Geology and Uranium Deposits of Montezuma Canyon Area San Juan County, Utah

GEOLOGICAL SURVEY BULLETIN 1190

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

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By L. C. HUFF *and* F. G. LESURE

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CONTENTS

ILLUSTRATIONS

[All plates are in pocket]

TABLES

GEOLOGY AND URANIUM DEPOSITS OF MONTEZUMA CANYON AREA, SAN JUAN COUNTY, UTAH

By L. C. Huff and F. G. Lesure

ABSTRACT

The Montezuma Canyon area of San Juan County, Utah, includes the flat uplands near Monticello and the deep canyon system of Montezuma Creek and its tributaries. Geological formations exposed in this area range from the Navajo Sandstone of Triassic (?) and Jurassic age to the Mancos Shale of Late Cretaceous age. In all, about 1,500 feet of sedimentary strata is exposed. The older formations, including the Navajo Sandstone and those of the overlying San Rafael Group of Jurassic age, are all exposed in cliffs and benches within the canyons. The Salt Wash Member of the Morrison Formation of Late Jurassic age contains many sandstone lenses that form a series of prominent tan cliffs and ledges higher on the sides of the canyons.

The Brushy Basin Member of the Morrison Formation consists of a thick series of easily eroded claystones and mudstones which forms a broad topographic bench above the sandstone cliff of the Salt Wash. Above this bench and separating it from the upland surface is a steep cliff composed of the Burro Canyon Formation and the Dakota Sandstone of Cretaceous age. The upland surface itself has a few hills composed of the easily eroded gray to black Mancos Shale of Late Cretaceous age. Unconsolidated formations of Pleistocene and Recent age include pediment gravel and loess on the upland, landslide and colluvial deposits near the cliffs, and alluvial deposits flooring the canyons.

The sedimentary rocks in this area are mainly horizontal. A structure map with contours drawn on the base of the Dakota Sandstone shows that dips are slightly southward at an angle of generally less than 1°. An east-west system of faults and small grabens crosses the head of Montezuma Canyon.

The uranium-vanadium deposits in the Montezuma Canyon area are chiefly in thick massive sandstone beds of the Salt Wash Member. Although some of the deposits have been mined and prospecting within the area has been extensive, the total production has been small—only a few mines have produced more than 1,000 tons of ore.

The ore deposits economically most important are in a relatively small area in middle Montezuma Canyon in a prominent sinuous asymmetric lens of sandstone near the middle of the Salt Wash Member. At both sides the lens grades into thinner sandstones separated by tongues of mudstones. No systematic relation between the location of the ore deposits and the shape of the sandstone lens is readily apparent. Some ore deposits are near the edges of the lens, whereas others are more centrally located; some are near the top; one is near the middle; and others are near the base.

The individual uranium-vanadium ore deposits have a systematic concentric zoning of mineralized and unmineralized rock. The zones, most easily recognized in small deposits, consist of a brown nonmineralized core, an olive-gray

mineralized shell, and a gray nonmineralized outer zone. The brown zone is iron-stained porous sandstone commonly containing abundant carbonaceous material. The curved mineralized layer of the ore zone completely encloses the brown zone, and is composed of oxidized uranium-vanadium minerals that impregnate sandstone. The gray zone is light-gray sandstone, tightly cemented with calcite and commonly freckled with limonitic specks. The ore shell is commonly an irregular flattened ellipsoid 20 to 40 feet long, 10 to 20 feet wide, and 4 to 10 feet thick. The ore layer forming the shell is commonly ¼ to 2 feet thick and follows the bedding or crossbedding of the sandstone except where it curves around to form the ends or the sides of the ore shell. Similar zones are recognizable at some of the larger deposits, but the zoning is more complicated, as if there may have been several stages in the development of overlapping zones.

Geochemical investigations of the distribution of the ore and associated elements within all geologic formations present, within the Salt Wash Member, and within the ore bodies indicate that the uranium-vanadium content of the sedimentary rocks that are more than 10 to 20 feet from the deposits is at virtually background levels. The narrow geochemical halo limits the feasibility of geochemical prospecting.

Geochemical study shows that the ore zone contains more magnesium than the other 2 zones and 10 times as much uranium and vanadium. In comparison with the gray zone, both the ore zone and the brown zone contain an abundance of iron, titanium, silver, cobalt, molybdenum, nickel, zirconium, and yttrium. The gray zone contains very little besides the common rock-forming elements of the quartz sand and its calcite cement.

Formation of the deposits most likely took place when the ore-bearing sandstones were deeply buried and saturated with connate waters. The concentration of organic material in the brown zone suggests that this zone was once saturated with a reducing solution containing hydrogen sulfide and soluble organic compounds like alcohols and aldehydes derived from the organic material. The gray zone, on the other hand, was probably saturated with an oxidizing solution containing uranium and vanadium. Where these two solutions came in contact oxidation-reduction reactions took place that caused the precipitation of low-valent uranium and vanadium minerals.

During this reaction, ore metals disseminated throughout the sandstone gradually diffused toward the brown zone and were precipitated in the ore layer. Weathering and oxidation have since altered the primary low-valent minerals to high-valent forms without noticeable leaching of the ore metals.

Zoning of the uranium-vanadium deposits is of economic interest. In many mines and prospects, ore has been found and partly mined either in the lower ore layer, the upper ore layer, or along part of the edge of an ellipsoidal ore shell. The possibility of more ore in the remaining layer or elsewhere along the edge of the shell has in some places not been tested. Recognition of the presence and habit of these shells may aid future prospecting.

INTRODUCTION

During the 1950's the increased value of uranium spurred an extensive prospecting program reminiscent of the early development of mining in the Western States. As part of the general program of geologic studies of radioactive materials for the U.S. Atomic Energy Commission, the U.S. Geological Survey has made many studies of the uranium-bearing and other formations on the Colorado Plateau to facilitate prospecting and mining. This report, on one of the many areas mapped in detail, describes Montezuma Canyon and vicinity, an area in which many small uranium-vanadium ore deposits occur in the Salt Wash Member of the Morrison Formation.

The Montezuma Canyon area is in San Juan County in the southeastern part of Utah. It includes about 350 square miles covering six 7½-minute quadrangles (pl. 1, figs. 1–2). Monticello, the county seat of San Juan County, is the only town within the map area, but Blanding, Utah, is a few miles to the west, and Dove Creek, Colo., a few miles to the east.

PREVIOUS WORK

J. S. Newberry was the first geologist to visit the Montezuma Canyon area. In 1859 he accompanied Captain Macomb's exploration expedition from Santa Fe, N. Mex., to the junction of the Grand

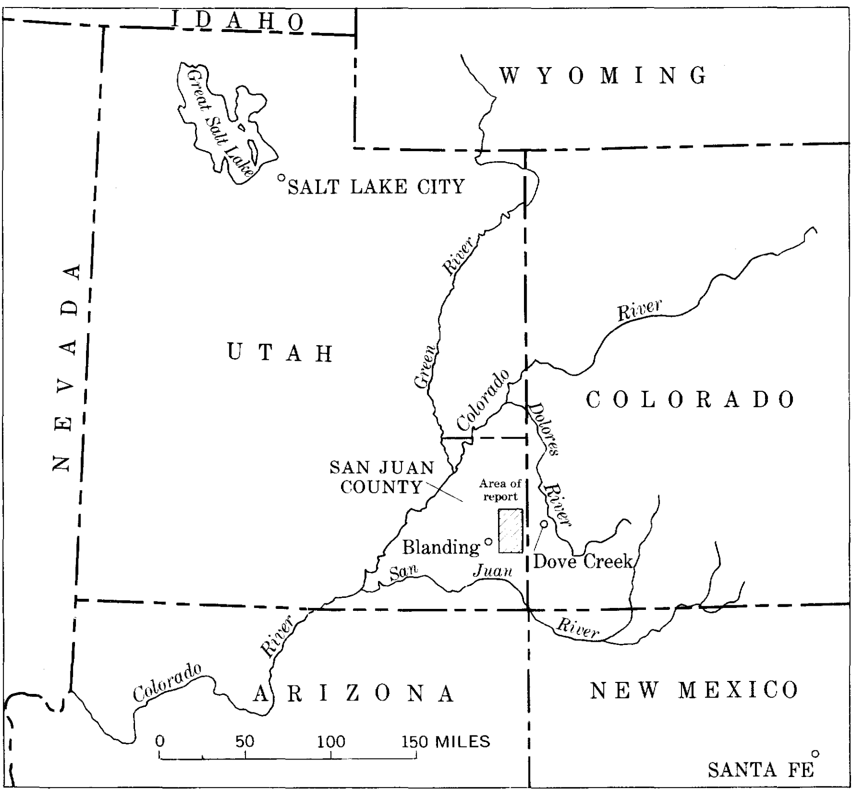

FIGURE 1.—Index map of Utah and adjoining States, showing San Juan County and the Montezuma Canyon area.

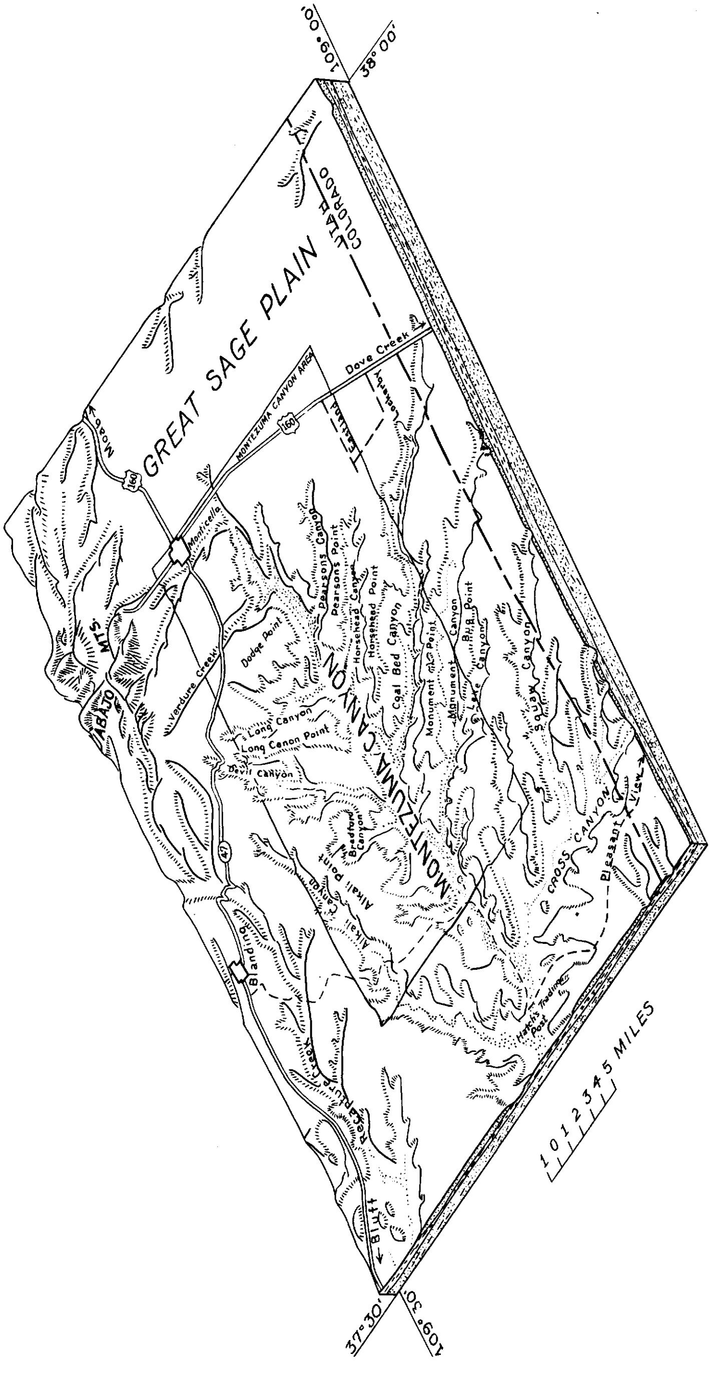

FIGURE 2.—Terrain diagram of Montezuma Canyon area, San Juan County, Utah.

(now the Colorado) and Green Rivers, Utah. This party crossed the broad upland surface east of Montezuma Canyon and named it the Great Sage Plain (fig. 2). On the return trip they crossed the part of the upland west of Montezuma Canyon. Newberry (1876, p. 84), recognized the Cretaceous age of both the Mancos Shale and the Dakota Sandstone (pl. 2) which form the upland surface.

W. H. Jackson (1878, p. 427–430), pioneer western photographer, traveled down Montezuma Canyon and explored its tributary canyons in 1875, studying and photographing the Indian ruins. He described the geology briefly, as did W. H. Holmes (1878, p. 189–193), who visited Montezuma Canyon in 1876. Holmes noted that the middle part of the canyon was about 1,000 feet deep and exposed "the red rocks of the Jura-Trias."

