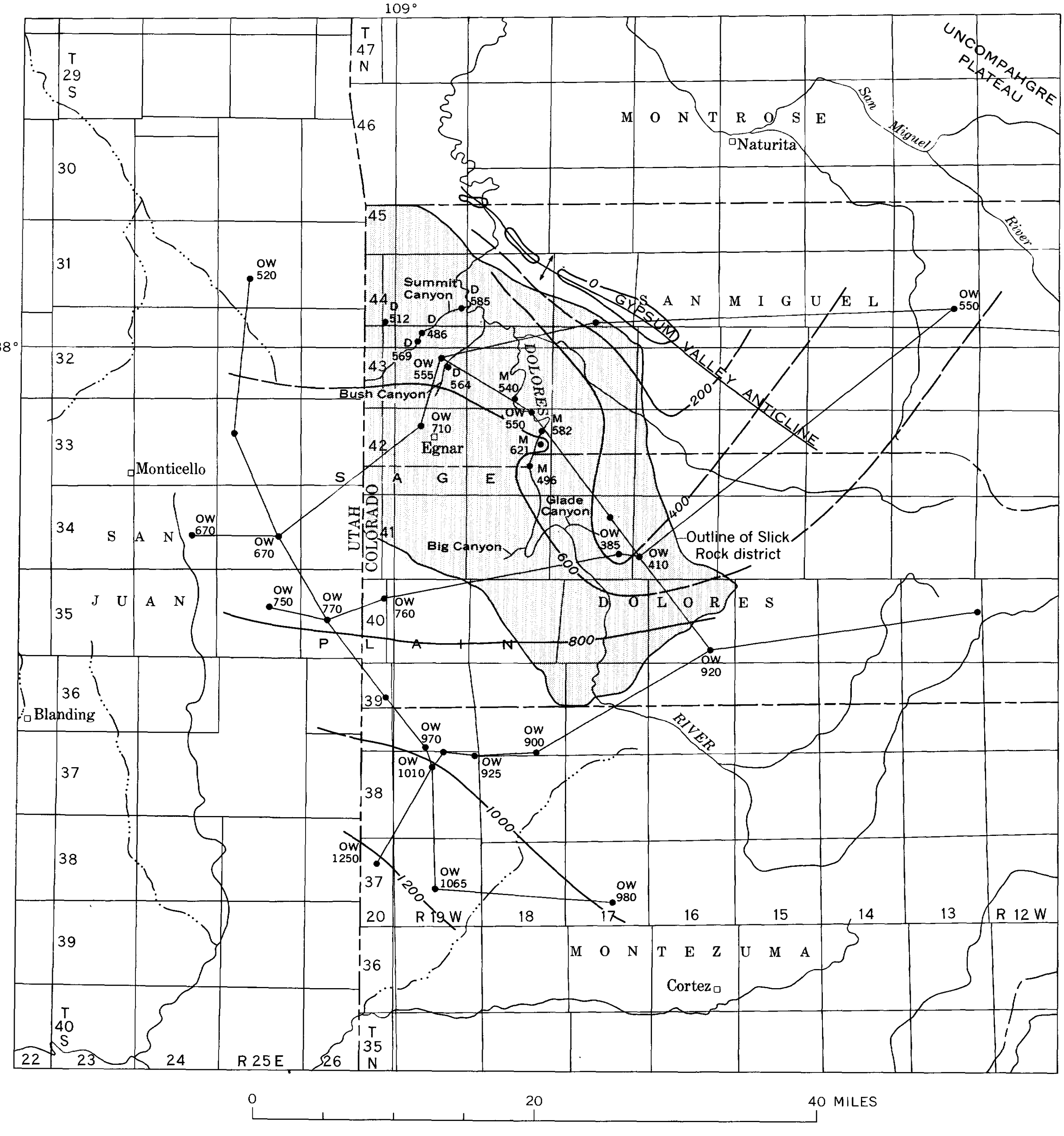

FIGURE 12.—Thickness of the Chinle Formation. Isopachs dashed where approximately located; interval 200 feet. Number by control point (dot) is measured thickness, in feet, of stratigraphic unit; letter indicates type of control point: OW, oil-test well; D, diamond-drill hole; M, measured section. Correlation diagrams between oil-test wells shown on plate 3.

Cater (1955a–f) mapped the unit as Wingate Sandstone.

In a thorough discussion of the age of the Glen Canyon Group, Harshbarger, Repenning, and Irwin (1957, p. 25–32) indicated that the Wingate Sandstone is Late Triassic in age.

Lithology

The gross appearance of the Wingate Sandstone in the district was well described by Cater (1955a–f): "It typically crops out as an impressive red or dark-brown wall, stained and streaked in places with a surficial red and black desert varnish." In most places the Wingate

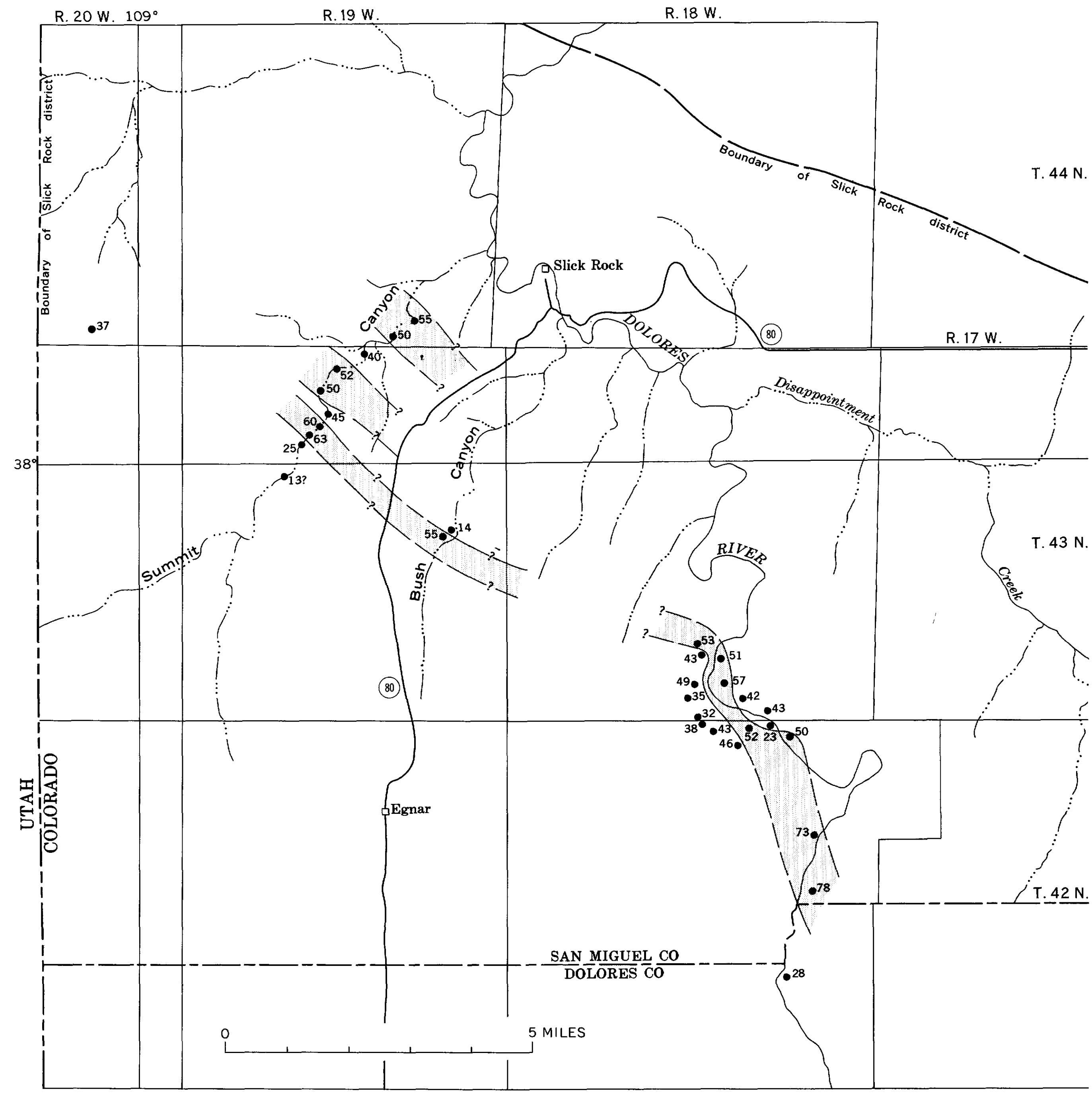

FIGURE 13.—Areas where the Moss Back Member of the Chinle Formation is more than 50 feet thick (stippled). Outlines of areas dashed where approximately located; queried where doubtful. Control points (diamond-drill hole or measured section) shown by dots; number is thickness, in feet, of the Moss Back Member.

wall is a nearly vertical cliff about 200 or more feet high (fig. 9) and is one of the most magnificent land forms in the Dolores River Canyon and in Summit Canyon where the full thickness of the formation is exposed.

The Wingate is composed of light-reddish-brown, light-orangish-brown, and light-buff fine to very fine grained sandstone. Minor medium-sized grains occur in the lower third of the formation. Throughout the district the formation consists largely of light-reddish-brown or light-orangish-brown sandstone, but in places in the Dolores River Canyon the top few feet consists of light-buff sandstone (fig. 9). In parts of Summit Canyon a greater thickness in the top part appears to be light buff. Sand grains are largely subrounded and moderately to well-sorted quartz; minor amount of pink and dark-gray grains are possibly feldspar and chert.

Sandstone of the Wingate contains abundant silt and clay in places, mostly in horizontally bedded parts in the lower half of the formation. Calcite, however, forms the chief cementing material, though it is not abundant. The sandstone is generally moderately friable.

The upper half of the formation is massive, with large-scale crossbeds as much as 50 feet thick, and the lower half has smaller scale crossbeds and horizontal beds. According to Cater (1955a–f), "The sandstone is divided into horizontal layers by extensive bedding planes spaced 2 to 50 feet apart. Within each horizontal layer the sandstone is crossbedded on a magnificent scale; great sweeping tangential crossbeds of eolian type, in places extending across the entire thickness of the horizontal layer, are disposed in all directions."

The Wingate Sandstone lies conformably upon the Chinle Formation except in the vicinity of Glade Canyon. In most places the presence of a few thin siltstone layers typical of the Chinle near the base of the Wingate and a few thin sandstone layers typical of the Wingate near the top of the Chinle suggest continuous deposition between the formations.

Surface distribution and configuration

The Wingate Sandstone is exposed in the Slick Rock district in the Dolores River, Summit, and Bush Canyons. The whole thickness is exposed only in the Dolores River Canyon for a distance of about 25 miles, and in Summit Canyon for about 5 miles.

An isopach map of the Wingate (fig. 14) was constructed on the basis of data from 18 deep oil-test wells drilled in and near the district, 3 diamond-drill holes drilled in the district, and 6 sections measured within the district. Like the Chinle, the Wingate is thinnest in the northeastern part of the district and thickens southwestward. In the northeastern part of the district it is generally about 200 feet thick, and southwest of the district it is more than 350 feet thick. Also like the Chinle, the Wingate thins abruptly or is pinched out across the Gypsum Valley anticline at the northeast edge of the district (Cater, 1955a, e, f), and it is locally thinner in the vicinity of Glade and Big Canyons and west-southwestward into Utah. A locally thick part, more than 400 feet thick, trends east-west just south of the district.

TRIASSIC(?) ROCKS—KAYENTA FORMATION

The Kayenta Formation is the middle formation of the Glen Canyon Group. The term Kayenta was first applied to rocks between the Wingate Sandstone and Navajo Sandstone by Baker, Dane, and McKnight (1931). These rocks were provisionally referred to as Todilto(?) by Gregory (1917, p. 56). In the first mapping in the Slick Rock district, by Coffin (1921, p. 58), what is now known as the Kayenta was included with rocks called the Dolores Formation and made up the upper part of the formation above what is now recognized as Wingate Sandstone.

Harshbarger, Repenning, and Irwin (1957, p. 25–32) indicated that the Kayenta Formation is most likely Early Jurassic in age but may be as old as Late Triassic. Lewis, Irwin, and Wilson (1961, p. 1437–1440) assigned a Late Triassic(?) age to the Kayenta Formation, which is the currently accepted age.

Lithology

The Kayenta Formation crops out as a series of steep, closely spaced ledges, though in a few places it is eroded to form a sheer cliff (fig. 9). It is composed chiefly of reddish-brown to purplish-gray sandstone, shaly siltstone, shale, and conglomerate showing sparse gray mottling in places. The sandstone is very fine to medium fine grained, and is composed of rounded to angular quartz grains and minor amounts of feldspar, mica, and heavy minerals—chiefly black opaque minerals. Clay forms the chief cementing material. The sandstone is generally thin bedded and crossbedded, but it is massive in places. It forms a wide range of different sized lenses which interfinger with each other and with lenses of shale, siltstone, and conglomerate. The conglomerate contains small pebbles of shale, sandstone, and limestone.

The Kayenta Formation appears to be conformable with the Wingate in most places, and according to Cater (1955a–f) the contact is gradational. Small local disconformities are common between the two formations, but they apparently intertongue in places.

The following section of the Kayenta measured at the Horseshoe Bend of the Dolores River Canyon is probably typical.

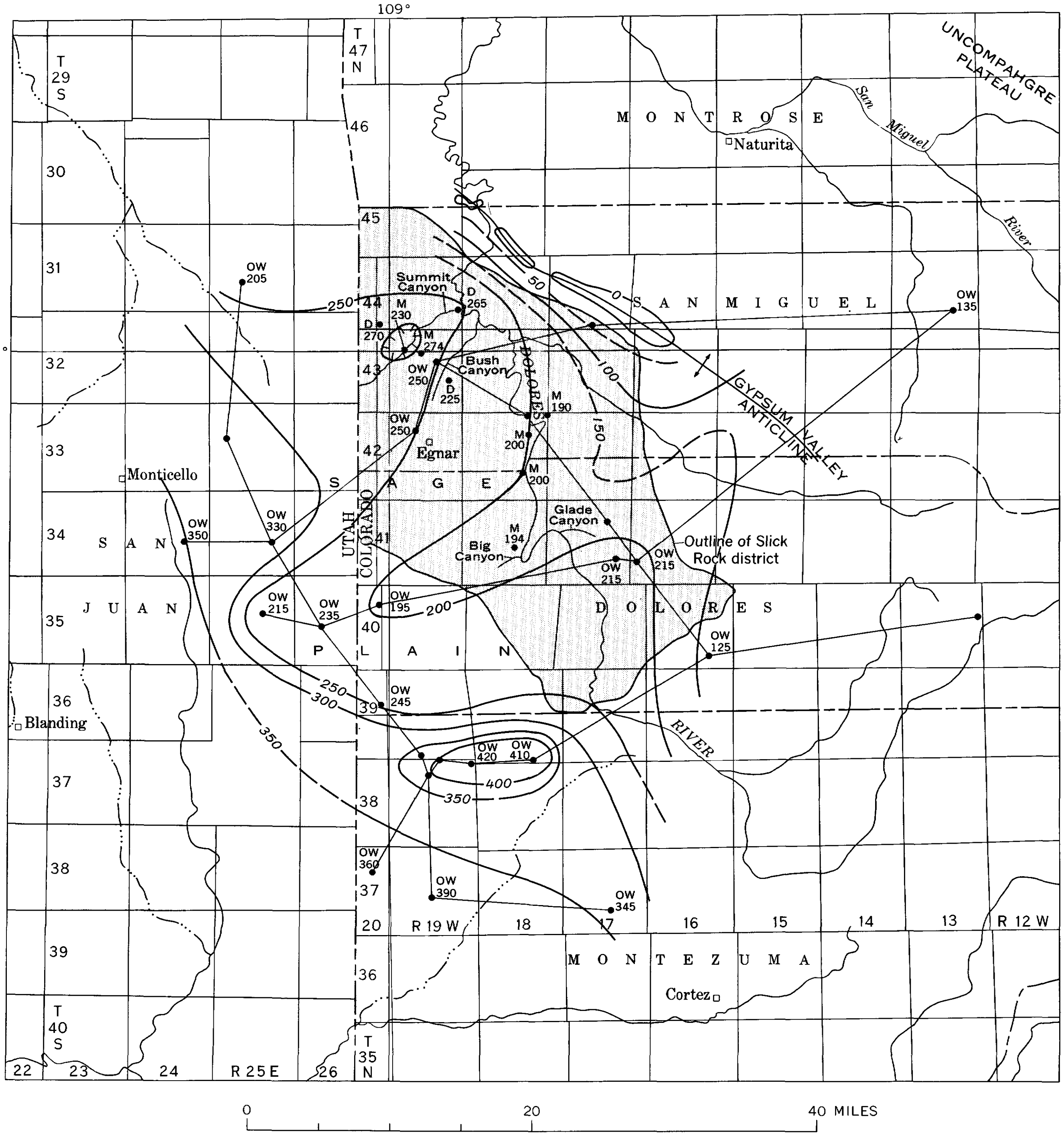

Figure 14.—Thickness of the Wingate Sandstone. Isopachs dashed where approximately located; interval 50 feet. Number by control point (dot) is measured thickness, in feet, of stratigraphic unit; letter indicates type of control point: OW, oil-test well; D, diamond-drill hole; M, measured section. Correlation diagrams between oil-test wells shown on plate 3.

Section of Kayenta Formation on north side of the Dolores River Canyon, sec. 6, T. 42 N., R. 17 W.

[Measured by L. C. Craig and J. D. Ryan, July 1949]

	Thickness (feet)
Kayenta Formation:	
4. Sandstone, light-colored, fine- to medium-fine-grained, channeled and cross-laminated; unit is subdivided into three parts on the basis of color: lowest is pale reddish brown, middle (containing a minor amount of muscovite) is light purplish gray, and upper is gray to pinkish gray; grains are subangular to angular clear quartz and minor amounts of other minerals	41
3. Sandstone, pinkish-gray, pale-reddish-brown, and moderate-reddish-brown, predominantly fine grained; shows horizontal and cross laminations; grains are subangular to subrounded clear quartz with minor amounts of pink and green grains that may be feldspar and chert; unit forms a cliff composed of gently wedging beds separated by thin reddish-brown shale partings	76
2. Conglomerate, gray; abundant limestone and clay pellets	4
1. Sandstone, moderate-reddish-brown (10*R* 5/6), fine to very fine grained; massive to horizontally laminated and in places thinly crossbedded; grains are subangular clear quartz and minor amounts of pink and dark-gray grains that may be feldspar and chert; unit contains several reddish-brown silty claystone and sandstone lenses	65
Total Kayenta Formation	186

Surface distribution and configuration

The Kayenta Formation is exposed in the Slick Rock district for about 25 miles along the Dolores River Canyon, for about 5 miles in Summit Canyon, and about 3 miles in Bush Canyon.

An isopach map of the Kayenta (fig. 15) was drawn using data from 18 deep oil-test wells in and near the district, 2 diamond-drill holes in the district, and 7 sections measured in the district. In the district the formation ranges in thickness, from 162 feet, in Big Canyon, to 208 feet, in Summit Canyon. Southwestward from the district the formation shows little change in thickness, but it thins rapidly along an east-northeasterly line at the southeast edge of the district, and it appears to be generally less than 50 feet thick southeast of the district. According to Cater (1955a, e, f) the Kayenta pinches out around Big Gypsum Valley at the northeast edge of the district.

TRIASSIC(?) AND JURASSIC ROCKS—NAVAJO SANDSTONE

The Navajo Sandstone is the upper formation of the Glen Canyon Group. It was named by Gregory (1917, p. 57–59) for exposures of the formation in the Navajo country of Arizona, New Mexico, and Utah. Coffin (1921) first mapped the unit in the Slick Rock district. He recognized the formation as a separate unit (pl. 61), which he called "Lower La Plata sandstone," and mapped it as such where the scale of his map allowed. Elsewhere Coffin included the Navajo Sandstone with the overlying Entrada Sandstone as the La Plata Formation. Since Stokes and Phoenix (1948) mapped in the district the unit here has been recognized as Navajo Sandstone.

The Navajo was considered by Harshbarger, Repenning, and Irwin (1957, p. 32) "to be Early Jurassic in age; however, there is a possibility that parts of it may be of Middle Jurassic [age], and also, because of intertonguing with the underlying Kayenta formation, a basal zone of the Navajo must be considered Jurassic (?), like the Kayenta." More recently, Lewis, Irwin, and Wilson (1961) indicated that the lower part of the Navajo Sandstone is Triassic(?) in age, and the remainder Jurassic.

Lithology

In the Dolores River Canyon and some of its tributary canyons, the Navajo crops out as a sheer cliff. Where it is not overlain by other formations it forms barren benches, remarkable for their lack of soil and vegetal cover. The formation is composed of mostly light-buff, but in places light-reddish-brown, very fine-grained to fine-grained sandstone exhibiting large-scale tangential crossbedding of eolian type. Grains are well sorted, rounded to well rounded, and composed largely of quartz, some feldspar, and minor amounts of heavy minerals. Calcite is the chief cementing material, but it is generally sparse.

At Big Canyon the Navajo is largely light-brown very fine grained sandstone with large-scale tangential crossbedding. At Horseshoe Bend in the Dolores River Canyon, it consists of moderate-orange-pink, weathering to light-orangish-gray, very fine grained to fine-grained calcareous sandstone, horizontally laminated near the base and with wedging crossbeds above.

In places the Navajo has fractures, many of which contain thin dikelets composed of very fine grained sandstone identical to that of typical Navajo. Several such sandstone dikelets in fractures in light-brown very fine grained cross-laminated sandstone in Summit Canyon, sec. 26, T. 44 N., R. 19 W., are oriented about N. 30° W. (fig. 16). Perhaps the dikelets formed at the time the Navajo was fractured before complete lithification, allowing intrusion of unconsolidated sand. The consistency of orientation of the fractures may indicate tectonic origin, or at least tectonic-controlled slumping, rather than merely random slumping of the sediments prior to consolidation.

The contact between the Navajo Sandstone and the underlying Kayenta Formation is generally slightly irregular. At Big Canyon where the upper half of the Navajo was probably removed by erosion prior to the deposition of the overlying Entrada Sandstone, the base of the unit interfingers with the Kayenta on a small scale, suggesting nearly continuous deposition from Kayenta time into Navajo time. At Horseshoe Bend in the Dolores River Canyon, most of the Navajo was removed by erosion prior to the deposition of the Entrada. Here the Navajo contains several continuous horizontal partings, more abundant near the base, and

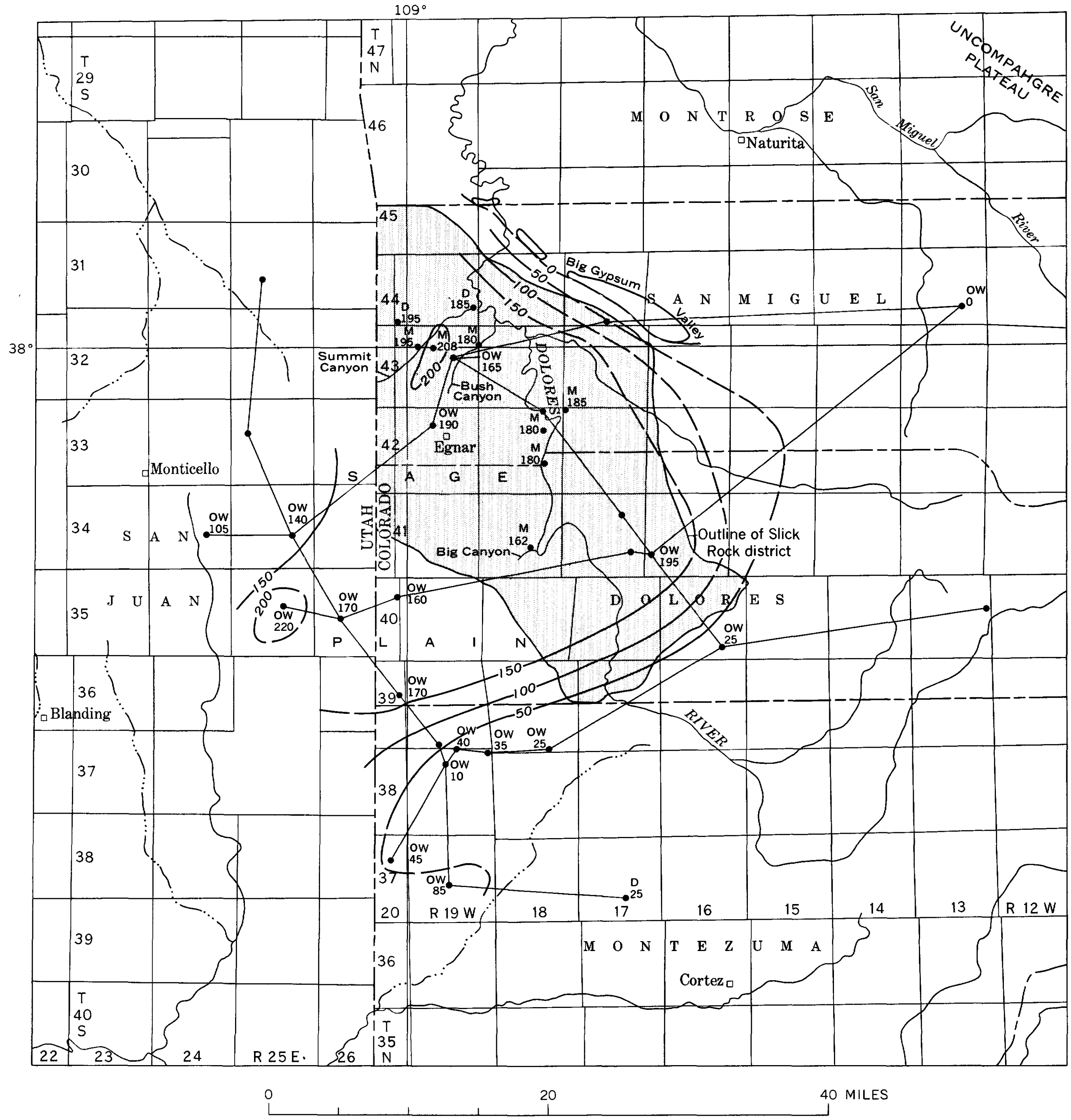

FIGURE 15.—Thickness of the Kayenta Formation. Isopachs dashed where approximately located; interval 50 feet. Number by control point (dot) is measured thickness, in feet, of stratigraphic unit; letter indicates type of control point: OW, oil-test well; D, diamond-drill hole; M, measured section. Correlation diagrams between oil-test wells shown on plate 3.

the contact with the underlying Kayenta is sharp, even, and conformable.

Surface distribution and configuration

The Navajo Sandstone is exposed throughout large parts of the Dolores River, Summit, McIntyre, Bush, Blue, and Morrison Canyons. The base of the formation is exposed only in the Dolores River, Summit, and Bush Canyons. In places southeast of the Spud Patch and southwest of Joe Davis Hill, the Navajo is absent because of erosion prior to the deposition of the overlying Entrada Sandstone (pl. 1; fig. 9).

An isopach map of the Navajo Sandstone (fig. 17) was constructed on the basis of data from 16 deep oil-test wells in and near the district, geologic maps of the district (Cater, 1955b, c, d), 5 sections measured in the district, and 2 diamond-drill holes in the district. Regionally the Navajo thins from about 400 feet west of the district in Utah to 0 east of the district. Superposed on the regional pattern is a locally thick part, as much as 420 feet thick, which is alined northwesterly and coincides in position with the Disappointment syncline. Southwest of here the Navajo is locally thinner in an area also alined northwesterly and coinciding in position with the Dolores anticline. In places along the Dolores anticline, the Navajo is absent, and according to Cater (1955a, e, f) it pinches out below the Entrada Sandstone toward the Gypsum Valley anticline.

FIGURE 16.—Nearly vertical sandstone dikelet oriented N. 30° W., in Navajo Sandstone; sec. 26, T. 44 N., R. 19 W., Summit Canyon.

JURASSIC ROCKS

ENTRADA SANDSTONE

Gilluly and Reeside (1928, p. 76) named the Entrada Sandstone from exposures at Entrada Point in the northern part of the San Rafael Swell, Utah, and included it in the San Rafael Group. At the type locality the San Rafael includes, in ascending order, the Carmel Formation, the Entrada Sandstone, the Curtis Formation, and the Summerville Formation. The Entrada Sandstone has since been subdivided into (ascending order) the Dewey Bridge Member, the Slick Rock Member, and the Moab Sandstone Member (Wright and others, 1962; Baker and others, 1927, p. 804; Baker, 1933, p. 49–50; Dane, 1935, p. 94). Units in the San Rafael Group had been mapped under other names and had been variously assigned. Gilbert (1877, p. 6–7) included the Entrada Sandstone of the Henry Mountains in the Flaming Gorge Group, a name now abandoned. Coffin (1921) correlated what is now know as the Slick Rock Member with the upper part of the later abandoned La Plata Sandstone (Cross, 1899, p. 3) in the nearby San Juan Mountains. Coffin (1921) included in the upper part of the La Plata Group rocks that are now known as the Dewey Bridge Member (Wright and others, 1962) and are similar in lithology and stratigraphic position to rocks that McKnight (1940, p. 87, 90) mapped as red earthy siltstone of the Carmel Formation in east-central Utah. Stokes and Phoenix (1948) and Cater (1955a–f) assigned these rocks in the Slick Rock district to the Carmel Formation, at the base of the San Rafael Group, and the rocks are shown on geologic maps as part of a unit called Entrada Sandstone and Carmel Formation undivided. Nevertheless, they considered the Carmel (Dewey Bridge Member) and Entrada (Slick Rock Member) as separate formations in the district. The Moab Member is absent in the Slick Rock district.

Changes in usage in the Slick Rock district are shown in table 3.

The Carmel Formation is considered to be Middle and Late Jurassic in age on the basis of fossils in the limestone facies of the formation in Utah (Imlay, 1953, p. 54–59). The partial time equivalency of the Dewey Bridge Member of the Entrada Sandstone and the Carmel Formation in Utah (Wright and others, 1962, p. 2057, 2062) suggests that the lower part of the Entrada is of Late Jurassic age. No fossils have been identified from the Slick Rock Member of the Entrada, and in the district the overlying Summerville Formation is not fossiliferous. However, in the San Rafael Swell the Entrada Sandstone is overlain by the fossiliferous Curtis Formation, which grades laterally and vertically into the Summerville Formation. A Late Jurassic age has been established (Gilluly and Reeside, 1928, p. 79)

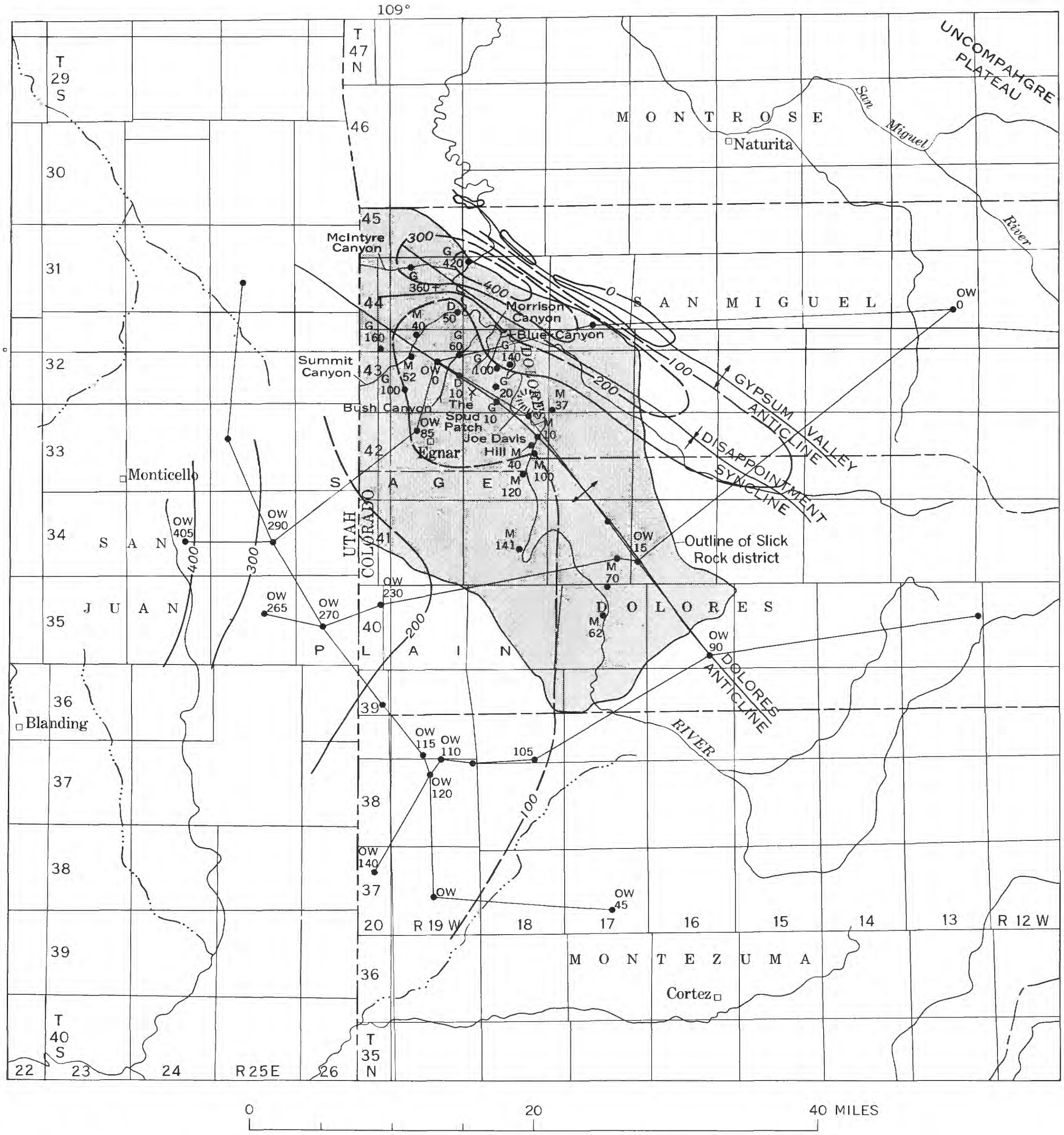

Figure 17.—Thickness of the Navajo Sandstone. Isopachs dashed where approximately located; interval 100 feet. Number by control point (dot) is measured thickness, in feet, of stratigraphic unit; letter indicates type of control point: OW, oil-test well; D, diamond-drill hole; M, measured section. Correlation diagrams between oil-test wells shown on plate 3.

for the Curtis Formation also, so the age of the upper part of the Entrada Sandstone is clearly fixed as Late Jurassic.

DEWEY BRIDGE MEMBER

Lithology

The Dewey Bridge Member of the Entrada Sandstone is exposed commonly as a slight recess under the Slick Rock Member of the Entrada Sandstone. At only a few places such as the vicinity of the town of Slick Rock, is it found without a protective cover of the Slick Rock, and at such places it consists of low mounds on benches of Navajo Sandstone. Where the Dewey Bridge lies below the Slick Rock it is typically a "humpy-faced" cliff composed of rounded blocky segments a few inches to a few feet across which constitute what is commonly called a "hoodoo weathering" surface.

The Dewey Bridge Member is composed chiefly of reddish-brown clayey siltstone and very fine-grained sandstone, which in places contains sparse well-rounded almost spherical medium to coarse sand grains called "Entrada berries" (Wright and others, 1962, p. 2063). Some layers are relatively clay rich, and these erode more deeply than surrounding rock and contribute to the humpy surface of the formation.

Locally the lithology at the base of the Dewey Bridge Member differs from the typical reddish-brown siltstone and sandstone. On the north side of Summit Canyon in sec. 26, T. 44 N., R. 19 W., the lower 5 feet of the member consists of reddish-brown fine-grained horizontally bedded sandstone with a conglomerate layer at places near the base. Pebbles are mostly irregular nodules of black and gray chert and slabs of reddish-brown to brown very fine grained quartzitic sandstone as much as 8 inches in diameter. The quartzitic sandstone is similar to that of the underlying Navajo and was probably derived from the Navajo, possibly after it was consolidated, eroded, and weathered. The sandstone enclosing the pebbles is coarser grained than the subjacent Navajo and perhaps came from outside the region or from coarser grained Navajo elsewhere.

On the southeast side of Summit Canyon and west of the Muleshoe Bend of the Dolores River, thin layers of light-gray cherty limestone lie at the base of the Dewey Bridge Member on top of Navajo Sandstone. The layers are lenses as much as 8 feet thick in places.

The contact between the Dewey Bridge Member and the Navajo Sandstone is generally a disconformity, conspicuous because of the abrupt change of lithology rather than the minor relief on the surface of the Navajo Sandstone. In places where the Navajo was deeply eroded prior to Dewey Bridge deposition, the unconformity separating the formations is slightly angular.

A typical section of the member follows.

Section of Dewey Bridge Member near the mouth of McIntyre Canyon E½SW¼NW¼ sec. 13, T. 44 N., R. 19 W.

[Measured by G. C. Simmons and N. L. Archbold, Sept. 13, 1956]

	Thickness (feet)
Dewey Bridge Member:	
6. Siltstone, brownish-red; abundant very fine sand grains and "Entrada berries;" massive; grades abruptly upward into Slick Rock Member	12
5. Sandstone, reddish-brown, very fine grained; abundant silt; sparse "Entrada berries;" forms ledge	1
4. Siltstone, brownish-red, sparse "Entrada berries;" horizontally bedded; ¼-in. thick laminae	2
3. Sandstone, reddish-brown, very fine grained; sparse "Entrada berries"	1
2. Sandstone, reddish-brown, very fine grained; very abundant silt; massive	12
1. Siltstone, reddish-brown; very abundant very fine sand grains; massive at top, thinly and horizontally bedded at base	5
Total Dewey Bridge Member	33

Surface distribution and configuration

The Dewey Bridge Member is exposed throughout almost the entire length of the Dolores River Canyon in the Slick Rock district and in McIntyre, Summit, Bush, Morrison, and Blue Canyons. The base of the member is visible in all of these exposures.

In the district the member is 20–35 feet thick. Differences in thickness have no regional trends nor are they related to known structural elements, but they correspond to slight erosional irregularities in the top of the Navajo Sandstone.

SLICK ROCK MEMBER

In this report three units of the Slick Rock Member which appear to be present throughout the district are distinguished—a lower massive unit, a middle cross-bedded unit, and an upper horizontally bedded unit (table 3).