The first geologic map of the area was made by H. E. Gregory (1938) in his reconnaissance study of the geography and geology of the San Juan country. In 1942, R. P. Fischer, J. D. Strobell, Jr., and R. T. Russell, all of the Geological Survey, studied the uranium-vanadium deposits of Montezuma Canyon (Fischer, 1944). In 1944 the area was mapped by the Union Mines Development Corp. for the Manhattan Engineer District (V. R. Chamberlin, written commun., 1946). Sections of the Morrison Formation measured in Montezuma Canyon by L. C. Craig and R. A. Cadigan were used in their regional study of the Morrison stratigraphy (Craig and others, 1955). In 1953 the Atomic Energy Commission conducted an exploration drilling program in Montezuma Canyon.

PRESENT WORK

The investigation described here was made during the period from July 1, 1954, to July 1, 1957. Besides the authors, those who took part in the geologic mapping and contributed otherwise to the fieldwork were geologists Albert J. Froelich and Fred Stugard, Jr., and field assistants Gerald K. Czamansky, Lewis J. Hamilton, and Arnold M. Hanson. X-ray analyses of the ore minerals were by Joan B. Davlin, those of the clay minerals by Richard G. Petersen, both of the U.S. Geological Survey. Preliminary geologic maps of the area on a scale of 1:24,000 have been published (Huff and Lesure, 1958 a, b, and c; Lesure, Huff, and Stugard, 1958 a, b; Lesure and Stugard, 1958).

Concomitant with this investigation similar U.S. Geological Survey mapping projects were in progress in other areas nearby. Some information concerning regional geologic trends obtained from these investigations outside the Montezuma Canyon area is incorporated in this report without special reference. Most of the oil wells of the area have been drilled since the geologic mapping was completed.

The locations of these wells is shown on the geologic map (pl. 1) and data from them are summarized, but no attempt has been made to study the subsurface formations in detail.

The geologic-quadrangle mapping of this area was done to determine the distribution, thickness, and structure of the various stratigraphic units and their relations to the ore-bearing sandstone and to the ore deposits (pl. 1). Detailed geologic mapping was done of the main producing area in middle Montezuma Canyon (pl. 3) and of four of the larger mines (pls. 5–8; fig. 14). Studies of the uranium-vanadium ores included collecting data at more than 80 claims and prospects and sampling 15 of the better exposed ore bodies. More than 1,000 rock samples were collected for use in investigating the geochemistry of the ore deposits and in testing geochemical prospecting methods.

The ore deposits were investigated in detail to find all characteristics of value as prospecting guides. Some of these guides—like the association of ore with thick sandstone, with bleached mudstone, and with carbonaceous materials—have been well established by previous recognition and use in other areas. Others—like the use of ore-zone identification and mapping—have not been recognized heretofore.

GEOGRAPHY

The Montezuma Canyon area is part of the broad upland surface or plateau named the Great Sage Plain by Newberry (1876, p. 84). Near Monticello, in the northern part of the area, the upland surface has an altitude of about 7,100 feet. The surface has been entrenched deeply by Montezuma Creek and its tributaries; a digitate series of canyons separated by innumerable narrow points and isolated mesas (fig. 2) has thus been formed. Montezuma Canyon has a maximum depth of 1,400 feet just north of Long Canyon, and the other canyons are nearly as deep. The upland surface slopes gently southward, and in the southern part of the area the canyons are wider and only about 700 feet deep. The canyons provide excellent outcrops for geologic study and expose about 1,500 feet of sedimentary strata of Jurassic and Cretaceous age. Because a general geography of the area is available (Gregory, 1938, p. 5–35) only a brief description of climate, vegetation, and culture is given here.

In general, rainfall is light; from 1904 to 1958 the mean annual precipitation was 13.58 inches at Blanding and 15.46 inches at Monticello. At Cedar Point on Montezuma Creek, 12 miles southwest of Dove Creek, Colo., the mean annual precipitation from 1947 through 1958 was 14.18 inches. Yearly variations, however, are great; the high was 29.96 inches in 1957 at Cedar Point, and the low 4.93 inches in 1956 at Blanding. Montezuma Creek flows continuously in its upper reaches, but many of its tributaries flow only during the spring and after summer thunderstorms. Flash floods occur sometimes during July and August in Montezuma, Long, and other canyons.

Because of the low precipitation, vegetation is sparse. A low forest consisting chiefly of pinyon pine and juniper, interspersed with open areas of sagebrush, covers much of the upland surface in the northern part of the area. This forest thins toward the south where the upland is lower and drier; here only a broad expanse of sagebrush is left. In the north, large areas of the original sagebrush and pinyon-juniper upland forest have been cleared for dry farming. Pinto beans, wheat, and hay are the principal crops.

Trees in the canyons are limited chiefly to broad-leafed cottonwoods which grow on the alluvium near stream channels. The rocky sides of the canyon have a very sparse vegetal cover consisting chiefly of scattered bushes, cactuses, and a few low scrubby trees. A few ponderosa pine are in the heads of Montezuma and Devil Canyons.

Since Gregory's geographic study of this area, many roads and trails have been built. Good paved highways extend from Monticello south to Blanding and east to Dove Creek. Just north of Verdure Creek a good gravel road leads from the upland surface down into Montezuma Canyon. This road extends along Montezuma Canyon as far south as Hatch's Trading Post south of the mapped area and connects with other gravel roads to Blanding and Pleasant View. Bulldozer trails on Pearsons and Horsehead Points on the east and on Long Canyon and Alkali Points on the west also afford access to Montezuma Canyon, but all these trails are steep and subject to washouts. The recent prospecting activity resulted in construction of many new mine roads and trails up the Montezuma Canyon walls and along the bottoms of many smaller canyons. These roads generally are steep and rough, and many of them are accessible only to four-wheel-drive vehicles. Many of the unpaved roads in the area are impassable when wet. The roads and other geographic features are shown in detail on the 1:24,000 and 1:62,500 scale topographic maps of this area published in 1953, 1955, and 1957 by the U.S. Geological Survey.

STRATIGRAPHY

The older, unexposed rocks of the Montezuma Canyon area are known chiefly from oil-well drilling. The deepest well drilled in the area, well 1 of table 4, bottomed in Cambrian strata at a depth of 8,680 feet. Wells 2 and 16 penetrated to Devonian strata, but most of the oil wells bottomed at a depth of about 6,000 feet in the Paradox Member of the Hermosa Formation of Middle Pennsylvanian age.

Many oil wells have been drilled in the area, and the cuttings and logs from them have yielded a wealth of stratigraphic information (pl. 2; table 1). Logs for wells 1 and 2 (table 4) are presented by Hansen, Scoville, and others (1955), and data for the other wells are available from Petroleum Information Service, American Stratigraphic Co., and from the oil companies. As the classification and correlation of these subsurface formations is being studied by many petroleum geologists, no detailed study of them was made during this investigation.

TABLE 1.—*Generalized stratigraphic section of subsurface rocks as determined from oil-well logs*

[nd, not determined]

Age	Stratigraphic unit		Thickness (feet)	Character
Jurassic and Triassic(?)	Glen Canyon Group	Navajo Sandstone	300–400	Light-colored massive sandstone.
Late Triassic(?)	Glen Canyon Group	Kayenta Formation	100–150	Red sandstone and red mudstone.
Late Triassic	Glen Canyon Group	Wingate Sandstone	250–350	Red massive sandstone.
Late Triassic	Chinle Formation	Undivided	600–700	Variegated claystone with some thin beds of siltstone and limestone.
Late Triassic	Chinle Formation	Moss Back Member	0–100	Light-colored conglomeratic sandstone.
	—Unconformity—			
Middle(?) and Early Triassic	Moenkopi Formation		50–100	Red mudstone and red sandstone.
	—Unconformity—			
Permian	Cutler Formation	De Chelly Sandstone Member	0–100(?)	Orange-red sandstone.
Permian	Cutler Formation	Organ Rock Member	0–600	Reddish-brown sandy mudstone.
Permian	Cutler Formation	Lower part	1, 200–1, 400	Red sandstone and mudstone.
Middle Pennsylvanian	Hermosa Formation	Upper member	1, 000–1, 200	Gray marine limestone, some shale and sandstone.
Middle Pennsylvanian	Hermosa Formation	Paradox member	nd	Halite, anhydrite, gypsum, shale, siltstone.
Middle Pennsylvanian	Hermosa Formation	Lower member	nd	Limestone, siltstone, and shale.

The exposed rocks in the Montezuma Canyon area consist of about 1,500 feet of sandstone, siltstone, and mudstone chiefly of Jurassic and Cretaceous ages (table 2). The Jurassic System includes the Carmel(?) Formation, the Entrada Sandstone, the Summerville and the Morrison Formations. The Cretaceous System includes the Burro Canyon Formation, the Dakota Sandstone, and the Mancos Shale. The unconsolidated sediments include pediment gravel, loess, colluvial and landslide deposits, talus, and alluvium of Quaternary age.

TABLE 2.—*Generalized stratigraphy of rocks exposed in the Montezuma Canyon area, San Juan County, Utah*

Age	Stratigraphic unit	Range in thickness (feet)	Lithology	Distribution
Quaternary (Recent and Wisconsin)	Alluvium	0–50	Silt and sand, some interbedded gravel.	Forms alluvial plains and low terraces along major streams.
	Landslide deposits	0–50	Large sandstone blocks mixed with smaller rock fragments, sand, and clay; derived by sliding from adjacent uplands.	Forms nearly continuous colluvial cover on bench of Brushy Basin below Burro Canyon Formation. Smaller masses present locally along inner canyon walls.
	Loess	0–25	Well-sorted red silt, and very fine sand; largely wind deposited, reworked partly by water; overlies deeply weathered soil zone developed on older rocks.	Forms agricultural soils on uplands.
(pre-Wisconsin)	Pediment gravel	0–50	Boulders, cobbles, and pebbles in a sandy matrix.	Forms upland surfaces near Monticello; underlies loess locally.
	Unconformity			
Late Cretaceous	Mancos Shale	0–380±	Gray marine shale, prominent *Gryphea* zone near base.	Forms a few gentle hills above upland surface.
	Dakota Sandstone	80–150	Light-brown and yellowish-brown sandstone, interbedded gray lenticular carbonaceous claystone and coal; plant fossils abundant. Thin conglomerate at base locally.	Crops out at crest of the "rim rock" cliff which separates upland from canyons.
	Unconformity			
Early Cretaceous	Burro Canyon Formation	50–180	Light-colored conglomeratic sandstone; interbedded greenish lenticular mudstone; silicified sandstone and limestone at top locally.	Forms face of "rim rock" cliff which separates upland surface from canyons.

TABLE 2.—*Generalized stratigraphy of rocks exposed in the Montezuma Canyon area, San Juan County, Utah*—Continued

Age		Stratigraphic unit	Range in thickness (feet)	Lithology	Distribution
		-Unconformity-			
		Brushy Basin Member	200–440	Varicolored mudstone; some sandstone and conglomerate lenses.	Forms slope below upland and above steep-walled inner canyons; generally covered with colluvium.
	Morrison Formation	Westwater Canyon Member	0–180	Yellowish- and greenish-gray lenticular sandstone and interbedded mudstone.	Forms intermediate slope below the gentle Brushy Basin slope and above the steep cliffs of Salt Wash Member in southern part of Montezuma Canyon area. Member grades into Brushy Basin Member to the north.
Late Jurassic	Morrison Formation	Salt Wash Member	300–520	Light-colored lenticular sandstone interbedded with reddish siltstones and mudstone. Uranium-vanadium deposits locally.	Forms series of steep cliffs and small benches of inner canyons.
		—Unconformity—			
	San Rafael	Summerville Formation	80–130	Even-bedded red sandstone interbedded with reddish siltstone and mudstone.	Forms steplike slope below steep canyon walls of Salt Wash Member.
	San Rafael	Entrada Sandstone	150–165	Light-colored massive crossbedded sandstone.	Forms rounded cliffs along the base of the canyon walls in upper Montezuma Canyon and its tributaries.
Middle Jurassic	San Rafael	Carmel(?) Formation	40–45	Irregularly bedded, red siltstone and sandstone.	Crops out in upper Montezuma Canyon just above the alluvium.
		-Unconformity-			
Jurassic Triassic(?)		Navajo Sandstone	26+	Light-colored massive crossbedded sandstone, base not exposed.	A few scattered outcrops in upper Montezuma Canyon near creek level.