LITHOLOGY

The Slick Rock Member of the Entrada Sandstone is perhaps the most impressive rock unit in the Slick Rock district, because it forms a striking light-colored rock layer whose persistent line as seen in canyon exposures clearly marks the broad folds in the sediments. The cliffs and slopes of the member, more than those of any other rock unit, are clean of soil and vegetation and present a bare and smooth face which has led to the picturesque designation of the unit as the "slick rim." Appropriately, this rock unit lends its early local name to the Slick Rock district and in turn was formally named for the town which derived its name from the informal designation of the unit (Wright and others, 1962).

Along much of its exposed length, especially in the Dolores River Canyon, the Slick Rock Member forms a steep cliff, slightly rounded at the top (fig. 9). Where the top of the Slick Rock has been eroded back, the member presents an even slope above a lower cliff (fig. 18).

The Slick Rock Member is composed of light-brown, or buff, and light-reddish-brown chiefly very fine grained to fine-grained moderately sorted to well-sorted, moderately rounded to well-rounded quartzose sandstone containing sparse grains of medium to coarse sand. It is generally not well cemented, but in places abundant calcite, quartz, or kaolinite forms a firm matrix (determined by differential thermal analyses by N. L. Archbold at the University of Michigan, written commun., May 1960). The formation is divided into massive, horizontally bedded, and crossbedded units. Light-brown sandstone is confined largely to the upper part of the formation; and light reddish brown, largely to the lower part. In places, however, the formation is entirely light reddish brown, such as in Disappointment Valley (as shown in a diamond-drill core) and in the vicinity of Big Canyon, and in places it is entirely light brown, such as near the axis of the Dolores anticline.

Measured sections of the Slick Rock Member are shown diagrammatically on plate 5, and an additional, typical, section follows.

Section of Slick Rock Member in Dolores River Canyon east of the Spud Patch, NE¼ sec. 33, T. 43 N., R. 18 W.

[Measured by G. C. Simmons and N. L. Archbold, Sept. 19, 1956]

	Thickness (feet)
Slick Rock Member:	
4. Sandstone, light-brown, very fine grained, horizontally bedded; contains abundant interstitial calcite which locally cements ¼-in. nodules; horizontally bedded unit	10
3. Sandstone, light-brown, very fine grained to fine-grained, steeply crossbedded; contains a few small spots of limonite and abundant ¼-in. nodules cemented with calcite; upper part of crossbedded unit	21
2. Sandstone, light-brown to brown, very fine grained to fine-grained; in alternating crossbedded and horizontally bedded layers about 5 ft thick; contains moderate small spots of limonite and abundant interstitial calcite which locally cements ¼-in. nodules; lower part of crossbedded unit	39
1. Sandstone; light brown in upper 10 ft, reddish brown mottled with light brown in lower 15 ft; very fine grained; contains a trace of ¼-in. nodules cemented with calcite, and abundant small limonite(?) spots in light-brown sandstone; light brown color in lower part occurs largely along nearly vertical fractures; lower massive unit; grades abruptly into Dewey Bridge Member below	25
Total Slick Rock Member	95

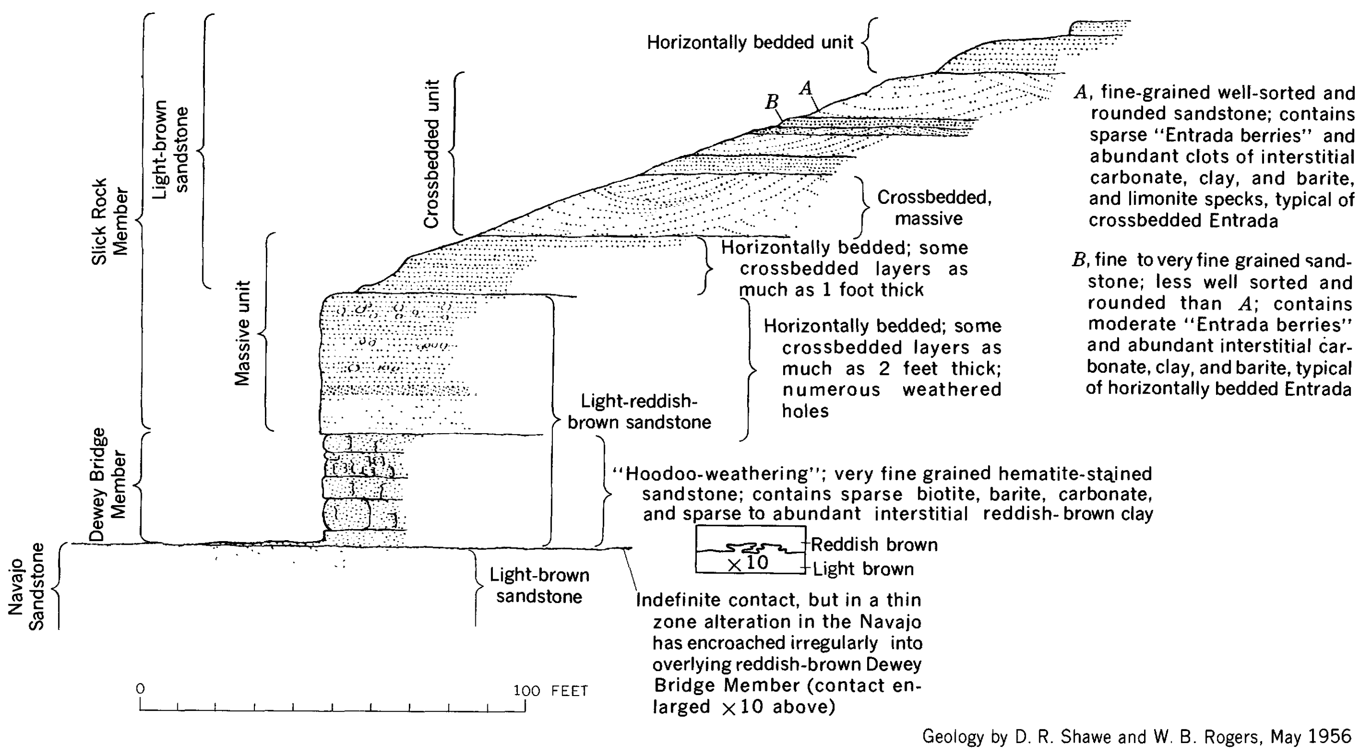

Figure 18.—Lithologic details of the Slick Rock and Dewey Bridge Members of the Entrada Sandstone on the northwest side of Corral Draw, NW¼NE¼ sec. 36, T. 44 N., R. 19 W.

Massive unit

The massive unit of the Slick Rock Member generally presents a smooth cliff (fig. 18) composed of massive very fine grained sandstone, in places with distinct horizontal bedding, small-scale crossbedding in layers as much as 3 feet thick, and more rarely larger scale crossbedding in layers as much as about 7 feet thick. Crossbedded layers are most numerous near the base of the unit. In places along horizontal layers, holes ranging from a few inches to more than a foot in diameter have weathered (fig. 18).

In many places the massive unit grades abruptly, within a few inches vertically, into the underlying Dewey Bridge Member. In a few places the Dewey Bridge–Slick Rock contact is sharp, and slight erosional relief shows at the top of the Dewey Bridge (fig. 19). At one such place on the north side of Summit Canyon (fig. 19), where the light-reddish-brown basal part of the massive unit is crossbedded, a crossbed layer within a foot of the contact is broken, and the breaks contain sand from the adjacent beds, suggesting deformation of the basal part of the Slick Rock Member after the crossbed layer was partly consolidated. The crossbed layer, in contrast to adjacent beds, contains abundant calcite, and local precipitation of calcite from pore waters may have caused early lithification of this bed. Although the crossbedded sandstone is probably of eolian origin, overlying horizontal and massive beds were likely deposited in water. The deformation of the crossbed layer may have resulted from compaction or slight slumping of only partly consolidated water-saturated sediment.

The upper contact of the massive unit is abruptly gradational with the overlying crossbedded unit, but it is quite sharp in places where horizontally layered sandstone apparently has been blown away and replaced by crossbedded sandstone displaying sweeping crossbeds of eolian type (fig. 20). The upper part of the massive unit was blown away locally down to a well-defined horizontal stratum (fig. 20), suggesting that the rock below this stratum may have been partly lithified at the time. Again, precipitation of calcite from pore waters in the lower part of the massive unit shortly after deposition of the upper part may have caused lithification.

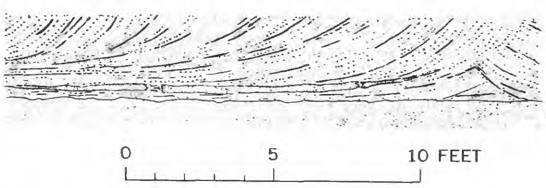

FIGURE 19.—Contact of the Slick Rock and Dewey Bridge Members of the Entrada Sandstone, north side of Summit Canyon, sec. 26, T. 44 N., R. 19 W. The contact is slightly irregular and has about 2 inches of relief.

Crossbedded unit

The crossbedded unit of the Slick Rock Member is seen commonly as a gently sloping surface (fig. 18) or as a convexly rounded cliff (fig. 21). In some places, especially in the axial region of the Dolores anticline, the unit is weathered to rounded humps where polygonal joints have permitted ingress of weathering solutions (fig. 22). Possibly the joints were localized near the axis of the anticline because of stresses related to folding. The joint polygons occur as individuals of one set, each about 10–20 feet in diameter, which contain individuals of a second set, each 1–2 feet in diameter. The unit consists of dominantly very fine to fine-grained well-rounded quartzose sandstone, chiefly in crossbedded

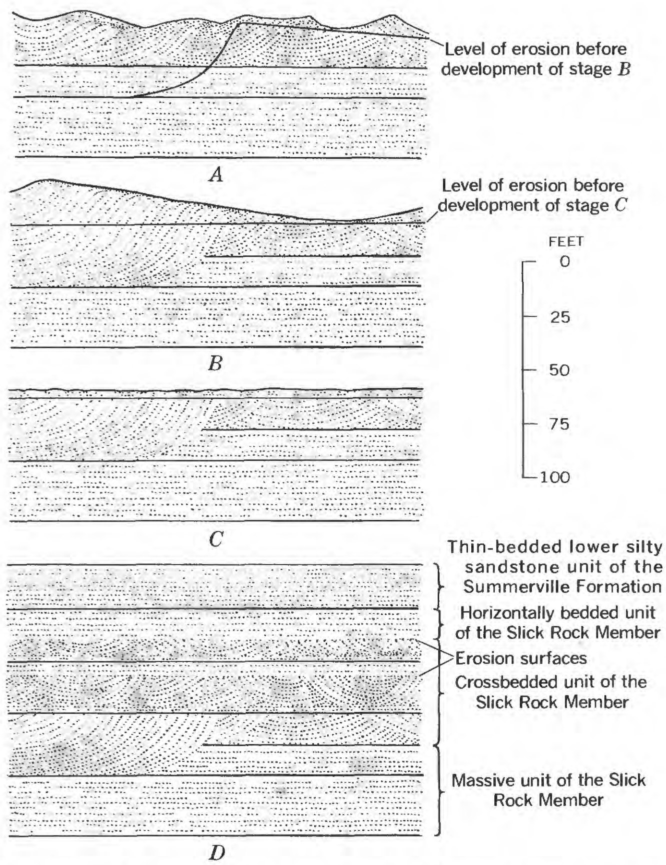

FIGURE 20.—Hypothetical depositional history of parts of the Slick Rock Member of the Entrada Sandstone and the Summerville Formation, north side of Tailholt Canyon, sec. 27, T. 44 N., R. 19 W. *A*, Deposition of the massive sandstone unit of the Slick Rock Member and the lower part of the crossbedded unit followed by erosion and development of an irregular surface. *B*, Further deposition of crossbedded sandstone followed by erosion and development of a level surface. *C*. Deposition of horizontally bedded sandstone. *D*, Present sequence which represents alternating stages of horizontally bedded and crossbedded sandstone deposition.

layers a few feet to as much as 25 feet thick. Individual crossbedded layers are composed of sweeping tangential crossbeds which dip gently to steeply, and which extend from bottom to top of the layer (figs. 20 and 21). The crossbedded layers are separated by thin layers of horizontally bedded sandstone, 1–5 feet thick, similar to parts of the massive unit or to the horizontally bedded unit of the Entrada. A few horizontal bedding planes contain very fine sand- or silt-size, sharply angular detritus that may be crystal tuff.

The crossbedded unit is abruptly gradational into the massive unit below or is in sharp contact with it where sweeping crossbed layers truncate the massive unit.

Horizontally bedded unit

The horizontally bedded unit of the Slick Rock Member most commonly exhibits a smoothly rounded bare surface (fig. 23). In some places where the member as a whole displays well-formed polygonal joints, the surface of the horizontally bedded unit is hummocky (fig. 22). The unit consists of dominantly very fine grained to fine-grained well-rounded quartzose sandstone, principally in even horizontal beds a few inches thick (figs. 18 and 21); many of the beds extend for hundreds and possibly thousands of feet.

The unit is in sharp contact with the crossbedded unit below, and the contact characteristically lies where the lowest horizontal bed truncates the underlying sweeping crossbeds (figs. 18, 21, and 23).

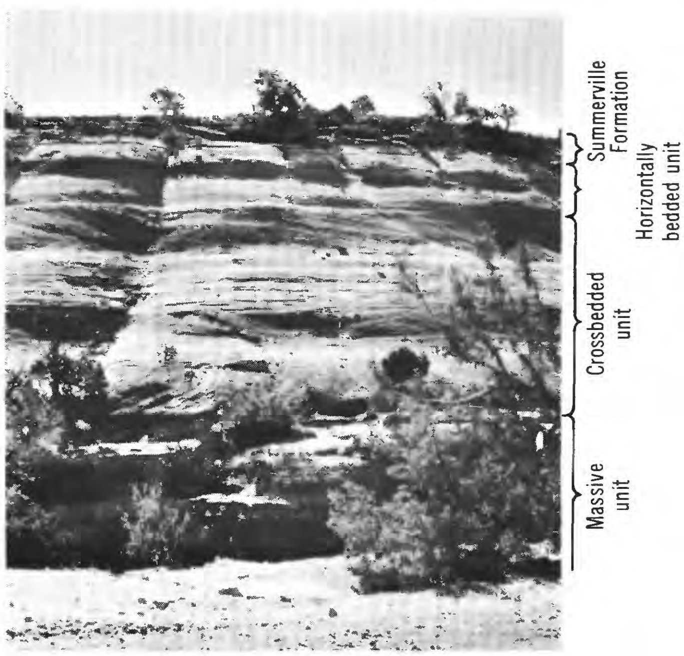

FIGURE 21.—Subdivisions of the upper part of the Slick Rock Member of the Entrada Sandstone, NE¼ sec. 36, T. 44 N., R. 19 W.

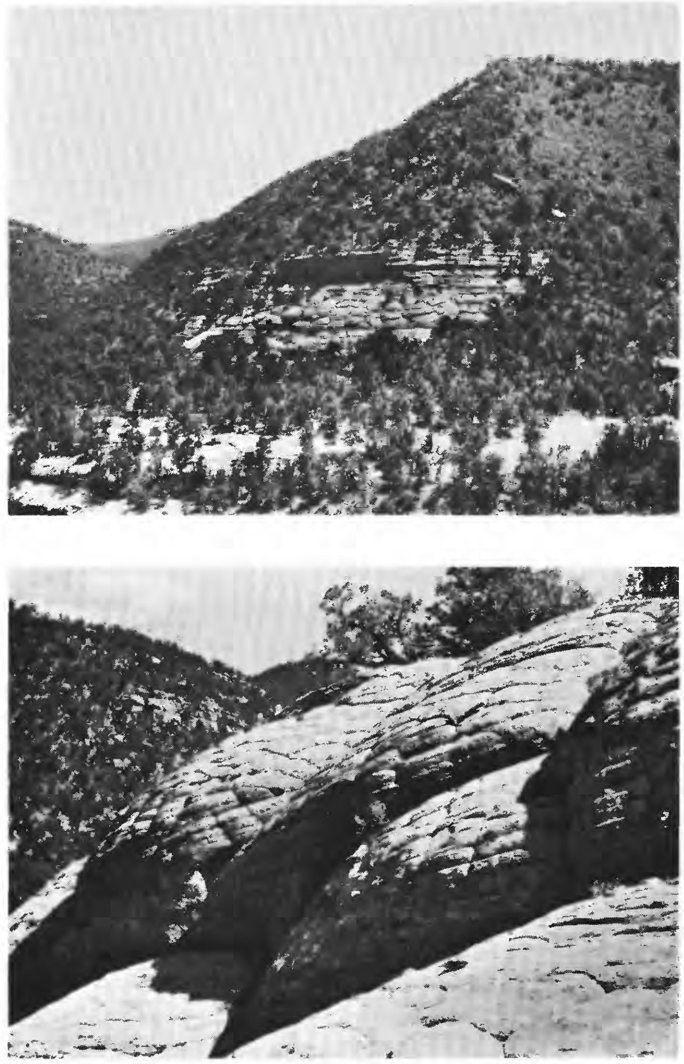

FIGURE 22.—Polygonal joint pattern in the crossbedded unit of the Slick Rock Member of the Entrada Sandstone, Bishop Canyon, SW¼ sec. 20, T. 43 N., R. 19 W. Upper photograph shows distant view; lower, near view.

SURFACE DISTRIBUTION AND CONFIGURATION

The Slick Rock Member of the Entrada Sandstone is exposed in the Slick Rock district throughout large parts of the Dolores River, Summit, McIntyre, Bush, Blue, and Morrison Canyons; its base is visible in all of these exposures.

The Slick Rock is 70–120 feet thick, as shown on the isopach map (pl. 5) which was constructed on the basis of data from 12 measured sections, 1 deep oil-test well, and 3 diamond-drill holes in the district. This map and subsequent isopach maps show data only within the boundary of the district. It was not always possible to correlate the more abundant data available in the district with the sparser data from the surrounding area. In general, the Slick Rock Member thickens westward, and superposed on this general thickness pattern is an area of relatively thin northwesterly oriented Slick Rock Member that lies on the northeastern limb of the Dolores anticline.

The massive unit of the Slick Rock Member is about 25–50 feet thick; it appears to be thickest in the Disappointment Valley area and thinnest near the axis of the Dolores anticline (pl. 5). The crossbedded unit ranges in thickness from about 30 to 60 feet, but is mostly about 50–60 feet thick. The horizontally bedded unit is about 2–15 feet thick, and it has no apparent pattern of thickness variation.

SUMMERVILLE FORMATION

The Summerville Formation, uppermost formation of the San Rafael Group in most of the Slick Rock district, was named by Gilluly and Reeside (1928, p. 80) for exposures at Summerville Point at the north end of the San Rafael Swell, Utah. In the Slick Rock district, Coffin (1921) included the Summerville with the overlying Morrison Formation, and called these strata the McElmo Formation. The unit was first identified in the district and mapped as the Summerville Formation by Stokes and Phoenix (1948). The lower part of the formation is probably equivalent to the Bilk Creek Sandstone Member of the Wanakah Formation, and the middle part is probably equivalent to the marl member of the Wanakah in the vicinity of Placerville, Colo. (Bush and others, 1959, p. 326–328). The lower part of the formation is also equivalent to the Moab Sandstone Member of the Entrada in east-central Utah (Wright and others, 1962, p. 2063). In the southern part of the district the upper part of the Summerville grades laterally into the Junction Creek Sandstone.

Because the Summerville Formation grades laterally into the Curtis Formation west of the district in Utah, where the Curtis has been dated as Late Jurassic in age (Gilluly and Reeside, 1928, p. 79), the Summerville is considered to be of the same age.

Lithology

The Summerville Formation characteristically forms a steep smooth slope, largely debris covered, where few good exposures are evident (figs. 9, 23). One bed in the formation, the so-called marker bed about two-thirds up from the base, is visible almost everywhere that the formation is exposed (for example, fig. 23). The formation is in large part composed of evenly bedded principally reddish-brown mudstone (in part shaly) and siltstone and some reddish-brown, brown, and light-greenish-gray very fine to fine-grained sandstone. The sandstone is most abundant in a transitional unit at the base of the Summerville equivalent to the Moab Sandstone Member of the Entrada Sandstone in east-central Utah (Wright and others, 1962, p. 2063) and also makes up the so-called marker bed in the upper part of the formation. The sandstone is finely laminated, in most places horizontally, but in many places the laminations are wavy and in some places crossbedded. Clay and calcite are the chief cementing materials in the sandstone. The siltstone and mudstone are reddish brown to orangish brown with thin layers and spots of greenish gray and show bedding similar to that of the sandstone. Locally, thin discontinuous lenses and nodules of fine-grained gray limestone occur at the top of the formation.

The transitional unit at the base of the Summerville consists of reddish-brown and greenish-gray very fine grained sandstone in layers a few inches to a few feet thick interbedded with thinner layers of claystone, mudstone, or siltstone (figs. 23 and 24). The lower contact with the Entrada is arbitrarily chosen as the lowest thin argillaceous layer. Commonly this reddish-brown mudstone layer is altered to greenish gray for a few inches just above the contact with light-buff Entrada. The transitional relation to the Entrada is demonstrated by the lateral interfingering of the thin argillaceous layers with horizontally bedded sandstone at the top of the Entrada. The interfingering, at least in places, is toward the northwest. The upper part of the transitional unit grades up into the more argillaceous rocks of the Summerville by an increase in thickness of interlayered argillaceous beds (fig. 23).

The argillaceous part of the Summerville above the basal transitional part and below the marker bed consists of dominantly reddish-brown thinly and horizontally bedded sandy siltstone and mudstone. Sandy layers commonly contain abundant oscillatory ripple marks.

The marker bed consists of reddish-brown to light-brown very fine-grained silty sandstone containing a few thin layers of siltstone. It is horizontally bedded and contains abundant oscillatory ripple marks, especially near its base and top (fig. 25). Oscillatory ripple marks in a large area in the vicinity of Summit Canyon have their trough axes oriented approximately N. 76° E., indicating wave action dominantly normal to this direction. The sandstone of the marker bed, where it is light brown, has layers rich in calcite, and other layers contain scattered quarter-inch nodules cemented with calcite.

The argillaceous part of the Summerville above the marker bed is lithologically similar to the argillaceous part below the marker bed. According to cores from diamond-drill holes at the northeast edge of Disappointment Valley just northwest of Gypsum Gap, the upper argillaceous part is largely greenish gray in contrast to reddish brown in most other parts of the district. Toward the south end of the district, the upper part of the Summerville changes lithology gradually by increase

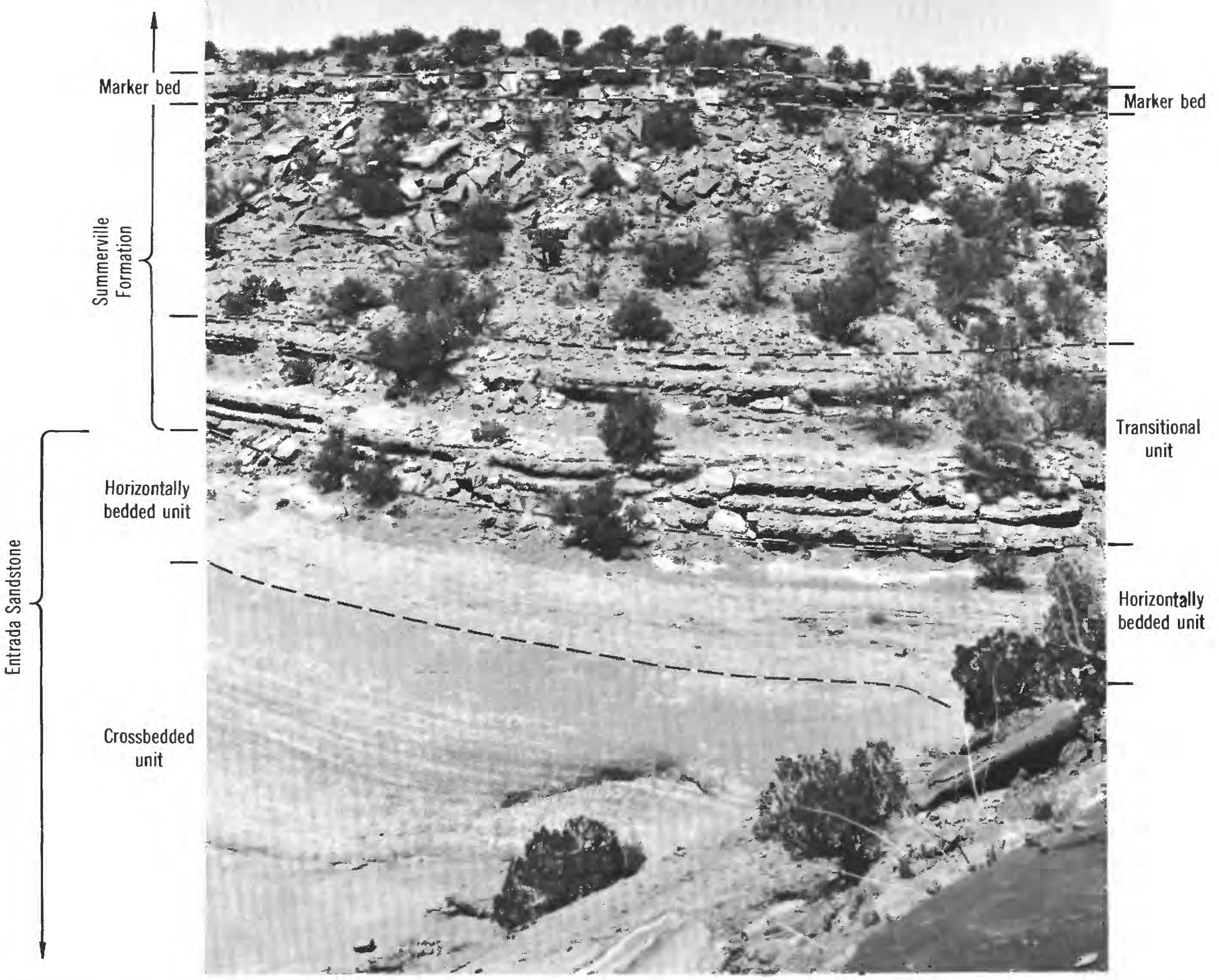

FIGURE 23.—Horizontally bedded unit of the Slick Rock Member of the Entrada Sandstone. Unit overlies the crossbedded unit of the Slick Rock Member and underlies the Summerville Formation. SE¼ sec. 24, T. 44 N., R. 19 W.

in sand content and merges laterally by facies change with the Junction Creek Sandstone.

A typical section of the Summerville follows.

Section of Summerville Formation near the head of Stevens Canyon, sec. 32, T. 44 N., R. 19 W.

[Measured by G. C. Simmons and N. L. Archbold, Sept. 9, 1956]

	Thickness (feet)
Summerville Formation:	
14. Mudstone and sandstone, reddish-brown, very fine grained; thin-bedded, poorly exposed	21
13. Sandstone, light-brown, very fine grained; contains rare dark minerals and a few flakes of greenish-gray clay	9
12. Mudstone, siltstone, and very fine grained sandstone, reddish-brown; occur as alternating thin beds	13
11. Sandstone, light-reddish-brown and light-brown, very fine grained to fine-grained, horizontally laminated; contains rare dark minerals and sparse calcite nodules; thin greenish-gray shaly mudstone layer at base; unit is the so-called marker bed	9
10. Mudstone and siltstone, reddish-brown	2
9. Sandstone, light-brown and light-gray, very fine grained; contains a small amount of dark minerals	2
8. Mudstone and siltstone, reddish-brown	10
7. Sandstone, light-brown, very fine grained, quartzitic; contains a small amount of dark minerals	1
6. Siltstone and mudstone, reddish-brown	12
5. Sandstone, light-greenish-gray, very fine grained; contains rare dark minerals; stained reddish to a depth of 1 in. by wash from overlying red beds	3
4. Mudstone and siltstone, reddish-brown	4
3. Sandstone, light-greenish-gray, very fine grained; thin horizontally bedded; alternates with thin layers of reddish-brown mudstone	7
2. Sandstone, light-greenish-gray, very fine grained, quartzitic, thin horizontally bedded; contains rare dark minerals; stained light brown on weathered surface; thin mudstone partings in lower half	15
1. Mudstone, reddish-brown	2
Total Summerville Formation	110

Surface distribution and configuration

The Summerville Formation is exposed in the Slick Rock district throughout most of the Dolores River Canyon and in McIntyre, Summit, Bush, Blue, and Morrison Canyons. The base of the formation is visible in all of these exposures.

FIGURE 24.—Transitional unit of the Summerville Formation and the underlying Entrada Sandstone, N½NW¼ sec. 25, T. 44 N., R. 19 W.

FIGURE 25.—Oscillatory ripple marks in the marker bed in the Summerville Formation near the center of the south edge of sec. 24, T. 44 N., R. 19 W. Pencil shows scale.

An isopach map of the Summerville (fig. 26) was constructed on the basis of about 40 measured sections and 5 diamond-drill holes. Parts of the map are of doubtful accuracy because of the difficulty of consistently placing a contact in the transitional beds above the Entrada Sandstone and in the Salt Wash and Summerville rocks in drill cores where gross bedding characteristics are not evident to permit distinction of the formations. The Summerville appears to generally

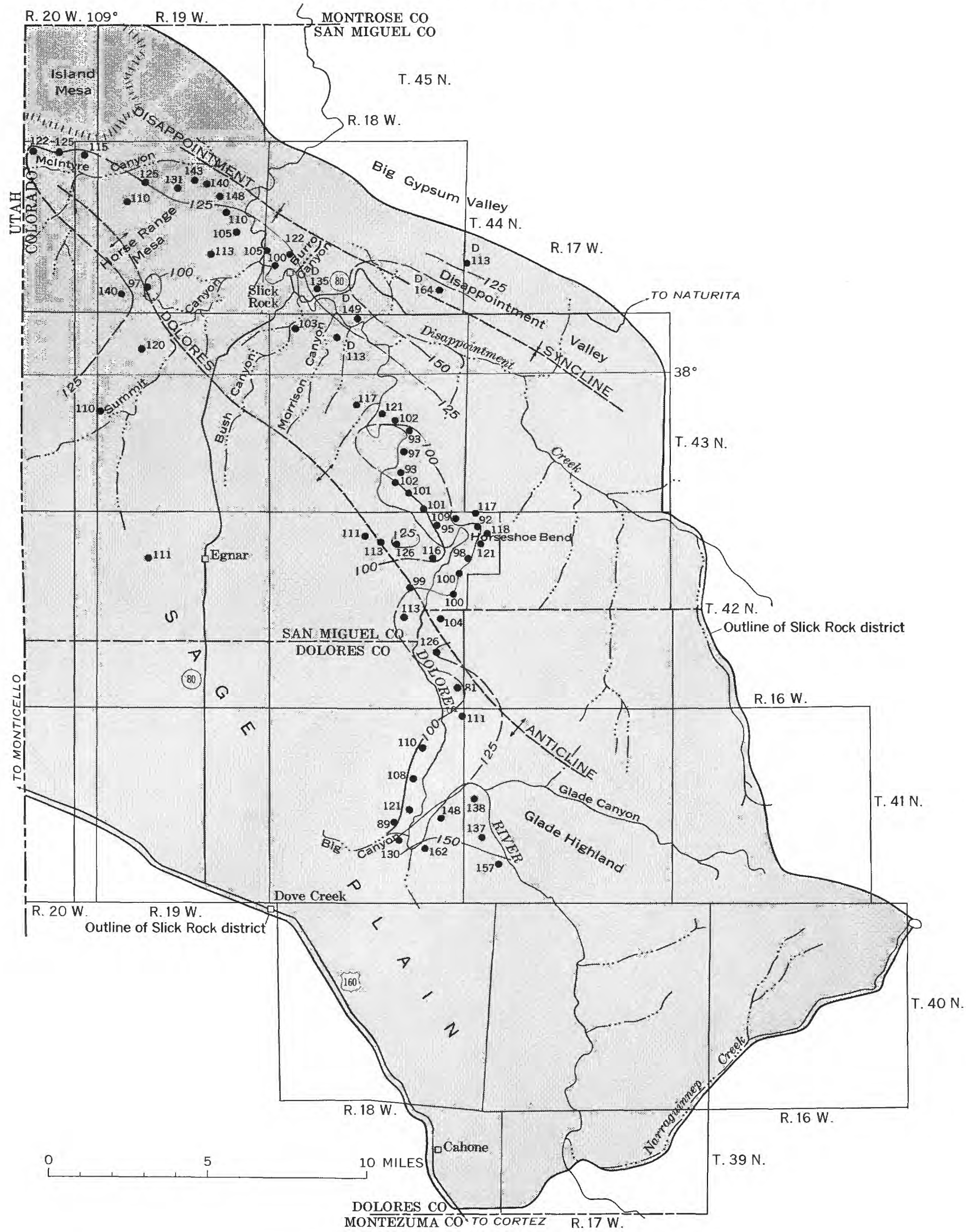

Figure 26.—Thickness of the Summerville Formation. Isopachs dashed where uncertain; interval 50 feet. Number by control point (dot) is measured thickness, in feet, of the Summerville Formation. Diamond-drill holes indicated by D; other control points are surface sections.

range in thickness from 80 feet, halfway between Horseshoe Bend and Big Canyon, to 160 feet east of Big Canyon and in Disappointment Valley. The isopach map suggests that the Summerville may be locally thinner in the vicinity of the Dolores anticlinal axis and locally thicker near the axis of the Disappointment syncline and southeast of Glade and Big Canyons.

The basal sandy part of the Summerville Formation appears to increase in thickness gradually from less than 10 feet in the southeastern part of the district to about 50 feet in the northwestern part. The lower argillaceous part appears to be thickest in Disappointment Valley. The marker bed generally ranges in thickness from 10 to 35 feet, apparently at random throughout the district. The upper argillaceous part of the formation is as much as 60 feet thick in Disappointment Valley, but it is absent in the southern part of the district where its position is occupied by the Junction Creek Sandstone.

JUNCTION CREEK SANDSTONE

The name Junction Creek Sandstone was first used by Goldman and Spencer (1941, p. 1750–1751) for massive sandstone displaying sweeping crossbeds along Junction Creek, a tributary of the Dolores River above the town of Dolores, Colo. It was recognized by Goldman and Spencer as the "Upper La Plata sandstone" of Cross (1907) and was renamed and assigned by them as a member of the Morrison Formation. The unit was subsequently considered as a separate formation (Eckel, 1949, p. 29), as a member of the Wanakah Formation (Read and others, 1949), and as a formation in the San Rafael Group (Craig and others, 1955, p. 133–134). In the Slick Rock district the Junction Creek Sandstone was first recognized by Cater (1955c), who followed the then-current assignment as a member of the Wanakah Formation. As the formation is thin and similar in appearance to sandstone in the Salt Wash Member in this area, Cater mapped the Junction Creek Sandstone with the Salt Wash. In this report Craig's terminology is used, and the Junction Creek Sandstone is given formation status at the top of the San Rafael Group because of its tonguing relation with the upper part of the Summerville Formation. Where the formation is thickest, in the southern part of the district, it is mapped as a separate unit (pl. 1); but where its thinness precludes mapping as a separate unit at the map scale, it is mapped with the Summerville Formation.

The Junction Creek Sandstone is correlative with the Bluff Sandstone of southeastern Utah, (Goldman and Spencer (1941, p. 1759; Craig and others 1955, p. 133). Harshbarger, Repenning, and Irwin (1957, p. 48) indicated that the Bluff Sandstone is a lower tongue of the Cow Springs Sandstone of northeastern Arizona.

Because it intertongues with the Summerville, the Junction Creek Sandstone is considered to be Late Jurassic in age.

Lithology

The Junction Creek Sandstone forms a sequence of low cliffs and rounded ledges alternating with thin argillaceous layers which erode as steep slopes. A few miles south of the district the formation displays its more typical character as a smooth and bare, convexly rounded steep slope somewhat similar in appearance to parts of the Entrada Sandstone (fig. 27). The Junction Creek in the district is composed of very light buff, very light brown, and light reddish-brown fine- to medium-grained sandstone with a few thin reddish-brown mudstone and sandy shale partings. The sand grains are poorly to well sorted, largely subrounded, and composed of mostly clear quartz, some amber quartz, and small amounts of orange, pink, and black minerals which probably include feldspar, chert, and heavy minerals. The sandstone is somewhat friable, and is poorly cemented by calcite and minor amounts of clay. Where the formation is thickest in the district, sandstone in the upper three-fourths shows sweeping crossbeds truncated in a few places by horizontally laminated beds. The

FIGURE 27.—Junction Creek Sandstone in the Dolores River Canyon south of the Slick Rock district, 9 miles downstream from Dolores, Colo. Sweeping crossbeds composing the entire unit extend hundred of feet without truncation and are virtually parallel.

lower part of the formation, which appears to be the same stratigraphic unit as the marker bed of the Summerville Formation, is principally horizontally bedded interbedded with a few thin crossbedded units. South of the district where the Junction Creek is a thick layer of very light buff eolian-type crossbedded sandstone, it consists of medium-grained well-sorted and well-rounded chiefly quartz sand, with a minor amount of dark minerals, that is loosely cemented by sparse carbonate and barite and contains a moderate number of minute limonite specks which stain surrounding grains and apparently have oxidized from pyrite or marcasite. Here the Junction Creek is unique in that it consists of one set of crossbeds that is more than a hundred feet thick (fig. 27).

Correlation of sections of the Junction Creek Sandstone (pl. 6) suggests the lateral changes in the formation from a point near the south end of the district, where the formation dips beneath the surface, to the vicinity of Big Canyon. The Junction Creek changes character by intertonguing and bedding changes within individual lithologic units and merges to the northwest with the upper part of the Summerville Formation (pl. 6). The lower part of the Junction Creek continues northwestward as the marker bed in the upper part of the Summerville. One section of the Junction Creek, measured in Big Canyon (near section A, pl. 6), consists of 24 feet of very light buff fine- to medium-grained sandstone, composed dominantly of clear quartz, a moderate amount of pale-yellow quartz, sparse red chert, and a trace of dark minerals; the unit is horizontally bedded except for a crossbedded unit 1 foot thick about 3 feet below the top.

A typical section of the Junction Creek where the formation occupies the entire interval between the marker bed in the Summerville and the Salt Wash Member of the Morrison Formation (measured in the vicinity of sections G–3E, pl. 6) follows.

Section of Junction Creek Sandstone, near Dove Spring, sec. 9, T. 40 N., R. 17 W.