TRIASSIC(?) AND JURASSIC SYSTEMS

GLEN CANYON GROUP—NAVAJO SANDSTONE

The lowest stratigraphic unit exposed in the Montezuma Canyon area is a fine-grained massive sandstone which is identified tentatively as the Navajo Sandstone. The lithology of this unit corresponds closely to the lithology of the type section in the Navajo Reservation first described by Gregory (1917, p. 57–59).

The only two exposures of the Navajo Sandstone in the Montezuma Canyon area are near Montezuma Creek. One is near a washed-out irrigation dam about 1 mile north of the mouth of Pearsons Canyon, where approximately 26 feet is exposed; the other is about 1 mile north of the dam and just north of a prominent fault, where approximately 10 feet is exposed on the west side of the creek and 8 feet on the east side. The total thickness of the Navajo in the area, as shown by oil-well logs, is about 350 feet.

The Navajo Sandstone in Montezuma Canyon ranges from very pale orange to grayish orange (10*YR* 8/2–7/4)[1] where fresh and from dark yellowish brown (10*YR* 6/6) to light brown (5*YR* 6/4) where weathered. At least 98 percent of the Navajo is composed of very fine to medium sand grains of quartz. Present in minor amounts are very fine to fine sand grains of orthoclase, plagioclase, chert, calcite, tourmaline, zircon, garnet, and magnetite. Most of the fine grains are subangular to rounded, but a few larger quartz grains are rounded, are generally frosted and stained light yellow or brown, and are concentrated chiefly along crossbedding laminae.

Although slightly recrystallized, the sandstone is only weakly cemented by calcite and is friable. Locally a white very fine granular material is present both as sand grains and as a matrix that cements quartz grains. Some of this white material is possibly sericite derived from altered feldspar and some is possibly chert. The upper few feet of the formation contains angular chert pebbles and small hollow siliceous concretions. The concretions are composed of silica-cemented sand grains with euhedral quartz crystals projecting into a hollow center; most of them also contain some calcite.

The Navajo Sandstone in Montezuma Canyon has large-scale and high-angle trough-type crossbedding which weathers in conspicuous relief as it does elsewhere on the Colorado Plateau.

The crossbedding of the Navajo Sandstone is similar to that of modern sand dunes and indicates an eolian origin (Gregory, 1917, p. 59; Gilluly and Reeside, 1928, p. 72; Hunt, 1953, p. 62). The Navajo Sandstone is unfossiliferous in Montezuma Canyon, and the correlation with the type section is based on its lithologic character and stratigraphic position below the San Rafael Group. The other formations of the Glen Canyon Group—the Wingate Sandstone and the Kayenta Formation—are not exposed in this area but are in their proper stratigraphic position beneath the Navajo Sandstone, as shown by oil-well logs. The age of the Navajo Sandstone has recently been designated as Triassic(?) and Jurassic (Lewis and others, 1961).

JURASSIC SYSTEM

SAN RAFAEL GROUP

In the San Rafael Swell, or type area, the San Rafael Group consists, in ascending order, of the Carmel Formation, the Entrada Sandstone, the Curtis Formation, and the Summerville Formation. Of these,

[1] Rock-color terms are from the "Rock-Color Chart" distributed by the National Research Council (Goddard and others, 1948).

757–270 O—65——2

only the Entrada Sandstone and the Summerville Formation definitely extend into the Montezuma Canyon area (section 1, p. 83), where their total thickness ranges from 280 to 340 feet. Gregory (1938, p. 56) recognized only 80 feet of "beds exposed on the floor of Montezuma Canyon at the mouth of Verdure Creek, tentatively assigned to the San Rafael." He apparently correlated the Entrada of Montezuma Canyon with the lithologically similar Bluff Sandstone to the south, and the Summerville Formation with the Recapture Shale Member of the Morrison, also to the south. The present correlation is based upon recent detailed tracing of beds into the San Rafael Swell.

CARMEL(?) FORMATION

A red sandy siltstone is exposed above the Navajo Sandstone and below the Entrada Sandstone on both sides of Montezuma Canyon for 3 miles north of Pearsons Canyon. This is possibly the Carmel Formation that was named by Gregory and Moore (1931, p. 71–72) from exposures near Mount Carmel, Kane County, Utah, and which has been traced across southern Utah into western Colorado and northeastern Arizona (Gilluly and Reeside, 1928, p. 73; Harshbarger and others, 1957, p. 33). Because the exposures in Montezuma Canyon are isolated geographically, the siltstone is here called Carmel(?) Formation.

The poorly sorted sandy siltstone is moderate to pale reddish brown (10*R* 5/6–5/4) and grades laterally and vertically into sandstone. Both are made up predominantly of silt and very fine to fine sand grains of amber-stained quartz. Coarse well-rounded frosted sand grains of quartz are scattered throughout the lower half of the formation but are sparse in the upper half. Accessory minerals, which form less than 2 percent of the total composition, include a few grains of opaque minerals, mostly magnetite and ilmenite, and a few grains of zircon, orthoclase, and plagioclase.

Bedding is thin and irregular but not contorted as it is in some areas to the north and west. The formation is loosely cemented with calcite, sericite, and a red iron oxide and is shaly to earthy weathering. The lower part forms soil-covered slopes but the upper part is generally a knobby-weathering recess below the cliff of Entrada Sandstone (fig. 4). Round light-colored spots from ¼ to 1 inch in diameter occur throughout the formation. These contain clear to white quartz grains and apparently represent local bleaching of the iron oxide that forms the amber stain.

An erosional unconformity separates the Carmel(?) Formation from the underlying Navajo Sandstone. The upper part of the Navajo Sandstone contains abundant siliceous concretions and its surface is hummocky. The lower foot or so of the Carmel(?) consists principally of sand- and pebble-sized fragments of concretions which were reworked from the Navajo and which fill depressions on the Navajo surface. This sand and pebble layer is interpreted to be a basal conglomerate. The relations indicate a considerable lapse of time between the deposition of the Navajo and that of the Carmel(?).

Where the Carmel(?) Formation is completely exposed in Montezuma Canyon (sec. 11, T. 35 S., R. 24 E.), it is about 40 feet thick. In Dolores Canyon, 20 miles northeast of the Montezuma Canyon area, the Carmel(?) is 10 to 25 feet thick (Cater, 1955a); along McElmo Canyon, 15 miles to the southeast of the area, it is 20 to 30 feet thick. However, 80 miles to the southwest, near Dinnehotso, Ariz., it is 100 feet thick (Harshbarger and others, 1957, p. 35); and along the middle part of Butler Wash, about 20 miles to the west, it is about 114 feet thick (Sears, 1956, p. 199). Thus, the Carmel(?) thins to the east and thickens to the west of the Montezuma Canyon area.

The marine origin of the Carmel Formation west of Montezuma Canyon is established by the presence of marine fossils in a limestone facies (Gilluly and Reeside, 1928, p. 74). The red shale and sandstone facies in the Montezuma Canyon area is probably of marginal marine origin. Local evaporites and the widespread thin horizontal bedding seem to indicate deposition in shallow marine waters. Local disrupted and contorted bedding of the Carmel(?) may be attributed to slumping caused by solution of evaporite beds.

No fossils have been found in the Carmel(?) Formation in Montezuma Canyon. In south-central Utah, however, the Carmel contains fossils of Middle and Late Jurassic age (Imlay, 1952, p. 963), and this age, or slightly younger, is assigned to the Carmel(?) in the report area. Wright and Dickey (1958, p. 177) suggested that the Carmel(?) here may be equivalent to the lower part of the Entrada Sandstone at the type section.

ENTRADA SANDSTONE

The most striking and easily recognized stratigraphic unit in the Montezuma Canyon area is the Entrada Sandstone, which forms a steep massive cliff that is exposed continuously for 12 miles along the bottom of Montezuma Canyon.

Gregory (1938, p. 56) correlated this sandstone with the Bluff Sandstone—considered by him to be the basal member of the Morrison Formation—at Bluff, Utah, and mapped only a small outcrop area as the San Rafael Group in Montezuma Canyon. Comparison of the stratigraphic sequence in Montezuma Canyon with measured sections from nearer the San Rafael Swell suggests that the cliff-forming sandstone is more likely Entrada. Gregory's Bluff probably pinches out south of the Montezuma Canyon area.

The Entrada Sandstone here may represent just the uppermost or clean sandstone facies of the Entrada at the type exposures to the northwest in the San Rafael Swell (Gilluly and Reeside, 1928, p. 76). The lowermost or red silty spheroidally weathering facies of the type exposures (Wright and Dickey, 1958) possibly could be what is considered here to be the Carmel (?) Formation.

In Montezuma Canyon the Entrada Sandstone is a light-colored clean well-sorted very fine-grained to medium-grained sandstone. It is moderate reddish orange (10*R* 6/6) to light brown (5*YR* 5/6) near the base and generally grayish orange (10*YR* 7/4) to nearly white in the upper part. Very small light-colored spots ranging from very pale orange (10*YR* 8/2) to grayish orange pink (10*R* 8/2) give the sandstone a speckled appearance on close inspection and make the overall color somewhat lighter.

The sandstone is composed chiefly of subrounded to rounded quartz grains, but contains a few grains of orthoclase, plagioclase, chert, magnetite, and tourmaline, and a few large well-rounded frosted sand grains of quartz. In general the sandstone contains little cement and is very friable. Locally where cemented with calcite or iron oxides the sandstone weathers in relief. In a few places the sandstone is cemented with a white argillaceous(?) material in spots 1 to 4 mm in diameter which form small raised bumps on weathered surfaces.

Although the Entrada generally forms a single massive cliff, it can be divided roughly into three units. The lower unit, which is a reddish-orange sandstone, is thin to medium bedded and in part laminated. It has small-scale subaqueous crossbedding. The middle unit is nearly white sandstone about 100 feet thick, and has large sweeping eolian crossbedding. The upper unit, 20 to 30 feet thick, is also nearly white. It has alternating medium-scale eolian and smaller scale subaqueous crossbedding. Throughout the formation, bedding features show best on weathered surfaces where differences in cementing have permitted them to weather in relief (fig. 3).

The Entrada has eroded to form a steep rounded cliff that contains numerous rock shelters, alcoves, small cavities, and long vertical grooves. Some larger alcoves and arch-roofed shelters are utilized by the local ranchers as storage rooms for grain and hay or as small corrals for livestock. A few shelters were also used by Indians of the Anasazai culture for small cliff dwellings, and many of the alcoves contain the small granaries typical of these people. In Montezuma Canyon north of Long Canyon and almost continuous group of these rock shelters line the west side of the canyon.

A distinctive biscuitlike weathered surface is locally well developed on the cliffs of Entrada. Solution of cement and removal of sand grains along crossbedding planes and along joints and fractures has left the "biscuits." A polygonal pattern is produced because the joints and fractures in the sandstone tend to be perpendicular to the crossbedding and to bend slightly from one crossbedded unit to the next.

The Entrada Sandstone lies conformably on the Carmel(?) Formation with a contact that is sharp and distinctive. In such places the lowermost part of the Entrada Sandstone is firmly cemented and forms a prominent ledge immediately above the poorly cemented Carmel(?) Formation (fig. 4).

The Entrada Sandstone is exposed along Montezuma Creek from a point about 2 miles north of the mouth of Verdure Creek to a point nearly a mile south of Dalton's Ranch where the sandstone dips below the valley fill. It is also exposed in the lower parts of Pearsons, Long, and Horsehead Canyons, tributaries to Montezuma Creek.

A complete section measured in the upper part of Montezuma Canyon (section 1, p. 83) showed 154 feet of Entrada Sandstone; the basal reddish-orange unit was about 30 feet thick. The formation is 100 to 120 feet thick about 20 miles to the northeast in the Joe Davis Hill quadrangle (Cater, 1955a) and 90 to 100 feet thick about 15 miles to the southeast along McElmo Canyon. It is 150 feet thick along Butler Wash 20 miles west of the Montezuma Canyon area

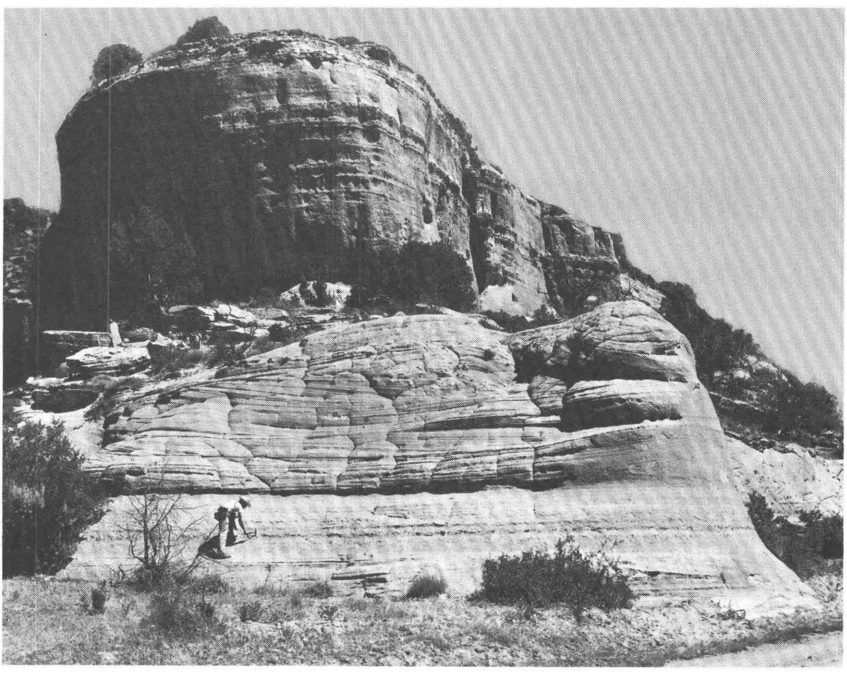

FIGURE 3.—Eolian and subaqueous crossbedding in outcrop of Entrada Sandstone near confluence of Long and Montezuma Canyons.