[Measured by L. C. Craig and V. L. Freeman, October 1949]

	Thickness (feet)
Junction Creek Sandstone:	
4. Sandstone, white to very pale orange; fine to medium grained, becoming predominantly medium fine to medium grained at the top; composition similar to unit 3 below; very poorly sorted with grains up to coarse size in the upper part; lower half is horizontally laminated and upper half is composed of interbedded horizontally laminated and cross-laminated sandstone that forms a cliff	36
3. Sandstone, white to very pale orange, fine- to medium-grained, poorly sorted; of subrounded to well-rounded clear quartz and abundant orange to pink and black to gray accessory minerals	30

Section of Junction Creek Sandstone, near Dove Spring, sec. 9, T. 40 N., R. 17 W.—Continued

	Thickness (feet)
Junction Creek Sandstone—Continued	
2. Claystone, dark-reddish-brown to moderate-reddish-brown, moderately sandy; forms a bench	8
1. Sandstone, grayish-orange-pink to white, fine-grained; of subangular to subrounded clear quartz and common orange and gray to black accessory minerals; shows undulatory horizontal laminations and even horizontal bedding planes; forms a prominent ledge; probably correlates with the marker bed in the Summerville Formation	27
Total Junction Creek Sandstone	101

Surface distribution and configuration

The Junction Creek Sandstone is exposed in the Slick Rock district only in the Dolores River Canyon near the south end of the district. It is exposed from a vaguely located point in the vicinity of Big Canyon where the formation merges with the Summerville (pl. 6), southeastward to the vicinity of Five Pine Canyon where it dips beneath the surface.

The Junction Creek thickens southeastward from the point of merging and is a little more than 100 feet thick where it disappears. Where it reappears outside the district several miles farther south, it is more than twice as thick.

MORRISON FORMATION

As the Morrison Formation contains more than half of the known uranium reserves in the United States, it is of prime economic importance. In the Slick Rock district important uranium-vanadium production has come from the Salt Wash Member of the Morrison Formation, and large reserves of ore, both known and inferred, make the Slick Rock district potentially the principal uranium and vanadium mining area in Colorado. Geologic data on the Morrison Formation in the district have been collected from nearly 3,000 Geological Survey diamond drill holes, from surface and underground geologic mapping, and from special field and laboratory studies.

The Morrison Formation was named by Eldridge (Emmons and others, 1896), but Cross (1894, p. 2) was the first to publish the name. At the type locality near the town of Morrison, Colo., the formation is undifferentiated, but it resembles the Brushy Basin Member of the Morrison of the Colorado Plateau. Early workers on the Colorado Plateau grouped the present Morrison with all or part of the underlying San Rafael Group and called the unit the McElmo Formation (Cross, 1907; Coffin, 1921, p. 77–97).

The Morrison Formation has long been famous for vertebrate fossils, notably the large dinosaurs, and the unit generally is well dated. The age of the formation is Late Jurassic, although the exact age of its upper part is not certain (Imlay, 1952, p. 953).

Although the Morrison Formation is fully discussed by Craig and others (1955) the formation in the Slick Rock district is described here in considerable detail because of its pertinence to the origin, genesis, and occurrence of the uranium-vanadium deposits, subjects to be discussed in later chapters of this report.

The Morrison is widely distributed in the Western Interior of the United States. In most places it is not subdivided, but on the Colorado Plateau it is divided into several members. Craig and others (1955) studied the regional characteristics of the formation on the Colorado Plateau, and part of their work is briefly reviewed here in order to relate the Morrison Formation of the Slick Rock district to the formation elsewhere. In eastern Utah and western Colorado the lower part of the Morrison consists of the Salt Wash Member, whereas in northwestern New Mexico and northeastern Arizona it consists of the Recapture Member. The Recapture and Salt Wash Members interfinger in the Four Corners area and no Recapture extends as far north as the Slick Rock district. Three facies of the Salt Wash Member are recognized: a conglomeratic sandstone facies in south-central Utah; a facies of alternating sandstone and mudstone layers surrounding the conglomeratic sandstone facies on the northwest, north, and east (in which area the Slick Rock district lies); and a claystone and lenticular sandstone facies in northeastern Utah and northwestern Colorado. Eastward, the third facies of the Salt Wash grades into claystone and limestone beds of the undifferentiated Morrison Formation at the type locality.

The upper part of the Morrison is divided into the Brushy Basin Member and the Westwater Canyon Member. In the Four Corners area the Westwater Canyon Member underlies the Brushy Basin Member; northward, the Westwater Canyon grades into the Brushy Basin and is absent in the Slick Rock district; southward from the Four Corners area, the Brushy Basin Member apparently was removed by pre-Dakota erosion. The Brushy Basin Member shows a wide range in lithology, but no consistent changes are evident and it has not been divided into regional facies.

The Morrison is thickest in the vicinity of the Four Corners area, in Disappointment Valley, and along the Colorado-Utah border just south of the Wyoming state line. A cored section of the Morrison Formation near the axis of the Disappointment syncline in the Slick Rock district is more than 1,100 feet thick, which is the greatest thickness known.

The lower part of the Morrison Formation is composed of sediments of fluvial origin, deposited both in stream channels and on flood plains. The channel-type deposits are lenticular crossbedded sandstones, and the flood-plain deposits are tabular thin and flat-bedded mudstones and sandstones. Channel-type deposits have greatest aggregate thickness in southeastern Utah, north of Gallup, and along the Utah-Colorado boundary about midway between Grand Junction, Colo., and the Four Corners. The direction of sediment transport in the lower part of the Morrison, as deduced from measurements of crossbedding, was toward the north, northeast, east, and southeast from south-central Utah.

The Slick Rock district thus lies in a region where only the Salt Wash and Brushy Basin Members of the Morrison Formation are present, where the Morrison Formation attains its maximum thickness, and where stream-type deposits (lenticular crossbedded sandstone) have their greatest aggregate thickness and maximum continuity.

AGE OF SOURCE ROCKS

Larsen method (lead-alpha) age determinations made on five samples of zircons separated from sandstone from the Morrison Formation in the Slick Rock district indicate that the ultimate source rocks of the Morrison were of late Precambrian to Early Cambrian age (table 4).

The ages represent an average age of the zircons in each sample, within the error of the method. Because nearly all (about 90 percent) of the zircons are well-rounded grains, the determined age for any sample is probably a good approximation of the age of the well-rounded zircons. The predominance of well-rounded zircons, whose form is a result of having passed through many sedimentation cycles, in itself argues for an ultimate source of considerable age; the late Precambrian and Early Cambrian determined ages are compatible with the present physical character of zircons in the Morrison Formation. Perhaps the difference in relative amounts of zircon types, that is, older well-rounded zircons and younger nearly euhedral zircons, in the different size fractions from sandstone of HD–1–366 accounts for the slightly different average ages of zircons in the two fractions. The zircons from the ore-bearing sandstone of the Salt Wash appear to be appreciably older than those from the Brushy Basin above and from the sandstone below the ore-bearing unit. Possibly the difference in age reflects different sources

TABLE 4.—*Ages of zircons from the Morrison Formation in the Slick Rock district*

[Determined by the Larsen method. Analysts: H. J. Rose, Jr., and H. W. Worthing]

Sample	Location	Description	Age, in millions of years
DVR-1-1303.2	Southeastern Disappointment Valley.	Slightly altered very light reddish brown sandstone from the middle part of the Brushy Basin Member; zircons separated from −97 +150 and −150 +200 mesh fractions, rejected in Frantz separator at 1.6 ampere, slope 15° and 20°, tilt 10°.	585±65
HD-1-366	Doss group of claims.	Unaltered light-reddish-brown sandstone from the ore-bearing sandstone of the Salt Wash Member; zircons separated from −200 mesh fraction, rejected in Frantz separator at 1.65 ampere, slope 20°, tilt 10°.	755±85
HD-1-366	do	Same as above, but −150 +200 mesh fraction, rejected in Frantz separator at 1.6 ampere, slope 20°, tilt 10°.	715±80
SH-4-55	Veta Mad mine area.	Unaltered light-reddish-brown sandstone from thin unit just below the ore-bearing sandstone of the Salt Wash Member; zircons separated from −200 mesh fraction, rejected in Frantz separator at 1.56 ampere, slope 20°, tilt 10°.	555±60
SH-10-57A	Cougar Canyon area.	Unaltered light-reddish-brown sandstone from unit below ore-bearing sandstone of the Salt Wash Member.	630±70

of sediment for the ore-bearing sandstone and for beds above and below it. Craig and others (1955, p. 150, 157) suggested two main source areas, one in west-central New Mexico and one in west-central Arizona and southeastern California, for parts of both the Salt Wash Member and the Brushy Basin Member, and perhaps the difference in age of the zircons indicates that the ore-bearing sandstone in the Slick Rock district was derived from one of these sources, and the middle part of the Brushy Basin Member and the unit below the ore-bearing sandstone in the Slick Rock district were derived from the other source.

SALT WASH MEMBER

The Salt Wash was named by Lupton (1914, p. 127) as a member of the McElmo Formation and was described from exposures in Salt Wash about 30 miles southeast of Green River, Utah. The name Salt Wash was retained for the same rocks, but as a member of the Morrison Formation, when the term McElmo was abandoned by Gilluly and Reeside (1928, p. 82).

LITHOLOGY

In the Slick Rock district the Salt Wash Member consists of light-buff (or light-gray below the water table where unweathered) to light-reddish-brown (also light-reddish-brown where unweathered) lenticular fine-grained sandstone layers that show scour and fill features and crossbedding typical of channel-type sediments, intercalated with reddish-brown flood-plain-type mudstone layers. The ratio of cumulative sandstone thickness to cumulative mudstone thickness generally ranges from 0.6 to 4.0 and most commonly ranges from about 1 to 2. In the north half of the district, where data are abundant, the highest sandstone-to-mudstone ratios occur near the axis of the Dolores anticline. An elongate area of high ratios appears to cross the axis of the Disappointment syncline diagonally. The areas of highest sandstone-to-mudstone ratios do not appear to show any consistent relation to major structures in the district.

The Salt Wash is expressed topographically as a series of steep slopes formed on mudstone layers alternating with cliffs and benches formed on the resistant sandstone lenses. The sandstone lenses in the Salt Wash are generally well exposed except on north slopes and at the higher elevations on the rim of the Dolores River Canyon, but the intercalated mudstone layers are generally covered by landslide debris, residual soil or talus, and vegetation.

The Salt Wash Member can be divided roughly into three parts. At the top and bottom of the member, lenses of sandstone coalesce and form fairly continuous layers of sandstone that contain numerous thin layers of mudstone. The middle part of the Salt Wash Member is composed dominantly of mudstone containing scattered, unconnected lenses of sandstone. The three parts of the Salt Wash Member interfinger and are more evident when viewed from a distance (fig. 28). They are also evident locally in the geologic sections on plate 7 and in the correlation diagram of plate 8. The threefold breakdown of the Salt Wash Member is primarily to facilitate discussion of the rocks. As is evident on plate 7, which was prepared to show detailed lithology in the Morrison Formation in the vicinity of the uranium-vanadium deposits, the three units were not mapped as such. Most of the significant uranium-vanadium deposits in the Morrison Formation in the district occur in the top sandstone layer or upper unit of the Salt Wash Member, which is commonly referred to as the ore-bearing sandstone.

SANDSTONE

Sandstone of the Salt Wash Member is characteristically either light red to reddish brown or light gray

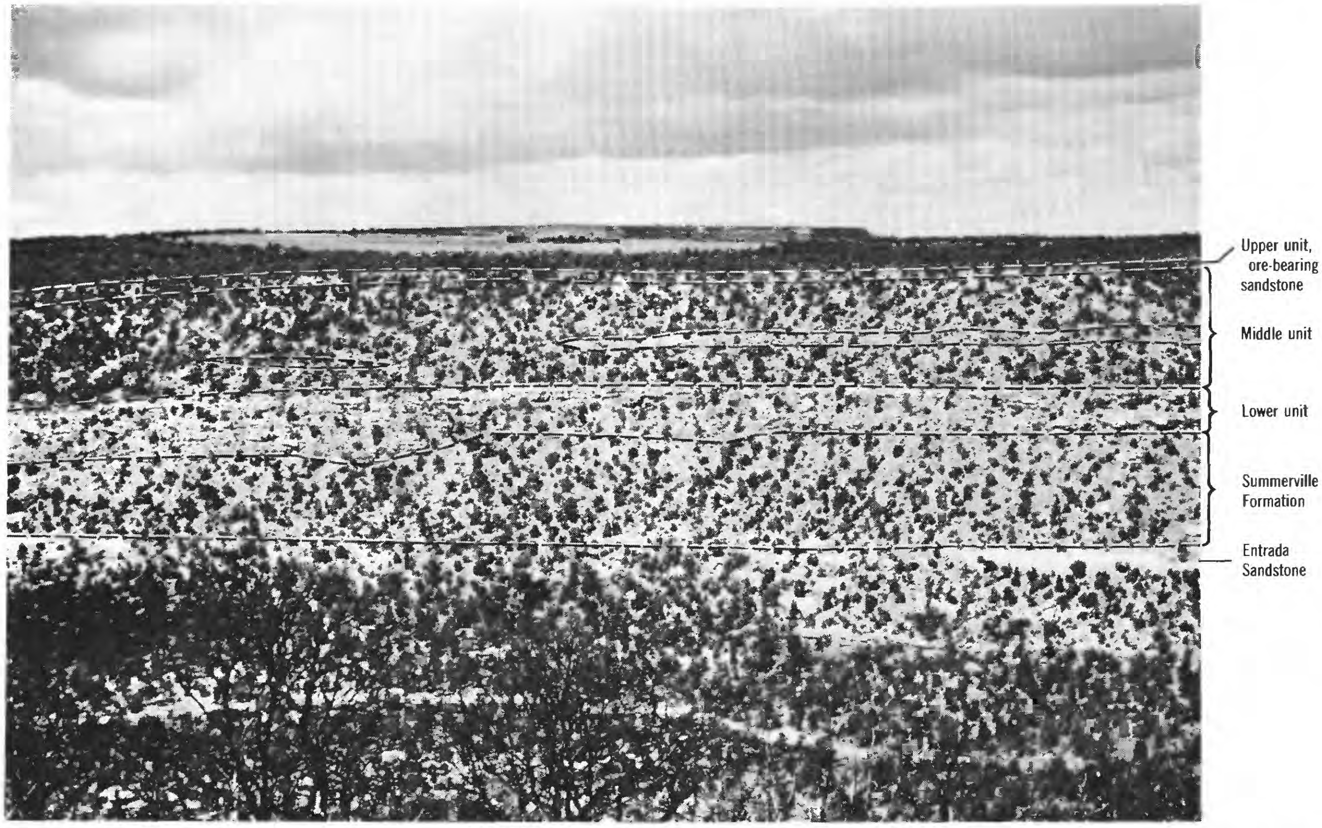

FIGURE 28.—Salt Wash Member of the Morrison Formation, showing lower, middle, and upper units. Individual sandstone lenses in the middle unit are also outlined. West side of Summit Canyon south of Summit Point.

to buff. Where reddish and light-gray to buff colors occur in the same sandstone layer, reddish is usually dominant in the upper part of the layer and light gray to buff is confined to the lower part. In the upper unit of the Salt Wash, areas where sandstone is light gray to buff are widespread, whereas in the middle and lower units, areas where sandstone is light gray to buff seem to be largely confined to a zone between the Dolores fault zone and the axis of the Dolores anticline and to the south end of Bishop Canyon (pl. 7).

The sandstone is quartzose, has moderately rounded grains, is moderately to poorly sorted and mainly very fine to medium grained, and has abundant coarser grains and some granules in places. Mudstone pebbles as much as 2 inches in diameter and films and thin layers of mudstone are common in the sandstone lenses. Carbonate minerals, silica, and clay serve as cementing agents in the sandstone, and sandstone lenses in the lower and middle units of the member are more tightly cemented than those in the upper unit (ore-bearing sandstone). Partly as a result of firmer cementation, sandstone in the lower and middle units is less porous and permeable than that in the upper unit. This aspect, only to a limited extent responsible for the greater "bleaching" or development of light colors in the rock due to alteration, is discussed in more detail in later chapters. Each sandstone lens, regardless of color, is most thoroughly cemented at its top and base where sandstone is in contact with mudstone (Archbold, 1955; 1959).

Sedimentary structures

Sandstone strata in the Salt Wash comprise a complex array of individual juxtaposed sandstone beds and sets of beds exhibiting a variety of bedding types, separated by more or less thin strata of mudstone. In a few places the mudstone strata are as much as 15 feet thick, and in other places they consist only of thin films of clay, which are thought to represent diastems. Where the sandstone strata appear to extend several hundred to a few thousand feet laterally, horizontal bedding is common. Where sandstone strata are more lenticular and extend laterally only a few tens to a few hundreds of feet, crossbedding appears to be more common. Some sandstone is structureless and massive. Crossbedded, horizontally bedded, and structureless layers are interbedded and intertongued in a complex manner. Crossbedded sandstone strata seem to be most common in the upper part of the Salt Wash and horizontally bedded layers are most common in the lower part, but both types are widely distributed throughout the member. Structureless strata are less common in all parts of the member.

Cross stratification in sandstone of the Salt Wash Member has commonly been indicated as the most typical bedding type in the member. Cross-stratification observed in the Salt Wash includes incline or torrential type, consisting of more or less parallel crossbeds such as the foreset beds of deltas, wedging sets of crossbeds, and festoon-type, consisting of a series of "nested" concentric spoon-shaped layers, open at the lower or downcurrent end.

The bedding character within individual sandstone lenses such as those shown in the cross section in figure 29 may be complex. For example, a lens may show torrential-type crossbedding apparently formed by currents flowing nearly normal to the long axis of the lens-filled scour, indicating that the sediment was laid down as a delta in a preexistent scour. In some lenses crossbedding appears to parallel, in festoon fashion, the basal mudstone layer lining the bottom of the scour and possibly was formed by currents flowing in and parallel to the scour. Or crossbedding may parallel the basal mudstone stratum near one edge of a lens and grade laterally into structureless sandstone occupying the opposite side of the lens. Some individual lenses display a complex of crossbedded, horizontally bedded, and structureless parts truncated by other younger crossbedded, horizontally bedded, and structureless parts. Some crossbedded scour-and-fill lenses appear to be laterally continuous with thinner horizontally bedded strata that may have been deposited contemporaneously as a sheet.

Craig and others (1955, fig. 26; p. 147) indicated that the dominant directions of transport of Salt Wash sediment in the region of the Colorado Plateau were northward, northeastward, eastward and southeastward, and in the area of the Slick Rock district, dominantly eastward to northeastward. In our study, directions of flow of the paleocurrents that deposited the sandstone layers of the Salt Wash Member in a small area in the Slick Rock district were determined from the orientation of festoon bedding sets and other cross-stratification structures, channel scours, current lineations, current ripple marks, and fossil logs. A few measurements of the orientation of festoon bedding sets and other cross-stratification structures in the upper unit of the Salt Wash Member indicate that the dominant direction

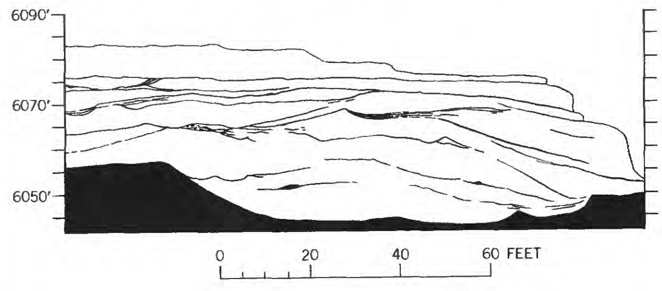

FIGURE 29.—Sketch section of the upper unit of the Salt Wash Member of the Morrison Formation drawn from rim exposure showing a basal channel fill and the lensing character of the sandstone, Cougar mine area. Location of the diagram is shown on plate 9 and in figure 31. Black represents mudstone, both as thick layer in lower part of sketch and as irregular thin layers within the overlying sandstone.

of current flow was easterly to southeasterly and ranged from northeasterly to southerly. A well formed southward-plunging festoon bedding set occurs in the upper unit at the Cougar mine, sec. 23, T. 44 N., R. 19 W. (fig. 30).

Channel scours in mudstone layers underlying the ore-bearing sandstone are common and probably indicate the general direction of currents that deposited the lowest parts of the ore-bearing sandstone. Generally the orientation of the scours is difficult to determine except where the base of the sandstone is known accurately and in detail. One such area is illustrated in figure 31, which shows contours on the surface of the mudstone below the ore-bearing sandstone in the Cougar Mine area after correcting the surface for the present attitude of the beds (N. 32° W., 3½° NE) and for minor displacement caused by northeastward-striking faults. With these corrections the surface is restored to its approximate attitude at the time sedimentation took place. If the restoration is correct the general slope of the surface was eastward at a gradient of about 50 feet per mile, and channel scours in the surface indicate an easterly to southeasterly stream flow. Local relief on the surface was about 10 feet. A cross section of one of the deeper scours is shown in figure 29.

Horizontally bedded and laminated sandstone of the Salt Wash generally exhibits well-formed current lineation, which is the longitudinal streaking of sand grains in individual depositional layers (fig. 32). Current lineation is most apparent in horizontally bedded sandstone which contains abundant black opaque minerals. It appears to have originated chiefly during planar deposition, and it indicates the orientation of the depositing current but not its direction of flow. Numerous current lineations are shown on plate 7. All the

FIGURE 30.—Festoon bedding in upper sandstone unit of the Salt Wash Member of the Morrison Formation, at the Cougar mine, sec. 23, T. 44 N., R. 19 W. Almost no truncation of individual thin beds is evident within the set; current lineation parallels the axis of the trough (alined with pocket knife) and is evident near the edges of the trough. The point of the knife indicates direction of paleocurrent flow.

mapped current lineations in the Morrison Formation, most of which are in the Salt Wash, are plotted in figure 33, which shows them to be oriented dominantly northeasterly to southeasterly as interpreted on the basis of measurements of directional structures. At one place in the upper unit at the Cougar mine a well-formed southward-plunging festoon bedding set shows current lineations parallel to the trough axis of the festoon set (fig. 30).

Fossil logs are commonly considered to lie parallel to the current direction of the depositing stream (Fischer, 1942, p. 381, 387), but some lie nearly at right angles to the current direction. Most fossil logs where they are abundant in the upper unit of the Salt Wash appear to lie dominantly parallel to the current direction (pl. 9).

Current ripple marks are sparse and poorly preserved in the Salt Wash Member, and by themselves do not adequately show the direction of sediment transport. A few mapped in underground workings appear to have their trough axes roughly normal to other sedimentary structures (pl. 9).

Carbonaceous material

Carbonaceous material (coalified and charcoallike plant fragments) is locally abundant in the sandstone. It is most abundant and widely distributed in the upper unit of the Salt Wash, and it occurs only in light-gray or light-buff sandstone in isolated and irregular areas throughout the Slick Rock district. The fragments of carbonized plants range in size from minute flakes to large tree trunks 3 feet in diameter and several tens of feet long. Locally, mudstone particles and carbonaceous material are concentrated in pockets in the sandstone. These pockets commonly are referred to as "trashy" zones. In some places in the Salt Wash, woody material was silicified or replaced by carbonate, even where carbonized material lies nearby. Possibly some of the woody material was replaced before it could become carbonized.

As Fischer (1942, p. 381) pointed out, most fossil logs appear to have drifted into place, but some have root systems enclosed in clay which was probably the soil in which the trees grew, and these could not have moved far from their site of origin. One small tree was observed apparently in its position of growth buried in a sandstone layer of the middle unit of the Salt Wash at the Strawberry Roan mine, Bishop Canyon (fig. 34). Although much of the carbonaceous material was moved at least locally to its position of deposition, some lies close to or at its site of origin.

Some carbonaceous material may have been redistributed, perhaps as a fluid derived from woody material, after the sediments were deposited. For example, asphaltitelike material with a density of 1.1 occurs in a vein 2 inches thick and a few feet long adjacent to a flattened carbonized log in the upper part of the Salt Wash at the Mary Ellen mine in the Dolores River Canyon northwest of Joe Davis Hill.

Structures in carbonized plant fragments are poorly preserved and few plants from the Salt Wash have been identified. However, a few specimens of silicified and calcified wood have been identified as *Auricarioxylin* by R. S. Scott of the Geological Survey (written commun., 1957).

Some fossilized vertebrate remains are known in the Salt Wash. In the Slick Rock district only single bones and fragments have been found, and none have been identified. These occur chiefly in sandstone where carbonized wood is abundant and are generally either carbonized or replaced by calcite and silica.

MUDSTONE

The mudstone in the Salt Wash Member consists of clays containing chiefly quartz detritus. The mudstone

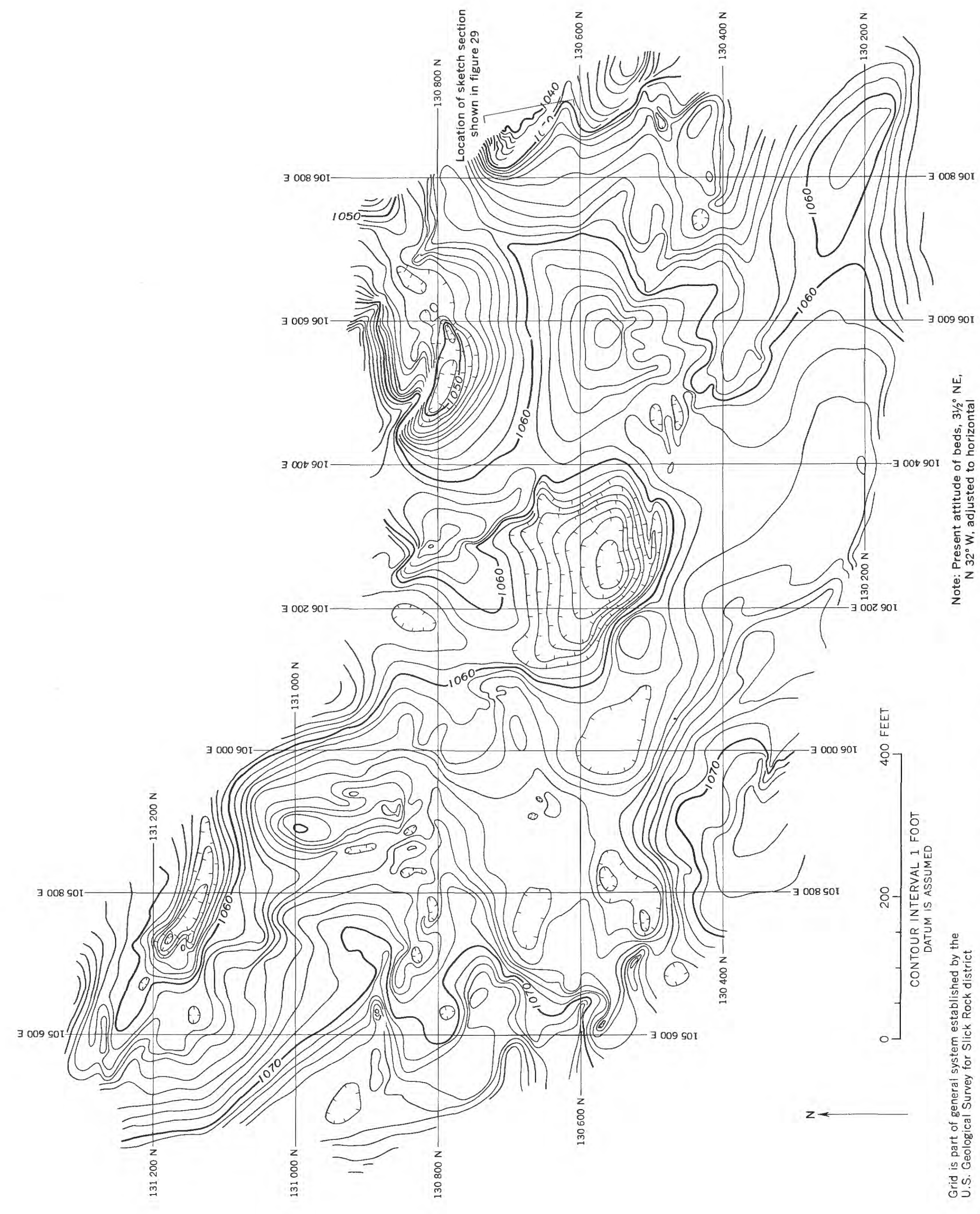

FIGURE 31.—Map showing configuration of surface prior to deposition of the ore-bearing sandstone of the Salt Wash Member of the Morrison Formation, Cougar mine area.

strata generally lack fissility and for the most part include a large proportion of rock that is properly termed siltstone and sandy siltstone. Quartz is probably the dominant component of these rocks, as both microscopically discernible detritus and clay-size detritus, but feldspar detritus is common. The carbonate content has a wide range. The clay minerals are mainly

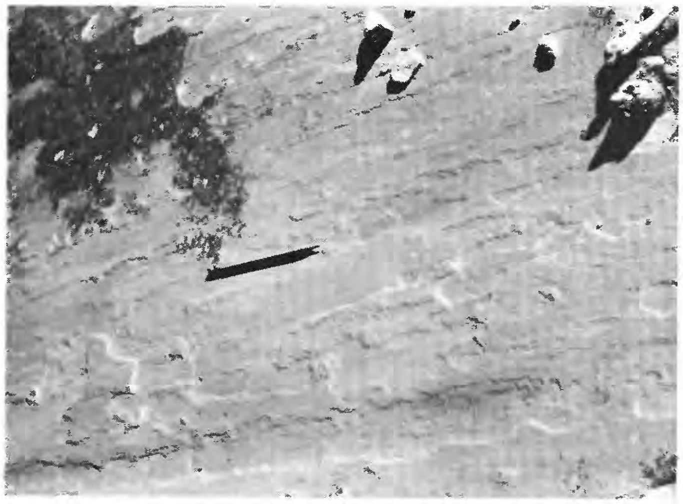

FIGURE 32.—Current lineation in horizontally bedded sandstone of the Salt Wash Member of the Morrison Formation, Slick Rock district. Pencil is parallel to lineation, which is manifested by longitudinal streaking of sand grains.

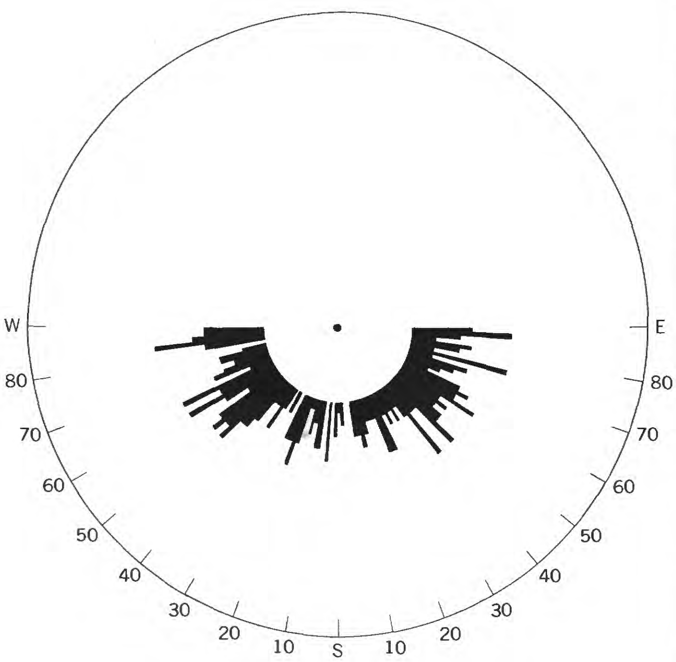

FIGURE 33.—Orientation of current lineations in the Morrison Formation. Each unit represents one lineation. Area covered is shown on plate 7.

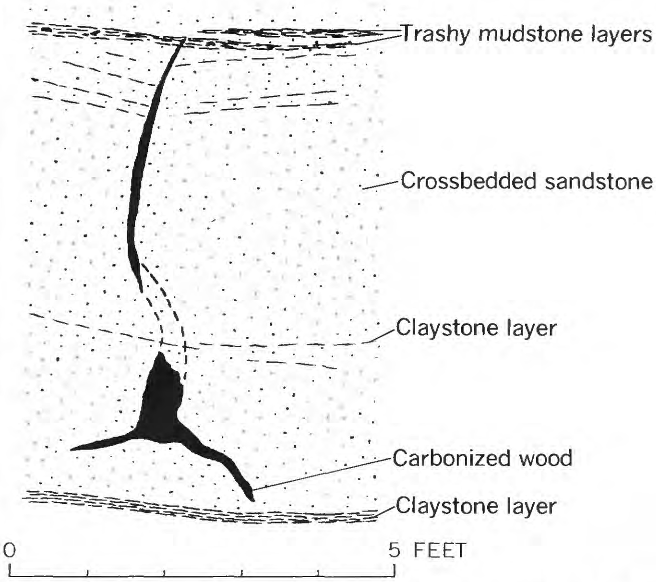

FIGURE 34.—Carbonized tree trunk buried in sandstone of the middle unit of the Salt Wash Member of the Morrison Formation, Strawberry Roan mine; dashed lines show projection of trunk behind face of mine working. Trunk appears to rise from root system in the position of growth.

nonswelling varieties, probably hydrous mica and kaolinite, according to data by A. D. Weeks (in Waters and Granger, 1953, p. 4) and Keller (1962, pl. 1). Numerous discontinuous layers of tightly cemented, very fine-grained to fine-grained sandstone as much as several feet thick occur within the mudstone. Locally, light-red to light-gray limestone and limy clay nodules as much as several inches in diameter are strung out along bedding planes or form irregular vertical layers, possibly along joints. In some places veins of fibrous calcite and much more rarely gypsum, generally less than 1 inch thick, occur along bedding planes and in small cross fractures in the mudstone. Mudstone in the Salt Wash is generally reddish brown with minor greenish-gray mottling, but it is greenish gray within and adjacent to the ore-bearing sandstone in the vicinity of uranium-vanadium deposits. Some layers within mudstone, generally not more than a few feet thick, appear to be almost wholly claystone. As seen in fresh exposures, the more clay-rich parts of mudstone commonly contain numerous small, irregular slickensided surfaces which probably formed during compaction and lithification of the muds, or perhaps during slumping when the muds were unconsolidated.

LOWER UNIT

The lower unit consists of the thickest, most prominent sandstone layer in the Salt Wash. This unit is complexly divided by thin, discontinuous mudstone strata. Commonly the basal part has a marked division into three laterally discontinuous sandstone strata; as such it forms a prominent cliff consisting of three nearly vertical faces separated by narrow benches at thin mudstone strata (fig. 28). The lower unit is especially thick and clearly defined between Bush and Morrison Canyons, and between Morrison and Bell Canyons as shown on section B–B′–B″ of plate 7. In the Slick Rock district the basal part of the Salt Wash contains only one or two known small uranium-vanadium deposits, although in other districts in the Uravan mineral belt it contains some large ore deposits.

Part of the sandstone of the lower unit is crossbedded, displaying torrential (incline) type crossbeds as well as festoon-type crossbeds. Most crossbedding is low angle and in places appears to be continuous with both horizontally bedded and structureless sandstone. Horizontally bedded sandstone also seems to be abundant throughout most of the lower unit. Sandstone in the bottom unit of the Salt Wash commonly contains light-colored, generally white, chalky coarse-grained angular detritus that is probably chiefly chert but may include altered feldspars. In rare places coarse-grained particles form granule conglomerate.

The contact of the lower unit of the Salt Wash with the underlying Summerville Formation is a disconformity marked by channel scours (fig. 35). Evenly bedded marine (?) strata of the Summerville give way to scour-and-fill fluvial beds of the Salt Wash. Some

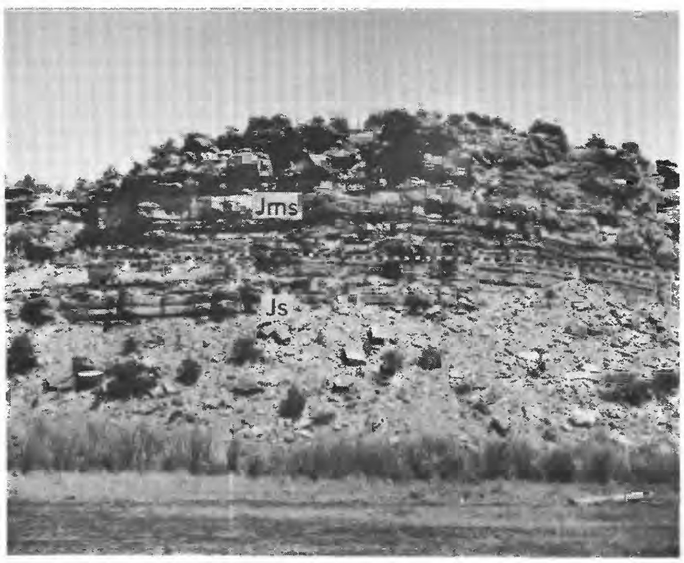

FIGURE 35.—Upper part of the Summerville Formation (Js) and lower part of the Salt Wash Member of the Morrison Formation (Jms). Note the irregular channeled contact; S½ SE¼ sec. 24, T. 44 N., R. 19 W.

workers have felt that the contact is marked by a zone of limy nodules and lenses which occurs a few feet to a few tens of feet below the lowest channeling sandstone of the Salt Wash (L.C. Craig and R. A. Cadigan, oral communs., 1957). In the Slick Rock district this limy zone is present only locally, and where it does occur it is commonly covered. The contact at the base of the lowest fluvial sandstone in the Salt Wash is a gently to sharply undulating surface that is generally well exposed and easily recognized in outcrops. This contact, however, is not easily identified in drill cores.

Some interfingering of the lower unit of the Salt Wash with the Summerville may exist, for in a few places, such as in the N½SW¼ sec. 24, T. 44 N., R. 19 W. (pl. 7), channeled sandstone lenses of typical Salt Wash appear to lie in horizontally bedded argillaceous rocks near the top of the Summerville.

The following sections of the lower unit of the Salt Wash Member are probably typical of the unit in four widely separated parts of the Slick Rock district and show the local variations characteristic of the unit.

Section of lower unit of the Salt Wash Member in Big Canyon, secs. 22 and 23, T. 41 N., R. 18 W.