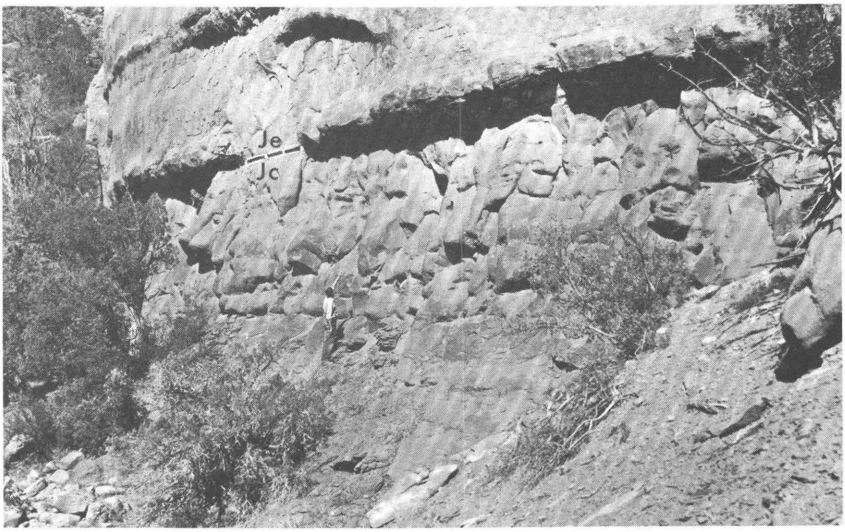

FIGURE 4.—Contact between the Entrada Sandstone (Je) and Carmel(?) Formation (Jc) in Montezuma Canyon 2 miles south of mouth of Verdure Canyon. Note man in picture for scale.

(Sears, 1956, p. 201). The thickness is comparatively uniform over a remarkably large area.

The even horizontal bedding planes throughout both the lower and upper parts of the Entrada indicate that much of the sandstone was deposited under water. The curved gently dipping crossbedding in the thick middle unit also indicates that at least some of the sandstone was deposited as sand dunes. Such a combination of aqueous and eolian origins for the Entrada Sandstone has been noted in other areas (Gilluly and Reeside, 1928, p. 78; Craig and others, 1955, p. 132; Harshbarger and others, 1957, p. 37). The clean sandy facies of the Entrada may represent deposits of both eolian and marine origin along the margin of the Carmel and Entrada sea (Harshbarger and others, 1957, p. 37).

No fossils were found in the Entrada Sandstone within the Montezuma Canyon area. The age of the Entrada, based on its stratigraphic equivalence to the Entrada Sandstone of the San Rafael Swell, is Late Jurassic (Imlay, 1952, p. 962).

SUMMERVILLE FORMATION

The Summerville Formation was named by Gilluly and Reeside (1928, p. 79–80) for "even-bedded red and white sandstones and maroon shales" exposed on Summerville Point in the San Rafael Swell. This formation has been traced over much of southeastern Utah and adjacent parts of Arizona, New Mexico, and Colorado where it maintains a similar lithology (Harshbarger and others, 1957, p. 39; Baker, Dane, and Reeside, 1936, p. 8; Craig and others, 1955, p. 132). In the Montezuma Canyon area the even-bedded red siltstone and sandstone of the Summerville Formation form a distinctive steplike slope above the steep cliff of Entrada and below the basal sandstone ledge of the Morrison Formation. Although Gregory (1938, p. 56) correlated these red beds with the Recapture Shale Member of the Morrison Formation, a comparison of the section in Montezuma Canyon with that northwest toward the San Rafael Swell suggests that the red beds are more likely Summerville.

The Summerville Formation in Montezuma Canyon is composed chiefly of fine-grained to very fine grained, well-sorted sandstone and very fine sandy siltstone.

The sandstone is predominantly pale reddish brown (10*R* 6/4) to moderate reddish orange (10*R* 5/6), although thin beds of moderate reddish-pink (10*R* 7/4), grayish-orange-pink (10*R* 8/2), pinkish-gray (5*YR* 8/1), and white sandstone occur locally near the middle of the formation. The sandstone is composed of fine to very fine sand grains of quartz. Most grains are subangular to rounded and have an amber stain of iron oxide that is the source of the distinctive red of the Summerville. Some large rounded and frosted sand grains of quartz are present. Summerville sandstone contains a small amount, generally no more than 1 to 2 percent, of chert, feldspar, tourmaline, and black opaque grains. Most of the sandstone contains grains which under the binocular microscope appear to be aggregates of a microcrystalline possibly argillaceous white mineral, and some sandstone contains as much as 5 to 10 percent of a similar white mineral in interstices. The sandstone is moderately to firmly cemented by carbonate minerals, argillaceous material, and iron oxide. A few white lenticular spots as much as half an inch in diameter, which occur locally throughout many of the sandstone beds, contain quartz grains that have little or no stain. These spots are places from which the iron-oxide grain coating apparently has been dissolved and removed.

The siltstone in the Summerville ranges from red (10*R* 5/2) to reddish brown (10*R* 4/4) with some moderate reddish brown (10*R* 5/6). It is composed of amber-stained quartz silt grains and usually 1 to 2 percent or more of dark heavy minerals. Most of the siltstone also contains some very fine to fine sand grains of amber-stained quartz. Near Dalton's Ranch the siltstone beds near the top of the Summerville contain abundant biotite flakes that locally may constitute as much as 5 to 20 percent of the rock. The siltstone is medium sorted, has a moderate to high carbonate cement, and contains some light-colored areas where the quartz grains are unstained.

Bedding in the Summerville is characteristically even and regular. It ranges from thin to laminated in the siltstone and silty sandstone to thick and massive in the better sorted sandstone. Individual massive sandstone beds can be traced for long distances along the canyon walls. There are only minor amounts of small-scale crossbedding, scour, and channel filling. Abundant ripple marks, mud cracks, and salt-crystal impressions occur locally in the siltstone beds.

The Summerville has a characteristic steplike slope, the massive sandstone beds forming ledges separated by slopes underlain by the thin-bedded sandstone and siltstone. The erosion of the massive sandstone ledges proceeds by the breaking off, along joints, of large rectangular blocks which mantle the siltstone slopes (fig. 5).

The Summerville Formation is exposed along the lower walls of Montezuma Canyon from a point about 2 miles north of Verdure Creek to the mouth of Coal Bed Canyon. It is also exposed along the lower parts of Long, Pearsons, Horsehead, and Coal Bed Canyons. The thickness of the formation is 89 feet in Montezuma Canyon 2 miles north of Pearsons Canyon, 97 to 130 feet in the vicinity of Long and Horsehead Canyons, and 107 feet just south of Dalton's Ranch. Its thickness is about 140 feet along McElmo Canyon 15 miles southeast of the map area; it ranges from a few feet to 120 feet in Gypsum Valley 20 miles northeast of the area (Stokes and Phoenix, 1948); and it averages 152 feet near Butler Wash 20 miles west of the area (Sears, 1956, p. 202). Regional trends are obscured by local variation in thickness caused by the erosional unconformity at the top of the formation.

The basal contact of the Summerville Formation with the underlying Entrada Sandstone is completely conformable in the Montezuma Canyon area. A thin ledge of light-colored sandstone, averaging about 5 feet in thickness and superficially resembling the Entrada Sandstone, lies a few feet above the basal reddish siltstone of the Summerville Formation (fig. 5). This sandstone and the underlying siltstone may be equivalent to the Moab Tongue of the Entrada Sandstone farther north (Baker, Dane, and Reeside, 1936, p. 9; Craig and others, 1955, p. 133). Unlike typical Entrada Sandstone, this ledge is even bedded and massive, lacks crossbedding, and contains some red coloring matter. Lithologically it is therefore more closely allied to the Summerville Formation than to the Entrada Sandstone, and in this report the Summerville-Entrada contact is placed below the lowest red siltstone.

The even bedding, the general lack of crossbedding, and the presence of ripple marks, mud cracks, and salt-crystal impressions in the Summerville Formation in the Montezuma Canyon area suggest deposition in shallow salt water. This formation probably was deposited here

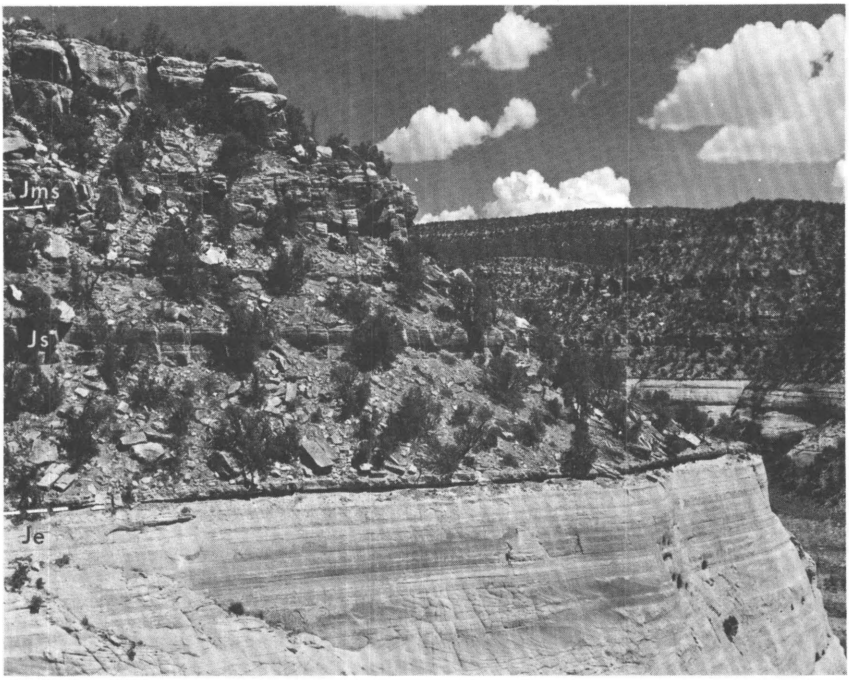

FIGURE 5.—Evenly bedded Summerville Formation (Js) above massive cliff of Entrada Sandstone (Je) and beneath lenticular sandstones of the Salt Wash Member of the Morrison Formation (Jms), in Montezuma Canyon, 2 miles south of mouth of Verdure Canyon.

under shallow marine conditions similar to those in the type section (Gilluly and Reeside, 1928, p. 80) and in the Navajo country to the south (Harshbarger and others, 1957, p. 39–42).

The Summerville Formation is unfossiliferous. The Late Jurassic age assignment of the formation here and elsewhere is based on its juxtaposition to the fossiliferous Curtis Formation in central Utah (Baker, Dane, and Reeside, 1936, p. 9; Imlay, 1952, p. 964).

MORRISON FORMATION

The Morrison Formation is of particular economic importance because it contains all the known uranium-vanadium deposits in the Montezuma Canyon area. The name Morrison was originally applied by Eldridge (1896, p. 60–62) to exposures of a series of fresh-water mudstones containing dinosaur remains at Morrison, Jefferson County, Colo. Later workers have used the name Morrison for much of the nonmarine deposits of the Upper Jurassic throughout the western United States (Stokes, 1944, p. 953–954). Within the Colorado Plateau area the Morrison Formation has been divided into several members. The name Salt Wash was proposed by Lupton (1914, p.

127) for a coarse-grained sandstone unit in the lower part of the Morrison Formation in Salt Wash, Grand County, Utah. Gregory (1938, p. 58–59) divided the Morrison Formation in San Juan County, Utah, into four members: in ascending order, the Bluff Sandstone Member, named for exposures along the San Juan River near Bluff, Utah; the Recapture Shale Member, named for exposures at the mouth of Recapture Creek east of Bluff; the Westwater Canyon Sandstone Member named for the canyon of that name southwest of Blanding; and the Brushy Basin Shale Member named for exposures in Brushy Basin west of Blanding. All but the Bluff, which is now classified as a formation of the San Rafael Group, are still considered members of the Morrison. Gregory (1938, p. 59) tentatively correlated his Westwater Canyon Sandstone Member with the Salt Wash Sandstone Member, but later stratigraphic work indicates that the Recapture intertongues with and grades into the Salt Wash Member (Stokes, 1944, p. 963–964; Craig and others, 1955, p. 127–178, 135).

Three members of the Morrison Formation are exposed in the Montezuma Canyon area. In the northern part of the area the thick prominent Salt Wash Member at the base is overlain by a thick Brushy Basin Member. In the southern part these two members are separated by and in part intertongue with a thin Westwater Canyon Member. Gregory indicated that the Bluff Sandstone and the Recapture Shale Member of the Morrison Formation extended into this area but well logs now show that these units thin and disappear north of Bluff. Subsurface correlations indicate that what Gregory considered to be Bluff and Recapture in Montezuma Canyon are actually the Entrada and Summerville Formations, respectively, of the San Rafael Group and that most of what Gregory considered to be Westwater Canyon is the Salt Wash Member. The Brushy Basin Member as used here is unchanged from that originally defined by Gregory. The well-developed erosional unconformity at the base of the Salt Wash in the Montezuma Canyon area indicates a natural stratigraphic division between the Morrison Formation above and the San Rafael Group below.

The age of the Morrison Formation is now generally accepted as Late Jurassic (Imlay, 1952, p. 953; Baker, Dane, and Reeside, 1936, p. 58–63). Within the Montezuma Canyon area the Morrison contains abundant plant fragments and some dinosaur bones in the Salt Wash, some dinosaur bones in the Westwater Canyon and Brushy Basin, and some fresh-water pelecypod shells in the Brushy Basin. Pelecypod shells from a conglomeratic sandstone about 40 feet above the base of the Brushy Basin Member, near the junction of Long and Montezuma Canyons, were identified by W. A. Cobban of the U.S. Geological

Survey as *Unio felchi* White. This species was first described by C. A. White (1886, p. 16) from the "*Atlantosaurus* beds," of the Morrison Formation 8 miles north of Canon City, Colo. Gregory (1938, p. 59) reported that dinosaur bones from the Brushy Basin in Montezuma Canyon were identified by C. W. Gilmore as including remains of a sauropod of the *Brontosaurus-Apatosaurus* group and a carnivorous dinosaur tentatively thought to be *Antrodemus* (*Allosaurus*). These are among the largest animals of any age.

SALT WASH MEMBER

Throughout Montezuma Canyon and its tributaries, the Salt Wash Member forms a series of steplike sandstone cliffs along the upper walls of the inner canyons. Cliff-forming massive sandstone in lenticular beds or lenses makes up about one-half to two-thirds of the Salt Wash. Between these sandstone lenses are red mudstone units containing some thin beds of very fine grained sandstone. This alternation of cliffs of resistant sandstone and debris-covered slopes underlain by less resistant mudstone units produces the steplike cliff characteristic of the Salt Wash Member.

The freshly exposed sandstone is generally white to yellowish gray (5*Y* 8/1) or pinkish gray (5*YR* 8/1) in the upper part of the member and ranges from grayish orange pink or pale red (10*R* 6/2–5/2) to pale reddish brown (10*R* 5/4) or very pale orange to pale yellowish orange (10*YR* 8/2–8/6) in the lower part. The lower ledges of sandstone have a distinctly reddish cast in comparison with the upper ledges. The weathered sandstone is somewhat darker than the fresh, and the lowest ledge commonly has an exceptionally dark-brown to black weathered surface.

The sandstone is medium to well sorted and is for the most part fine grained. It is composed predominantly of very fine to medium, locally coarse, sand grains of quartz. The grains range from angular to rounded and many have sutured or interlocking grain boundaries. In the upper part of the member most of the standstone has scattered small yellowish-brown limonitic freckles. In the lower part of the member, half or more of the quartz grains have an amber iron-oxide stain which causes the reddish color of the lower sandstone ledges.

Accessory minerals, which constitute less than 5 percent of the sandstone, include very fine to fine sand grains of zircon, tourmaline, feldspar, chert, magnetite, ilmenite, and other dark minerals. The dark heavy minerals are concentrated in part along crossbedding planes. Much of the sandstone also contains a small percentage of a white argillaceous material either in angular grains or as a granular matrix. Some of this material is composed of altered feldspar and some is probably altered tuff. The sandstone is porous but is moderately to well cemented by silica and calcite.

The large massive lenses of sandstone may extend along the canyon wall for half a mile or more (pl. 3). Although these lenses range in thickness from 1 foot to more than 100 feet, most of them are from 20 to 60 feet thick. They are made up of smaller crossbedded units that represent channel and scour fillings. The crossbedding corresponds to the trough cross-stratification of McKee and Weir (1953, p. 387). Current lineations and fluviatile ripple marks are present locally. Carbonized plant fragments ranging in size from macerated material a fraction of an inch in diameter to fossil logs as much as 30 feet long are present in some of the sandstone lenses, as are a few dinosaur bones as much as 5 feet long. Locally, thick beds of sandstone are separated by thin layers and lenses of mudstone or by accumulations of mudstone pellets. Local accumulations of plant material and mudstone fragments form the so-called trashy zones commonly mineralized in the uranium mines.

The sandstone lenses crop out as rocky ledges and cliffs along the walls of the inner canyons of Montezuma Creek and its tributaries (fig. 6). Commonly the cliff face is a series of intersecting vertical joint surfaces. Polygonal sandstone joint blocks, which have spalled off the cliffs, generally cover the intervening slopes and benches. Much of the sandstone rubble disintegrates to sand at the foot of the cliffs and is removed by slope wash. Large rockfalls, however, do occur sporadically along the canyon walls, and a few boulders larger than 20 feet across are known to have fallen to the canyon floors.

Interbedded with the massive sandstone lenses of the Salt Wash are mudstone units containing evenly bedded grayish-red (10*R* 4/2) mudstone and thin beds of very fine grained reddish sandstone and siltstone. The coarser fraction of the mudstone is composed of silt and very fine sand grains of quartz and mica. X-ray analyses of the clay-size fraction of typical mudstone samples indicate the presence of abundant illite, some montmorillonite, some mixed-layer clays, a little kaolinite, and a little chlorite. Mudstone in contact with sandstone beds is generally altered in color from the predominant grayish red to a light greenish gray (5*GY* 8/1–5*G* 8/1). Semiquantitative tests for iron indicate more total iron in the grayish-red mudstone than in the greenish-gray; the alteration is apparently the result of reduction and removal in solution of iron from the originally all-red mudstones. Generally the mudstones contain abundant carbonate as cement.

The very fine grained sandstone and siltstone in the mudstone units range from pale red (10*R* 6/2) and grayish red (10*R* 4/2) to greenish gray (5*GY* 6/1) and grayish orange pink (10*R* 8/2). The sandstone

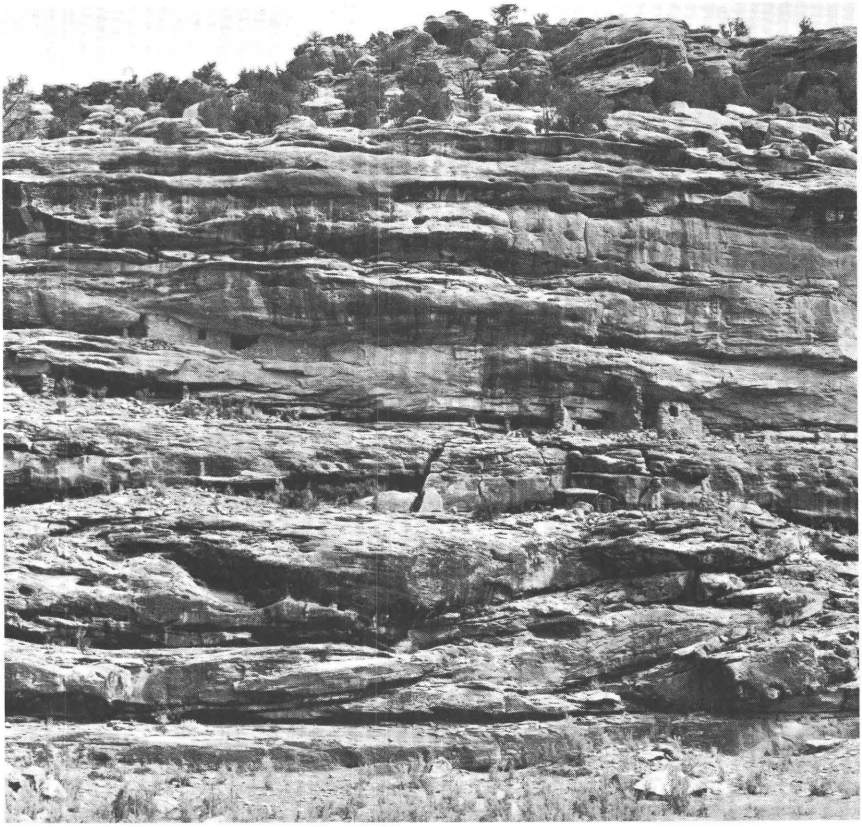

FIGURE 6.—Lenticular sandstone beds in Salt Wash Member, Morrison Formation, near mouth of Bradford Canyon. Salt Wash here contains an uncommonly high proportion of sandstone. Cliff dwellings give scale.

is composed of medium-sorted, angular to subrounded, very fine to fine, amber-stained sand grains of quartz mixed with a few grains of dark accessory minerals, and is typically well cemented with carbonate minerals. The sandstone is generally in regular to slightly lenticular beds, 1 to 2 feet thick.

The mudstone units in the Salt Wash Member weather to slopes and benches that are for the most part covered by sandstone debris. They range in thickness from lenses or seams less than 1 foot thick to lenticular masses more than 50 feet thick and, like the sandstone units, vary considerably in thickness and position throughout the area. Some of these variations are described in the part of this report concerning ore deposits.

The Salt Wash Member crops out along the walls of Montezuma and tributary canyons but dips under the valley fill about a mile south of the mapped area. Within the Montezuma Canyon area the

Salt Wash has a large range in thickness. It is about 372 feet thick where measured near the mouth of Verdure Creek (section 2, p. 85) and 370 to 520 feet thick elsewhere in the northern part of Montezuma Canyon. In the middle part of Montezuma Canyon between the mouths of Long and Horsehead Canyons it ranges from 319 to 402 feet in thickness. To the south, near the mouth of Coal Bed Canyon the Salt Wash is 453 feet thick (section 3, p. 87); to the east and west in Coal Bed and Devil Canyons it is from 380 to 440 feet thick. This variation in thickness of the Salt Wash Member is related partly to local channeling at the base of the Salt Wash and partly to local intertonguing at the top; nevertheless, the Salt Wash seems generally to be somewhat thinner in the middle part of Montezuma Canyon than elsewhere.

The thickness of the Salt Wash Member about 10 miles north of the Montezuma Canyon area is approximately 340 feet; about 20 miles to the northeast, in the Gypsum Valley area, it averages 350 feet (Stokes and Phoenix, 1948). About 15 miles southeast of the Montezuma Canyon area, along McElmo Creek, the thickness of the Salt Wash is approximately 100 feet; about 20 miles southwest of the area, along Recapture Creek, it is less than 50 feet; and 15 miles west of the area, along Butler Wash, it is about 70 feet. In these areas to the south much of the thinning of the Salt Wash is due to lateral gradation into the Recapture Shale Member.

In the Montezuma Canyon area the Salt Wash Member rests with erosional unconformity on the Summerville Formation. The basal sandstones of the Salt Wash locally occupy distinct channels cut in the Summerville, and some of the red material in these basal sandstones of the Salt Wash may be reworked red sand from the Summerville. The erosional unconformity indicates a considerable age difference between the Morrison Formation and the beds underneath.

The Salt Wash Member was deposited by streams flowing generally east and northeast. The relations suggest a braided stream system that deposited thick sand lenses in stream channels, and mud, silt, and very fine grained sand on broad flood plains (Craig and others, 1955).