[Measured by G. C. Simmons and N. L. Archbold, September 1956]

	Thickness (feet)
Lower unit:	
9. Sandstone, light-reddish-brown, very fine grained; abundant black opaque minerals; trace of limonite spots; a few thin reddish-brown mudstone layers	5
8. Sandstone, gray, fine-grained; moderate amount of dark minerals and limonite spots, abundant light-colored chert and altered feldspars, and abundant greenish-gray mudstone pebbles in the lower foot	27
7. Mudstone, reddish-brown, poorly exposed	12
6. Sandstone, gray to very light brown, medium-fine-grained; abundant interstitial calcite; abundant dark minerals; trace of limonite spots	12
5. Mudstone and siltstone; reddish-brown with moderate greenish-gray mottling; contains sandstone beds as much as 6 in. thick	10
4. Sandstone, gray, fine- to medium-fine-grained; abundant dark minerals; trace of interstitial greenish-gray clay	9
3. Mudstone, reddish-brown; grading upward into greenish gray	2
2. Sandstone, gray, fine-grained; abundant interstitial calcite; abundant dark minerals; contains numerous thin reddish-brown mudstone layers	16
1. Sandstone, light-brown, fine-grained; abundant interstitial calcite, abundant limonite spots; a greenish-gray mudstone layer 1 ft thick lies 20 ft above the base	28
Total lower unit	121

Section of lower unit of Salt Wash Member at the Horseshoe Bend of the Dolores River Canyon, sec. 31, T. 43 N., R. 17 W., and sec. 6, T. 42 N., R. 17 W.

[Measured by L. C. Craig and J. D. Ryan, July 1949. Designated lower unit by the present authors]

	Thickness (feet)
Lower unit:	
7. Sandstone, pinkish-gray, light-brown weathering, medium-fine- to fine-grained; of subangular clear quartz with pink and black accessories; channeled and cross laminated	14
6. Poorly exposed; reddish soil suggests red sandy claystone	11
5. Sandstone, pinkish-gray, white- to pale-brown-weathering, medium-fine- to fine-grained; of subangular clear quartz with numerous pink and black accessories; channeled and cross laminated	10
4. Claystone, dark-reddish-brown (10*R* 3/4), slightly silty; shaly weathering	4
3. Not exposed	4
2. Sandstone; similar to that below, becoming medium fine grained near the top	22
1. Sandstone, pinkish-gray (5*YR* 8/1), light-brown-weathering; predominantly fine grained; highly calcareous; of subangular clear quartz with minor pink, red, and black accessories; channeled and cross laminated	21
Total lower unit	86

Section of lower unit of Salt Wash Member near the head of Stevens Canyon, sec. 32, T. 44 N., R. 19 W.

[Measured by G. C. Simmons and N. L. Archbold, Sept. 12, 1956]

	Thickness (feet)
Lower unit:	
9. Sandstone, light-reddish-brown, medium-fine-grained; abundant black opaque minerals	24
8. Mudstone, reddish-brown	5
7. Sandstone, reddish-brown, fine-grained; abundant black opaque minerals, sparse limonite spots, sparse light-colored chert and altered feldspars	8
6. Sandstone, reddish-brown, fine-grained; very abundant calcite nodules and limonite spots, abundant light-colored chert and altered feldspars, moderate amount of black opaque minerals; a thin mudstone layer lies at the base	12
5. Sandstone, light-yellowish-brown, medium-fine-grained	14
4. Mudstone and siltstone, reddish-brown	8
3. Sandstone, reddish-gray, medium-fine- to medium-grained; sparse black opaque minerals, abundant light-colored chert and altered feldspars, moderate number of limonite spots, a few pebbles of reddish-brown mudstone	9
2. Mudstone and siltstone, reddish-brown	9
1. Sandstone, light-reddish-brown, fine-grained; moderate amount of black opaque minerals and flakes of reddish-brown mudstone	19
Total lower unit	108

282-180 O—68——5

Section of lower unit of Salt Wash Member on north side of McIntyre Canyon, SW¼ sec. 1, NW¼ sec. 12, T. 44 N., R. 20 W.

[Measured by L. C. Craig and V. L. Freeman, 1950. Designated lower unit by the present authors]

	Thickness (feet)
Lower unit:	
8. Sandstone, white to very pale orange, with minor moderate-orange-pink and yellowish-gray, medium-fine-grained; of subangular to subrounded clear quartz with common white, pink, and gray accessories; channeled; cross laminated	32
7. Covered; probably includes some reddish-brown claystone	22
6. Sandstone, white to grayish-orange-pink to very pale orange, medium-fine- to medium-grained; of subangular to subrounded clear quartz with abundant white angular and common varicolored accessories; channeled; cross laminated	15
5. Claystone, pale-reddish-brown to dark-reddish-brown, slightly silty to fine-grained sandy; shaly to earthy weathering; moderate-reddish-orange very fine-grained to fine-grained slabby weathering sandstone; chlorite flakes in places	10
4. Sandstone, white to grayish-orange-pink to very pale orange, medium-fine- to medium-grained; of subangular to subrounded clear quartz with abundant white angular and common varicolored accessories; contains local lenses of white angular chert and altered feldspars up to granule size; channeled; cross laminated; forms a small ledge	10
3. Sandstone and claystone, interbedded; similar to basal part but sandstone layers are thinner and claystone is more abundant	5
2. Sandstone, moderate-orange-pink to pale-red, medium-fine- to fine-grained; of clear and amber-stained quartz with common to abundant black, pink, red, green, and orange accessories; channeled; fine-scale cross laminated; forms a small massive ledge	9
1. Sandstone, moderate-reddish-orange, dominantly fine-grained; in a few places medium fine grained; of subangular clear quartz with some varicolored accessories; minor interlayered pale-reddish-brown very fine grained sandy claystone; beds are lensing; sandstone forms massive rounded ledges	5
Total lower unit	108

MIDDLE UNIT

The middle unit of the Salt Wash Member is composed of discontinuous lenses of sandstone as much as 60 feet thick and from a few hundred feet to a few miles long interbedded with thick mudstone strata as much as 80 feet thick (pl. 7). Proportions of mudstone to sandstone range commonly between 2 to 1 and 5 to 1. In many places sandstone and mudstone strata in the middle unit merge laterally into the lower unit or into

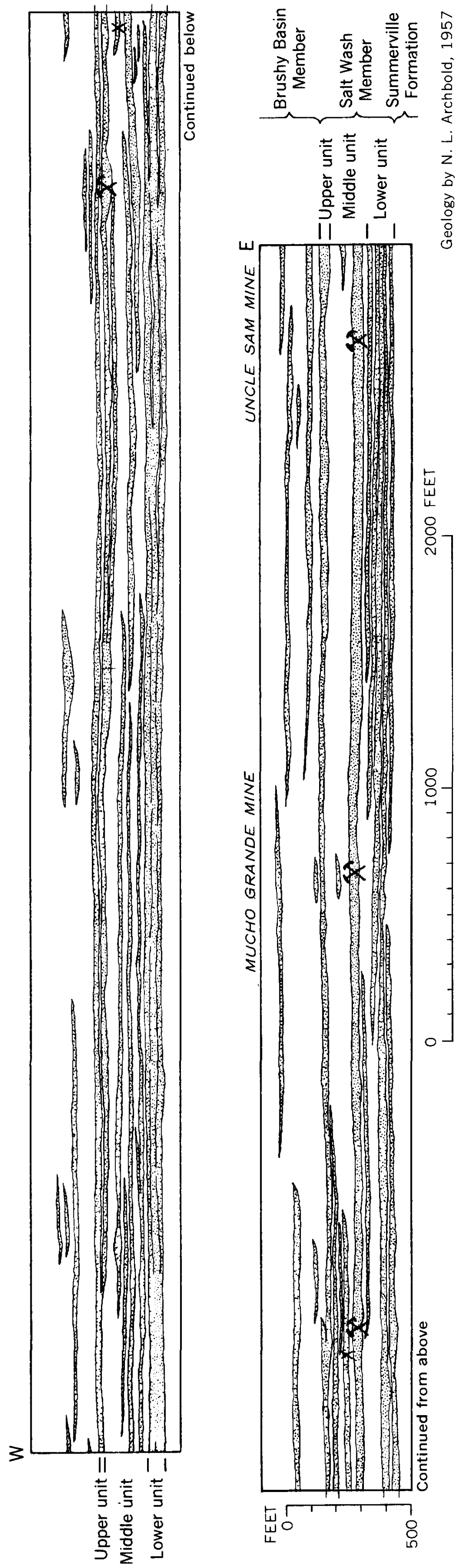

FIGURE 36.—Diagrammatic section of the Salt Wash and lower part of the Brushy Basin Members of the Morrison Formation showing intertonguing of the members and of the units in the Salt Wash Member on the north rim of the Dolores River Canyon, sec. 6, T. 42 N., R. 17 W., and secs. 1 and 2, T. 42 N., R. 18 W. Stippled pattern is sandstone, unpatterned is mudstone. Positions of mines are indicated by crossed picks, prospects by X. Scales are approximate.

the upper unit (fig. 36). Minor uranium-vanadium production in the Slick Rock district and other districts of the Uravan mineral belt has come from the middle unit of the Salt Wash Member where more persistent sandstone lenses are thickest.

Sandstone in the middle unit is similar to that in the lower unit except that it contains much less light-colored coarse-grained angular detritus. The areal distribution of colors in the middle unit throughout the district is similar to that in the lower unit. Mudstone of the middle unit in which the sandstone strata occur contains an appreciable amount of thin and horizontally bedded claystone, argillaceous siltstone, and argillaceous sandstone. In places these show crossbedding on a minute scale, probably the same type of structure termed "ripple cross-lamination" by McKee (1939). Complete gradations between claystone and siltstone, and claystone and sandstone, characterize the middle unit. Some parts of the unit that have been called mudstone may in reality contain more than 50 percent silt- or sand-size detritus and properly should be called argillaceous siltstone or sandstone, but the deep color imparted to the rock by abundant interstitial reddish-brown clay makes it appear similar to the more abundant mudstone. The dominant color of the mudstone is reddish brown, but parts are mottled or interlayered with greenish-gray mudstone.

The following stratigraphic sections of the middle unit measured in four widely separated parts of the Slick Rock district are typical of the unit in those areas and show the variation that characterizes the unit throughout the district.

Section of middle unit of Salt Wash Member in Big Canyon, secs. 22 and 23, T. 41 N., R. 18 W.

[Measured by G. C. Simmons and N. L. Archbold, September 1956]

Middle unit:	*Thickness (feet)*
5. Mudstone, reddish-brown; sparsely mottled with greenish gray; poorly exposed at the top	41
4. Sandstone, light-gray, fine- to medium-fine-grained; abundant altered feldspars, abundant limonite spots, sparse dark minerals, sparse flakes of greenish-gray clay; contains a greenish-gray mudstone layer 1 ft thick 18 ft above the base	58
3. Mudstone, reddish-brown; poorly exposed	42
2. Sandstone, light-reddish-brown, fine-grained; abundant black opaque minerals and limonite spots	17
1. Mudstone, reddish-brown; poorly exposed in lower 35 ft	41
Total middle unit	199

Section of middle unit of Salt Wash Member at the Horseshoe Bend of the Dolores River Canyon, sec. 31, T. 43 N., R. 17 W., and sec. 6, T. 42 N., R. 17 W.

[Measured by L. C. Craig and J. D. Ryan, July 1949. Designated middle unit by the present authors]

Middle unit:	*Thickness (feet)*
5. Siltstone and claystone, red; contains a few beds of red and gray very fine grained to fine-grained sandstone; poorly exposed	66
4. Sandstone, light-gray to grayish-pink, medium-fine- to fine-grained; of subangular clear quartz with abundant varicolored accessories; channeled; cross laminated to ripple laminated	20
3. Claystone, grayish-red and light-greenish-gray, silty; interbedded with greenish to grayish orange-pink very fine-grained to fine-grained slabby bedded sandstone; poorly exposed	26
2. Sandstone, white to very light gray, pale-brown weathering, predominantly medium fine grained; of subangular clear quartz with minor orange to pink and black accessories; channeled and cross laminated	29
1. Claystone, pale-reddish-brown and pale-greenish-yellow, silty; poorly exposed	22
Total middle unit	163

Section of middle unit of Salt Wash Member near the head of Stevens Canyon, sec. 32, T. 44 N., R. 19 W.

[Measured by G. C. Simmons and N. L. Archbold, Sept. 12, 1956]

Middle unit:	*Thickness (feet)*
6. Sandstone, reddish-brown and gray, fine-grained; minor black opaque minerals, altered feldspars, limonite spots, interstitial clay; contains abundant thin mudstone layers	21
5. Mudstone, reddish-brown	30
4. Sandstone, reddish-brown, very fine grained; abundant interstitial clay; thin bedded	5
3. Mudstone, reddish-brown	10
2. Sandstone, light-reddish-brown, fine-grained; minor black opaque minerals; contains abundant thin layers of reddish-brown mudstone	7
1. Mudstone, reddish-brown	22
Total middle unit	95

Section of middle unit of Salt Wash Member on the north side of McIntyre Canyon, SW¼ sec. 1, NW¼ sec. 12, T. 44 N., R. 20 W.

[Measured by L. C. Craig and V. L. Freeman, 1950. Designated middle unit by the present authors]

Middle unit:	*Thickness (feet)*
2. Claystone, grayish-red (10*R* 6/2) to pale-reddish-brown, slightly silty to fine grained sandy; earthy weathering; thinly interbedded with an equal amount of pale-red (10*R* 4/2), brownish-weathering very fine grained to fine-grained massive to ripple laminated sandstone of clear quartz, with abundant varicolored accessories, that forms slabby ledges; laterally the sandstone forms a thick lenticular body	103
1. Not exposed; probably reddish-brown mudstone	32
Total middle unit	135

UPPER UNIT, OR ORE-BEARING SANDSTONE

The upper unit of the Salt Wash Member, the ore-bearing sandstone, consists of a persistent stratum made up of numerous juxtaposed sandstone lenses. In some places it is a single massive unit and in others it occurs as two or three sandstone strata separated by mudstone strata as much as 15 feet thick. In places sandstone lenses that are laterally continuous with the main body of the upper unit at the bottom or at the top of the unit tongue out in mudstone. Such "splitting off" of parts of the upper unit in places where exposures are poor or where drill hole data are inadequate locally makes delineation of the unit difficult. Plate 7 (including geologic sections *A–A″* and *B–B′–B″*), figure 36, and plate 10 make clear the continuity of the upper unit but also show the intertonguing character of the bottom and top of the unit.

Crossbedding and scour-and-fill structures are more marked in the ore-bearing sandstone than in other parts of the Salt Wash. Even so, horizontally bedded sandstone with numerous current lineations is common in the upper unit.

The lateral persistence of the ore-bearing sandstone throughout the Slick Rock district belies its extreme complexity. A geologic cross section compiled from a line of 27 diamond-drill holes which extends about 3,800 feet through the Easton B group of the Charles T area, shown in plate 11, demonstrates the rapid lateral changes in the unit resulting from intertonguing and "splitting" of sandstone. In a few places scouring and filling in the upper unit was so extensive that beds at the top of the unit are older than beds at the base of the unit just a few hundred feet away. South of Tailholt Canyon, in SW¼ sec. 27, T. 44 N., R. 19 W., two principal sandstone layers originally made up the upper unit. The whole unit later was swept away completely in places and replaced by additional sand layers of similar total thickness. Finally, the upper part of these later layers was swept away locally and replaced by a still younger sand layer. The order of deposition of the different parts of the unit is evident from figure 37.

Carbonaceous material in the ore-bearing sandstone, though not ubiquitous, is abundant and widely distributed in contrast to that in sandstone in the middle and lower units of the Salt Wash Member and in the overlying Brushy Basin Member, which is sparse and only locally present. Wherever found, it is in light-buff or light-gray sandstone; in virtually no place is it in light-reddish-brown sandstone. In many places the ore-bearing sandstone is light buff or light gray in its lower part and light reddish brown above, perhaps reflecting a common tendency for carbonaceous material to be abundant in the lower part of the ore-bearing sandstone and absent in the upper part. Carbonaceous material is present in almost all light-buff and light-gray ore-bearing sandstone within the area of the detailed map of the Morrison Formation (pl. 7). Even within this area, however, ore-bearing sandstone in smaller patches as much as a mile across is devoid of visible carbonaceous material, as determined from diamond-drill cores. Outside the area of the detailed map, the ore-bearing sandstone is mostly devoid of carbonaceous material except locally west and southwest of Egnar, northwest of Horse Range Mesa, in the northwestern part of Disappointment Valley, and in scattered patches elsewhere; some of these areas are as much as several miles across.

Mudstone and claystone in the ore-bearing sandstone appear to be similar in most respects to those in the underlying middle unit of the Salt Wash. But according to the data of Archbold (1959, figs. 3, 5), mudstone collected from the ore-bearing sandstone contains appreciably less calcite than does mudstone from the middle unit of the Salt Wash. According to Keller (1959, p. 118) two samples of mudstone from an unmineralized part of the ore-bearing sandstone collected in the Lower Group area near the town of Slick Rock contain hydrous mica as the only determinable clay mineral.

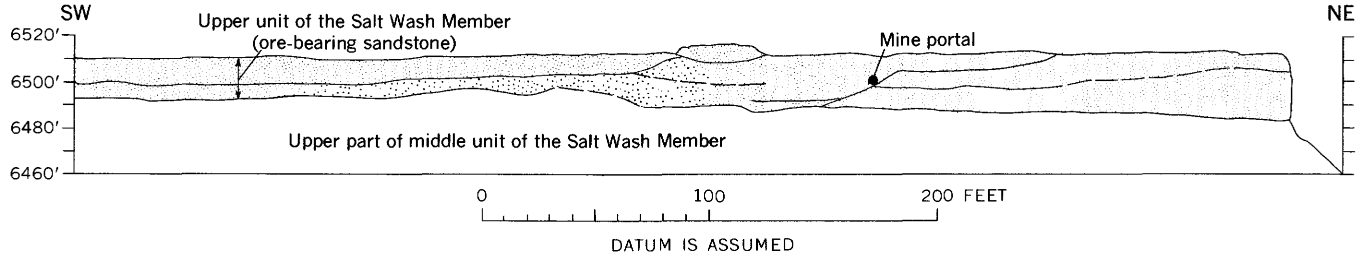

FIGURE 37.—Diagrammatic section of the ore-bearing sandstone showing lateral differences in age of sandstone layers. South of Tailholt Canyon, SW¼ sec. 27, T. 44 N., R. 19 W. Light stipple is light-buff sandstone; dark stipple is light-reddish-brown sandstone. Older layers are to the right.

The amount of carbonaceus material in mudstone and claystone in the ore-bearing sandstone commonly reflects the amount in the adjacent sandstone.

The contact of the ore-bearing sandstone with the underlying middle unit of the Salt Wash is generally an erosional contact marked by extensive channel scouring, but, as indicated in figure 36 and on plate 11, it is locally intertonguing. Tongues of sandstone overlie erosional surfaces and thus emphasize the ubiquity of scour and fill effects; none of the erosional surfaces can represent a significant time interval. Many sandstone tongues are merely lenses, enclosed in mudstone at one side and abutting sandstone at the other side.

Although the following stratigraphic sections of the upper unit were measured in four widely separated parts of the district, they might have been measured within a few hundred feet of each other, so complex and variable is the upper unit in detail.

Section in Big Canyon, secs. 22 and 23, T. 41 N., R. 18 W.

[Measured by G. C. Simmons and N. L. Archbold, September 1956]

Upper unit:	Thickness (feet)
1. Sandstone, gray, fine- to medium-fine-grained; minor dark accessories, altered feldspars, limonite spots, and interstitial calcite	24
Total upper unit	24

Section measured at the Horseshoe Bend of the Dolores River Canyon, sec. 31, T. 43 N., R. 17 W., and sec. 6, T. 42 N., R. 17 W.

[Measured by L. C. Craig and J. D. Ryan, July 1949. Designated upper unit by the present authors]

Upper unit:	Thickness (feet)
2. Sandstone, light-gray, fine-grained; composition as below; in slabby structureless ledges as much as 1 ft. thick	5
1. Sandstone, light-gray to white, light-brown- to pale-yellow-weathering, medium-fine- to medium-grained; of clear rounded to subangular quartz with minor varicolored accessories and white chert	41
Total upper unit	46

Section near the head of Stevens Canyon, sec. 32, T. 44 N., R. 19 W.

[Measured by G. C. Simmons and N. L. Archbold, Sept. 12, 1956]

Upper unit:	Thickness (feet)
3. Sandstone, grayish-red, fine-grained; minor black opaque minerals, altered feldspars, limonite spots, interstitial clay	2
2. Sandstone, grayish-red, fine-grained; abundant interstitial clay; poorly exposed	9
1. Sandstone, gray, fine-grained; minor dark acessories, altered feldspars, limonite spots, interstitial clay; contains a few thin red mudstone layers	64
Total upper unit	75

Section on the north side of McIntyre Canyon, SW¼ sec. 1, NW¼ sec. 12, T. 44 N., R. 20 W.

[Measured by L. C. Craig and V. L. Freeman, June 1950. Designated upper unit by the present authors]

Upper unit:	Thickness (feet)
3. Sandstone, white to grayish-orange-pink (10*R* 8/2), weathers white, fine- to medium-fine-grained; of clear subangular quartz with common to abundant white, red, pink, orange, green, and gray accessories; channeled; cross laminated	15
2. Claystone and minor sandstone (30 percent); claystone, grayish red (10*R* 4/2 below and 5*R* 4/2 above), silty to very fine grained sandy, earthy weathering; sandstone, light greenish gray to moderate reddish orange, very fine to fine grained; of clear subangular quartz with abundant colored accessories; slabby; one sandstone layer contains pebbles of limestone as much as ½ in. in diameter	21
1. Sandstone, white to very pale orange, very light brown weathering, fine- to medium-grained; of clear subangular partly overgrown quartz, with common white, orange to pink, and gray accessories; channeled; cross laminated; contains rare beds with worm borings(?); forms prominent continuous ledge	52
Total upper unit	88

SURFACE DISTRIBUTION AND CONFIGURATION

The Salt Wash Member crops out over much of a broad area on the crest and northeast limb of the Dolores anticline and in an area southeast of Island Mesa. It appears in a narrow strip along the northeast edge of the district and in narrow sinuous strips on either side of the Dolores River Canyon and at the southeast edge of the district along Narraguinnep Canyon (pl. 1).

In the district the thickness of the Salt Wash is related to the major folds (fig. 38) and ranges from about 275 feet along the crest of the Dolores anticline to about 400 feet near the axis of the Disappointment syncline. The lower unit appears to be thickest (130–140 ft) in the Disappointment Valley area, thinnest (60–100 ft) in an area from the Horseshoe Bend of the Dolores River northwestward to McIntyre Canyon, and intermediately thick (about 120 ft) in the vicinity of Big Canyon. It therefore appears to be thinnest in the axial region of the Dolores anticline. The middle unit is thinnest (100–120 ft) near and southwest of the town of Slick Rock and is thicker (130–200 ft) peripheral to this area. The area of thinnest middle unit corresponds to only a segment of the axial region of the Dolores anticline. The upper unit varies in thickness erratically and abruptly throughout the district. It is perhaps most consistently thick (40–100 ft) in most of the Disappointment Valley area, in the vicinity of Summit Canyon, and west of Egnar. Thicker parts of the ore-bearing sandstone appear to have elongate and sinuous configurations in plan and probably represent areas of the more persistent stream courses. Some locally abrupt changes in thickness of each unit are a result of intertonguing and do not appear to be associated with the main structures in the district.

BRUSHY BASIN MEMBER

The Brushy Basin Shale Member was named by Gregory (1938, p. 59) for exposures in Brushy Basin, west of Blanding, Utah. The Brushy Basin in the Slick Rock district is rather similar to that in the type area.

The member is expressed topographically as a steep slope underlain by mudstone and broken by a few benches where sandstone and conglomeratic sandstone lenses crop out. Best exposures of the Brushy Basin are found at lower elevations in the northern part of the district (pl. 7) where, because of more arid conditions, soil is thinner and vegetation is sparser than elsewhere in the district.

LITHOLOGY

The Brushy Basin Member in the district consists dominantly of variegated bentonitic mudstone containing interbedded sandstone and conglomeratic sandstone lenses, more numerous in the lower part than in the upper part of the member. Mudstone makes up about three-fourths of the member, but the proportion of mudstone to sandstone and conglomerate ranges from less than 2 to 1 to nearly 100 percent mudstone. The mudstone strata are evenly bedded, similar to floodplain-type layers in the underlying Salt Wash Member. Sandstone lenses are chiefly crossbedded and fill channel scours like the fluvial or channel-type lenses in the Salt Wash. Limestone beds and nodules as much as a foot thick occur at many levels in the member but appear to be most abundant in the middle part.

Carbonaceous material is present but not abundant in the Brushy Basin Member, and occurs principally in sandstone and conglomeratic sandstone lenses in the lower half of the unit. Carbonized plant remains are generally much smaller than those in the Salt Wash Member; large fossil tree trunks are not known in the district. Thin layers of carbonaceous mudstone occur sparsely throughout the member. Silicified plant debris in the Brushy Basin is more abundant than in the Salt Wash.

Dinosaur bones are more common in the Brushy Basin Member than in the Salt Wash Member and along with silicified wood fragments are abundant in some horizons in the lower half of the member. One horizon about 100 feet above the base of the Brushy Basin, at the base of a sandstone layer about 20 feet below the top of hill 6102, SE¼ sec. 5, T. 43 N., R. 18 W. (location shown on pl. 1), contains some large fragments of dinosaur vertebrae and other bones. Other animal fossils are rare in the member. A gastropod collected from the drill core of hole DV–89, sec. 27, T. 44 N., R. 18 W., Disappointment Valley (location shown in fig. 2), about 160 feet above the base of the member, was identified by J. B. Reeside, Jr. (written commun., 1956), as "a species of *Gryaulus* commonly called *G. veternus* (Meek and Hayden)"; this fossil was associated with material identified as "probably stems of a characeous alga."

The Brushy Basin Member can be divided conveniently into three parts; not all are present everywhere in the district, but all are fairly well defined in most of the area of the detailed map of the Morrison Formation (pl. 7) and in the area of deep diamond drilling in western Disappointment Valley. The three units are not shown as such on plate 7 because the map was prepared primarily to show details of smaller rock units. The three parts of the Brushy Basin are evident principally on the basis of their dominant color, either reddish brown to brownish gray or greenish gray, and are therefore called here, in stratigraphic succession, the lower brown unit, the middle green unit, and the upper brown unit. The three units have generally distinctive lithologic characteristics that substantiate their division on the basis of color. Locally the upper brown unit has a greenish-gray zone at its top, in part lithologically distinct from the upper brown unit, which may be transitional into the overlying Burro Canyon Formation. The units of the Brushy Basin are shown in a geologic cross section (pl. 12) drawn through five diamond-drill holes in the western Disappointment Valley area.

MUDSTONE

Rocks described generally as mudstone in the Brushy Basin Member include a variety of types such as claystone, silty and sandy claystone, limy claystone, siliceous claystone, clayey siltstone, clayey and sandy siltstone, and limy siltstone. These rocks are in the main frothy weathering where they contain abundant swelling clay, hackly weathering where calcite rich, and shaly weathering where swelling clay and calcite are sparse. Siliceous parts, generally thin, weather out as resistant low ledges. The mudstone is generally poorly fissile or nonfissile. Mudstone described as a specific rock type indicates an argillaceous rock containing less than 50 percent silt or sand grains. Some parts called mudstone may contain more than 50 percent silt- or sand-size detritus, but the color imparted to the rock by abundant interstitial clay makes it look similar to the more prevalent mudstone.

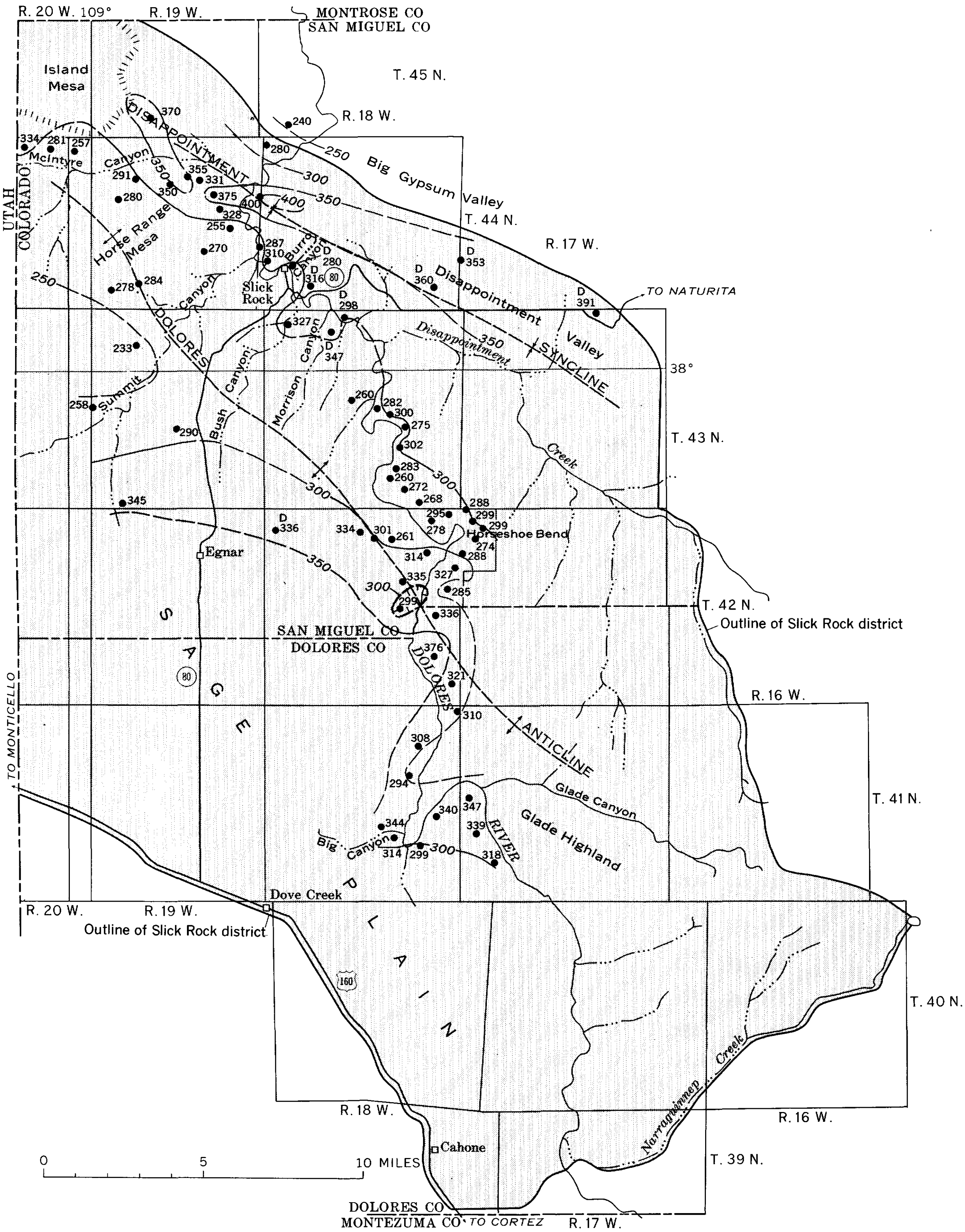

FIGURE 38.—Thickness of the Salt Wash Member of the Morrison Formation. Isopachs dashed where uncertain; interval 50 feet. Number by control point (dot) is measured thickness, in feet, of the Salt Wash Member. Diamond-drill holes indicated by D; other control points are surface sections.

The mudstone is dominantly reddish brown, brownish gray, and greenish gray, but a great variety of colors characterizes the Brushy Basin, and seemingly all gradations of these colors may occur within a few feet stratigraphically. Color layering and mottling both are common.

Horizontally bedded and thinly laminated mudstone is predominant in the Brushy Basin although some parts show mashed and fragmented beds and laminae, probably a result of slumping when the strata were still unconsolidated. Crossbedding on a small scale is evident in silty and sandy parts in a few places; some is typical of scour-and-fill structures, and some is probably equivalent to the "ripple cross lamination" of McKee (1939).

Clay in the mudstone is chiefly montmorillonite, although kaolinite and hydrous mica are also present and probably abundant locally. (For example, see the data of Weeks, in Waters and Granger, 1953, and of Keller, 1962.) Calcite is the dominant carbonate, but dolomite and siderite occur locally. Calcite content shows a wide range, from almost none to more than half of the rock. Calcite-rich types grade into limestone. Detrital grains, which make up less than 50 percent of the mudstone, are poorly sorted, silt to coarse-sand size, and sharply angular to well rounded.

The abundance of shard structures in clay, the sharply angular fragments of detrital minerals, and the fairly high plagioclase content of the mudstone leave little doubt that much of the Brushy Basin mudstone is of volcanic origin and that it was deposited as ash falls or in streams or lakes and on flood plains as mixtures of airborne volcanic material and waterborne sediment.

SANDSTONE AND CONGLOMERATE

Sandstone in the Brushy Basin Member ranges from very fine grained to coarse-grained and is conglomeratic and quartzose with detrital particles, mainly subrounded to angular. The sandstone typically is crossbedded in lenses as much as 50 feet thick and perhaps a mile across, though commonly smaller, and shows the scour-and-fill structures of fluvial deposits. Some thin strata of very fine grained clayey and silty sandstone are evenly bedded to massive and structureless and probably were deposited in quiet water; these appear to be laterally more extensive than the crossbedded lenses. Sandstone in the member shows a wide range in cementation; in different places it is porous, moderately cemented, and tightly cemented with clay, carbonate, or silica. Some thin layers of fine-grained sandstone are quartzitic and extremely hard; such layers have caused some trouble in drilling in the Disappointment Valley area.

The chief differences in composition between Brushy Basin sandstone and Salt Wash in the district are the lower quartz (including silica cement) content and higher plagioclase, rock fragment, calcite, clay, hematite, and chlorite contents of the Brushy Basin sandstone.

Conglomeratic sandstone and conglomerate are abundant in the Brushy Basin Member. Granules and pebbles, mostly chert, as much as 1½ inches in diameter, are red, green, gray, yellow, white, and black, but most commonly red and green, leading to the designation "Christmas tree" conglomerate for some of the more colorful rocks. Conglomeratic sandstone lenses of the Brushy Basin are commonly highly silicified for an inch or so where they are in contact with enclosing mudstone.

Sandstone, conglomeratic sandstone, and conglomerate in the Brushy Basin may be almost white, light gray, light brown, greenish gray, light red, or reddish brown. In general, the color varieties are distributed in accord with the overall color units already indicated.

In a study of the conglomeratic sandstone lenses in the lower part of the Brushy Basin Member near Slick Rock, Phoenix (1958, p. 407, 409; figs. 1, 4, 5) has shown that the dominant direction of sediment transport was easterly, based on a general easterly decrease in the size of pebbles, and was apparently along separated and well-defined channel systems about a quarter of a mile to half a mile wide, elongated in the direction of sediment transport. Craig and others (1955, p. 157) suggested a general southwesterly source for the Brushy Basin as a whole. Cadigan (1959, p. 22) indicated that material of volcanic origin in the Brushy Basin is most abundant in the northwestern part of the Colorado Plateau, which suggests a northwesterly source for the volcanic material.

The contact between the Brushy Basin Member and the underlying Salt Wash Member is conformable and in many places difficult to locate. We have not placed it in the same position as some earlier workers, for example Craig and others (1955), who used the base of a lensing conglomeratic sandstone containing red, green, and white chert pebbles as the basal contact of the member in western Colorado and eastern Utah. "Where the basal conglomerate is absent in western Colorado, the top of the uppermost scour-fill sandstone of the Salt

Wash member is used as the contact" (Craig and others, 1955, p. 156). Instead, we have used the top of the ore-bearing sandstone of the Salt Wash exclusively as the contact, chiefly because in this area it is a more persistent and recognizable horizon than that used by Craig and his coworkers. In drill cores the top of the ore-bearing sandstone is commonly the only recognizable contact. Although the base of the conglomeratic sandstone, where present, marks a more pronounced change from Salt Wash to Brushy Basin lithology, it is impractical to use in subsurface correlations. The local absence of a basal conglomeratic sandstone lens, together with the common tendency for individual lenses to occur at different stratigraphic horizons, also makes the top of the ore-bearing sandstone a more practical contact to locate in outcrops. The thickness of the stratigraphic interval between the contact we have selected and that of Craig and his coworkers is generally 10–40 feet.

LOWER BROWN UNIT

The lower brown unit, because of our choice for the position of the Salt Wash-Brushy Basin contact, is a transitional sequence of mudstone, sandstone, and conglomerate strata in which some of the lower sandstone layers have virtually the same lithology as the sandstone in the Salt Wash Member. Mudstone in this interval is likewise similar to Salt Wash mudstone in composition inasmuch as it contains less swelling clay than is general throughout the rest of the Brushy Basin. Mudstone to sandstone ratios in the unit are chiefly between 2 to 1 and 4 to 1. The unit is evident everywhere in the area of the detailed map of the Morrison Formation (pl. 7) where the lower part of the Brushy Basin is not mantled by surficial debris and likewise is present in most of the subsurface in the areas of diamond drilling for uranium-vanadium deposits (for example, pl. 12). In a few places near its base the unit contains small uranium-vanadium deposits in sandstone similar to the ore-bearing sandstone of the Salt Wash, a tongue of which extends into the base of the lower brown unit (pl. 13, *A–A′*). Sandstone in the lower brown unit is generally lenticular (pl. 13, *A–A′*). The upper boundary of the lower brown unit (not shown on pl. 13) lies near the horizon of the sandstone lens containing the Full Moon mines. Most of the lenses shown in section *A–A′* are light-buff to light-greenish-gray conglomeratic sandstone with chert granules, but a few near the base of the unit are light-reddish-brown sandstone similar to Salt Wash sandstone. Mudstone is virtually all reddish brown, except for selvages a few inches thick of greenish-gray mudstone around lenses of light-buff to light-greenish-gray conglomeratic sandstone.

Mudstone in the lower brown unit of the Brushy Basin probably contains more bentonitic clay (montmorillonite), recognized by its swelling properties, than does mudstone in the Salt Wash, and material of volcanic origin is probably present in appreciable amounts.

Fine-grained to very fine grained sandstone in the lower brown unit is similar to sandstone in the Salt Wash Member. The sandstone consists of poorly to moderately sorted chiefly angular to subrounded, but in part well-rounded, grains.

Conglomeratic sandstone and conglomerate lenses are abundant in the lower brown unit, especially near the top of the unit, and are lithologically similar to such rocks in the middle green unit. They are light reddish brown and light buff to light greenish gray.

Limestone nodules and strata perhaps as much as a foot thick occur in a few places in the lower brown unit.

Section of the lower brown unit of the Brushy Basin Member, near Slick Rock, sec. 30, T. 44 N., R. 18 W.