WESTWATER CANYON MEMBER

The Westwater Canyon Member in the Montezuma Canyon area consists of a series of greenish sandstone lenses, 5 to 10 feet thick, interbedded with minor amounts of light-greenish-gray or grayish-red mudstone. These beds are less resistant than sandstone ledges of the Salt Wash and generally form a minor cliff set back from the Salt Wash. Although the Westwater Canyon can be identified by its minor differences in composition, texture, and color, its intertonguing with the Salt Wash beds below and with Brushy Basin beds above makes its stratigraphic limits difficult to distinguish, hence the Westwater Canyon is mapped here mainly on the basis of topographic expression and color. It thins to the north and east and pinches out in the central part of the area. North of this pinchout line a few thin greenish-sandstone lenses similar to the Westwater Canyon are not thick enough or continuous enough to be mapped separately and have been included in the Brushy Basin Member.

The sandstone beds in the Westwater Canyon Member range from yellowish gray (5*Y* 7/2–8/1) to yellowish green (5*GY* 6/2). Locally some beds are grayish yellow (5*Y* 8/4), pinkish gray (5*YR* 8/1), or very pale orange (10*YR* 8/2). The sandstone very typically has grayish-brown to light-brown limonitic freckles. Weathered surfaces generally are stained moderate to dark brown by iron and manganese oxides. The sandstone is moderate to well sorted and is composed predominantly of subangular to rounded very fine to medium sand-size grains of quartz, some angular grains of tuff, and a few grains of plagioclase, chert, biotite, and dark accessory minerals. Most of the sandstone has a white argillaceous or granular matrix which completely fills all interstices. Stringers of coarse sand, chert pebbles, and white tuff pellets occur locally near the base of the Westwater Canyon Member; some of the sandstone lenses contain abundant rounded tuff pellets and pebbles and are conglomeratic. The tuff fragments are white and very porous and fracture like typical tuffs from volcanic areas. In general, the sandstone of the Westwater Canyon Member contains more feldspar, more tuffaceous matrix, and less authigenic quartz than the sandstone of the underlying Salt Wash.

The sandstone of the Westwater Canyon is moderately to weakly cemented by the argillaceous matrix and some carbonate and silica. Some outcrops have a very dark and tightly cemented or "case-hardened" weathered surface. The cement appears to be silica deposited by evaporation near the surface of the rock.

The thickness of the Westwater Canyon Member in the Montezuma Canyon area ranges from 180 feet in the southern part to less than 40 feet near the line of pinchout in the central part, just north of the mouth of Horsehead Canyon. Local variations in thickness are large because of interbedding with members above and below (pl. 3). The Westwater Canyon is about 200 feet thick along Recapture Creek 20 miles southwest of the Montezuma Canyon area, 279 feet thick in Butler Wash about 15 miles west of the area, and about 80 feet thick along McElmo Canyon 15 miles southeast of the area. The member is not present north of the Montezuma Canyon area (Craig and others, 1955).

The origin of the Westwater Canyon Member, like that of the Salt Wash, is fluvial. According to Craig and others (1955, p. 156–157), streams depositing the Westwater Canyon Member had their origin in west-central New Mexico south of Gallup. These streams formed a broad fan-shaped alluvial plain. At the outer edge of this plain near the central part of the Montezuma Canyon area the streams from the southeast depositing the Westwater Canyon coalesced with streams from the southwest depositing the upper part of the Salt Wash and lower part of the Brushy Basin. The intertonguing of the members in the central part of the Montezuma Canyon area is a result of this coalescing of the drainage from the two different source areas.

BRUSHY BASIN MEMBER

Of all the rocks in the Montezuma Canyon area the Brushy Basin Member of the Morrison Formation has the poorest exposures. The unconsolidated mudstone and claystone beds and the few thin lenticular sandstone beds making up this member generally are covered either by their own debris or by rockslides and colluvium from the more resistant Burro Canyon and Dakota Formations above. In the northern part of the area the few good exposures are limited to gullies cut through the colluvial cover; in the south the upland surface composed of the Burro Canyon and Dakota Formations has largely been stripped away, the alluvial cover is sparse, and the Brushy Basin is exposed in extensive areas on a wide topographic bench (fig. 7).

The Brushy Basin is composed of silty claystone and mudstone in pale red, pale red purple, and light greenish gray (section 4, p. 92). The bedding is thin and regular and is distinguished mainly by color variations. Units of a single color are generally 1 to 2 feet thick but may be as much as 5 to 10 feet thick. Some claystone is bentonitic and tends to swell when wet, producing a popcornlike weathered surface when dry. X-ray diffraction analyses of Brushy Basin clays indicate they are mostly sodium montmorillonite. The mudstone contains silt and very fine angular sand-size grains of quartz, chert, feldspar, and devitrified volcanic glass. Some of the mudstone contains a few scattered highly polished and rounded chert pebbles 1 to 3 inches in diameter which may be dinosaur gastroliths (Baker, Dane, and Reeside, 1936, p. 9).

The claystone and mudstone beds have only minor amounts of carbonate cement and are poorly consolidated. Some beds, however, are well compacted and subfissile; others are hard and silicified. Locally the beds contain veinlets or nodules of red chert, and limestone or clay ironstone concretions. Much of the organic remains found in the Brushy Basin, such as wood fragments and dinosaur bones, are silicified and generally contain red chert.

In the northern part of the map area scattered lenticular beds of sandy conglomerate containing small pebbles of red, green, yellow, and

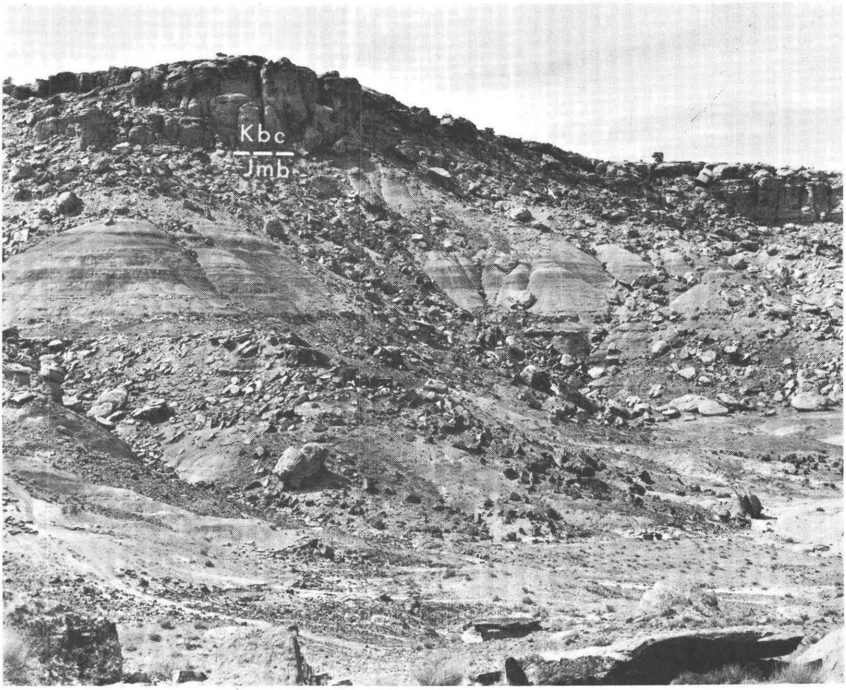

FIGURE 7.—Variegated claystone of Brushy Basin Member of Morrison Formation (Jmb) exposed beneath 100-foot sandstone cliff of Burro Canyon Formation (Kbc) south of Hatch's Trading Post and 12 miles south of mapped area.

black chert occur 20 to 50 feet above the base of the Brushy Basin Member. These lenses range from a few feet to as much as 20 feet in thickness and generally are stained dark brown or black on weathered surfaces. Some beds are firmly cemented with iron-stained silica, others are cemented with calcite. The lenses are discontinuous and do not extend more than a few hundred to a few thousand feet along the canyon walls. The conglomerates are not in a particular horizon but generally occur near the base of the Brushy Basin Member. These and similar conglomerate lenses in western Colorado and eastern Utah have been interpreted as the base of the Brushy Basin Member (Craig and others, 1955, p. 155). Because these lenses are discontinuous, do not occur at the same horizon, and would be very difficult to map, the mudstone just above the uppermost sandstone ledge of typical Salt Wash (or Westwater Canyon where present) is considered here to be the base of the Brushy Basin.

In the southern part of the area several lenticular beds of conglomerate as much as 20 feet thick and several thousand feet long occur near the top of the Brushy Basin. These beds contain well-rounded small to medium pebbles of light-colored chert; they are sim-

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ilar lithologically to the overlying conglomerate of the Burro Canyon except that they generally weather to a dark brown or black and grade laterally into greenish-gray very fine grained sandstone. The conglomerate beds are separated from the Burro Canyon by typical Brushy Basin mudstone beds. Similar conglomerates are in the Brushy Basin Member south and southeast of the map area, particularly along McElmo Canyon.

The thickness of the Brushy Basin Member ranges from 260 to over 400 feet in the northern part of the area and from 150 to 270 feet in the southern part. Locally in the central part of the area it is 400 feet or more. Variations in thickness of the Brushy Basin are due partly to interbedding along its lower contact and partly to the unconformity between the Brushy Basin and overlying Burro Canyon Formation.

The thickness of the Brushy Basin Member is approximately 200 feet in McElmo Canyon about 15 miles southeast of the map area; 250 feet in lower Recapture Creek about 20 miles south of the area, 215 feet in Butler Wash about 15 miles west of the area, and 335 feet on the northwest rim of the Great Sage Plain about 10 miles north of the area. It averages 400 feet in Gypsum Valley 20 miles northeast of the area (Stokes and Phoenix, 1948).

The fresh-water mollusks found in a sandstone lens of the Brushy Basin in upper Montezuma Canyon, the abundant dinosaur bones, and the pieces of silicified wood all suggest that the Brushy Basin Member is of continental origin. The mudstone and claystone beds probably represent deposits in lakes or on extensive alluvial plains, the sandstone and conglomeratic beds represent stream deposits formed by rivers meandering over this plain. The Brushy Basin conglomerates probably came from a source area to the southwest (Craig and others, 1955, p. 157), but devitrified glass fragments and most of the montmorillonite probably are of volcanic origin and may have come from more distant sources (Craig and others, 1955, p. 156; Stokes, 1944, p. 964).

CRETACEOUS SYSTEM

LOWER CRETACEOUS SERIES

BURRO CANYON FORMATION

One of the most conspicuous formations in the Montezuma Canyon area is the Burro Canyon Formation, which forms much of the steep prominent cliff that rims the upland surface. This formation was named (Stokes and Phoenix, 1948) for exposures in Burro Canyon, a small tributary to the Dolores Canyon in the Slick Rock area about 20 miles northeast of the Montezuma Canyon area. The formation includes mainly the same rocks as those called "Post-McElmo" by Coffin (1921, p. 97). In the San Juan country, Gregory (1938, p. 60–62) included what is now called Burro Canyon in his Dakota(?) Sandstone.

Massive white conglomerate and sandstone comprise, on the average, more than two-thirds of the total thickness of the Burro Canyon Formation. The conglomerate and sandstone are interbedded and grade from one into the other, but most of the conglomerate is near the base. The formation also contains some light-green mudstone, a few local beds of gray cherty limestone, and, in the vicinity of Monument Canyon, some reddish-brown siltstone.

The conglomerate is composed of rounded small to large pebbles and a few small cobbles mixed with sand. The pebbles and cobbles are rounded fragments of chert, silicified limestone, and quartzite, and are white, pale red, yellow, pale brown, gray, or black. Some of the darker ones are silicified Paleozoic limestone, and a few of these contain brachiopods, crinoid material, and other fossils. Most of the pebbles are relatively fresh, but a few have white-weathering rinds as much as a quarter of an inch thick. The conglomerate generally is white to yellowish white where fresh and gray where weathered. It is medium to well cemented with carbonate, silica, and limonite, and the beds commonly weather by solution of their cement to a mass of friable sand and pebbles.

The sandstone in the Burro Canyon is white to grayish orange (10*YR* 7/4), medium to fine grained, and generally well sorted. It is composed of subangular to rounded very fine to medium sand grains of quartz, a few grains of plagioclase and dark accessory minerals, and generally, some fine white argillaceous grains. The quartz sand grains are typically etched and corroded; some grain boundaries are sutured, and discontinuous authigenic quartz overgrowths are common. The sandstone is well to poorly cemented with silica, limonite, sericite, and some carbonate.

The conglomerate and sandstone are massive crossbedded units formed by a series of interbedded lenses. Most lenses are 5 to 10 feet thick, but locally lenses are less than 1 and more than 20 feet thick. A few are as much as 80 feet thick. Each represents a scour filled with arcuate trough-type cross strata (McKee and Weir, 1953). Many lenses that are conglomeratic at the base grade upward and laterally into sandstone.

In places the Burro Canyon Formation contains light-green claystone and mudstone intermixed with some sand in thin even beds. X-ray analyses indicate the clay to be mostly kaolinite with minor amounts of illite and sodium-montmorillonite.

Limestone is interbedded with claystone and mudstone at the top of the Burro Canyon Formation near Boulder and Horsehead Canyons. The limestone is light to medium gray and fine grained. Commonly it is silicified and in places it contains nodular masses of thin radiating calcite crystals. The bedding is poorly defined and locally the limestone grades into calcareous mudstone.

The upper 20 to 25 feet of the Burro Canyon Formation generally is silicified. Where sandstones form the uppermost beds, they are cemented by silica to form thin layers and rounded masses of hard, resistant quartzite 2 to 4 feet long. Locally the silicified zone is a layer of vuggy chert 2 to 20 inches thick that replaced limestone or calcareous mudstone. Vugs in the mudstones contain well-formed quartz crystals, and some opaline nodules with colloform surfaces contain fibrous quartz crystals. Elsewhere mudstone beds have been silicified to a hard silty chert. This silicified zone appears to be remnants of an ancient soil which formed during a long period of weathering and soil formation following the Burro Canyon deposition; this soil is discussed in greater detail in the description of the Dakota Sandstone. (See p. 33.)

Much of the Burro Canyon Formation is exposed throughout the area along nearly vertical cliffs. The massive conglomeratic sandstone forms most of the 100- to 200-foot upper or "rim rock" cliff which separates the canyons from the flat upland of the Great Sage Plain. In places, resistant basal sandstone beds of the Dakota are exposed at the top of the cliff, but elsewhere the Burro Canyon Formation forms the entire cliff. Where present, the mudstone, siltstone, and limestone beds of the Burro Canyon Formation form soil-covered slopes.

The basal contact of the Burro Canyon Formation in most of the Montezuma Canyon area is concealed by large talus blocks and other erosional debris. In most places, this contact consists of cliff-forming Burro Canyon conglomeratic sandstone resting unconformably on Brushy Basin mudstone. The contact has been exposed in a few places by recent gullying; where unexposed it was located for mapping purposes on the basis of topographic interpretation.

The thickness of the Burro Canyon Formation varies considerably because of the lenticularity of the conglomerate and sandstone beds and the unconformableness of the upper and lower contacts. Near the head of Montezuma Canyon the formation is 186 feet thick but several miles south near the mouth of Pearsons Canyon it is only 119 feet thick (section 5, p. 93). It is thinnest in the southern and eastern part of the area.

South of the area and a few miles east of Hatch's Trading Post the Burro Canyon is 129 feet thick, but a little farther to the south it is only about 50 feet thick. Near the type locality along the Dolores Canyon and in Gypsum Valley about 30 miles northeast of the Montezuma Canyon area it is 150 to 260 feet thick (Stokes and Phoenix, 1948). It is only 91 feet thick in Wild Horse Draw on the north edge of the Great Sage Plain about 12 miles north of Monticello, but it is locally 260 feet thick in the La Sal Mountains 25 miles north of the Montezuma Canyon area. About 10 to 15 miles east of the area, in Cross and Yellowjacket Canyons, the Burro Canyon ranges from 60 to 85 feet in thickness.

The Burro Canyon Formation is a continental deposit of Early Cretaceous age. It represents coarse fluviatile sediments interbedded with some flood-plain and possibly lacustrine deposits. Older sedimentary rocks acted as a source for much of the chert pebbles and probably the sand. The source of this sediment is not known definitely. No evidence of intertonguing of the Burro Canyon and Dakota Formations as described by R. G. Young (1960) was found in the Montezuma Canyon area. In fact, cementing and weathering of the Burro Canyon and local channel cutting prior to the Dakota deposition indicate a considerable age difference of these formations (Carter, 1957). No diagnostic fossils have been found in the Burro Canyon in the Montezuma Canyon area, but nonmarine invertebrate and plant fossils in the Burro Canyon from the Slick Rock area near the type locality are reported to be Early Cretaceous in age (Stokes, 1952, p. 1767–1768; Brown, 1950, p. 50; Simmons, 1957).

UPPER CRETACEOUS SERIES

DAKOTA SANDSTONE

The Dakota Sandstone, which consists chiefly of yellow sandstone interbedded with light- to dark-gray siltstone and claystone and a few thin beds of coal, underlies most of the flat upland surface of the Great Sage Plain. At the edge of the upland the sandstone beds commonly form the rocky ledges or steep cliffs of the canyon rim and the siltstone, claystone, and coal commonly underlie colluvium-mantled slopes.

The name Dakota was first introduced by Meek and Hayden (1862, p. 419–420) as the Dakota Group for alternating beds of sandstone, clay, and lignite of Cretaceous age in Dakota County, Nebr. The name Dakota has since been applied to beds of similar lithology and age throughout many of the Western States. Holmes (1878, p. 189) first used the name Dakota Sandstone in the Montezuma Canyon area including in his Dakota the sandstone beds described as the Burro Canyon Formation in this report (table 1). Gregory (1938, p. 60–62) used the name Dakota(?) Sandstone for the same beds to indicate the questionable correlation with the typical Dakota east of the Colorado Front Range.

Typical Dakota Sandstone is yellowish gray (5*Y* 8/1) to grayish yellow (5*Y* 7/4), well sorted, fine grained, and firmly cemented. It consists mostly of subrounded quartz grains showing stylolitelike solution surfaces where they are in contact and authigenic crystalline overgrowths where they are not. The crystal faces of the overgrowths glitter in sunlight. A few of the grains are altered feldspar; a very few are magnetite and other dark minerals. Some tiny cubic limonite grains present may have replaced original cubes of pyrite. A white or yellow argillaceous matrix partly fills interstices in much of the sandstone. The sandstone grades into conglomerate where the base of the formation fills channels cut into the underlying Burro Canyon Formation.

Most of the sandstone is firmly cemented with silica or carbonate minerals. The brownish color is caused by a coating of hydrous iron oxides on the sand grains. Some of this coloring forms bands and belts of liesegang rings which crossbedding structures and crudely parallel joints. Locally the sandstone is cemented by hydrous iron oxides to form ferruginous sandstone concretions. Much of the sandstone contains molds of plant fragments coated inside with hydrous iron oxides or with sooty carbonaceous material.

The sandstone commonly forms massive crossbedded lenses 10 to 50 feet thick and several thousand feet long. Each sandstone lens is composed of an interbedded series of smaller crossbedded units, from ½ to 2 feet thick, composed of subparallel crossbeds which curve tangentially toward the common base. Dip of the crossbeds ranges from a few degrees to as much as 30°. The sets of cross strata are thicker and coarser near the base of the Dakota, particularly where they occupy channels cut into the underlying sediments. Oscillatory ripple marks are present locally.

The sandstone lenses of the Dakota are interbedded with light- to dark-gray siltstone, claystone, and black coaly beds. Much of the claystone is gray, noncalcareous, and plastic. It forms thin horizontal beds. Above and below the coal beds are several inches of a pure light-gray plastic clay analogous to fireclay. An X-ray analysis of this clay indicated it to be dominantly kaolinite with a little illite. Other varieties of the claystone are different chiefly in their content of tiny carbonaceous plant fragments. All gradations exist between carbonaceous gray clay, black coaly clay, and coal. The coal is bituminous, and beds as much as 2 feet thick locally are composed chiefly of dull coal with thin laminae of vitreous coal (clairain) and contain sulfur along joints. Some of the coal is slightly radioactive. In a section measured east of Dove Creek (section 6, p. 94) the three coal beds present had a radioactivity detectable, with a scintillation counter, of about three times that for any of the other rocks nearby. Possibly this radioactivity represents a slight accumulation of uranium by the coal similar to that believed to have taken place near organic material in the Morrison Formation.

Both to the south (Repenning and Page, 1956, p. 259–261) and to the north (Carter, 1957, p. 309–311) of the Montezuma Canyon area the Dakota generally has been divided into three parts: a basal sandstone unit, a middle carbonaceous unit, and an upper sandstone unit. In the Montezuma Canyon area the sandstone, shale, and coal represent interbedded facies having no simple sequence within the formation. The sandstone facies of the Dakota intertongues with the overlying Mancos Shale, and the top of the Dakota is considered simply as the top of the uppermost sandstone ledge.

The base of the Dakota commonly is well exposed. By lithologic differences the Dakota can be distinguished readily from the underlying Burro Canyon Formation, except where the Dakota Sandstone rests upon Burro Canyon sandstone. The Dakota beds contain plant fossils, iron-stained sandstone, and gray mudstone that are not in the Burro Canyon, and they lack the massive conglomerate, green claystone, greenish silicified mudstone, and quartzite characteristic of the Burro Canyon. Locally a basal conglomerate or an ancient soil along their contact provide additional criteria for separating these two formations, and demonstrate a significant unconformity at the base of the Dakota Sandstone.

The basal conglomerate is present only where the Dakota Sandstone fills channels cut into the underlying Burro Canyon Formation. Such channels may be as much as 30 feet deep but the conglomerate is commonly less than 10 feet thick and pinches out completely within short distances laterally. The conglomerate consists mostly of rounded pebbles of chert and quartzite like those in the Burro Canyon Formation, plus angular pebbles, cobbles, and boulders of sandstone and quartzite derived by erosion of partly consolidated Burro Canyon sandstone. Good exposures of this conglomerate are in Coal Bed, Monument, and Cross Canyons, and on the point between Long and Devil Canyons; excellent exposures are on Peters Hill (fig. 8) and at other places 5 to 15 miles north of the Montezuma Canyon area (Carter, 1957, p. 311–313).

Elsewhere in the area, what probably is an ancient soil separates typical Burro Canyon and the overlying Dakota Sandstone. Commonly the soil is a poorly sorted loamy sand which has been silicified to become a hard mudstone commonly underlain by silicified beds. Silicification is particularly prominent where large rounded quartzite

FIGURE 8.—Basal conglomerate of Dakota Sandstone where particularly well developed on Peters Hill, about 10 miles north of mapped area. Conglomerate contains sandstone boulders similar to Burro Canyon sandstone near feet of observer.

masses have been formed by the complete cementation of Burro Canyon sandstone. The silicification of mudstone and limestone beneath the contact has produced argillite, chert, and quartz geodes.

The Dakota commonly crops out as a series of sandstone ledges. In many places a Dakota ledge caps the rimrock cliff which separates the uplands and the canyon lands. Elsewhere, as around the head of Montezuma Canyon, where Burro Canyon claystone separates the massive Burro Canyon conglomerates from the lowermost sandstones of the Dakota, the Dakota has been stripped back by erosion so that the Dakota-Burro Canyon contact is a mile or so removed from the rimrock cliff. The siltstone, claystone, and carbonaceous beds of the Dakota commonly underlie slopes mantled with colluvium and can be examined best in artificial exposures. One particularly good artificial exposure in a freshly dug trench (section 6, p. 94) showed that large blocks of sandstone broken from the sandstone ledges had settled upon, squeezed, faulted, and distorted the softer Dakota beds underneath. On natural slopes nearby, these soft beds are not to be observed at all, yet they constitute more than one third of the total thickness of the formation.

In the Montezuma Canyon area the thickness of the Dakota ranges approximately from 50 to 180 feet. In general, the Dakota is thickest in the eastern part of the area and thins toward the west. Where measured near Cahone, Colo., 15 miles east of the area, it is 108 feet thick; near Yellowjacket Canyon, Colo., it is 148 feet thick. The Dakota is only about 47 feet thick near Monticello. Ten miles west of the Montezuma Canyon area, near Blanding, and about 80 miles west in the Henry Mountains, the Dakota is discontinuous and is commonly less than 50 feet thick. About 80 miles southwest of the area the Dakota averages 80 feet in thickness on Black Mesa (Repenning and Page, 1956, p. 261). About 20 miles northeast of the area in Gypsum Valley the Dakota is about 125 feet thick (Stokes and Phoenix, 1948).

The Dakota Sandstone generally is considered to be a transgressive littoral deposit of the Late Cretaceous sea which spread toward the south and west (Repenning and Page, 1956, p. 282; Hunt, 1953, p. 79). Possibly the sandstone beds originally formed beach ridges behind which plant fragments, silt, and clay were deposited in brackish- and fresh-water swamps The basal sandstones and local conglomerate are considered by some (Carter, 1957, p. 313; Repenning and Page, 1956, p. 282) to be of fluvial origin. If so, these sediments were probably deposited very close to sea level (Repenning and Page, 1956, p. 282–283). It is possible that these basal deposits represent reworking by both streams and tidal currents of the regolith developed on the Burro Canyon Formation during the pre-Dakota weathering. Such an origin explains the chert, quartzite, and sandstone fragments derived from the upper part of the Burro Canyon which are found in the basal beds of the Dakota. The upper beds of the Dakota, which probably represent offshore marine deposits, grade upward into the dark marine shales of the Mancos Shale.