[Measured by L. C. Craig, November 1948. Designated lower brown unit by the present authors]

	Thickness (feet)
Lower brown unit:	
1. Claystone and sandstone interbedded. Claystone, dark-red, silty to very fine sandy; small amounts of greenish-gray claystone. Sandstone, light-greenish-gray (5GY 8/1), weathering light brownish gray, very fine-grained to fine-grained; composed of subangular clear quartz with numerous orange-red, pink and black accessory minerals; structureless, slabby, in 1- to 2-ft thick beds	46
Total lower brown unit	46

Section of the lower brown unit of the Brushy Basin Member from drill cores from diamond drill hole DVR–1 in Disappointment Valley, sec. 30, T. 43 N., R. 16 W.

[Measured by D. R. Shawe, June to November 1955]

	Thickness (feet)
Lower brown unit:	
4. Mudstone and siltstone, chiefly reddish brown; sandy in places; contains sparse to abundant calcite. Interval contains 0.6-ft limestone nodule 24 ft above base; 1-ft silicified light brownish-gray fine-grained sandstone 20 ft above base	27.0
3. Sandstone, light-reddish-brown to brownish-gray, very fine to fine-grained; contains sparse black opaque minerals, a moderate amount of red and green chert grains, a moderate amount of calcite, abundant interstitial reddish-brown and gray clay, and sparse flakes and pebbles of greenish-gray mudstone	5.9

Section of the lower brown unit of the Brushy Basin Member from drill cores from diamond drill hole DVR-1 in Disappointment Valley, sec. 30. T. 43 N., R. 16 W.—Continued

	Thickness (feet)
Lower brown unit—Continued	
2. Sandstone, very light brown, medium-grained; contains sparse black opaque minerals, abundant 15 ft above base; abundant red, green, dark-gray, and buff chert grains and pebbles in places, abundant altered feldspar in places, sparse interstitial light-gray clay, sparse greenish-gray clay flakes, no calcite. Interval contains carbonaceous mudstone seam 7 ft above base	16.6
1. Mudstone and siltstone, chiefly reddish brown, light greenish gray and light brownish gray in places; sandy in places; contains abundant to sparse calcite. Interval contains 2-ft-thick very light brown very fine grained quartzitic sandstone 49 ft above base and 5-ft-thick light-reddish-brown fine-grained sandstone with abundant interstitial reddish-brown clay and sparse black opaque minerals 23 ft above base	55.6
Total lower brown unit	105.1

MIDDLE GREEN UNIT

The middle green unit of the Brushy Basin Member is characterized by dominance of greenish-gray colors. It contains mudstone and sandstone in proportions ranging chiefly between 2 to 1 and 4 to 1. The unit generally has a higher proportion of conglomeratic sandstone and conglomerate than do underlying and overlying parts of the member. In addition it contains a large amount of material of volcanic origin; in this respect it is like the Brushy Basin as described by other workers (Hess, 1933, p. 463–464; Stokes, 1944; Waters and Granger, 1953; Craig and others, 1955, p. 156; Cadigan, 1959, p. 21–22). Even so, the coarser clastic parts of the unit, despite abundant evidence of volcanic material, are composed dominantly of material derived from the erosion of sedimentary rocks. The unit is not present everywhere in the district, but it is well defined between the Horseshoe and Muleshoe Bends of the Dolores River on the east side of the river canyon, near and west of Slick Rock (pl. 7), and in the area of deep drilling in Disappointment Valley (pls. 12 and 14). The middle green unit commonly intertongues with the underlying and overlying units (pls. 12 and 14). Because the middle green unit seems to be partly zone of altered mudstone surrounding a core of numerous altered sandstone lenses (pl. 12), some of the tonguing out of the unit may reflect only the pinching out of individual sandstone lenses. In some places, such as those illustrated in figure 39, the whole green unit appears to pinch out in response to the pinching out of the sandstone lenses.

In a few places the unit contains small uranium-vanadium deposits in carbonaceous conglomeratic sandstone, and parts of the unit show much-higher-than-background radioactivity in an area east of the Moon group of mines and north of the Muleshoe bend of the Dolores River.

Mudstone in the middle green unit is typically bentonitic, shows abundant shard structures, and is probably dominantly of volcanic origin. Clastic material in the mudstone is in part rounded and of sedimentary origin, but much is sharply angular or consists of broken euhedra and is chiefly quartz, plagioclase, and potassium-feldspar. Parts of the rock appear to be much altered or recrystallized, and mineral segregations, well-formed metacrysts (authigenic euhedra), and vug fillings are common. Mudstone is dominantly greenish gray or light greenish gray, but parts are mottled or interlayered with different shades of reddish gray, brownish gray, purplish brown, purplish gray, and reddish brown.

Sandstone in the middle green unit ranges from very fine grained to coarse-grained and conglomeratic, and the different types are interbedded and juxtaposed in a complex manner in lenses that show fluvial scour-and-fill structures.

Thin limestone layers and nodules are fairly abundant in claystone and mudstone in the middle green unit.

Typical section of the middle green unit of Brushy Basin Member, near Slick Rock, sec. 30, T. 44 N., R. 18 W.

[Measured by L. C. Craig, November 1948. Designated middle green unit by the present authors]

	Thickness (feet)
Middle green unit:	
4. Siltstone, claystone, sandstone, and limestone; predominantly shades of greenish gray with some dark brown. Siltstone, hackly and rubbly weathering. Claystone, slightly bentonitic. Sandstone, very fine grained, dense and hard; in 1- to 2-ft-thick ledges. Limestone, light-gray, weathering yellowish brown, sublithographic	148
3. Sandstone, pale-yellowish-green, weathering brownish gray, fine- to medium-fine-grained; composed of subrounded clear quartz, with abundant red chert and orange and black accessory minerals; green clay matrix	14
2. Claystone and sandstone interbedded. Claystone, silty to nonsilty, predominantly greenish gray. Sandstone, grayish-yellowish-green, weathering brownish gray, very fine grained; massive and structureless, with beds as much as 3 ft thick	49
1. Sandstone, conglomeratic, light-greenish-gray to white, weathering light brownish gray, medium-fine- to coarse-grained, poorly sorted; composed of subrounded clear quartz with abundant white, pink, red, orange, green, and black accessory minerals; contains granules of white and tan chert as much as ½ in. in diameter	11
Total middle green unit	222

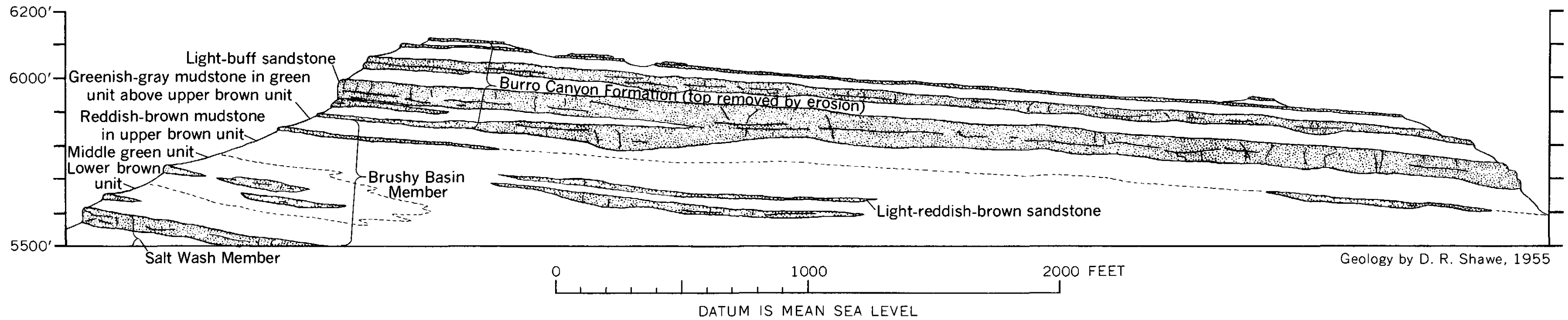

Figure 39.—Diagrammatic section of parts of the Burro Canyon and Morrison Formations, north side of Dolores River and Joe Davis Canyon, secs. 32 and 33, T. 44 N., R. 18 W. The lowest sandstone at the left is the upper unit (ore-bearing sandstone) of the Salt Wash Member of the Morrison. Scales are approximate; vertical exaggeration is 4/3.

Section of middle green unit of the Brushy Basin Member from cores from diamond drill hole DVR–1 in Disappointment Valley, sec. 30, T. 43 N., R. 16 W.

[Measured by D. R. Shawe, June–November 1955]

	Thickness (feet)
Middle green unit:	
2. Sandstone, light-greenish-gray, coarse-grained, medium-fine-grained near base; contains sparse black opaque minerals, abundant red and green chert grains, a trace of calcite, abundant flakes and pebbles of red and green mudstone and abundant interstitial gray and greenish-gray clay	4.6
1. Mudstone and siltstone, chiefly greenish gray; contains sparse to abundant calcite; bentonitic in places	21.0
Total middle green unit	25.6

UPPER BROWN UNIT

The upper brown unit of the Brushy Basin Member is principally mudstone; it contains only minor proportions of sandstone, conglomeratic sandstone, and conglomerate in discontinuous lenses (for example, see pls. 12 and 13, and fig. 39). The ratio of mudstone to other rock types is commonly 10 to 1. Parts of the mudstone are sandy, silty, and limy, and in a few thin layers these grade into fine-grained horizontally bedded sandstone and siltstone, or into limestone. Locally, particularly in the vicinity of Disappointment Valley, the upper part of the upper brown unit is dominantly greenish gray, ranging from a thin selvage just beneath sandstone in the Burro Canyon Formation to one interval which is 220 feet thick and which contains relatively more sandstone than the rest of the unit; it appears to be a transitional interval grading from Brushy Basin to Burro Canyon lithology (pl. 12 and fig. 39). The intertonguing of the unit with both the underlying middle green unit and the overlying Burro Canyon Formation appears to be the result of tonguing out of sandstone lenses and their accompanying halos of altered mudstone, as well as simple thinning and disappearance of layers of altered mudstone at the top and base of the unit.

Mudstone in the upper brown unit, though similar in appearance to that in the lower brown unit, probably contains appreciably more bentonitic material and may be more like the middle green unit in this respect. Parts of the unit contain nonswelling clay, however, and near the top of the unit an apparently gradual decrease in bentonitic clay marks the transition into lithology of the overlying Burro Canyon Formation. Such a contact where Burro Canyon mudstone rests on Brushy Basin mudstone was described in the Ute Mountains area south of Slick Rock by Ekren and Houser (1961). The calcite content of mudstone in the upper brown unit is generally sparse and is abundant only locally, generally in lighter colored patches, small veinlets, and siltier parts. In some layers calcite is abundant enough to make the rock an argillaceous limestone.

Siltstone is common in the upper brown unit; it may be most prevalent near the top of the unit where greenish-gray colors predominate.

Sandstone in the upper brown unit ranges from very fine grained to coarse and conglomeratic and from poorly to moderately well sorted. Fine-grained layers tend to be thin and laterally extensive in the lower part of the unit (pl. 12). Conglomeratic sandstone seems to be most abundant near the top of the unit, especially where the top is dominantly greenish gray, and occurs in disconnected small but fairly thick lenses (pls. 12 and 13).

Section of upper brown unit and overlying strata of the Brushy Basin from cores from diamond drill hole DVR–1 in Disappointment Valley, sec. 30, T. 43 N., R. 16 W.

[Measured by D. R. Shawe, June–November 1955. In this area the Brushy Basin Member is unusually thick, and in places, as in this section, the upper brown unit is overlain by a green unit]

	Thickness (feet)
Green unit above upper brown unit:	
13. Mudstone, greenish-gray; trace of calcite	2.5
12. Mudstone, reddish-brown; lower 1.2 ft is light-greenish-brown fine-grained sandstone	10.7
11. Sandstone, light-greenish-gray, very fine grained to medium-grained; silty in places; contains very sparse black opaque minerals, biotite, and pyrite; sparse to a trace of calcite; very abundant interstitial light-greenish-gray clay; abundant red and green chert granules in lower 1 ft. Interval contains thin reddish-brown clay laminae. Silicified in lower 2.7 ft	8.0
10. Mudstone, reddish-brown. Interval contains ½-ft silicified very fine grained light-greenish-gray sandstone near middle	7.0
9. Mudstone, greenish-gray	.2
8. Sandstone, light-greenish-gray to white, medium grained in upper part, fine grained in lower part; contains sparse pyrite, biotite, black opaque minerals, a moderate amount of red and green chert grains, altered white chert in places, sparse calcite in places, abundant at 11, 6, and 1 to 2.5 ft above base of interval; very abundant interstitial light greenish-gray clay at top, in middle, and at base; buff and light-red chert and green mudstone pebbles in lower 0.5 ft. Interval contains 0.1-ft green mudstone layer 18 ft above base	28.0
7. Claystone, light-greenish-gray; contains abundant biotite, a moderate amount of black opaque minerals, abundant fine quartz sand grains	.4

Section of upper brown unit and overlying strata of the Brushy Basin from cores from diamond drill hole DVR–1 in Disappointment Valley, sec. 30, T. 43 N., R. 16 W.—Continued

	Thickness (feet)
Green unit above upper brown unit—Continued	
6. Mudstone, light-greenish-gray; contains sparse to moderate coarse chert and quartz sand grains; dense in places; silty in lower 14 ft; lower 1 ft sandy with sparse biotite, black opaque minerals. Interval contains purplish-brown mudstone 0.1 ft thick above 0.2-ft greenish-gray mudstone at base	22.8
5. Sandstone, light-greenish-gray interlayered with white, fine-, medium-, and coarse-grained, interlayered; quartz grains stained green in places; contains a moderate amount of black opaque minerals, red and green chert grains, sparse to moderate calcite, sparse barite, abundant interstitial white and greenish-gray clay; cement rarely is red chert. Interval contains greenish-gray mudstone and buff, light-gray, and reddish-brown chert pebbles in layers 2 ft and 0.7 ft thick 20 ft above base and at base, respectively; light-reddish-brown very fine grained sandstone 0.7 ft thick with very abundant black opaque minerals in upper 0.3 ft, 24 ft above base. 4-ft interval 1 ft above base is silicified and very light reddish brown	43.1
4. Mudstone, greenish-gray	.4
3. Mudstone, reddish-brown, mottled greenish gray near base	2.7
2. Mudstone, greenish-gray; dense in places; mudstone conglomerate in sandy places	3.4
Total green unit above upper brown unit	129.2
Upper brown unit:	
1. Mudstone and siltstone, dominantly reddish brown, some light greenish gray and light brownish gray, light brownish gray increases toward base; color layers are 0.1–10 ft thick; fine to very fine grained sandy in places; very dense in places, especially 33 and 13 ft above base; contains sparse calcite in upper 20 ft, alternating sparse, moderate, and abundant calcite below, chiefly sparse, generally abundant at base; abundant ramifying red chert "spiders" 120 and 50 ft above base; ¼ in. barite crystals 80 ft above base. Interval contains 0.3-ft-thick bentonitic claystone layer 147 ft above base, 1-ft-thick silicified light-reddish-brown fine-grained sandstone with abundant black opaque minerals 95 ft above base, 1-ft-thick light-brownish-gray very fine grained quartzite 70 ft above base, and 3.5-ft-thick light-brownish-gray fine-grained sandstone with abundant black opaque minerals and barite 20 ft above base	220.2
Total upper brown unit	220.2

Section of the upper brown unit of the Brushy Basin Member near Slick Rock, sec. 30, T. 44 N., R. 18 W.

[Measured by L. C. Craig, November 1948. Designated upper brown unit by the present authors]

	Thickness (feet)
Upper brown unit:	
1. Siltstone and claystone, predominantly dark red. Siltstone weathers with hackly fractures to soilless rubble. Claystone is slightly bentonitic	187
Total upper brown unit	187

SURFACE DISTRIBUTION AND CONFIGURATION

The Brushy Basin Member crops out over broad areas on the northeast limb and near the crest of the Dolores anticline and along the southwest rim of Gypsum Valley. It appears also in narrow sinuous strips on either side of the Dolores River Canyon and at the southeastern edge of the district along Narraguinnep Canyon (pl. 1).

Figure 40 shows the combined thickness of the Brushy Basin Member and the overlying Burro Canyon Formation. These units are not shown separately because of the intertonguing character of the Brushy Basin–Burro Canyon contact; in addition the contact is difficult to determine in some drill logs. Nevertheless, evaluation of thicknesses of the two formations throughout the area of figure 40 shows that both possess the same general pattern of thickness variation indicated for the combined interval.

The lower brown unit of the Brushy Basin Member is generally about 100 feet thick and ranges from 50 to 200 feet in thickness. The middle green unit is generally 100–150 feet thick but ranges from 0 to 280 feet in thickness. The upper brown unit is generally 200–250 feet thick but ranges from 120 to 460 feet in thickness. Differences in thickness of the separate units in part reflect lateral facies changes rather than simply a response to structural deformation, as for example near the east end of the section on plate 12.

Because the three units of the Brushy Basin Member occur sporadically throughout the district, their thickness variations are not described in detail. Even so, the general distribution of the middle green unit, which perhaps has significance for an interpretation of the geologic history of the district, is described. The unit is thickest—generally about 200–250 feet thick—in Burro Canyon and vicinity and eastward nearly across Disappointment Valley. Outside this area, it appears to thin in all directions, splits into more than one unit, or is absent (pls. 7, 12, and 14). Gray to greenish-gray mudstone strata that constitute the middle green unit thin appreciably from Morrison Canyon northeastward

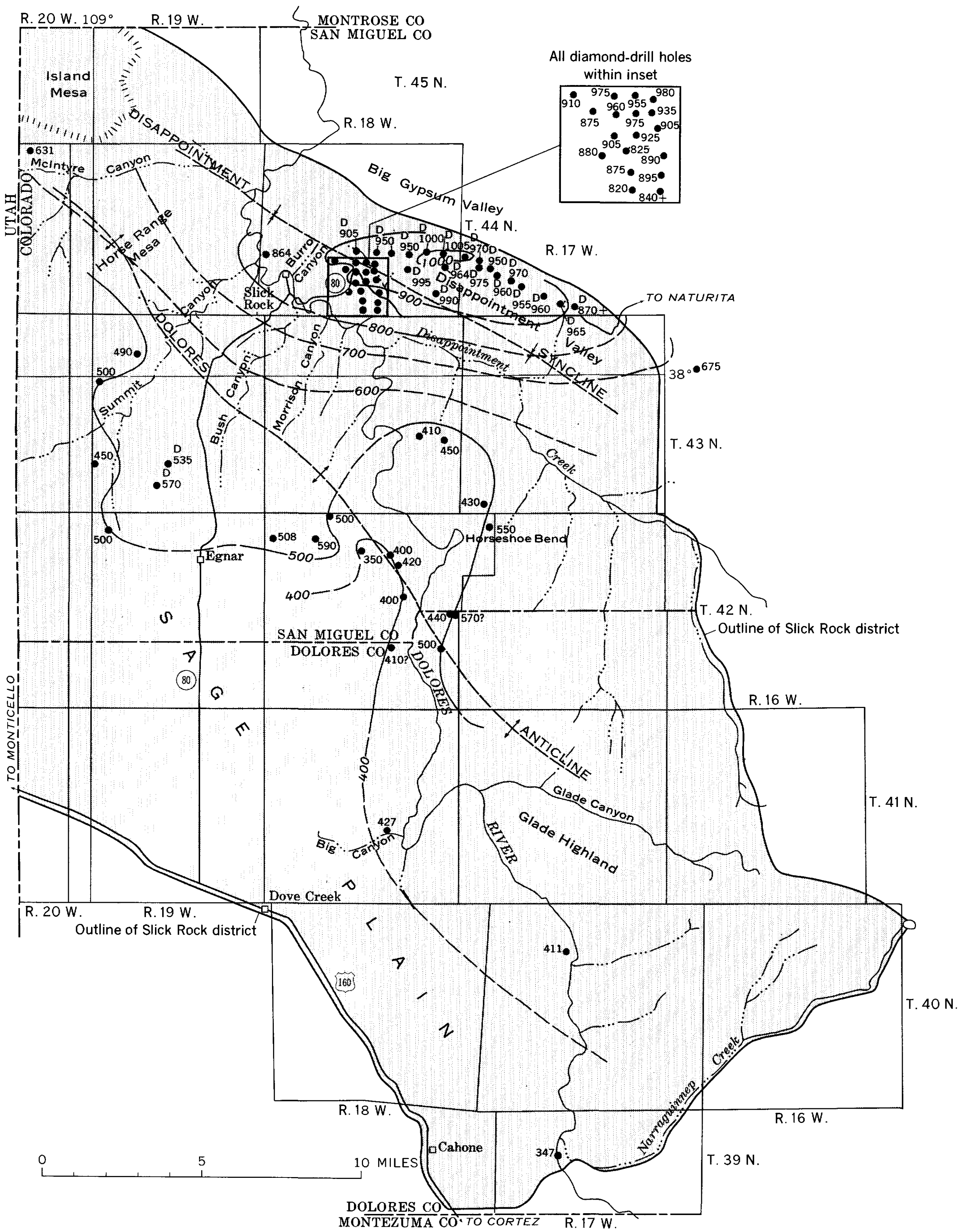

Figure 40.—Thickness of the Brushy Basin Member of the Morrison Formation and the Burro Canyon Formation combined. Isopachs dashed where uncertain; interval 100 feet. Number by control point (dot) is measured thickness, in feet, of contoured units. Diamond-drill holes indicated by D; other control points are surface sections.

(pl. 7, B′–B″). If the middle green unit were as thick in the area of Bush and Summit Canyons, prior to its erosion there, as it is in the Burro Canyon area, the area of thick middle green unit would be roughly coincident with the area of ore deposits in the Salt Wash Member. For this reason the middle green unit is discussed in a later chapter in the light of its possible genetic relation to the origin of the ores.

CRETACEOUS ROCKS

BURRO CANYON FORMATION

The name Burro Canyon Formation was proposed by W. L. Stokes (Stokes and Phoenix, 1948) for a sequence of noncarbonaceous terrestrial rocks, probably of Early Cretaceous age, lying between the Morrison Formation and the Dakota Sandstone. The formation includes virtually the same rocks as those designated "post-McElmo" by Coffin (1921, p. 97–113, especially p. 103–104), as shown in table 3 of this report. The type locality designated by Stokes is in Burro Canyon, sec. 29, T. 44 N., R. 18 W. The total thickness of the formation is not exposed in sec. 29, however, and the upper part of the type section probably extends into sec. 28 to the east. Stokes described the formation as consisting of "alternating conglomerate, sandstone, shale, limestone and chert ranging from 150 to 260 feet in thickness." As Simmons (1957, p. 2522) pointed out, the Burro Canyon Formation at its type locality is not characteristic of the formation in most of the Slick Rock district. Away from Burro Canyon and the Disappointment Valley area the formation consists of one conglomeratic sandstone layer, generally somewhat less than 100 feet thick, which contains a few thin greenish-gray mudstone beds and locally is overlain by a few feet of greenish-gray mudstone.

Age

The Early Cretaceous age of the Burro Canyon Formation was first assigned by Stokes (1952, p. 1767) on the basis of fossils collected about 1 mile east of the junction of Disappointment Creek and the Dolores River, T. 43 N., R. 18 W. Plant fossils collected from a small outcrop of black shale near the top of the formation in a dry wash south of the creek were identified by Brown (1950) as *Frenelopsis varians* Fontaine which he regarded (p. 50) "as a Lower Cretaceous time index." Fossils in a much larger collection made by us near Stokes' original locality (Simmons, 1957, p. 2525–2526) corroborate this age. According to Simmons the fossils occur in a 10-foot-thick zone of interbedded black to green shale, green siltstone, and fine-grained sandstone. The top of the interval is 18 feet below the top of the Burro Canyon. Fossils identified include: *Protelliptio douglassi* Stanton; *Lampsilis farri* Stanton; *Nippononaia asinaria* Reeside; *Nippononaia* sp.; viviparid gastropod; *Cypridea*?; *Darwinula*?; ganoid fish scales; *Frenelopsis varians* Fontain; *Pinus susquaensis* Dawson; and fern pinnules. Of the pelecypods *Protelliptio douglassi* and *Lampsilis farri* are well known and widespread Early Cretaceous (Aptian) species, and the new species of *Nippononaia* belong to an Early Cretaceous genus of Japan (Reeside, 1957, p. 651). The ostrocodes were examined by I. G. Sohn who identified *Cypridea*? and *Darwinula*? with a great deal of uncertainty. The plant material, examined by R. W. Brown, contained abundant *Frenelopsis varians* and only one specimen of *Pinus susquaensis*. Both Reeside and Brown assigned a certain Early Cretaceous age to the fossil assemblage.

Lithology

The Burro Canyon Formation is composed of sandstone, conglomerate, mudstone, siltstone, limestone, and chert. Interbedded sandstone and conglomerate occur as thick layers as much as 100 feet thick separated by thinner strata of mudstone. Siltstone is most common as evenly bedded strata in mudstone. Limestone and chert occur as thin beds in mudstone, mostly in the upper part of the formation in Disappointment Valley and vicinity. The formation is expressed topographically as an alternating series of nearly vertical cliffs in the sandstone strata and steep even slopes in the mudstone strata (pl. 13 and fig. 39).

Throughout most of the western and southern parts of the Slick Rock district, the Burro Canyon Formation is a single-cliff-forming unit averaging somewhat less than 100 feet in thickness. The cliff-forming unit consists of sandstone and conglomeratic sandstone lenses and layers of like lithology which in places coalesce to form a single sandstone unit but which in many other places are separated by mudstone into two, three, or more sandstone layers or lenses. The sandstone strata in the unit appear to be fluvial scour-and-fill deposits like those of the Morrison Formation. Although the unit as a whole can be correlated readily in surface exposures, its component parts clearly are discontinuous. A section measured in one place may show a single stratum of sandstone 50 feet thick; in another place two strata of sandstone of like lithology, each 50 feet thick, separated by 5 feet of mudstone; and in yet another place three strata of sandstone of like lithology, each 10–30 feet thick, separated by 5–10 feet of mudstone. The cliff-forming unit extends into the Disappointment Valley area, in the northeastern part of the district, where it is overlain by other strata of the formation that aggregate one to three times the thickness of the unit.

In the Disappointment Valley area, just above the basal sandstone unit and separated from it by mudstone, is a second sequence of sandstone lenses which, like the basal unit, is internally discontinuous. At the top of the formation is a sequence of alternating strata of mostly greenish-gray mudstone, some sandstone and limestone, and minor chert. Some of the sandstone strata in the upper part are as much as 20 feet thick and are very similar to the lower sandstone layers. In the Disappointment Valley area, therefore, the Burro Canyon Formation in places contains as many as six distinct sandstone strata that generally range from 10 to 50 feet in thickness. The general character of the formation in the area is shown on plates 12 and 13, and in figure 39.

Coffin (1921, p. 109) pointed out that the strata in the upper part of the formation thin to the north and south of Disappointment Valley. "This thinning is accomplished by a wedging out of the calcareous and cherty layer and the green shales * * *." Whether the absence of beds above the basal unit outside the Disappointment Valley area is a result of nondeposition or of post–Burro Canyon and pre–Dakota erosion, or partly both, we do not know. In any case an erosional unconformity marks the contact between the Burro Canyon Formation and the Dakota Sandstone throughout the Slick Rock district exclusive of Disappointment Valley. In Disappointment Valley the Burro Canyon–Dakota contact apparently is conformable for it lacks scour features, and in places the Burro Canyon contains a carbonaceous layer about 20 feet below the top of the formation (Simmons, 1957, p. 2525, 2526), suggesting affinity with the Dakota. The contact is sharp, however, and no evidence of intertonguing between the two formations was found in Disappointment Valley or elsewhere in the Slick Rock district and vicinity.

In many places within the Burro Canyon Formation, individual sandstone and conglomerate strata contain a "basal" conglomerate (pl. 13, *B–B′*). Unlike the common "indigenous" conglomerate of much of the Burro Canyon, whose pebbles were derived from outside the region of Burro Canyon deposition and likely had the same source as much of the conglomerate matrix, the "basal" conglomerate contains pebbles, cobbles, and even boulders derived from underlying layers of sandstone, mudstone, shale, quartzite, chert, and limestone. The presence of the "basal" conglomerate shows that parts of the formation had become lithified before overlying parts were deposited, and suggests that during the deposition of the formation, hiatuses of fairly long duration occurred when no deposition and possibly considerable weathering and erosion took place.

In places the base of the Burro Canyon Formation is prominently channeled into the underlying Brushy Basin Member of the Morrison Formation (pl. 13, left end of diagram *B–B′*, and left end of fig. 39.) In other places the lower part of the Burro Canyon clearly intertongues with the Brushy Basin (pl. 13, right end of diagram *B–B′*, and right half of pl. 12). The base of the lower cliff-forming unit is interpreted from subsurface data to be both channeled and intertongued in the Legin area, about 3 miles northwest of Egnar, where the unit makes up all of the Burro Canyon Formation (fig. 41). Such a contact is similar to many internal contacts in both the Burro Canyon and the Brushy Basin. That the formational contact is of regional disconformity as suggested by Young (1960) is doubtful. For example, Craig (1961) stated "an individual scour surface at the base of or within a sandstone unit [of the Burro Canyon interval] may have been formed in an exceedingly short time * * * and to dignify each of the many scour surfaces in this sequence by calling it a disconformity is impractical."

The sandstone is generally light greenish gray (where clay is abundant), light brownish gray, or light yellowish brown; a minor amount is light reddish brown. Much of the sandstone is brownish as a result of weathering of pyrite and marcasite, but it is generally lighter colored than that in the overlying Dakota, owing to the greater amount of iron sulfide in that unit. The Burro Canyon sandstone is very fine to coarse grained, commonly conglomeratic, and friable to firmly cemented with calcite, silica, and greenish-gray clay. The sandstone beds are massive to lenticular and crossbedded. Pebbles in the conglomeratic parts consist of chert—mostly white and lesser amounts of red, gray, brown, and green—quartz, siliceous limestone, quartzite, sandstone, mudstone, and shale.

Siltstone is mostly greenish gray and similar in composition to the sandstone, but it has a higher proportion of clay minerals and commonly grades into mudstone.

Mudstone in the Burro Canyon Formation, unlike the bentonitic mudstone that predominates in the underlying Brushy Basin Member of the Morrison Formation, is nonswelling. It also seems generally to be more clay-rich than that of underlying formations. The mudstone is evenly and thinly bedded and dominantly light greenish gray; a small amount of light-reddish-brown and minor gray carbonaceous mudstone is present locally in the formation near the base, in the middle, and near the top. Clastic detritus in the mudstone is

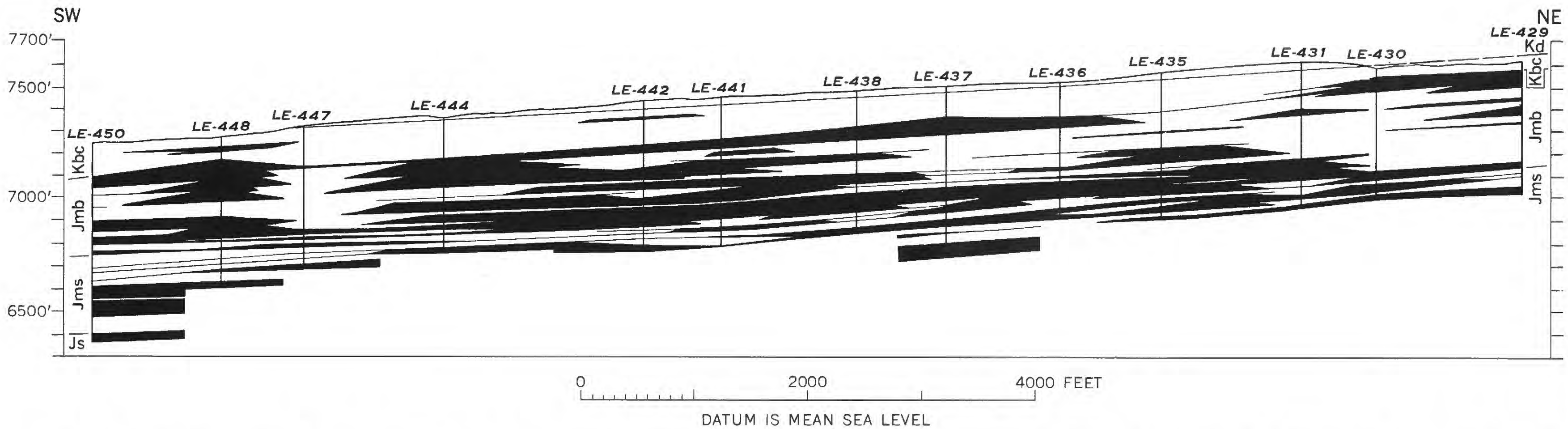

FIGURE 41.—Geologic section of the Burro Canyon Formation, Brushy Basin Member of the Morrison Formation, and associated strata, Legin area. Blank parts of diagram are mostly mudstone; black parts are mostly sandstone. Stratigraphic units are indicated by smybol: Dakota Sandstone (Kd); Burro Canyon Formation (Kbc); Brushy Basin Member (Jmb) and Salt Wash Member (Jms) of the Morrison Formation; Summerville Formation (Js). Logs of drill holes *LE–436*, *438*, and *441* not complete in upper part; geology is projected from adjacent holes.

largely silt size and ranges from sharply angular to moderately rounded.

In places layers are true claystone, and some are shaly. Rare carbonaceous shale in the upper part of the Burro Canyon is "paper shale."

Limestone occurs as thin beds and as nodules commonly disposed in thin layers. The limestone is mostly in the upper part of the formation in the vicinity of Disappointment Valley, but it can be found at many levels in the formation throughout the district. The limestone is mostly light gray, but in places it is light greenish gray or light bluish gray. Strata of limestone as much as 8 feet thick commonly contain dark-gray chert beds locally as much as 5 feet thick.

Nodules of limestone are common in the Burro Canyon Formation. For example, just north of the center of the south side of sec. 34, T. 44 N., R. 18 W., in Disappointment Valley, a layer 15 feet thick of greenish-gray mudstone with some thin sandstone layers, about 15 feet below the top of the Burro Canyon, contains abundant nodules of limestone ½–6 inches in diameter. One of the nodules from this horizon is shown in figure 42. The nodule consists of a number of irregularly convoluted oblong globular masses, wrapped one upon the other, that must have had their origin by an accretionary process. The interior of the nodule has vugs lined with calcite crystals between the globular masses, and each mass displays internal shrinkage cracks that are filled with calcite and silica. The vugs and shrinkage cracks probably formed when the limestone contracted as a result of water loss and probably before the enclosing strata were deeply buried.

Chert in the Burro Canyon Formation, aside from clastic particles, is mostly confined to limestone strata or limy mudstone and claystone strata. It occurs as thin to thick beds and as small irregular nodules within limestone or limy strata. Chert in limestone is mostly dark gray and in beds as much as 5 feet thick; elsewhere it is typically light greenish gray, in layers about 2 feet or less thick. Some beds of siltstone and mudstone are dense and chertlike. Some of these layers are quartzitic, but others appear to have been replaced by chert. One stratum 1–3 feet thick near the top of the formation (near the right end of B–B′, pl. 13) appears to be silici-

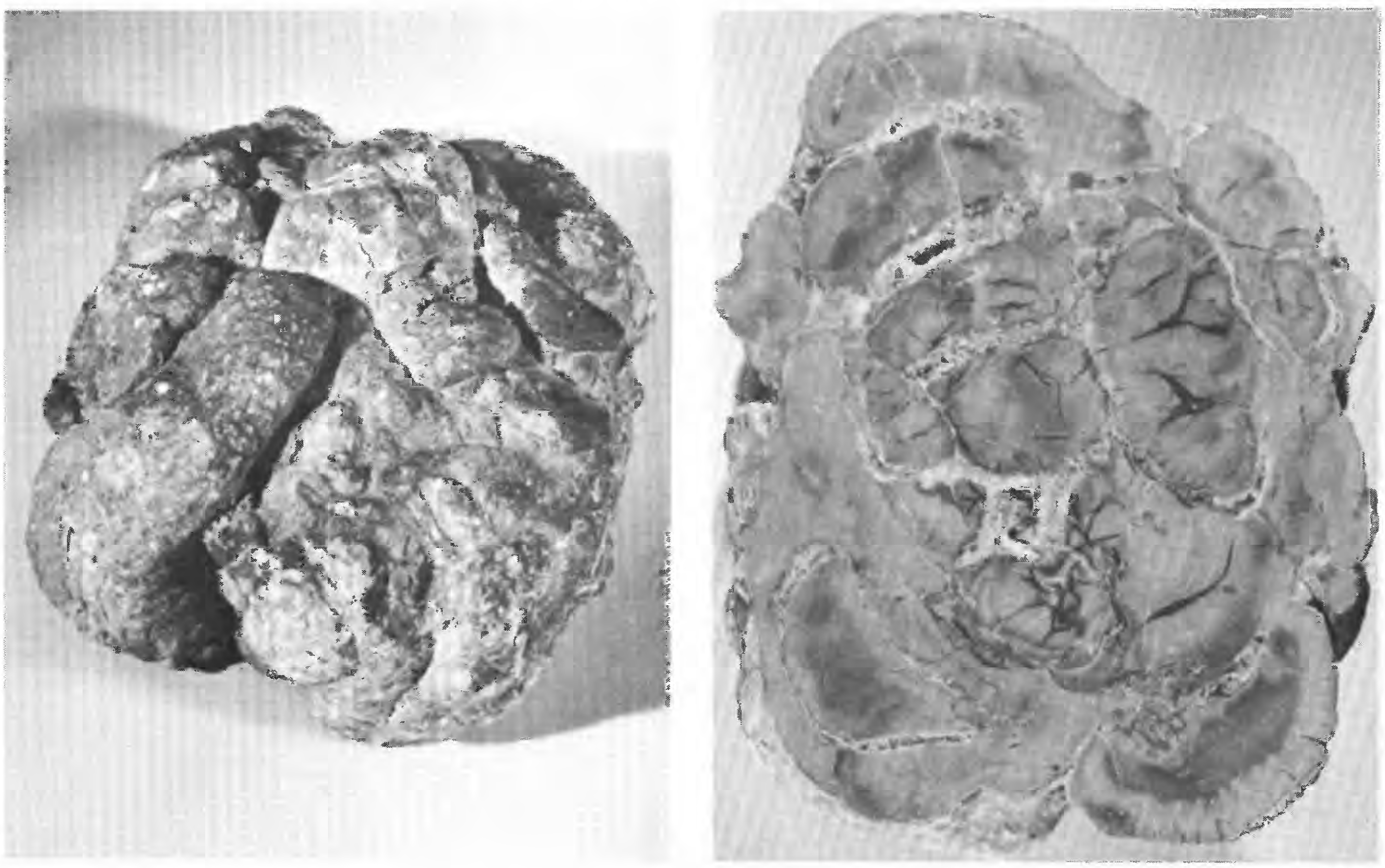

FIGURE 42.—Limestone nodule from a greenish-gray mudstone layer near the top of the Burro Canyon Formation, Disappointment Valley. Note the irregularly convoluted oblong globular masses, wrapped one upon the other in left photograph. A sawcut through the middle of the nodule, right photographs reveals internal features: vugs lined with calcite between the globular masses, and shrinkage cracks filled with calcite and silica. About half size. Photographs by F. H. Spence.

fied silty claystone, and in places is chertlike. According to an X-ray analysis by L. G. Schultz of the Geological Survey, this rock contains some kaolinite. The layer, commonly called a marker bed because of its conspicuous outcrop and lateral persistence just below the base of the Dakota Sandstone, is light greenish gray and contains numerous calcite crystals about 1 mm in size. In one place the marker bed is overlapped about 5 feet higher by a similar bed, which appears to be continuous beyond the extent of the underlying bed, and is therefore virtually a continuation of the marker bed.

Measured sections of the Burro Canyon Formation follow.

Section of the Burro Canyon Formation, Slick Rock district, sec. 8, T. 39 N., R. 17 W., west side of the Dolores River and north of Williams Draw

[Measured by G. C. Simmons and W. B. Rogers, September 1956. A relatively thin section that is otherwise typical of the formation in the western and southern parts of the district (location shown on pl. 1)]

	Thickness (feet)
Burro Canyon Formation:	
2. Sandstone, greenish-gray and light-brown, fine- to medium-grained; sparse small chert pebbles; sparse interstitial greenish-gray clay; crossbedded. Disconformably overlain by Dakota Sandstone	10
1. Sandstone, light-brown, fine-grained and conglomeratic, pebbles more abundant toward base; crossbedded. Underlain by Brushy Basin Member of the Morrison Formation	30
Total Burro Canyon Formation	40

Section of the Burro Canyon Formation in Big Canyon, sec. 22, T. 41 N., R. 18 W.

[Measured by G. C. Simmons and N. L. Archbold in September 1956. Thickness of this section is nearly typical of the formation in most of the district]

	Thickness (feet)
Burro Canyon Formation:	
2. Mudstone, limestone, and chert, greenish-gray and gray; poorly exposed. Overlain disconformably by Dakota Sandstone	36
1. Sandstone, gray to light-brown, fine-grained and conglomeratic; sparse to moderate chert pebbles; sparse to moderate limonite stain; sparse dark minerals. Underlain by Brushy Basin Member of the Morrison Formation	44
Total Burro Canyon Formation	80

Section of the Burro Canyon Formation along a pipeline trench on the northeast side of Disappointment Valley, sec. 24, T. 44 N., R. 18 W.

[Measured by G. C. Simmons and D. R. Shawe, July 1956. This section is typical of the thicker part of the formation]

	Thickness (feet)
Burro Canyon Formation:	
19. Mudstone, green, and limestone, gray; poorly exposed. Top of Burro Canyon Formation	19
18. Sandstone, light-gray, grayish-green, and light-greenish-brown, fine-grained, conglomeratic; some limonite-stained greenish-gray mudstone pellets; some current lineations	19
17. Siltstone, greenish-gray, limy	6
16. Sandstone, gray, fine-grained and conglomeratic; sparse to moderate white chert grains, greenish-gray mudstone pellets, limonite specks; thin and evenly bedded	2
15. Limestone, chert, and mudstone, gray and greenish-gray	10
14. Siltstone and mudstone, greenish-gray, limy	17
13. Limestone, gray	8
12. Siltstone, light-green, limy	1
11. Sandstone, light-tan, fine-grained and conglomeratic; sparse dark minerals; moderate red and white chert grains	44
10. Mudstone, greenish-gray and light-brown	1
9. Sandstone, light-tan, fine- to medium-grained; sparse red and white chert pebbles and greenish-gray mudstone pebbles; sparse limonite spots	28
8. Mudstone, greenish-gray	1
7. Sandstone, light-gray, fine-grained	1
6. Mudstone, greenish-gray	1
5. Sandstone, light-tan, very fine grained to fine-grained; sparse dark minerals; sparse quartz overgrowths	12
4. Mudstone, brownish-red and grayish-green	22
3. Sandstone, gray and greenish-gray, very fine grained to medium-fine grained; 0.3 ft of greenish-gray mudstone at base	28
2. Mudstone, brownish-red	4
1. Sandstone, light-tan, light-gray, and greenish-gray, fine-grained and conglomeratic; sparse light-red and greenish-gray chert granules; abundant buff chert granules. Base of the Burro Canyon Formation	14
Total Burro Canyon Formation	238

Log of diamond-drill core from hole DVR-1, sec. 30, T. 43 N., R. 16 W., Disappointment Valley

[Prepared by D. R. Shawe. Shows details of lithology of the Burro Canyon Formation]

	Thickness (feet)
Lower part of the Dakota Sandstone (incomplete):	
19. Mudstone, medium-gray overlying black; abundant pyrite near base; very abundant carbonaceous material in lower 2 ft	7.8
18. Sandstone, light-gray interbedded with minor dark-gray, very fine grained to fine-grained overlying coarse-grained; sparse black opaque minerals, barite, and pyrite; 1-in. pyrite nodules near top; trace of calcite near base; abundant flakes, films, seams, and pebbles of carbonaceous material; abundant interstitial light-gray clay; some granules and small pebbles of quartzite and chert in lower 2 ft. Base of Dakota Sandstone	6.6
Total incomplete Dakota Sandstone	14.4

Log of diamond-drill core from hole DVR-1, sec. 30, T. 43 N., R. 16 W., Disappointment Valley—Continued

	Thickness (feet)
Burro Canyon Formation:	
17. Mudstone, light-greenish-gray; moderate amount of very fine grained pyrite, coarse grained in places; trace of calcite; sparse chert granules, abundant red chert grains; sparse black opaque minerals; light-gray chert-calcite seam 18 ft above base; chert seam with moderate calcite and pyrite 22 ft above base; abundant calcite in mudstone 7–17 ft above base, mottled calcite in lower 5 ft; sandy; very sandy in lower 12 ft, grades into sandstone below	26.7
16. Sandstone, light-gray to white, fine- to medium-grained, sparse coarse grains; coarse grained with abundant chert granules near base; sparse to abundant calcite in ½- to 2-ft thick layers; sparse calcite in lower 7 ft; abundant red chert grains, sparse chert pebbles and granules in places; dark-gray and red chert granules and interstitial pyrite 4 ft above base; sparse black opaque minerals; abundant light-greenish-gray clay in top part; interstitial white clay in lower 10 ft, very light greenish gray near base	13.0
15. Sandstone, light-gray to white, fine-grained; sparse to a trace of calcite; sparse black opaque minerals; sparse red chert grains, small granules in places; interstitial light-gray clay near top, white near base	12.0
14. Sandstone overlying conglomerate, light-gray, medium- to coarse-grained; trace of calcite; sparse black opaque minerals; abundant red, gray, and green chert grains and red and dark-gray chert pebbles; abundant greenish-gray and white claystone pebbles; abundant interstitial purple, white, and greenish-gray clay	2.3
13. Sandstone, light-gray to white, medium-grained, coarse grained in places; very sparse black opaque minerals; trace of calcite; abundant interstitial white clay; light-greenish-gray sandy mudstone with sparse pyrite in two thin layers about 2 ft above base	10.2
12. Sandstone, white, fine-grained; sparse black opaque minerals; trace of calcite, moderate amount 1 ft above base; abundant pyrite at base, with greenish-gray mudstone; sparse greenish-gray mudstone pebbles; sparse interstitial white clay; thin brownish-gray mudstone layer 7 ft above base; thin conglomerate layers at 7, 12, and 13 ft above base	19.6
11. Mudstone, greenish-gray; very sandy in places; trace of calcite; mottled contact at base	2.6
10. Mudstone, purplish-brown; sandy in places; trace of calcite; moderate dispersed carbonaceous material	3.8
9. Mudstone, greenish-gray, mottled with dark-reddish-brown 2–3 ft above base; trace and abundant calcite, interlayered; ½-in. limestone layers inclined 30° from horizontal, bright green in places, 2½ ft above base; sparse carbonaceous material 3½ ft above base; mudstone grades irregularly into sandstone below	5.0

Log of diamond-drill core from hole DVR-1, sec. 30, T. 43 N., R. 16 W., Disappointment Valley—Continued

	Thickness (feet)
Burro Canyon Formation—Continued	
8. Sandstone, very light greenish gray to greenish-gray; fine to medium grained with sparse coarse grains in upper part, very fine grained in lower part; trace to sparse calcite; ¼-in. calcite layers 10 ft below top, trace of calcite in lower 22 ft, sparse calcite 2 ft above base; sparse black opaque minerals and chert grains; sparse pyrite, moderate amount 10 ft below top; moderate number of dark sulfide clots, 1/16-in. across, 6–8 ft below top; moderate to very abundant interstitial irregularly distributed greenish-gray clay, sparsely distributed in clean light-greenish-gray sandstone in lower 22 ft	34.0
7. Mudstone, greenish-gray; sandy; trace of calcite	.5
6. Sandstone, very light greenish gray, bottom 1 ft greenish gray, fine- to medium-fine-grained; conglomerate with white and light-gray pebbles as much as ¾ in. across in 1-ft layers every 2–5 ft; trace of calcite; sparse black opaque minerals; sparse to abundant interstitial light-greenish-gray clay; sparse thin silicified sandstone layers	34.8
5. Conglomerate, light-greenish-gray to buff; coarse-grained matrix; pebbles as much as 1 in. across of reddish-brown, white, and buff chert, about 10 percent light-reddish-brown and white quartz and gray quartzite and minor greenish-gray mudstone; sparse black opaque minerals and pyrite; trace of calcite; sparse to abundant interstitial greenish-gray and white clay	8.8
4. Sandstone, light-greenish-gray to buff, interlayered medium- and coarse-grained; sparse calcite locally, moderate amount 6–7 ft above base; sparse black opaque minerals; abundant red and gray chert grains, pebbles as much as 1½ in. across; cores of some buff chert pebbles are reddish brown; some pebbles greenish-gray and white mudstone; 1- to 2-ft layers of clean sandstone separate conglomeratic layers; ½-ft dense quartzite 1 ft below top; sparse to abundant interstitial greenish-gray and white clay	16.9
3. Conglomerate, light-greenish-gray to buff; coarse-grained matrix; sparse greenish-gray mudstone pebbles; sparse black opaque minerals; sparse to abundant interstitial greenish-gray and white clay	4.0
Total Burro Canyon Formation	194.2
Upper part of the Brushy Basin Member of the Morrison Formation (incomplete):	
2. Mudstone, greenish-gray; trace of calcite	2.5
1. Mudstone, reddish-brown; lower 1 ft of light-greenish-brown thin-bedded fine-grained sandstone	10.7
Total incomplete Brushy Basin Member	13.2

Surface distribution and configuration

The Burro Canyon Formation crops out as a narrow band along the edge of the Sage Plain in the southwestern part of the district and across the canyon of the Dolores River to the east. It appears also in many narrow canyons that extend down the northeast flank of the Dolores anticline south of Disappointment Valley, and it forms a platter-shaped rim of cuestas dipping inward around the periphery of Disappointment Valley. It forms the capping strata on several mesas in the northwest corner of the district, including Island Mesa, Steamboat Hill, and much of Horse Range Mesa (pl. 1).

Thickness variations of the Burro Canyon Formation are similar to those already described for the Brushy Basin Member of the Morrison Formation. An isopach map of the combined Brushy Basin and Burro Canyon interval is shown in figure 40. The thickness of the formation from the latitude of Egnar south is generally 40–90 feet; in the northwest corner of the district it is 60–180 feet (fig. 41); and in the Disappointment Valley area, about 200 to more than 400 feet (pl. 12).

A locally thin part of the Burro Canyon a few miles east of Egnar nearly coincides with a similar thin part of the combined Brushy Basin and Burro Canyon interval (fig. 40).

East of the Dolores River and north of Narraguinnep Creek, sec. 9, T. 39 N., R. 17 W., fluvial sandstone of the Burro Canyon is locally pinched out. Argillaceous horizontally bedded rocks of Brushy Basin character occur as lateral equivalents of the sandstone. The pinchout is not shown on the geologic map (pl. 1) as its limits were not determined.

DAKOTA SANDSTONE

Early usage of the term Dakota Sandstone in the region around the Slick Rock district was described by Junius Henderson (in Coffin, 1921, p. 115): "It apparently occupies the same stratigraphic position as in eastern Colorado, lying immediately beneath the marine Lower Mancos (Benton horizon), and resting upon the McElmo variegated shales and sandstones which appear to be equivalent to the Morrison."

Gilluly and Reeside (1928, p. 82) pointed out some of the variations in usage of McElmo on the Colorado Plateau which led to their abandoning the term. Baker, Dane, and Reeside (1936, p. 38–40) explained the various usages of the term in southwestern Colorado. Though the base of the McElmo Formation has had different positions according to different workers, the top of the formation seems to have been placed consistently at the base of what was considered the Dakota Sandstone. However, in early studies the Dakota likely included the Burro Canyon Formation in western Colorado and the Lower Cretaceous Cedar Mountain Formation in central and eastern Utah.

Coffin and Henderson (in Coffin, 1921, p. 97–118) first recognized the current, more restricted, usage of Dakota Sandstone in southwestern Colorado. Coffin mapped the top of the McElmo Formation in western Colorado at what is now called the top of the Morrison Formation. He informally designated as post-McElmo a rock unit lying between the McElmo and the Dakota. The recognition of the post-McElmo rocks, formerly considered part of the Dakota Sandstone, limited the Dakota Sandstone to its current usage in the Slick Rock district. But not until Stokes (Stokes and Phoenix, 1948) defined the Burro Canyon Formation, which is coincident with the post-McElmo rocks of Coffin, did the present delineation become generally recognized.

Age

Several collections of fossils from the Dakota Sandstone in the Slick Rock district indicate that the formation in this area is of early Late Cretaceous age. Stokes (1952, p. 1767) described a collection of plant fossils from a quartzitic sandstone layer at the base of the Dakota in Disappointment Valley, about 20 feet higher and a short distance from his locality of Lower Cretaceous fossils from the Burro Canyon Formation near Disappointment Creek, T. 43 N., R. 18 W. The fossils include: *Anemia* sp., *Sterculia towneri* (Lesquereux) Berry, *Sassafras cretaceum* Newberry, *Ficus daphnogenoides* (Heer) Berry, and *Capsulocarpus dakotensis* Berry. The fossils were regarded by R. W. Brown, of the Geological Survey, as of Late Cretaceous age.

Three collections were made in the district by G. C. Simmons. One consists of a single type of leaf found on the west side of a dry wash in the W½NE¼ sec. 11, T. 43 N., R. 18 W., probably within a half mile of Stokes' collection site. The specimens found in a sandstone lens 1–5 feet above the base of the Dakota are *Sterculia towneri* (Lesquereux) Berry and could be from the Lower or Upper Cretaceous (R. W. Brown, written commun., 1956).

A second collection consists of leaves found at a point 31,700 feet south of lat 37°45′ N., and 3,500 feet east of long 108°45′ W., about 1 mile north of the Bradfield ranch, on the west side of the Dolores River Canyon. This collection, from a coal prospect in the middle carbonaceous shale unit of the formation, includes *Aneimia* sp., ?*Dewalquea pulchella* Knowlton and fragmentary and whole dicotyledonous leaves which suggest early Late Cretaceous age, but no definite assignment can be made (R. W. Brown, written commun., 1956).

A third collection, from the Sage Plain about 6 miles north of Dove Creek, near the center of the SE¼ sec. 1, T. 41 N., R. 19 W., was taken from a narrow zone about half an inch above the base of a 3-inch-thick siliceous light-gray shale bed in the middle (carbonaceous shale) unit of the Dakota. This collection consists of ferns and other plant material identified by R. W. Brown as follows: *Gleichenia kurriana* Heer, *Asplenium* sp., and *Bolbitis coloradica* Brown. According to Brown these fossils are from low in the Upper Cretaceous.

Determination of the lower age limit of the Dakota Sandstone in the Slick Rock district depends upon the interpretation given to one plant species, *Sterculia towneri* (Lesquereux) Berry, found at the base of the formation, which Brown (1950, p. 52) considered could be either Early or Late Cretaceous. Judging from Brown's discussion and from his description of specimens collected in Disappointment Valley, we consider a Late Cretaceous age more likely than an Early Cretaceous age for the lower part of the Dakota in this area. Because an Early Cretaceous age has been assigned to a collection made in the upper part of the Burro Canyon Formation about 20 feet stratigraphically below the Dakota collections, the base of the Dakota Sandstone likely marks the boundary between Lower and Upper Cretaceous in this area.

Lithology

The Dakota Sandstone is composed mostly of sandstone and lesser amounts of conglomerate, carbonaceous shale and mudstone, and impure coal. Throughout the district, except in the Disappointment Valley area, the Dakota consists of an upper arenaceous unit, a middle carbonaceous shale unit, and a lower arenaceous, locally conglomeratic unit. In the vicinity of Disappointment Valley the lower unit is not well defined, and it merges with the middle unit. Henderson (in Coffin, 1921, p. 113) pointed out that the interval that he considered to be Dakota in many parts of Colorado and adjacent States consists of "an upper sandstone member, a medial shale and sandstone member, and a massive lower sandstone and conglomerate member."

Over most of its outcrop area the Dakota forms a slightly undulating surface, particularly on the Sage Plain and the northeast flank of the Dolores anticline. In general, the Dakota surface in much of the district reflects the underlying structure because it has tended to retard erosion that proceeded relatively rapidly in the overlying soft Mancos Shale. Along the Dolores River Canyon the Dakota forms one and in some places two cliffs which correspond to the thicker sandstone units in the formation. Around the periphery of Disappointment Valley the formation forms hogbacks and cuestas.

Sandstone in the Dakota is chiefly fine to medium grained, light brown to dark gray, and carbonaceous. It is thin bedded to massive and is generally crossbedded. Sandstone in the lower arenaceous unit of the Dakota typically occurs in lenses, is festoon crossbedded, and shows abundant scour-and-fill structures characteristic of fluvial sediments. That in the upper arenaceous unit shows crossbedding that is dominantly of the torrential or incline type in thin flaggy sandstone strata as much as a foot thick. Individual beds appear to be laterally more extensive than those in the lower unit. Sandstone in the upper unit is ripple marked in places and locally shows abundant sand-filled "worm borings." This sandstone is interpreted as mostly of marine or marginal marine origin.

The conglomerate contains pebbles of sandstone, quartzite, and chert, in most places colored drab gray and brown in contrast to the generally brighter colored pebbles in the underlying Burro Canyon Formation. Locally, conglomerate at the base of the Dakota contains cobbles as much as 1 foot in diameter.

The shale, mudstone, and coal are thin bedded and generally evenly bedded. The shale and mudstone are characterized by great abundance of carbonaceous material, and the mudstone contains appreciable silt- and sand-size detrital particles. In many places these rock types grade laterally or vertically into sandstone, siltstone, and coal. The mudstone commonly is massive but some parts weather into fissile fragments and are distinctly shaly.

In the upper part of the middle carbonaceous shale unit of the Dakota, thin layers of medium-gray claystone are common. They are not closely associated with layers of coal, which are common in the lower part of the middle carbonaceous shale unit, and are likely not an underclay type. Possibly some are bentonitic, for they swell and break up readily when they are alternately wet and dried and probably are of volcanic origin.

Coal occurs typically in thin beds such as those described in measured sections 3 and 4 (p. A82–A83). Locally, coal beds may be as much as 10 feet thick, as in diamond drill hole DV–125, or 25 feet thick, as in hole DV–126 (pl. 1) in northeastern Disappointment Valley. The coal is dull and contains 10–20 percent fine-grained gray sandstone and gray claystone.

Despite the great abundance of carbonaceous material in the sandstone of the Dakota and the general lithologic similarity of the lower sandstone layers to those in the ore-bearing sandstone of the Salt Wash Member of the Morrison Formation, uranium deposits in the Dakota in the Slick Rock district are practically unknown. In only one place in the district was appreciable radioactivity, probably attributable to uranium and daughter products, detected in the Dakota. About three-quarters of a mile south of Lookout Point (pl. 1) in the southern part of the district, a road leading to uranium claims in the Salt Wash Member exposes black carbonaceous shale in the middle part of the Dakota on the west rim of the canyon of the Dolores River. Here a layer of shale 1–2 feet thick and perhaps 10–20 feet along bedding shows abnormally high radioactivity suggesting a U_3O_8 content on the order of at least a few hundredths of a percent.

The base of the Dakota has been described as a typical basal conglomerate in some parts of the Colorado Plateau (for example, Carter, 1957). Although this is unquestionably true for the areas described, a basal conglomerate is not a reliable criterion for locating the base of the Dakota in much of the Slick Rock district. First of all, as pointed out in previous pages, "basal" conglomerates occur at several horizons in the Burro Canyon Formation, and where sandstone of the Dakota overlies sandstone of the Burro Canyon, the presence of such a conglomerate within the Burro Canyon incorrectly indicates the contact of the two formations. Secondly, where a basal conglomerate occurs locally at or near the base of the Dakota, other lithologic criteria serve better to distinguish the two formations, even though the occurrence and position of the basal conglomerate correctly reflect the disconformity of the contact. Typical relationships are shown on plate 15. Near the right end of the diagram the "basal" conglomerate shown consists of angular fragments of quartzite in silicified sandstone that also contains some iron-stained molds of plant fragments. But the thin layer of "basal" conglomerate immediately underlies carbonaceous shale typical of the Dakota and is only local, so that the base of the lowest carbonaceous shale serves as a more practical contact than does the "basal" conglomerate. Moreover, a short distance to the southeast, "basal" conglomerate, which is clearly not at the same stratigraphic horizon as that just under the carbonaceous shale, lies in sandstone beneath layers of greenish-gray shale of characteristic Burro Canyon lithology. Here the contact can be drawn reasonably only at the base of the carbonaceous shale; this contact, moreover, correlates precisely with that established to the northwest. Shown at the left end of plate 15 is a "basal" conglomerate consisting of angular fragments of quartzite and lying near the top of a sandstone layer of Burro Canyon lithology, immediately below carbonaceous shale. Here the "basal" conglomerate is an integral part of a depositional unit that has Burro Canyon rather than Dakota characteristics. Again the contact is reasonably placed at the base of lithology that characterizes the Dakota—carbonaceous shale—and again this contact correlates precisely with the contact established on the same basis to the northwest.

These relationships in no way negate the validity of a disconformable contact between the Dakota and the Burro Canyon in most of the Slick Rock district, as described in detail by Simmons (1957, p. 2524–2525). Simmons pointed out that the contact between the formations in the Disappointment Valley area is commonly one of carbonaceous shale upon greenish-gray shale and is "conformable, sharp, and not gradational" (p. 2525). Nevertheless, even in the Disappointment Valley area basal conglomerate has been observed at the base of the Dakota. For example, drill cores from diamond-drill hole DVR–2, sec. 36, T. 44 N., R. 18 W. (pl. 1), show that the lower 1 foot of the Dakota overlying greenish-gray mudstone of the Burro Canyon consists of light-gray conglomerate, whose pebbles are gray and greenish-gray mudstone, and some fragments of carbonized wood. Clearly the Burro Canyon was partly consolidated and was being eroded in nearby areas when the first stratum of the Dakota was deposited in the Disappointment Valley area.

Measured sections of the Dakota Sandstone follow.

Section of the Dakota Sandstone, north of Bradfield Ranch on the west side of the Dolores River north of Williams Draw, T. 39 N., R. 17 W.

[Measured by G. C. Simmons and W. B. Rogers with Brunton and tape, September 1956. Here the formation shows its characteristic tripartite division]

	Thickness (feet)
Dakota Sandstone:	
7. Sandstone, light-brown, fine- to medium-grained; trace of dark minerals; moderate amount of carbonaceous material; moderate number of limonite stains and spots; flaggy; locally crossbedded. Upper part poorly exposed; interval is the upper arenaceous unit of the Dakota; unit may be thicker than measured. Overlain by Mancos Shale	25
6. Shale, dark-gray, carbonaceous, some coal; contains leaves identified by R. W. Brown as *Aneimia* sp. and *Dewalquea pulchella* Knowlton and dicotyledonous leaves. Upper part of middle carbonaceous shale unit	10
5. Sandstone, brown, very fine grained; trace of dark minerals; moderate amount of carbonaceous material; moderate number of limonite stains; crossbedded. Contains a few thin layers of dark-gray carbonaceous shale. Lower part of middle carbonaceous shale unit	6
4. Sandstone, light-gray and light-brown, medium-fine- to medium-grained; trace of dark minerals and carbonaceous material; abundant interstitial calcite; abundant limonite spots; crossbedded. Upper part of lower arenaceous unit	20
3. Sandstone, light-gray and light-brown, fine-grained and conglomeratic; trace of dark min-	

Section of the Dakota Sandstone, north of Bradfield Ranch on the west side of the Dolores River north of Williams Draw, T. 39 N., R. 17 W.—Continued

	Thickness (feet)
Dakota Sandstone—Continued	
erals and carbonaceous material; abundant small pebbles; crossbedded	13
2. Conglomerate, light-brown; abundant pebbles and large angular blocks of sandstone and chert from the Burro Canyon Formation as much as 1 ft in diameter concentrated toward the base; moderate number of limonite stains; crossbedded	8
1. Sandstone, light-brown, fine- to medium-grained; sparse to moderate limonitic plant impressions. Lower part of lower arenaceous unit. Contact with underlying Burro Canyon Formation disconformable	4
Total Dakota Sandstone	86

Section of the Dakota Sandstone, also showing tripartite division, in Big Canyon, sec. 22, T. 41 N., R. 18 W.

[Measured by G. C. Simmons and N. L. Archbold with Brunton and tape, September 1956]

	Thickness (feet)
Dakota Sandstone:	
3. Sandstone, gray and light-brown; medium-fine- to fine-grained; trace to moderate dark minerals and limonite stains. Upper arenaceous unit. Top of Dakota is eroded and locally covered with loess, but top of exposure is probably within a few of top of formation	68
2. Sandstone, brown, very fine grained to fine-grained, interbedded with dark-gray shale; poorly exposed. Middle carbonaceous shale unit	23
1. Sandstone, light-brown and gray, fine-grained; trace of dark minerals; abundant limonite spots; lower 15 ft conglomeratic, with boulders as much as 1 ft in diameter in lower 5 ft. Lower arenaceous unit. Disconformably overlies the Burro Canyon Formation	34
Total Dakota Sandstone	125

Section of the Dakota Sandstone lacking a clearly defined lower arenaceous unit, northeast side of Disappointment Valley, SE¼ sec. 17, T. 43 N., R. 16 W.

[Measured by G. C. Simmons and W. B. Rogers, November 1955, by tape from plane table control points]

	Thickness (feet)
Dakota Sandstone:	
16. Sandstone, light-brown, fine-grained; trace of carbonaceous material; moderate number of limonite stains; massive, crossbedded; sand grains chiefly quartz, well rounded. Forms cliff. Upper part of upper arenaceous unit	15.2
15. Sandstone, light-brown, fine-grained; moderate number of limonite stains; crossbedded; massive at top becoming thin bedded at base; friable. Lower part of upper arenaceous unit	18.8
14. Shale, light-brown and gray; abundant silt and sand; 20 percent carbonaceous material on	

Section of the Dakota Sandstone lacking a clearly defined lower arenaceous unit, northeast side of Disappointment Valley, SE¼ sec. 17, T. 43 N., R. 16 W.—Continued

	Thickness (feet)
Dakota Sandstone—Continued	
bedding planes; trace of limonite stains; fissile	.9
13. Coal, black; 40 percent shale; abundant limonite stains	1.3
12. Shale, light-brown, weathers white; abundant carbonaceous material; silicified	.1
11. Coal, black; 10 percent shale	.6
10. Shale, black, gray, and brown; abundant carbonaceous material; abundant limonite stains; slightly silicified in top 0.1 ft	.3
9. Shale, light-brown; weathers white; abundant carbonaceous material; silicified	.1
8. Coal and shale, black; a few thin siliceous shale layers	12.7
7. Coal and shale, black; poorly exposed	28.0
6. Sandstone, very light brown, medium-fine- to fine-grained; abundant carbonaceous material; thin bedded	8.5
5. Sandstone, light-brown, fine-grained; moderate number of limonite stains; massive, crossbedded. Forms cliff	18.6
4. Selenite; abundant carbonaceous material	.1
3. Shale and coal, black; sparse limonite stains	5.5
2. Sandstone, light-gray, very fine grained to fine-grained; abundant carbonaceous material; trace of limonite stains	1.4
1. Coal and shale, black. Conformably overlies sandstone of the Burro Canyon	5.9
Total Dakota Sandstone	118.0

Section of the Dakota Sandstone measured about 2 miles southwest of the foregoing section

[Measured by D. R. Shawe from drill cores taken from diamond-drill hole DVR–1, sec. 30, T. 43 N., R. 16 W.]

	Thickness (feet)
Mancos Shale (incomplete):	
45. Mudstone, dark-gray, dark-reddish-gray 2-ft layer 9 ft above base; silty in places; sand grains 3.5 ft above base, lower 1 ft sandy, gradational into sandstone below; very abundant calcite; moderate to abundant pyrite as cubes up to ¼ in. across in lower 5 ft; sparse biotite; abundant dispersed carbonaceous material, sparse flakes of carbonaceous material; ⅛-in. seam of light-gray claystone 12 ft above base; 3-in. medium-gray limy nodule 10 ft above base; very abundant *Gryphaea* in 1-ft layer 19 ft above base	22.3
Total incomplete Mancos Shale	22.3
Dakota Sandstone:	
44. Sandstone, dark-gray in upper 2 ft and lower 10 ft, mottled light gray and dark gray between, medium-fine-grained; lower 9 ft fine grained, massive; sparse black opaque minerals, biotite and pyrite; calcite abundant in thin layers 17, 16, 15, and 2 ft above base, sparse	

Section of the Daktoa Sandstone measured about 2 miles southwest of the foregoing section—Continued

Dakota Sandstone—Continued	*Thickness (feet)*
elsewhere; very abundant seams and interstitial carbonaceous material; moderate amount of interstitial white clay; near top and base abundant interstitial gray clay; sparse greenish-gray clay granules; abundant sand-filled "worm borings." Gradational into mudstone below	18. 8
43. Mudstone, dark-gray; sparse calcite; abundant flakes of carbonaceous material; very abundant fine to medium sand grains. (Most mudstone in drill cores is massive but upon wetting and drying breaks up as poorly fissile shale. The common presence of sand grains makes the term "mudstone" generally appropriate.)	3. 2
42. Claystone, light-gray; abundant pyrite, biotite, moderate black opaque minerals; trace to no calcite	. 05
41. Mudstone, dark-gray; sparse calcite; moderate amount of dispersed carbonaceous material	3. 0
40. Claystone, medium-gray; sparse calcite seams, biotite and pyrite	. 5
39. Mudstone, dark-gray; sparse calcite and ¼-in. pyrite nodules; abundant dispersed carbonaceous material; thin layer of granules composed of quartz, chert, claystone, and carbonaceous material 9 ft above base	11. 4
38. Claystone, medium-gray; sparse biotite and pyrite; black opaque minerals; sparse quartz sand grains	. 4
37. Limestone, light-gray; sparse pyrite; nearly horizontal webwork of ⅛-in.-thick calcite layers; sparse interlaminated claystone lenses	. 3
36. Mudstone, dark-gray; slighty sandy with moderate number of thin sandstone laminae; sparse calcite interlayered with moderate amount of calcite; abundant dispersed carbonaceous material and flakes of carbonaceous material	5. 6
35. Sandstone, light-gray to white, very fine grained, generally massive; sparse black opaque minerals and biotite; moderate flakes and films of carbonaceous material, laminae about every ½–2 ft, very abundant carbonaceous material in lower 1.5 ft; sparse to moderate interstitial white clay. Gradational into mudstone below	20. 1
34. Mudstone, dark-gray; abundant dispersed carbonaceous material	1. 6
33. Sandstone, light-gray overlying dark-gray, very fine grained; sparse black opaque minerals; very abundant carbonaceous material; sparse interstitial white clay. Gradational into mudstone below	5. 7
32. Mudstone, dark-gray interlayered with black; sparse pyrite, abundant in coaly part; very abundant carbonaceous material, coaly in bottom ½ ft; 0.1-ft thick very fine grained sandstone layer 10 ft above base	11. 5
31. Siltstone, light- to medium-gray; sparse ¼-in. pyrite nodules; abundant fragments, films, and flakes of carbonaceous material	1. 0
30. Claystone, medium-gray; trace of carbonaceous material	1. 0
29. Mudstone and sandstone, dark-gray interlayered with light-gray; sandstone very fine grained; moderate pyrite nodules; very abundant fragments, flakes, seams, and dispersed carbonaceous material; interstitial gray clay in sandstone	1. 2
28. Coal, black; moderate number of ½-in. pyrite nodules; ½-in. dark-gray mudstone layers 1.2, 0.8, and 0.7 ft. above base; impure in thin layers about 1 and 2 ft. below top; vitreous coal in lower 1.3 ft	4. 3
27. Mudstone, dark-gray to black; very abundant seams and dispersed carbonaceous material	. 3
26. Coal, black, vitreous	. 9
25. Mudstone, dark-gray overlying medium-gray; abundant pyrite nodules; sparse calcite; abundant flakes of carbonaceous material	. 8
24. Coal, black; sparse pyrite; impure	. 6
23. Mudstone, black; sparse pyrite; coaly; leaf imprints	. 8
22. Coal, black, vitreous; sparse calcite in fractures	. 5
21. Mudstone, black, coaly	. 7
20. Mudstone, dark-gray; sparse to moderate carbonaceous plant fragments	2. 7
19. Mudstone, black, coaly; sparse pyrite nodules	5. 8
18. Coal, black; impure in thin layers at base and 1, 1½ and 2½ ft. above base	3. 3
17. Mudstone, black, coaly; impure coal and vitreous coal seams in places; calcite seams in vitreous coal	1. 4
16. Mudstone, dark-gray; trace of calcite; moderate carbonized plant fragments abundant 4 ft. above base	8. 8
15. Mudstone, black; abundant ½-in. pyrite nodules at base; very abundant carbonaceous material	1. 9
14. Coal, black, vitreous; sparse ½-in. pyrite nodules	1. 0
13. Mudstone, black; very abundant carbonaceous material; coaly in places	. 1
12. Coal, black; abundant calcite in fractures	. 3
11. Mudstone, black; very abundant carbonaceous material; coaly in places	. 7
10. Coal, black, vitreous	. 8
9. Mudstone, black; very abundant carbonaceous material; sandy near base	3. 4
8. Sandstone; light-gray interlayered with dark-gray in ½–2-in. layers; very fine grained; sparse pyrite and black opaque minerals; sparse to abundant interstitial gray clay; moderate amount of interstitial white clay;	

Section of the Daktoa Sandstone measured about 2 miles southwest of the foregoing section—Continued

	Thickness (feet)
Dakota Sandstone—Continued	
abundant flakes, films, and interstitial carbonaceous material	2.6
7. Mudstone, black; sparse pyrite nodules; coaly; silty near base	2.6
6. Siltstone, light-gray interlayered with medium-gray; sparse mica, black opaque minerals and calcite; moderate number of flakes of carbonaceous material; abundant interstitial gray clay; mudstone layers in places	3.2
5. Mudstone, medium-gray; sparse flakes of carbonaceous material; slickensided	2.0
4. Sandstone, light-gray, very fine grained; sparse black opaque minerals; moderate amount of biotite; sparse to abundant calcite; sparse flakes of carbonaceous material; moderate amount of interstitial white clay	1.9
3. Mudstone, medium-gray overlying black; abundant pyrite near base; very abundant carbonaceous material in lower 2 ft	7.8
2. Sandstone, dominantly light-gray interlayered with minor dark-gray, very fine grained to fine-grained overlying coarse-grained; sparse black opaque minerals, barite and pyrite; 1-in. pyrite nodules near top; trace of calcite near base; abundant flakes, films, seams, and pebbles of carbonaceous material; abundant interstitial light-gray clay; granules and small pebbles of quartzite and chert in lower 2 ft	6.6
Total Dakota Sandstone	151.1
Burro Canyon Formation (incomplete):	
1. Mudstone, light-greenish-gray; moderate amount of very fine grained pyrite, coarse grained in places; trace of calcite, abundant in 10-ft. thick layer 7 ft. above base, mottled sparse to abundant in lower 5 ft.; sparse black opaque minerals; abundant red chert grains, sparse chert granules; light-gray chert and calcite seams 18 and 22 ft. above base, moderate pyrite in the higher; sandy; very sandy in lower 12.5 ft., grades into sandstone below	26.7
Total incomplete Burro Canyon Formation	26.7

Surface distribution and configuration

The Dakota Sandstone is widely exposed in the Slick Rock district, underlying most of the south half of the district. Except where it is soil covered, it makes up almost the entire surface of the Sage Plain, the northeast flank of the Dolores anticline, and the Glade Highland; it was removed by erosion only along the canyon of the Dolores River, Narraguinnep Canyon, and small canyons that drain the northeast flank of the anticline. In the north half of the district it is exposed in a platter-shaped strip of cuestas around the periphery of Disappointment Valley and in patches on Horse Range Mesa.

Complete sections of Dakota Sandstone are rare on the Sage Plain and Glade Highland. However, as erosion into the Dakota has been slight in many places, and thickness measurements in these places correspond to complete sections nearby, the Dakota Sandstone is believed to have a rather uniform thickness of about 120 feet over most of the district. The formation is noticeably thicker in the Disappointment Valley area, with a maximum well-established thickness of about 180 feet, determined in diamond drill hole DV–126. An isopach map of the Dakota is shown in figure 43. The area where the Dakota is thicker than about 125 feet nearly coincides with the thicker part of the Brushy Basin and Burro Canyon interval and is directly opposite the large evaporite cell in adjacent Big Gypsum Valley.

MANCOS SHALE

The Mancos Shale was named by Cross (1899, p. 3–4). The type locality is in the Mancos Valley surrounding the town of Mancos, between the La Plata Mountains and Mesa Verde in southwestern Colorado, about 35 miles southeast of the Slick Rock district. Both the upper and lower contacts of the Mancos are arbitrary because of gradational lithology and the Mancos and associated formations show mutual lateral transitions; for these reasons usage of Mancos imposes various problems with increasing distance from the type locality. The proximity of the Slick Rock district to the type locality minimizes such problems, however, and our usage is in essence the same as that of Cross.

Owing to erosion no complete section of the Mancos remains in the district. According to data from diamond-drill hole DVR–1, about 860 feet of the lower part of the Mancos remains in the center of Disappointment Valley near the east edge of the district (pl. 1).

In Gypsum Valley, at the northeast edge of the district, an apparently complete section of the Mancos Shale is about 1,600 feet thick. In Disappointment Valley, about 8 miles southeast of drill hole DVR–1, a complete measured section of the Mancos totals about 2,300 feet.

Outside the Slick Rock district the Mancos Shale is overlain by dominantly terrestrial sandstone, mudstone, and coaly beds of the Mesaverde Group of latest Cretaceous age, and younger units such as the Wasatch and Green River Formations of Tertiary age, which once must have extended across the district. These units, totaling possibly 5,000 feet in thickness were removed by erosion following middle Tertiary uplift of the Colorado Plateau.

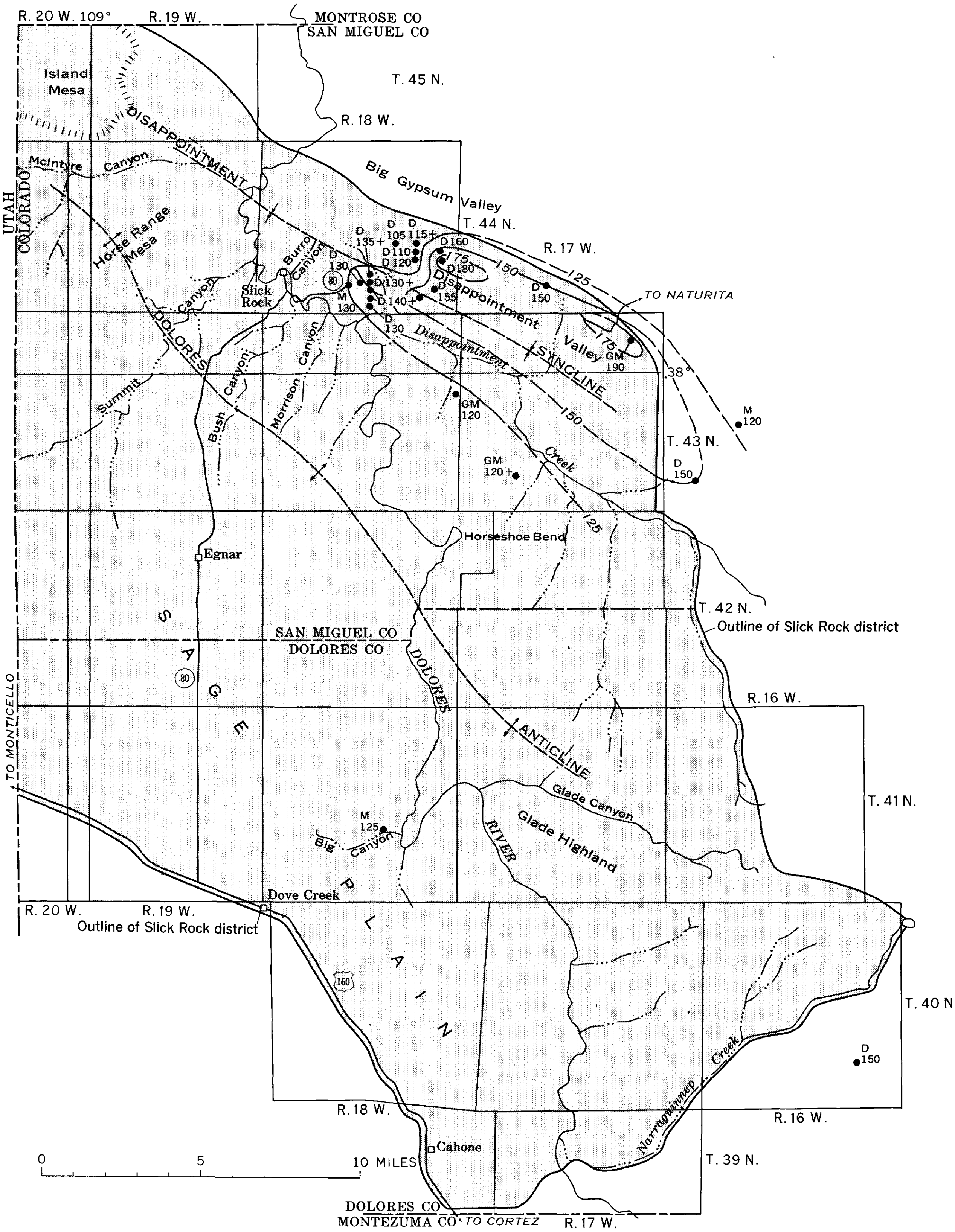

FIGURE 43.—Thickness of the Dakota Sandstone. Isopachs dashed where uncertain; interval 25 feet. Number by control point (dot) is measured thickness, in feet, of the formation; letter indicates method of measurement: M, measured section; D, diamond-drill hole; GM, geologic map.

Age

Marine fossils are abundant throughout most of the Mancos Shale, and there are few outcrops where fossils cannot be found. Large collections made by Shawe (1963b) from cores of diamond drill holes DVR–1 and DVR–2 and by O. T. Marsh from three measured sections indicate that the Mancos is equivalent in age to this succession of strata: upper middle and upper parts of the Greenhorn Limestone, Carlile Shale, Niobrara Formation, Telegraph Creek Formation, Eagle Sandstone, and lower part of the Pierre Shale of the Western Interior of the United States. These rocks, in terms of the standard European stage names, are in, successively, the upper part of the Cenomanian, the Turonian, and the lower part of the Senonian Stages of the Upper Cretaceous (pl. 16).

The lower part of the Mancos, about 860 feet thick, in Disappointment Valley was divided by the late J. B. Reeside, Jr. (written commun., March 1956), principally on the basis of fossils in drill core from hole DVR–1, into six fossil zones as follows:

The Mancos Shale can perhaps best be classified by equivalence to subdivisions recognized in the Great Plains. I would assign the highest fossils in the cores to a later Niobrara equivalent and would extend this to about 225 feet depth. In this interval *Inoceramus stantoni* Sokolow, *Baculites codyensis* Reeside, *B. asper* Morton, *Phlycticrioceras oregonense* Reeside are more distinctive species, and *Ostrea congesta* Conrad ranges throughout. The next 150 feet, to about 375 feet depth, must represent the earlier Niobrara, but there are few distinctive fossils in the cores. I would assign the next 170 feet to about 540 feet depth, to the later Carlile, in which interval *Inoceramus dimidius* White, *I. fragilis* Hall and Meek, *Scaphites whitfieldi* Cobban, *S. ferronensis* Cobban, *Prionocyclus macombi* Meek, and *P. wyomingensis* Meek are distinctive. The next 240 feet, to about 780 feet depth, must represent the earlier Carlile, but *Collignoniceras hyatti* (Stanton) in the upper part and *C. woollgari* (Mantell) in the lower part are the only distinctive fossils. One would expect a late Greenhorn fauna in the next 45 feet, to 825 feet depth, but nothing distinctive is available. The remaining cores, to 855 feet depth, contain chiefly *Gryphaea newberryi* Stanton, which is associated with the early Greenhorn, in Gilbert's original sense of the name, or with the next-to-the-top of four units, in the broader sense of Greenhorn now prevalent. *G. newberryi* is widespread in Utah, western Colorado and Arizona at or near the base of the marine Upper Cretaceous beds.

Reeside described (written commun., May 1956) fossils from drill cores of hole DVR–2, representing a much narrower stratigraphic interval at the base of the Mancos. He stated,

I would assign the first 127 feet to an equivalent of the lowest part of the Carlile shale, the zone of *Collignoniceras woolgari* (Mantell). The next lower 46 feet to about 173 feet depth, like the similar interval in DVR–1, would be expected to yield an uppermost Greenhorn fauna, but nothing distinctive is available. The remaining 13 feet of the hole, to 189.0 feet depth, contains the distinctive forms *Gryphaea newberryi* Stanton and *Exogyra columbella* Meek, which mark the lower part of the Greenhorn of Gilbert or the upper middle part of the Greenhorn, as the term is now applied.

The interval described on the photogeologic map of the Mancos (pl. 1) as late middle Greenhorn age and characterized by the presence of *Gryphaea newberryi* is the unit shown on plate 16 as equivalent to the next-to-the-top of four Greenhorn members.

One fossil collection, made by G. C. Simmons, from the Mancos in sec. 30, T. 41 N., R. 16 W., where the road to Big Spring crosses The Glade, was described by Reeside (written commun., August 1956): as follows:

The only significant species in this lot I would call *Inoceramus labiatus* (Schlotheim), which is characteristic of a late Greenhorn equivalent. The most abundant fossil is a small, simple oyster (*Ostrea* sp.) that has no time value. One or two blocks show Globigerina on weathered surfaces, but this again has no time value. A fragment of wood or bark and the impression of a fish vertebra complete the list.

The three sections measured by O. T. Marsh, in May 1955, are in the southeastern part of Disappointment Valley; sections A and B are shown on plate 1 and section C is on the southwest side of the valley about 3 miles southeast of the southeast corner of the area shown on the detailed map of the Mancos Shale, plate 1. Macrofossils and microfossils in collections from the measured sections were identified by J. B. Reeside, Jr., and Ruth Todd, respectively (written communs., 1955), both of the Geological Survey. In each measured section abundant *Gryphaea newberryi* identify beds equivalent to the upper middle part of the Greenhorn at the base of the Mancos Shale. In all three sections no fossils were collected from the intervals that are likely of late Greenhorn and earlier Carlile age.

One fossil collection from strata of later Carlile age (measured section B, pl.1) contains *Prionocyclus macombi* Meek and *Inoceramus dimidius* White.

The macrofossils and microfossils from the Mancos Shale measured sections A and C (pl. 16) were used to correlate the Mancos in the Slick Rock district with Upper Createaceous units elsewhere. This was done by comparing the collections with the Cretaceous correlation chart of Cobban and Reeside (1952, facing p. 1011). The lower part of the Mancos, as already indicated, can be correlated readily with the standard section for the Western Interior. The upper part is less easily correlated because most fossils are foraminiferra whose ranges are unknown; further, those whose ranges are known are too wide-ranging to provide more than approximate correlations. Even so, most of the collections are probably equivalent to the Taylor Marl of the Gulf Coast, of Campanian age, though some of the lower collections may be correlative with the upper part of the Austin Chalk of the Gulf Coast, of Santonian age.

Lithology

The Mancos Shale is principally dark-gray carbonaceous calcareous shale containing abundant silt and sand grains, pyrite, biotite, and glauconite in many layers. Minor limestone, siltstone, sandstone, and bentonitic shale or claystone make up some strata. The Mancos is remarkably evenly bedded, and in strata containing arenaceous detritus it commonly displays graded bedding. Limestone occurs as thin even beds a fraction of an inch to about 3 feet thick and as layers of nodules ranging from spherical "cannonballs" about 6 inches in diameter to large oblate concretions several feet across. Siltstone and sandstone occur as evenly bedded strata a fraction of an inch to as much as 40 feet thick. Bentonitic shale beds are thin layers a fraction of an inch to a foot or so thick that contain very little carbonaceous material and are therefore light gray to light greenish gray, and contrast with the dark-gray shale that predominates in the Mancos. The formation abounds in marine invertebrate fossils, chiefly pelecypods and cephalopods in the lower part and foraminifera in the upper part, which consistute a distinct lithologic aspect of the rocks.

Where capped by resistant materials such as sills in the southeastern part of Disappointment Valley and gravels in the vicinity of Glade Mountain (pl. 1) or by sandstone of the Mesaverde Group outside of the district, the Mancos Shale forms steep slopes. Where unprotected, the soft strata are eroded into subdued topography such as that which characterizes Disappointment Valley (pl. 1).

Perhaps the most characteristic aspect of shale in the Mancos is its dark-gray color imparted by a fairly small amount (only a few percent) of carbonaceous material in the form of carbonized plant fragments and possibly material of petroliferous character. Calcite is commonly much more abundant in the shale, making up as much as 25 percent of the rock, but its chief effect on the appearance of the rock is only to lighten its tone.

Iron sulfide, chiefly pyrite, is common but unevenly distributed. In the lower part of the Mancos, the pyrite content ranges from nearly 0 to several percent of the rock in the intervals of strata that are correlative in age with the upper middle part of the Greenhorn, the upper part of the Greenhorn, the upper part of the Carlile, and the lower part of the Niobrara. Pyrite is sparse to practically absent in the lower part of the Carlile and the upper part of the Niobrara, where it is generally not visible in hand specimens but can be detected under the microscope. The distribution of pyrite in the upper part of the Mancos Shale is not well known, but it is locally abundant and locally absent. In dark-gray shale the pyrite occurs as replacements of fossils, as nodules that are aggregates of irregularly crystallized or cubic pyrite, and as well-formed crystals up to half an inch across, chiefly of cubic habit. Some pyrite is dispersed evenly as minute grains in clay, although commonly such occurrences tend to show concentrations along bedding planes. Marcasite probably also is present in the Mancos Shale, and locally may be abundant. Where iron sulfide was abundant in the Mancos, at the surface the rocks are stained brownish to yellowish gray by limonite developed as a result of oxidation of the sulfide.

Even though shale is the dominant rock in the Mancos, much of it is not particularly fissile, especially where it contains abundant grains of silt and sand and calcite. Unweathered samples of the rock, such as drill cores, are characteristically massive, and this fact together with the presence of appreciable silt and sand prompted the use of the term "mudstone" in the core logs of the Mancos.

Where sand grains are particularly abundant, the mudstone is massive and tends to stand up in outcrop above the softer shale around it, as in unit D of the calcareous pyritic shale of later Carlile age and the middle part of the calcareous shale of later Niobrara age shown on plate 1.

Freshly broken drill cores of mudstone from a few horizons in the Mancos have a strong petroliferous odor.

Limestone in the Mancos Shale occurs as thin beds a fraction of an inch to about 3 feet thick and as layers of nodules that range from small spherical bodies about 6 inches in diameter to large disk-shaped concretions as much as 5 feet across. The limestone, both in layers and in nodules, is typically silty or sandy. A few thin limestone layers consist of coquina. Microfossil tests, probably largely foraminifera, are visible in most thin sections of limestone layers. Pyrite is abundant in much of the limestone, in amounts up to about 15 percent of the rock. Carbonaceous material is abundant in many limestone layers but is not evident in limestone concretions. Although limestone occurs throughout the Mancos Shale, it is a major rock type in only a few horizons, such as in unit A of the calcareous pyritic shale of later Carlile age shown on plate 1. It also occurs as a bed a few feet thick in the interval of calcareous pyritic shale of late and late middle Greenhorn age in an outcrop along Colorado Highway 80 in Disappointment Valley, in the middle of the south boundary of sec. 35, T. 44 N., R. 18 W. (pl. 1).

Nearly all of the limestone concretions are septarian nodules. The nodules occur in certain layers, rather than scattered at random throughout the formation. They contain cores of calcite with numerous irregular arms or septa of calcite extending radially outward toward the surface of the nodule. A cross section of a "cannonball" septarian nodule is shown in figure 44. Many of the cores of the nodules are vuggy, lined with rhombohedral crystals of calcite.

Numerous thin beds of light-gray to light-greenish-gray bentonitic shale or claystone occur throughout the Mancos Shale. In the lower part of the Mancos, they are restricted to strata equivalent to the Greenhorn, the Carlile, and the lower part of the Niobrara. The bentonitic beds are sparse in strata equivalent to the upper part of the Niobrara. This distribution parallels that of pyrite in the lower part of the Mancos and, indeed, pyrite is clearly most abundant in bentonitic beds even though it occurs also in mudstone throughout the intervals in which bentonitic beds are numerous. Where the bentonitic beds are weathered at the surface they are light yellowish gray to light brownish green because of the oxidation of pyrite to limonite. The layers are composed dominantly of clay that swells appreciably when alternately wet and dried, and they likely represent volcanic ashfall material. Some layers contain appreciable amounts of silt and very fine to fine sand-size detritus and could be called mudstone, but unlike the more prevalent dark-gray mudstone the bentonitic layers do not have a continuous size range of particles from clay to silt or sand. Instead, relatively well sorted grains of silt or sand are dispersed throughout clean mineral clay.

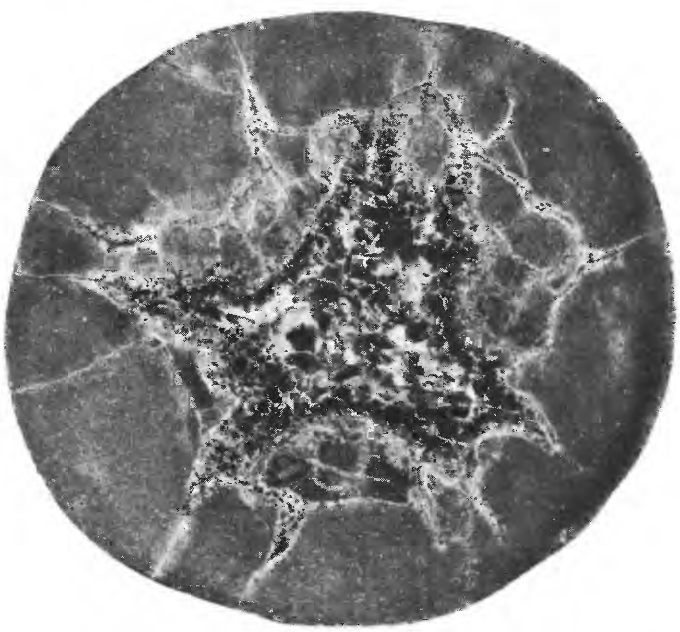

FIGURE 44.—Cross section of a limestone septarian nodule 5 inches in diameter from the lower part of the Mancos Shale, Disappointment Valley; calcite fills septa in sandy limestone. Photograph by F. H. Spence.

The Mancos Shale is transitional with the underlying Dakota Sandstone in two respects. First, sandstone layers at the top of the Dakota that are probably of marine origin extend eastward and tongue out in shale of the basal part of the Mancos (for example, Young, 1960, p. 180) and indicate transgression of the Mancos sea westward over the Dakota. Second, sandstone layers at the top of the Dakota grade upward imperceptibly through a thickness of a few feet into mudstone or shale at the base of the Mancos, which has suggested to other writers that the Mancos is conformable upon the Dakota and was deposited with westward transgression of the Mancos sea over the Dakota (Reeside, 1924, p. 9; Baker, 1933, p. 54; and Repenning and Page, 1956, p. 261).

Measured sections of the Mancos shale follow.

Section of the Mancos Shale where it conformably underlies the Mesaverde Group east of the Slick Rock district

[Measured by O. T. Marsh with Jacob staff and Abney hand level, May 1955]

	Thickness (feet)
Mancos Shale:	
23. Shale, dark-gray; contains foraminifera; OTM coll. loc. 27	2
22. Shale, dark-gray	476
21. Shale, dark-gray; contains foraminifera; OTM coll. loc. 26	2
20. Shale, dark-gray	123
19. Shale, dark-gray; contains foraminifera; OTM coll. loc. 25	2
18. Shale, dark-gray	113
17. Shale, dark-gray; contains foraminifera; OTM coll. loc. 24	2
16. Shale, dark-gray	133
15. Shale, dark-gray; contains foraminifera; OTM coll. loc. 23	2
14. Shale, dark-gray	14
13. Shale, dark-gray; contains *Inoceramus* sp. and *Baculites* sp	1
12. Shale, dark-gray; contains a 1-ft-thick bed of yellowish-brown highly calcareous siltstone at base	10
11. Shale, dark-gray	113
10. Shale, dark-gray; contains a persistent 1-ft-thick bed of platy, light-brown, highly calcareous siltstone in layers ⅛–¼ in. thick; the shale contains foraminifera; OTM coll. loc. 21	2
9. Shale, dark-gray; a prominently outcropping continuous ledge of shale 20 ft thick occurs 55 ft above the base of the unit (860 ft above the base of the Mancos); the ledge probably partly corresponds to the middle silty and sandy part of the calcareous shale of later Niobrara and possibly younger age shown on plate 1	505
8. Shale, dark-gray; contains moderately abundant fragments of pelecypods (including large *Inoceramus* sp.) and, at top of unit, rare fragments of large, thick-ribbed ammonites; OTM coll. loc. 20 at top of unit, and OTM coll. loc. 18, 30 ft above base of unit	185

Section of the Mancos Shale where it conformably underlies the Mesaverde Group east of the Slick Rock district—Continued

	Thickness (feet)
Mancos Shale—Continued	
7. Shale, dark-gray	94
6. Sandstone, dark-gray, weathering yellowish brown, fine-grained, highly calcareous; in beds as much as 1 in. thick; contains fossils; OTM coll. loc. 17	3
5. Shale, dark-gray	13
4. Sandstone and some dark-gray shale; sandstone is yellowish brown, platy, very thinly bedded, fine grained, and contains fossils; OTM coll. loc. 16	15
3. Shale, dark-gray; interbedded with light-brown, very thinly bedded (beds ⅛–¼ in. thick), platy, fine-grained to very fine grained sandstone; shale contains discoidal nodules as much as 1 ft. in diameter and 5 in. thick; also gypsum and thin layers of yellowish-brown, cone-in-cone calcite; some limonitic layers. Two layers of nodular limestone occur at 372 and 427 ft. above base of Mancos (probably within unit A shown on plate 1) and are 2–3 ft. thick, dark gray, weathering yellowish brown and consist of irregular to well-rounded calcareous bodies, locally veined with dark-purple calcite; some have cores of coarsely crystalline white calcite	380
2. Shale, dark-gray; contains very abundant *Gryphaea newberryi* and rare sharks' teeth; at top of unit is a 6-in.-thick ledge of very light gray weathering dark-gray fine-grained glauconitic sandstone with flaky fracture	25
1. Shale, dark-gray	90
Total Mancos Shale	2, 305

Section of the lower 856 feet of the Mancos Shale showing details of lithology

[Measured by D. R. Shawe from drill cores taken from hole DVR–1 in Disappointment Valley, June–November 1955]

	Thickness (feet)
Mancos Shale (incomplete):	
58. Mudstone, dark-gray, silty, broken, badly weathered; mixed with soil and other alluvium in top part. Where weathered the Mancos displays its shaly character; in drill cores the fresh rock is poorly fissile though well bedded, and the common occurrence of silt and sand particles in the dominant clay make the term mudstone generally appropriate for the rock	21.0
57. Mudstone, dark-gray (*N*3.5), bottom 1 ft darker, silty; very abundant calcite; moderate amount of very fine grained mica flakes; sparse small shell fragments; abundant medium-grained biotite 2½ ft above base; fibrous calcite in thin convoluted septa, probably shell fragments, 6½ ft above base	35.2
56. Sandstone, light-gray, fine-grained; very abundant biotite; sparse calcite; light-gray interstitial clay	.02
55. Mudstone, dark-gray (*N*3.5), darker gray (*N*3) 28–33 ft above base, silty; very abundant calcite; moderate amount of very fine grained mica flakes; darker gray interval shows salt efflorescence and contains very abundant fossil fragments and abundant calcite; very abundant fossils in 1-ft-thick layer 35 ft above base; very sparse brown clay pebbles and granules 6–29 ft above base; ¼-in.-thick siltstone layer with very abundant fine-grained biotite 56 ft above base; thin siltstone and fine-grained sandstone laminae 37 and 28 ft above base; 10-ft-thick layer 64 ft above base contains abundant very thin layers of light-gray siltstone; mudstone is very silty in 1½-ft layer 46 ft above base; thin greenish-gray claystone layer with abundant biotite 71 ft above base; thin calcite lamina containing randomly oriented crushed fibrous rods 40 ft above base; petroliferous odor 44 ft above base	163.1
54. Claystone, light-greenish-gray; very abundant very fine grained pyrite; moderate amount of fine-grained biotite; no calcite	.05
53. Mudstone, dark-gray (*N*3.5), silty; sparse brown claystone pebbles in lower 9 ft; ¼-in.-thick claystone layer with abundant fine-grained biotite, no calcite, 0.2 ft below top; biotite-rich gray siltstone 1 ft above base; petroliferous odor 2–3 ft below top	11. 3
52. Claystone and siltstone, light-gray; very abundant very fine grained pyrite	. 02
51. Mudstone, dark-gray (*N*3.5), silty; sparse brown claystone pebbles ½–4 ft above base; abundant biotite in very sparse thin light-gray layers; abundant pyrite 6–9 ft above base; petroliferous odor in lower part; some ⅛–¼-in.-thick layers of claystone and siltstone with abundant fine-grained biotite and pyrite and sparse calcite	15. 6
50. Claystone and siltstone, light-gray	. 3
49. Mudstone, dark-gray, silty; very abundant calcite; very abundant very fine grained biotite; sparse calcite and sparse pyrite locally	3. 0
48. Claystone, light-greenish-gray; sparse pyrite; abundant very fine grained biotite; no calcite	. 07
47. Mudstone, dark-gray (*N*3.5), silty; abundant to very abundant calcite; sparse very fine-grained mica; abundant carbonaceous material and pyrite in seam 0.3 ft above base; sparse to abundant $\frac{1}{16}$–½-in. nodules of pyrite and disseminated pyrite 10–34 ft above base, calcite less abundant with pyrite; abundant medium-grained glauconite, biotite, and pyrite in 0.3-ft-thick layer 10 ft above base, and 1½-ft-thick layer 3 ft above base	50. 2
46. Claystone, light-greenish-gray; very abundant fine-grained biotite	. 1
45. Mudstone, dark-gray (*N*3.5), silty; abundant calcite; sparse $\frac{1}{16}$-in. pyrite nodules in top 3 ft; moderate amount of pyrite 41 ft below top; pyrite with fossil fragments 3 ft above	

Section of the lower 856 feet of the Mancos Shale showing details of lithology—Continued

	Thickness (feet)
Mancos Shale (incomplete)—Continued	
base; sparse dark sulfide 13 ft above base; abundant medium-grained biotite 9 ft below top and 2–3 ft above base; very sparse carbonized plant fragments; very sparse brown clay pebbles and granules and greenish-gray pebbles 10 ft below top; mudstone generally contains very sparse pyrite and fossils; very thin light-greenish-gray claystone with abundant biotite 57 ft below top; moderate glauconite granules and grains with sparse pyrite in ½-ft-thick layer 21 ft above base; fossils, pyrite, medium-grained biotite, and thin gray siltstone laminae more abundant in bottom 10 ft	115.8
44. Claystone, light-gray; abundant pyrite and fine-grained biotite	.1
43. Mudstone, dark-gray; abundant fine- to medium-grained biotite; very abundant calcite; moderate number of fossile fragments	4.4
42. Claystone, light-gray; abundant fine-grained biotite; no calcite	.3
41. Mudstone, dark-gray (N3.5); moderate amount of very fine-grained biotite, very abundant calcite; very abundant pyrite with fossil fragments and small fossils 8, 8½, and 10 ft below top and in lower 23 ft; sparse to moderate thin light-gray limy siltstone seams; thin light-gray claystone seam 18 ft above base; 3-in. limestone concretion 6 ft above base	37.7
40. Claystone, light-greenish-gray; trace of calcite; moderate amount of pyrite and fine-grained biotite; sparse silt grains	.2
39. Mudstone, dark-gray; very abundant calcite; very sparse fossils in top 2 ft	6.6
38. Claystone, light-gray; moderate amount of fine-grained biotite; sparse calcite; sparse silt and sand grains; ½-in.-thick dark-gray mudstone layer in middle	.4
37. Mudstone, dark-gray; very abundant calcite; very sparse to moderate very fine grained to medium-grained biotite; sparse to moderate pyrite in 1-ft-thick layer 15 ft above base; moderate number of light-gray silty limestone seams; thin light-greenish-gray claystone seam 22 ft above base; ¼-in.-thick light-greenish-gray claystone layer with moderate amount of medium-grained pyrite and biotite, no calcite, 20 ft above base; generally abundant fossils, sparse in lower 2 ft; imperfect cone-in-cone structure in 5-ft-thick layer 15 ft above base; petroliferous odor in same layer	24.4
36. Claystone, medium-light-gray (N6.5); trace of calcite; moderate amount of fine-grained biotite; some fine quartz sand grains	5
35. Limestone, medium-gray; moderate amount of dispersed clay, claystone seams	.1
34. Mudstone, dark-gray; very sparse irregular brown claystone granules and pebbles; abundant limestone layers, some silty, as much as 1 in. thick; sparse pyritized fossils; ½-in.-thick claystone seam with moderate amounts of pyrite, fine-grained biotite and quartz 5 ft below top; every 2–5 ft mudstone is fissile and blacker and has salt(?) efflorescence through thickness of 2–4 ft; limy layers generally have abundant small fossil fragments; minor slickensides throughout Mancos down to this level, especially near irregular limestone layers	15.9
33. Claystone, light-gray; sparse pyrite; abundant medium sand grains; no calcite; bentonitic	.1
32. Mudstone, dark-gray; fossil wood twig 0.1 ft above base	1.8
31. Claystone, medium-gray; sparse fine-grained pyrite; moderate amount of biotite, moderate number of quartz grains	1.1
30. Mudstone, dark-gray; sparse pyritized fossils	6.2
29. Limestone, light-gray; sparse fine-grained pyrite; shows healed irregular fractures; trace of calcite in mudstone above and below limestone; selvage of light-gray claystone at top and bottom of limestone; contact inclined 30° at top and 45° at bottom suggesting that the limestone is part of an oblate nodule	.9
28. Mudstone, dark-gray; sparse very fine grained biotite; interlayered sparse, moderate, and abundant calcite; very sparse limestone laminae; sparse fossils, some pyritized; weak petroliferous odor locally	22.7
27. Coquina, dark-gray; abundant pyrite; made up of very abundant fossile fragments in dense dark-greenish-gray clay matrix	.3
26. Mudstone, dark-gray (N3.5); interlayered sparse, moderate, and abundant calcite; sparse carbonaceous material; abundant thin limy laminae, some silty; moderate small plant fragments in laminae 5 ft above base; very thin gray claystone seam with sparse pyrite and biotite ½ ft above base	16.7
25. Claystone, medium-gray; very abundant fine sand grains; no calcite	.05
24. Mudstone, dark-gray	1.1
23. Claystone, light-greenish-gray; abundant pyrite in ¼–½-in. nodules; very abundant fine sand grains	.1
22. Mudstone, dark-gray; sparse calcite, abundant in a few places; sparse pyrite in a few limy siltstone laminae; sparse carbonaceous material; ½–1-in. siliceous nodules 20 ft above base; fissile in top 8 ft; large irregular fossil fragments composed of calcite, and carbonized plant fragments in 0.1-ft-thick light-gray mudstone layer ½ ft above base	28.5
21. Claystone, light-gray; moderate amount of calcite; abundant medium biotite and quartz grains	.2
20. Mudstone, dark-gray, medium-dark-gray (N4) in bottom 5 ft; calcite sparse to absent except	

Section of the lower 856 feet of the Mancos Shale showing details of lithology—Continued

	Thickness (feet)
Mancos Shale (incomplete)—Continued	
for ⅛-in. calcite seams 17 ft above base; sparse very fine grained biotite; sparse carbonized plant fragments; abundant silt with sparse to abundant very fine glauconite grains in 3-ft-thick layer 4½ ft below top; mudstone generally has very uniform lithology; more silty in 30-ft-thick layer containing abundant thin siltstone (*N*4.5) layers with glauconite 35 ft above the base; no silt in bottom 10 ft; ½-in.-thick light-gray claystone layers with no calcite 46½ and 46 ft above base; very sparse fish scales	100.7
19. Claystone, medium-gray (*N*5); sparse fine-grained biotite and quartz; no calcite	.1
18. Mudstone, medium-dark-gray above dark-gray; no calcite; silty at base	2.1
17. Claystone, medium-light-gray (*N*6); abundant fine-grained biotite and quartz; no calcite	.05
16. Mudstone, dark-gray (*N*3.5); trace of calcite, abundant in bottom 1 ft; sparse carbonized plant fragments; some thin siltstone laminae with sparse to abundant calcite 10 ft above base; 1½- by 3-in. calcite nodule with minute cone-in-cone structure 12 ft above base	47.8
15. Claystone, light-gray; abundant fine-grained pyrite and medium-grained biotite; moderate amount of fine-grained quartz; no calcite	.1
14. Mudstone, dark-gray; abundant calcite	19.4
13. Claystone, light-greenish-gray; trace of calcite; abundant fine-grained pyrite; moderate amounts of fine-grained biotite and quartz	.1
12. Mudstone, dark-gray; abundant calcite; minute pyrite nodules 8½ ft above base, ⅛- by ½-in. nodules near base; thin light-gray claystone seam 9 ft below top	21.2
11. Claystone, light-yellowish-gray; moderate amount of fine-grained black opaque minerals; no calcite	.05
10. Mudstone, dark-gray; abundant calcite	.3
9. Claystone, light-greenish-gray; abundant fine- to medium-grained biotite; no calcite	.1
8. Mudstone, dark-gray (*N*3.5); abundant calcite, very abundant in lower 39 ft; moderate amount of very fine to fine-grained biotite; moderate number of thin limestone laminae with abundant fossil fragments; locally mudstone is dense and massive with very abundant calcite and sparse to abundant pyrite; between 21 and 3 ft above base the mudstone is chiefly very dense with abundant pyrite; ½-in. pyrite nodules 20 ft above base, 1/16-in. cubes with fossils 11 ft above base, ⅛-in. cubes with fossils 6 ft above base	42.1
7. Claystone, light-gray	.2
6. Mudstone, dark-gray; bedding compressed around ½-in. pyrite nodule containing cubes smaller than 1/16-in	2.8
5. Claystone, light-gray; sparse pyrite and biotite; moderate amount of black opaque minerals; no calcite; gradational into mudstone above	.5
4. Mudstone, dark-gray; sparse to moderate fine- to medium-grained biotite; very abundant calcite; moderate fossils	13.0
3. Claystone, light-gray; sparse fine-grained black opaque minerals; sparse medium-grained biotite; sparse calcite	.1
2. Mudstone, dark-gray; very abundant calcite, sparse in lower 1 ft; abundant pyrite cubes 17, 14, and 1 ft above base; very abundant fossils in 1-ft layer 14 ft above base; ¼-in thick light-gray claystone seams 17, 16, and 2 ft above base; sandy in lower 4 ft, gradational into sandstone below	20.2
Total incomplete Mancos Shale	856.0
Dakota Sandstone (incomplete):	
1. Sandstone, dark-gray above light-gray, medium-fine-grained; sparse black opaque minerals; sparse to moderate pyrite; sparse calcite interlayered with abundant calcite in top 1 ft, sparse below; very abundant carbonaceous material, both interstitial and in seams; moderate amount of interstitial white clay; sparse granules of greenish-gray claystone; dark-gray clay and carbonaceous material abundant in top 2 ft	8.2
Total incomplete Dakota Sandstone	8.2

Units 1 and 2 above do not coincide in detail with corresponding units 44 and 45 of the measured section in the description of the Dakota Sandstone, also from cores of DVR–1. A drill hole drilled to a depth of 864 feet, and from which the Mancos section was measured, was abandoned because of drilling difficulties, and a new hole nearby was plugged to a depth of 830 feet. The log of cores below that depth in the second hole, also called DVR–1, provided the data for all deeper strata encountered.

Surface distribution and configuration

The Mancos Shale in the Slick Rock district is confined to Disappointment Valley, the area of Glade Mountain and The Glade, a few scattered small areas southwest of Glade Mountain and The Glade, and an area 2 miles northwest of Dove Creek.

Because of the restricted distribution of the Mancos and the scarcity of complete sections of the formation in the vicinity of the Slick Rock district, variations in thickness are poorly known. One complete section of the Mancos is about 1,600 feet thick where the formation has been preserved in a large foundered block in the axial part of the collapsed Gypsum Valley anticline (Cater, 1955e). A complete section measured in the southeastern part of Disappointment Valley, near the axis of the Disappointment syncline, is about 2,300 feet thick. In view of the clear evidence that the variations in thickness of many formations older than the Mancos Shale are related to the axes of the folds, it seems reasonable that if other complete sections of the Mancos were present in this area they too would reflect this pattern.

Strata of late middle Greenhorn age at the base of the Mancos are 30–115 feet thick. In the position of drill hole DVR–1 and measured section B (pl. 1) the interval is thinnest; in the position of drill hole DVR–2 and measured section A (pl. 1) the interval has an intermediate thickness; and in the position of measured section C farther southeast in Disappointment Valley the interval shows its greatest measured thickness. Strata from late Greenhorn through later Niobrara age, inclusive, appear to be of similar thickness where data are available, except that all these intervals are thicker in measured section A (total of 1,100 ft) than in drill hole DVR–1 (total of 830 ft) (pl. 1 A′–A′). No detailed data are available on possible thickness variations in the upper part of the Mancos.

TERTIARY IGNEOUS ROCKS

Igneous rocks in the Slick Rock district are known at the surface only on Glade Mountain (pl. 1), where they crop out in a few very small areas. The outcrops are alined approximately on a projected fault and are probably part of a dike intruded along the fault. Igneous rocks are also known from the cuttings of deep oil-test wells in and near the district, including the vicinity of Glade Mountain. They appear to be intruded mostly in the salt unit of the Paradox Member of the Hermosa Formation as sills (pl. 3), and are probably the same rock as, and physically connected with, the surface rocks at Glade Mountain. A series of sills intruded in the Mancos Shale and Dakota Sandstone about 1 mile east of the east edge of the district, in Disappointment Valley (pl. 1), are related to the igneous intrusions at Klondike Ridge, at the southeast end of Gypsum Valley, and were described briefly by Vogel (1960).

ANDESITE PORPHYRY AT GLADE MOUNTAIN

Near the top of Glade Mountain a few outcrops of igneous rock lie along the north side of the Glade graben and are interpreted as parts of a dike intruded along a fault. The outcrops consist of large to small angular blocks of light-gray andesite porphyry. In hand specimen the rock shows flow layers and some lineation of mafic minerals. According to an estimate of the mineral composition of a thin section, the andesite consists of a little more than 50 percent crystals in a microcrystalline groundmass. Phenocrysts as much as 2 mm across include about 45 percent sodic labradorite, mostly unzoned with rare crystals slightly zoned; 5 percent augite, mostly rounded and partly resorbed, with common solution embayment along the *c* crystallographic direction in the manner of etched sedimentary pyroxenes; 3 percent magnetite, commonly resorbed; 1 percent biotite, some considerably resorbed, with reaction rims of augite and magnetite; and a trace of apatite, mostly enclosed in labradorite. Part of a thin section of the andesite porphyry is illustrated in figure 45. Judged from the chemical composition of the rock, shown in table 5, the matrix of the rock is much more silicic than the phenocrysts and probably consists chiefly of quartz, potassium feldspar, and plagioclase more sodic than labradorite.

The andesite is likely related to the igneous rocks of the San Juan Mountains, being similar in composition to rocks described by Larsen and Cross (1956); chemically similar rocks include "quartz latite" and "rhyolite" (Larsen and Cross, 1956, table 21, samples 8, 19, 36, and 55) from their "Potosi volcanic series" of Miocene age, "quartz latite" in the Fisher Quartz Latite (Larsen and Cross, 1956, table 23, p. 190, sample 9) of Miocene or late Tertiary age, and intrusive "quartz latite" such as the Cimarron Creek Latite of the Ouray area (Larsen

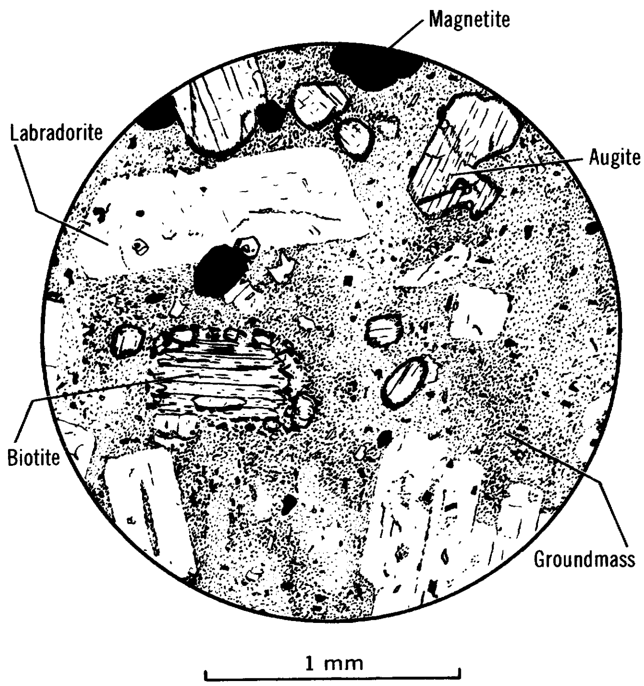

FIGURE 45.—Pen-and-ink drawing of thin section of andesite porphyry from Glade Mountain. Phenocrysts of labradorite and partly resorbed augite, magnetite, and biotite lie in a groundmass composed probably of quartz, potassium feldspar, and plagioclase more sodic than labradorite. Sample SH–69–56.

and Cross, 1956, p. 216; table 26) of Miocene or Pliocene age. The andesite is not chemically like rocks with similar SiO_2 content in the Colorado Plateau laccolithic centers, for example the Henry Mountains (Engel, 1959, table 10), being appreciably higher in total iron oxides, MgO, K_2O, and TiO_2, and lower in Al_2O_3, CaO, and Na_2O. In addition, the phenocrysts in the andesite porphyry, both in composition and in marked resorption effects, are similar to those in rocks from the San Juan field (Larsen and Cross, 1956) and unlike those from the Colorado Plateau laccoliths (for example, Hunt, 1958, p. 319–320).

Float identical to the andesite porphyry on Glade Mountain was found in the vicinity of Rock Spring about 4 miles northwest of Glade Mountain (pl. 1). The rock was not found in place, but it may occur as a dike intruded locally along the Springs fault 2–3 miles northeast of The Glade (pl. 1). Andesite porphyry may also be present in other places northwest of Glade Mountain.

TABLE 5.—*Chemical and semiquantitative spectrographic analyses of andesite porphyry from Glade Mountain*

[Sample SH-69-56(F2422). Chemical analysis by P. M. Montalto; semiquantitative spectrographic analysis by R. G. Havens]

Chemical analysis (in percent)		Semiquantitative spectrographic analysis [1]	
SiO_2	61.82	Ba	0.07
Al_2O_3	15.89	Be	.0015
Fe_2O_3	3.89	Ce	.015
FeO	2.36	Co	.0015
MgO	2.16	Cr	.0015
CaO	4.32	Cu	.003
Na_2O	3.25	Ga	.0007
K_2O	3.99	La	.007
H_2O+	.41	Nd	.007
H_2O-	.23	Ni	.0015
TiO_2	.74	Pb	.0015
P_2O_5	.32	Sc	.0015
MnO	.11	Sr	.07
CO_2	.01	V	.015
Cl	.01	Y	.003
F	.08	Yb	.0003
		Zr	.015
Total	99.59		
Less O	.03		
Total	99.56		
Powder density	2.73		

[1] Figures are reported to the nearest number in the series 7, 3, 1.5, 0.7, 0.3, 0.15, etc., in percent. These numbers represent midpoints of group data on a geometric scale. Comparisons of this type of semiquantitative results with data obtained by quantitative methods, either chemical or spectrographic, show that the assigned group includes the quantitative value about 60 percent of the time.

SILLS IN THE PARADOX MEMBER OF THE HERMOSA FORMATION

Two deep oil-test wells penetrate igneous rocks in the salt unit of the Paradox Member of the Hermosa Formation in and near the Slick Rock district, and two others are bottomed in thick sills at the same horizon about 20 miles east of the district (pl. 3). As suggested on plate 3, the intrusives may be connected at depth and be part of one large sill-like intrusive averaging perhaps 500 feet in thickness with a volume of many cubic miles, but these projections between drill holes are purely conjectural. Sections *B–B′* and *D–D′* on plate 3 show an offshoot of the sill in the Paradox extending up one of the faults bounding the Glade graben; east of the intersection of these sections the rock comes to the surface as the outcrops of andesite porphyry on Glade Mountain.

Igneous rock penetrated in the Buss deep oil test 1, sec. 26, T. 44 N., R. 13 W., a little more than 20 miles east of the district (pl. 3; fig. 10), according to a log by the American Stratigraphic Co., consists of about 350 feet "quartz monzonite." The hole was bottomed in igneous rock, and the intrusive, if a sill, must be thicker than 350 feet. Sedimentary rocks at least 60 feet above the igneous contact, according to the log, were metamorphosed, presumably by the intrusive, and the igneous rock contains shale inclusions apparently derived from the Paradox Member. Cuttings from the sill penetrated in the Lone Dome test 1, sec. 26, T. 40 N., R. 16 W., just south of the district (pl. 3; fig. 3), are made up of calcic plagioclase, potassium-feldspar(?), quartz, augite, biotite, magnetite, and apatite. In the small fragments of rock that comprise the cuttings, the crystals appear to be mostly less than 1 mm in size. The rock may be the same as that described by Bush, Marsh, and Taylor (1960, p. 451–460) as microgranogabbro or microgranodiorite in the Little Cone quadrangle a little more than 30 miles east of the Slick Rock district. Although the rock seems to have a higher proportion of dark minerals than the andesite porphyry on Glade Mountain, the mineral species are the same, and it seems likely that the two rocks originated from the same magma or through related igneous processes. The rock bodies may well be physically connected.

MICROGRANOGABBRO SILLS IN DISAPPOINTMENT VALLEY

Fine-grained dark igneous rocks occur as a series of thin columnar-jointed sills in a northerly alined zone in Disappointment Valley (pl. 1). A few small dikes, most not shown on the map because of the map scale, occur near the south and north ends of the zone of intrusives. The north part of the zone makes up the group of igneous intrusives in the Klondike Ridge area (Vogel, 1960). The rocks of the sills and dikes are microgranogabbro (Vogel, 1960, p. 42), which is intruded mostly in the lower part of the Mancos Shale and partly in the Dakota Sandstone and older rocks. Even though most of the exposed igneous rock in Disappointment Valley is in the form of sills, it was probably intruded to its present level along dikes which at depth may be alined roughly north-south and parallel to the surface faults at either side of the north end of the zone of intrusives, and consequently parallel to the elongate zone itself.

A sample of a sill from the Klondike Ridge area acquired from R. M. Wallace of the Geological Survey was studied in thin section. The rock is porphyritic; some crystals are several millimeters long but most are much smaller. Plagioclase, about 65 percent of the rock, is about intermediate andesine, is clouded by alteration, and shows widely varying types of zoning—mostly progressively more sodic in outer layers. Cores of many crystals have albite twins, and the clearer outside zones show few or no twins. The largest plagioclase crystals are about 7 mm long, but most are much smaller. Biotite makes up about 10 percent of the rock; it is red brown (X = pale yellow; Y, Z = deep metallic red brown), and is partly altered to chlorite. Augite, about 5 percent of the rock, occurs in crystals as much as 4 mm long but most are smaller. About 5 percent magnetite, up to one-half mm in size, 5 percent chlorite, 5 percent quartz as irregular interstitial blebs—some containing minute apatite crystals, and some euhedral where chlorite and carbonate are abundant—and a minor amount of carbonate and apatite make up the remainder of the rock. Stumpy apatite crystals are concentrated in augite, but some needlelike crystals as much as 1.5 mm long extend through adjoining plagioclase and biotite crystals. This rock has features of both microgranogabbro and microgranodiorite in the Little Cone quadrangle described by Bush, Marsh, and Taylor (1960, p. 451–453, 458–459); it could be called quartz andesite porphyry on the basis of the sample described above. Probably the rock varies slightly in composition from sill to sill, or possibly within sills. In any case the rock clearly has affinities with the cited rocks described by Bush and his coworkers in the western part of the San Juan field.

The Mancos Shale is "baked" for a short distance both above and below the sills in Disappointment Valley. Intrusive tongues of the sill extend along bedding in places. Locally, masses of shale are entirely engulfed in igneous rock. The sills as a whole are not at one stratigraphic horizon, but transgress upward in the section toward the axial region of the Disappointment syncline. Furthermore, the sills near the axis of the syncline are at a lower altitude than those on the limbs of the fold. These relationships suggest that the syncline was slightly folded at the time of intrusion and that it was further folded after intrusion. These interpretations are valid if the assumption is correct that the sills were intruded along a nearly horizontal zone. This seems reasonable if the level of intrusion were controlled principally by the thickness of overlying rocks; if the surface were nearly horizontal, intrusion may have taken place in some nearly horizontal zone where the physical character of the host was favorable and lithostatic pressure was low enough to permit the intruding magma to lift the overlying rocks.

WELDED ANDESITE TUFF AT GLADE MOUNTAIN

Near the summit of Glade Mountain a small patch of angular rock rubble about 40 feet across consists wholly of a single type of volcanic rock. None of the rock is clearly part of an outcrop, but the size and homogeneity of the patch and the angularity of the fragments suggest that the rock may be virtually in place. On the other hand, it may be simply remnants of a large block among the heterogeneous volcanic rubble that makes up glacial debris and gravel on Glade Mountain. The rock is a pinkish-brown welded tuff consisting of about 30-percent crystals averaging about 1 mm in size in a devitrified glassy matrix composed of flattened and alined glass shards (fig. 46). Because the principal phenocrysts are andesine and because more definitive data are lacking, the rock is called an andesite, although it may be more silicic than this name suggests. In addition to about 15 percent andesine showing sharp carls-

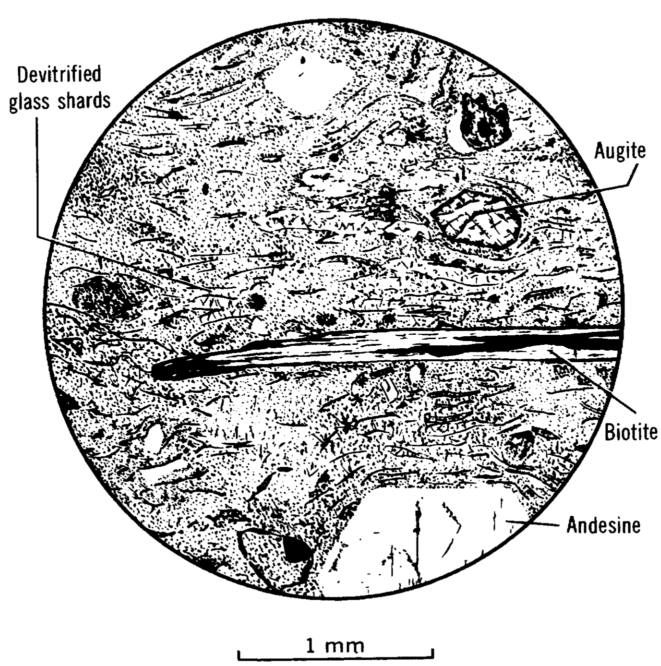

FIGURE 46.—Pen-and-ink drawing of thin section of welded andesite tuff; devitrified flattened glass shards surround scattered crystals of biotite, augite, andesine, and sanidine (not shown). Sample SH-68-56, Glade Mountain.

bad and albite twins and faint oscillatory zoning, the rock contains an estimated 6 percent sanidine with carlsbad and baveno twins in some crystals, 4 percent biotite, which is yellowish to orangish brown with black streaks along cleavage representing hematite formed by oxidation of the biotite during eruption, 1 percent augite, 1 percent magnetite, and 3 percent rock fragments.

AGE

The igneous rocks in the Glade Mountain dike, in Disappointment Valley sills and dikes, and in the sills lying near sea level in the Paradox Member beneath Glade Mountain and a wide area to the east, appear to be petrographically alike, and in addition are similar to a series of intrusive rocks that crop out near the western edge of the San Juan igneous field. The geographic association, similarity of intrusive form, and like petrographic character of all the rocks suggest that they were intruded during a single igneous episode. The time of intrusion was after the deposition of the Mancos Shale, of course, for this formation is intruded by many of the igneous bodies. The exact time of intrusion is impossible to ascertain in the Slick Rock district and vicinity, but it can be estimated within certain limits.

Because some of the intrusions were guided by faults that likely formed after the Mancos was deeply buried and consolidated, it may be that a considerable period of time elapsed between Mancos deposition and intrusion of the igneous rocks. If it is assumed that the sills were intruded in a nearly horizontal plane, an assumption hardly subject to proof, then it appears that the rocks have since been slightly folded as the sills now dip about 50 feet to the mile toward the axis of the Disappointment syncline. Thus, the Mancos Shale was slightly folded at the time of instrusion, for the strata on the limbs of the syncline now dip about 100 feet to the mile. The likely time of intrusion of the sills was somewhere in the early Cenozoic, because the Disappointment syncline at the horizon of the basal part of the Mancos had acquired about a fifth of its structural relief by the end of the Cretaceous and about four-fifths during the Cenozoic, possibly mostly in the late Cenozoic.

The igneous rocks intruded in the Slick Rock district and vicinity may be Miocene in age, but this conclusion is based on extrapolation and interpretation. Larsen and Cross (1956) concluded that those igneous rocks of the San Juan region similar in chemical composition to the andesite porphyry on Glade Mountain were irrupted during the Miocene. Bush, Marsh, and Taylor (1960) estimated that granogabbro bodies of similar composition in the Little Cone quadrangle are no older than Miocene and may be younger. If the Disappointment Valley sills were intruded before extensive erosion on the Colorado Plateau gave the surface considerable topographic relief—considered by Hunt (1956, p. 77) to have been during the Miocene, Pliocene, and Quaternary—then their age can be limited to not younger than Miocene, but this assumption is speculative.

QUATERNARY SURFICIAL DEPOSITS

A variety of surficial deposits, all thought to be Quaternary in age, occur in the district. These deposits are here grouped according to type in an order which approximates the suspected sequence of deposition. The surficial deposits include glacial till, terrace gravels, alluvial fans, landslide debris, loess, other soil, alluvium, colluvium, and talus.

GLACIAL TILL ON GLADE MOUNTAIN

A heterogeneous deposit of a great variety and size range of angular rock fragments on and near Glade Mountain is interpreted to be glacial till. It lies mostly above an altitude of about 9,000 feet. The till consists chiefly of intermediate volcanic rocks ranging in size from minute particles to boulders as much as 10 feet across, mixed randomly in an earthy matrix. None of the fragments was seen to be striated, possibly because of the effect of weathering. Near the top of the mountain the rock fragments are mostly angular, but to the west and generally below an altitude of about 9,000 feet the material is mixed with progressively more and more stream-rounded and better sorted material. Presumably the change marks the transition from a terminal moraine deposit to glacial outwash on the old plain footing the glacier. The most likely source of the till was the western part of the San Juan Mountains, 15 miles or more east of the district. Except for Belmear Mountain (alt. 9,515 ft), 10 miles east of Glade Mountain, most of the land between Glade Mountain and the San Juan Mountains lies below an altitude of 9,000 feet, attesting to considerable dissection since the glaciation that left the till on Glade Mountain. Just east of Glade Mountain at least 1,000 feet of Mancos Shale has been eroded since deposition of the till. Conceivably the elevation of the till on Glade Mountain is partly due to uplift on the fault on the north side of the mountain, but even if such displacement had occurred, the erosion now apparent must have taken place since the glaciation.

The age of the glacial till is not known; it likely is correlative with some of the material in the San Juan Mountains called Cerro Till, considered by Atwood and Mather (1932, p. 107–111) to be very early Pleistocene in age. The name Cerro Till was abandoned by Dickinson (1965) as the material at the type locality was not deposited by a piedmont glacier but by mass-wasting

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processes, primarily landsliding. Nevertheless, the reality of older till in the San Juan Mountains is not doubted. Although Atwood and Mather admitted the lack of accurate means of dating what they called Cerro Till, they pointed out its deeply weathered character and its occurrence on an old surface, deeply dissected since the glaciation, as evidence of great age. They also pointed out its similarity to glacial tills in other parts of the western United States that are dated as older Pleistocene (p. 110–111). Richmond (1957, p. 240–250) described characteristics similar to those of the till on Glade Mountain to indicate pre-Wisconsin age. Pre-Wisconsin ice (Atwood and Mather, 1932, p. 28) spread out from the San Juan Mountains as a piedmont glacier and extended many miles over the surrounding plains, unlike ice of the younger glaciations in the San Juan Mountains, which was largely confined to valleys and canyons. Despite the tenuous correlation with glacial till of uncertain age in the San Juan Mountains, the most likely age of the till on Glade Mountain appears to be pre-Wisconsin.

TERRACE GRAVELS

Stream-deposited gravels occurring in terraces in the Slick Rock district consist mostly of volcanic rocks, with lesser amounts of sedimentary types intermixed. The lower terrace levels appear to have a larger percentage of sedimentary rocks than higher levels. Perhaps the relative amounts of different rock types in the different levels of terraces might permit correlations of the terraces which would substantiate the correlations based on lateral projections (fig. 47). Volcanic rocks in the terrace gravels include varieties common in the San Juan Mountains to the east. Rounded volcanic fragments on the west side of Glade Mountain are chiefly andesite and basalt. The andesite is composed of labradorite, augite, minor iron ores, biotite, and apatite in a glassy matrix. The basalt consists of labradorite, augite, olivine, and iron ores; phenocrysts of all these minerals occur in a coarse intersertal groundmass that contains variable amounts of interstitial chlorite. The basalt is very likely the same as the olivine basalt of the latite-basalt of the Pliocene(?) Hinsdale Formation described by Larsen and Cross (1956, p. 199–203), and probably the andesite is derived from this same sequence. A few rocks consist of welded latite tuff in which about 80 percent of the groundmass is made up of flattened devitrified glass shards and includes phenocrysts of sanidine, labradorite (?), biotite, and minor amounts of quartz, augite, iron ores, zircon, and sphene. A small percentage of the gravel on the west side of Glade Mountain consists of quartzite pebbles and cobbles.

Because much of the gravel on Glade Mountain seems to be material from the Hinsdale Formation, it was likely eroded at a time when the Hinsdale covered a much more extensive area than now, in particular when it spread over the western part of the San Juan Mountains (Larsen and Cross, 1956, p. 196). Judged from the great amount of erosion required to strip the Hinsdale from such a large area, the gravels associated with glacial material on Glade Mountain likely are early Pleistocene in age. Probably they are outwash gravels reworked from glacial till dropped by an ancient piedmont glacier, and they may be correlative with old glacial material that makes up part of the Cerro Till of former usage.

The terrace gravels contain well-rounded pebbles and cobbles that tend to be somewhat flattened. A few small boulders are present, and these are notably slablike.

Stream gravels in residual terraces occur in two principal areas in the Slick Rock district, one in Disappointment Valley and the vicinity of the Dolores River from the junction with Disappointment Creek downstream almost to McIntyre Canyon, and the other at the south end of the district near the junction of Narraguinnep Creek and the Dolores River and in the vicinity of Glade Mountain (pl. 1).

Gravels are widely distributed in residual dissected terraces in Disappointment Valley and along the Dolores River in the vicinity of Slick Rock (pl. 1). The positions of most of these terraces were plotted in profile in order to show which of these groups of terraces seem to correlate (fig. 47). They were plotted above the present stream profile of the Dolores River and Disappointment Creek in this area. The terraces generally lie at only a few clearly defined horizons, which mostly parallel the present gradient of the adjacent stream (fig. 47). In one segment (shown near the center of fig. 47) some groups of terraces have a gradient of about 100 feet per mile; others in the area have gradients of about 20–40 feet per mile. Moreover, the gradients of Section 12 and Joe Davis Canyon levels of terraces, and possibly of the Ellison-Burro level, in this area are parallel where the levels overlap. Because all three levels of terraces project above the VABM (vertical angle bench mark) level of terraces just above and nearly parallel to the present profile of Disappointment Creek (right half of fig. 47), the steeper gradient (shown near the center of fig. 47) is interpreted to reflect structural uplift. Following deposition and dissection of the Ellison-Burro, Joe Davis Canyon, and Section 12 levels, uplift in the area (represented by the right half of fig. 47) warped the old stream profiles. Grade was reestablished with deposition of the lowest terrace, VABM level (shown in the right half of fig. 47), and is still maintained.

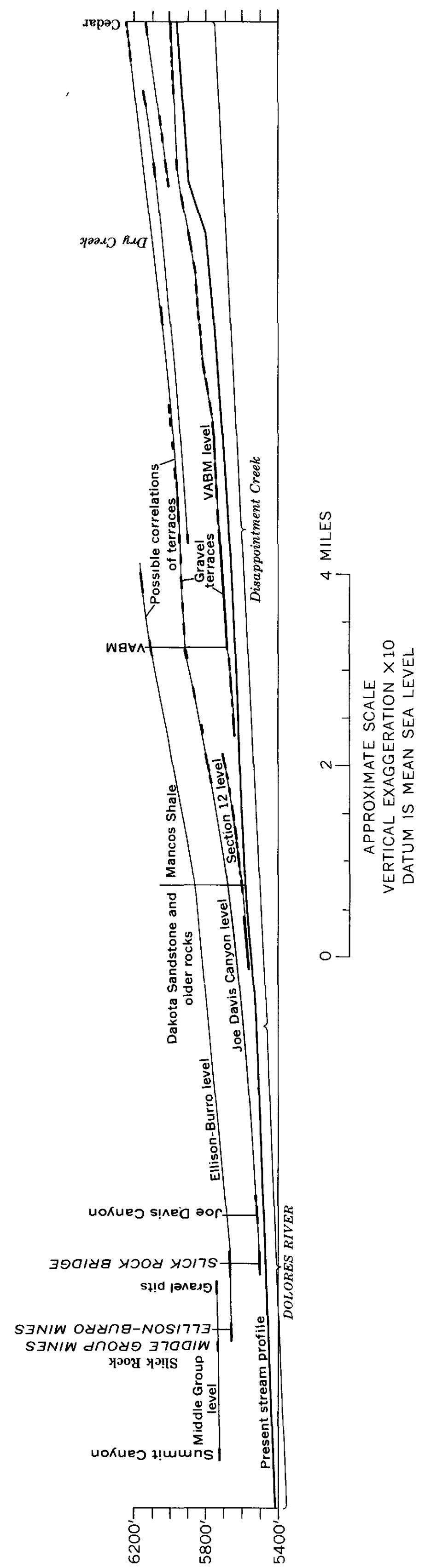

FIGURE 47.—Profile of the Dolores River and Disappointment Creek between Summit Canyon and Cedar and possible correlations of gravel terraces.

If the interpretations are correct for the correlations of terraces shown in the right half of figure 47, the Joe Davis Canyon and Ellison-Burro levels appear to project to equivalents along the Dolores River near Slick Rock, and both lie below a higher terrace level shown as the Middle Group level. The apparent warping of the old stream profiles shown in the left half of figure 47 thus bears out that which is more convincingly shown in the right half of the diagram.

Probably the oldest gravels—those containing abundant material from the Hinsdale Formation and likely of early Pleistocene age—are exposed near the south end of the district in a few isolated patches overlying deeply weathered Mancos Shale (pl. 1; fig. 48). The gravels probably were deposited by streams that cut an erosion surface on the Mancos; the surfaces on which the gravel lies can be projected as a slightly warped plane that truncates bedding in the Mancos (fig. 48). The Mancos is bleached for several feet beneath the gravel, and locally the basal part of the gravel contains a whitish calcareous matrix or caliche. The Mancos Shale was likely unweathered when it was truncated by the streams that left the old gravel deposits. Deep weathering of the shale occurred after gravel deposition, as indicated by the caliche, in gravel just above the shale, which must have been derived from calcite-rich Mancos rather than from the volcanic rocks that constitute the gravel. Younger gravel terraces in the Dolores River Canyon near the junction of Narraguinnep Creek and the river are found at levels about 100, 350, and 650 feet below the projected old erosion surface (fig. 48). These gravels were deposited at successive stages of downcutting of the Dolores River Canyon, and each marks the bottom of the canyon at the time of its deposition.

Similar vertical spacing of terraces along the Dolores River near Narraguinnep Canyon, and along the Dolores River near Slick Rock and Disappointment Creek, hints that the sequences of terraces in the two areas are correlative. For example, the Ellison-Burro, Joe Davis Canyon, and VABM levels near Slick Rock and along Disappointment Creek lie about 75, 250, and 500 feet below the Middle Group level; corresponding levels near Narraguinnep Creek are 100, 350, and 650 feet, respectively, below the old erosion level. If the correlation is correct, it appears that the Dolores River Canyon was deeply incised in the vicinity of Slick Rock before it began to erode in the vicinity of Narraguinnep Creek. But because of the evidence of structural warping in the district during the period of terrace formation, such correlations are tenuous and perhaps meaningless.

At Glade Mountain and on the mesa southeast of Narraguinnep Canyon, fairly extensive deposits of gravel, probably glacial outwash, overlying weathered Mancos Shale are associated with the glacial deposits previously described. Southeast of the canyon a layer of gravel extends almost continuously from a zone of merging with glacial till south of Glade Mountain for a distance of about 10 miles to the rim of the Dolores River Canyon. Toward its southwest end the layer thins, loses much of its earthy matrix, and its constituent pebbles become generally well rounded, better sorted, and smaller. In addition, volcanic rocks, which make up nearly all of the glacial material, are mixed near the river with a small amount of cobbles and pebbles derived from sedimentary rocks.

ALLUVIAL FANS

Alluvial fans are sparse in the district, and where they do appear they are not currently active and are slightly indurated. Their age is attested to by their position above the present canyon bottoms and by dissection due to recent erosion. Small alluvial fans are exposed in a few places on a bench in the Salt Wash Member of the Morrison Formation on the east side of the Dolores River and about 200 feet above the river a few miles north of Slick Rock. A larger group of old coalescing fans occurs on the south side of Horse Range Mesa (pl. 7) where present erosion has cut deeply into the alluvium. The fans are clearly of local origin and the materials of which they are composed are easily traced to the rocks from which they were derived. Much of the alluvium in the fans consists of angular pebbles about 2 inches across in an earthy matrix. Near the Burro Canyon Formation rim at the south side of Horse Range Mesa the old alluvium contains some large blocks of sandstone from the Burro Canyon. Some of the gravel on the northwest side of Disappointment Valley (pl. 1) occurs probably as remnants of eroded alluvial fans.

The alluvial fans are mostly above the level of the oldest terrace gravels in the vicinity of Slick Rock. Though they are not necessarily older than these terrace gravels, they probably predate the latest period of canyon cutting; they may have been deposited during one or more of the interglacial periods of rapid erosion and are likely of Pleistocene age.

Some small modern alluvial fans occur in Disappointment Valley. They are composed mostly of clay washed from the Mancos Shale and in many places are difficult to distinguish from the Mancos except by form. Generally, weathered slopes of Mancos grade imperceptibly into alluvium downslope, and most contacts between the two are arbitrary. (See pl. 1.)

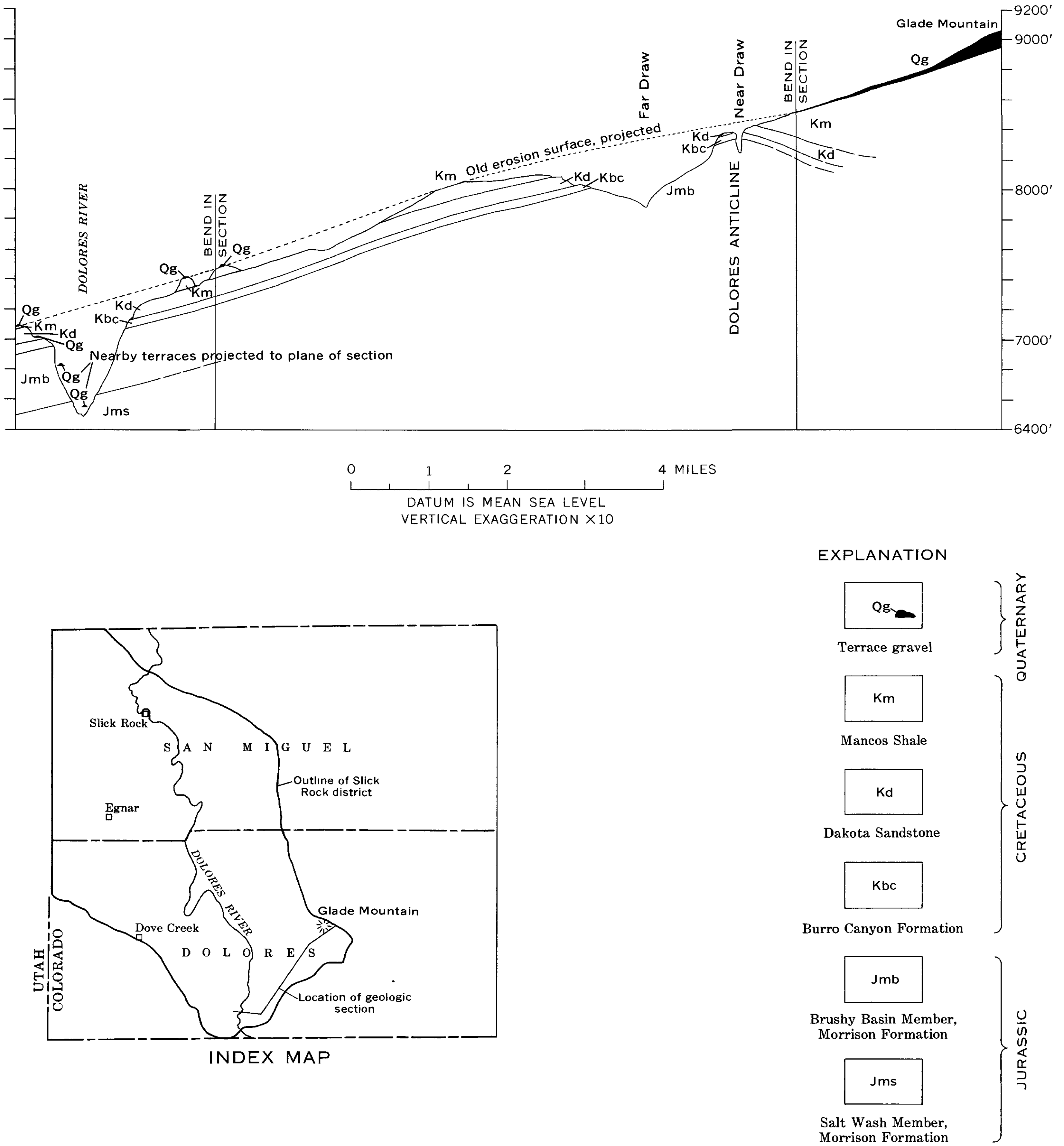

FIGURE 48.—Geologic section between the Dolores River Canyon and Glade Mountain, showing warping of projected old erosion surface. Location of section shown on index map and on plate 1.

LANDSLIDES

Landslides, some covering nearly a square mile, are common in the Slick Rock district (pls. 1 and 7). By far the greatest number and the largest of the slides are on slopes of the Brushy Basin Member. They consist of a great jumble of rock materials in all attitudes and sizes lying on steep slopes of the Brushy Basin. In places large masses several tens to perhaps a few hundreds of feet across are detached from higher strata and now lie with discordant attitude farther downslope from their original position. None of these landslides are now active and most of them show clear signs of considerable erosion. Because of their abundance on the mudstone slopes of the Brushy Basin, the slides probably formed during a period of greater precipitation than the present, when widespread water saturation of the bentonitic mudstone allowed extensive slipping. Many of the slides have the aspect of mudflows; that is, they occur on low slopes and display lobelike configurations, suggesting extensive water saturation as an agent in their formation.

Most of the landslides are thought to be Pleistocene in age because of the suggestion that abundant precipitation accompanied their formation, they are considerably dissected by erosion, and they are inactive. Since they obviously are not older than the present canyons, however, they must have formed during the latest period of heavy moisture, and are probably of late Pleistocene age.

One large landslide in Mancos Shale on the north side of Glade Mountain may be of more recent age. Others occur along the steep walls of The Glade where Dakota Sandstone has slumped onto Mancos Shale in the Glade graben.

Although most of the landslides in the district are thought to be old, at least three small slides occurred during the period 1953–56. We observed these slides shortly after they occurred, each after heavy autumn rains. Even though they occurred because of softening of strata by rain water, they were more like rockfalls than mudflows. The first occurred in the autumn of 1953 when large blocks of sandstone of the Burro Canyon Formation broke loose from the rim north of the Dolores River in sec. 32, T. 44 N., R. 18 W. and fell on Colorado Highway 80, blocking it temporarily. The second slide took place not far away, in October 1955, when huge blocks of sandstone of the ore-bearing sandstone at the top of the Salt Wash Member slid onto a mine road near the Slick Rock bridge. The third slide occurred in the fall of 1956; again large blocks of sandstone from the lower part of the Burro Canyon Formation, some weighing at least several hundred tons, fell onto Colorado Highway 80 in Joe Davis Canyon, sec. 33, T. 44 N., R. 18 W., blocking the road temporarily. The occurrence of all three slides within a mile or two of each other probably was coincidental, for the canyons in this area are no steeper walled than many others in the district where rock slides have not been observed recently. The slides demonstrate the common character of erosion in the canyonlands country: nonresistant strata are sapped by rain wash with the eventual result that, when the nonresistant strata are water saturated, overlying resistant strata can no longer be supported.

LOESS

A generally thin mantle of loess blankets much of the Sage Plain, including the southern part of the Slick Rock district west of the Dolores River as far north as Egnar. Much of the alluvium shown on plate 1 in this area is loess, which has proved to be amenable to the cultivation of pinto beans by dry-farming methods. The loess is considered to be pre-Wisconsin by Hunt (1956, p. 38). The entire deposit extends for nearly 100 miles along the Colorado-Utah State line, has a maximum width of about 70 miles, and covers approximately 3,500 square miles. The deposit probably exceeds 50 feet in thickness in only a few places. Loess occurs in scattered patches elsewhere in the district, including the canyons in the northern part of the district. Near the Cougar mine north of Slick Rock, a small canyon about 10 feet deep was filled with loess and is being exhumed as a result of modern erosion. Locally, loesslike material overlies some of the lower terrace gravels, and in one place it overlies a mudflow. At these localities the loess may have been reworked, so the original age relationships are not clear.

Loess deposited as a thin blanket on the Sage Plain during the Pleistocene later may have been strongly eroded by the wind in places (Shawe, 1963a).

SOIL, ALLUVIUM, COLLUVIUM, AND TALUS

Soil on the pre-Wisconsin loess on the Sage Plain is classified by the U.S. Department of Agriculture as a well-developed Chestnut soil according to Hunt (1956, p. 38; fig. 6). Thorp and Smith (1952) show soil in this area to be well-developed Brown soil and soil in other areas in the district to be well-developed Gray-Brown Podzolic soil. Soil cover in much of the district is thin or absent. The soil is thickest on the Sage Plain where large areas of pinyon and juniper have been cleared since the dustbowl days of the 1930's when displaced farmers came into the region and began cultivating beans and other dry-farm crops. Soil is thin in a few places on both the Mancos Shale and alluvium in Disappointment Valley where farming is meager. Small patches of alluvium along the Dolores River are covered by thin soil that supports a little farming.

Alluvium is most abundant in Disappointment Valley and along the Dolores River and tributary canyons (pls. 1 and 7). It ranges from clayey material, common in Disappointment Valley, to sandy and silty gravel, most abundant along the Dolores River. Silty alluvium from sec. 25, T. 44 N., R. 18 W., in Disappointment Valley, contains heavy minerals in proportions almost identical to those in loess on the Sage Plain. Local bedrock sources of alluvium in the valley contain very much less black opaque minerals than the alluvium, and it is concluded that the alluvium here contains a large amount of windblown loess. Gravel along the river is similar to the terrace gravels (which in fact it will become following the next stage of downcutting). It contains perhaps more sedimentary rocks than the terrace gravels, bespeaking the continuing erosional destruction of the San Juan volcanic pile and concomitant exposure of larger areas of underlying sedimentary rocks.

Small patches of colluvium, shown on pl. 7 included with mantle, are common only on the intermediate slopes in the deeper canyons in the district. Alluvium in Disappointment Valley (pl. 1) is imperceptibly gradational into colluvium locally, and the two were not distinguished in mapping there. The colluvium was formed by mass wasting of intermediate slopes.

Talus debris was also included with mantle in the detailed mapping of the Morrison Formation (pl. 7). It occurs in small patches only on fairly steep predominantly north-facing slopes, attesting to the influence of moisture on mass wasting of oversteepened topography.

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INDEX

[Italic page numbers indicate major references]

U.S. GOVERNMENT PRINTING OFFICE: 1968 O—282-180