According to Brown (1950, p. 47) the Dakota Sandstone of southwestern Colorado is Late Cretaceous in age. Fossil plants from the Dakota east of Hatch's Trading Post a few miles south of the Montezuma Canyon area have been identified by Brown (written communication, 1956) as *Equisetum* sp., *Bolbites coloradica* Brown, and *Juglans crossipes* Heer. The same plants have been found in the Dakota Sandstone of southwestern Colorado northeast of the Montezuma Canyon area (Brown, 1950, p. 48–50).

MANCOS SHALE

The lowermost part of the Mancos Shale is exposed on the upland near Monticello. This formation was named by Cross (1899, p. 4) for exposures in Mancos Valley and near the town of Mancos about 50 miles east of Montezuma Canyon.

The Mancos Shale consists of medium- to olive-gray shale and minor amounts of fine-grained gray limestone and siltstone. The shale is brittle and fissile where fresh, but it weathers rapidly to light-gray or yellowish-gray clay chips. It is composed mostly of clay-size material including clay minerals, some quartz, and possibly some feldspar. Some of the shale has a high carbonate content and locally it grades into gray fine-grained, thin-bedded blocky limestone. Locally the shale is silty or sandy, but no beds of sandstone were found in it.

Bedding in the Mancos Shale is thin and well developed. Much of the shale is laminated; the laminae are regular and parallel and control fissility. The formation is subdued topographically, and commonly forms low rounded hills or gentle slopes partly covered by surficial materials.

Small black carbonaceous fragments and shell fragments are common throughout the Mancos Shale. Well-preserved shells of marine pelecypods are especially abundant in several zones 20 to 50 feet above the base of the formation. Specimens collected from a limestone bed about 50 feet above the base of the formation in the northeastern part of the map area were identified by W. A. Cobban of the U.S. Geological Survey as *Inoceramus labiatus* (Schlotheim). Cobban also identified other pelecypods collected from exposures in the Mancos south of Monticello as *Gryphaea newberryi* Stanton and possibly *Inoceramus* cf. *I. pictus* Sowerby.

The thin layer of Mancos Shale in the Montezuma Canyon area is just the lowermost part of this formation, the erosional remnant of what was once a very thick cover. Mancos Shale is exposed beneath the pediment gravels along several dry washes near Monticello. Along the Blanding road ¼ mile south of Monticello about 300 feet of Mancos is exposed in 1 small valley. East of Monticello are small isolated hills, partly covered by loess, where about 100 feet of Mancos is preserved. The Mancos Shale is about 1,200 feet thick in its type locality near Mancos, Colo. In the Henry Mountains area about 80 miles to the west it has an aggregate thickness of 3,100 to 3,500 feet (Hunt, 1953, p. 37).

The Mancos Shale lies conformably on the Dakota Sandstone. In the Montezuma Canyon area the contact is considered to be the top of the uppermost sandstone ledge of the Dakota.

A marine origin is indicated for the Mancos Shale by the abundant marine pelecypods. The formation is generally considered to have been deposited in the Late Cretaceous sea that transgressed southwestward. This transgression is indicated in part by the characteristic fossil *Gryphaea newberryi* Stanton which occurs in a prominent zone about 125 feet above the base of the formation near the type locality (Cross, 1899, p. 4), but is about 50 feet above the base near Monticello, and is near the base and in the Dakota Sandstone in the Henry Mountains area (Hunt, 1953, p. 80.) The presence of *Inoceramus labiatus* (Schlotheim) and *Gryphaea newberryi* Stanton in the Mancos of the Montezuma Canyon area indicates its equivalence to the basal part of the Mancos of the type locality and to the Greenhorn Limestone (Reeside, 1924, p. 10; Cobban and Reeside, 1952, p. 1017–1018, chart 10b) of early late Cretaceous age.

QUATERNARY SYSTEM

PEDIMENT GRAVEL

Pediment gravel covers the flat upland surface from the Abajo Mountains west of the mapped area to a point 4 miles east of Monticello. From north of the mapped area the gravels extend south of Verdure Creek to Dodge Point. An isolated mass of gravel also occurs on Long Point several miles south of the main mass. The pediment generally has the shape of an alluvial fan with its surface sloping away from the mountains at an angle of about 2°. Along Montezuma Creek and its tributaries the pediment surface has been dissected and its gravel cover stripped away.

The gravel is composed chiefly of semirounded boulders, cobbles, and pebbles of porphyry and some fragments of silicified sandstone, shale, and vein quartz. The rock types represented are those exposed in the Abajo Mountains. Interbedded with the gravel are lenses of sand, silt, and clay. The largest fragments in the gravel gradually decrease in size outward from the mountains; pebbles and cobbles are abundant in the gravel near Monticello, but boulders are present only near the foot of the Abajo Mountains.

Most of the gravel forms long thin lenses with gently dipping fluviatile crossbedding. Several unusual bedding features were observed in excellent exposures in gravel pits. In the pit 2 miles north of Verdure rounded masses of gravel from 2 to 4 feet in diameter are imbedded in sand and clay, and similar masses of silty clay are imbedded in gravel. These masses or "boulders" of unconsolidated material may have been transported and deposited as frozen chunks; similar "boulders" are in outwash in many glaciated areas.

The pediment gravel ranges in thickness from a few feet to 20 feet. In the west where it is thickest, it lies on the Mancos Shale, but to the east and south it lies on the Dakota Sandstone and Burro Canyon Formation, indicating that the pediment surface bevels the older formations underneath. Although originally the gravel probably formed a continuous fan-shaped deposit, the present drainage, which is entrenched from 50 to 300 feet below the pediment surface, has eroded the periphery of the gravel into long fingerlike outcrops.

The pediment gravel is deeply weathered. Porphyry boulders, cobbles, and pebbles in the topmost 5 to 10 feet of the gravel deposit are partly decomposed and many can be broken easily by hand. Gravel in this weathered zone is heavily coated with caliche and stained with iron. Just above the weathered gravel is a layer, 1 to 2 feet thick, of red silty friable clay containing siliceous fragments. Above the clay is the younger deposit of red silty loess. The weathered gravel is interpreted here to be the *C* horizon and the clay the *B* horizon of an ancient soil or paleosol formed and partly eroded before loess deposition. Unconformable relations of the loess and ancient soil are shown by a diagrammatic cross section (fig. 9).

The gravel was deposited on the pediment surface by streams that headed in the Abajo Mountains. These swift mountain streams could carry a relatively heavy load of sand and gravel along their steeper gradients but upon leaving the mountains and crossing the much less steep pediment surface they deposited nearly their entire load in several coalescing alluvial fans. Because the deposited gravel was more resistant to erosion than the surrounding Mancos Shale, drainage routes changed rapidly and extended deposition across a broad plain.

The pediment gravels are believed to be of early Quaternary age. Since their deposition the paleosol was formed and then the pediment was dissected by the present drainage. The pediment surface and the gravel deposits at one time were continuous across the Verdure Creek valley, and there has been at least 300 feet of downcutting by Verdure Creek since. Downcutting since pedimentation has been extensive also along upper Montezuma Canyon. Both the soil formation and the later pediment dissection must have required considerable time. Gravel "boulders" are typical features of glacial outwash, but no glacial deposits have been identified in the Abajo Mountains. If such deposits are present the pediment gravel probably is a pre-Wisconsin glacial outwash. The paleosol, to correlate with similar paleosols (Hunt, 1956, p. 38), is probably also of pre-Wisconsin age. The evidence necessary to positively identify the age of the pediment gravels has not been found in the Montezuma Canyon area.

COLLUVIAL DEPOSITS

The Montezuma Canyon area contains some landslide and other colluvial deposits, but only the large landslide deposits are of quantitative significance. Colluvial slope-wash and rock-fall debris cover the benches at the foot of many of the sandstone cliffs. Along the base of the canyon walls and particularly along the cliff of Entrada Sandstone are numerous small talus cones.

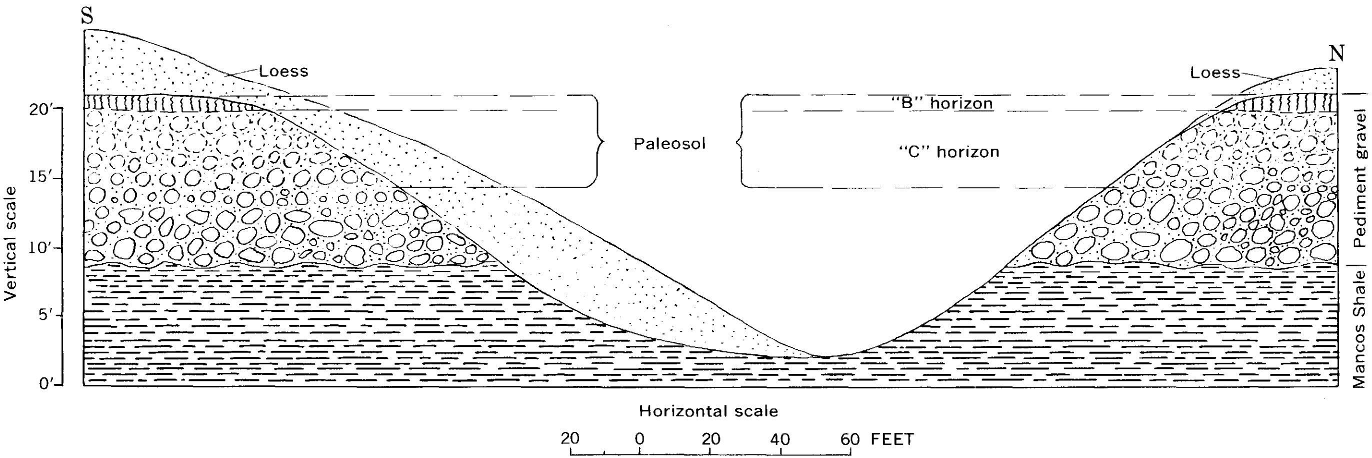

Figure 9.—Diagrammatic cross section showing relations of pediment gravel, paleosol, loess, and present topography south of Monticello, Utah. "B" horizon is a red silty clay; "C" horizon is argillized and weathered gravel coated with caliche.

The extensive landslides on the Brushy Basin Member contain sandstone blocks derived from the Dakota and Burro Canyon Formations in a matrix of plastic Brushy Basin clay. These landslide deposits range in thickness from less than 1 foot to 50 feet or more. An extensive nearly continuous landslide cover is on the Brushy Basin in the upper part of Montezuma Canyon and its tributaries generally north of Coal Bed Canyon. Separate individual slides are present on the Brushy Basin south of Coal Bed Canyon.

Much of the landslide cover on the Brushy Basin appears to be remnants of large slides from the sandstone cliff above. All these landslides have been modified greatly by weathering and erosion. Most of the landslide material has lost the distinctive physiographic form of fresh landslides and has been trenched and dissected by the present drainage. In the southeastern part of the area a large tilted block of Burro Canyon sandstone, which is 1,000 feet from the cliff face, has the ruins of a small pueblo built on top of it. The walls that remain are vertical and indicate no movement of the block since the building was erected, which was probably over 700 years ago. Most of the landsliding probably occurred when the ground was moist during a more humid period than the present. The more extensive deposits may be of periglacial origin formed in a more humid period during the Wisconsin (Hunt, 1956, p. 38).

ALLUVIUM

Alluvial deposits of unconsolidated pebbles, sand, and silt form isolated terrace remnants, the extensive valley fill, and recent stream deposits in Montezuma Canyon and its tributaries.

In a few scattered areas in Montezuma Canyon, beds of alluvial gravel are exposed that are distinctly older, coarser, and topographically higher than the extensive valley fill. These beds, which generally are composed of a high percentage of rounded pebbles and boulders of porphyry from the Abajo Mountains, have been identified at three places along Montezuma Creek: (1) on the lowest side of Montezuma Creek one-half mile south of the mouth of Devil Canyon, (2) near an old irrigation dam about a mile north of the mouth of Pearsons Canyon, and (3) just south of the mouth of Long Canyon. Near Devil Canyon these deposits form a small terrace remnant almost 100 feet above creek level, but the other deposits are closer to creek level and are partly covered by younger deposits. These deposits are highly weathered, stained with iron, and heavily coated with caliche. They are undoubtedly remnants of terrace gravels deposited during a temporary interruption in the deepening of Montezuma Canyon. The advanced weathering indicates a probable pre-Wisconsin age.

The most prominent alluvial deposit in the area is the thick valley fill in Montezuma Canyon and its tributary canyons. Recently arroyos have been cut 10 to 50 feet beneath the original level of this fill, producing excellent exposures of the alluvium in low alluvial terraces. The fill is made up of interlayered sand and clay beds; a few small lenses of gravel and coarse sand; and, locally near the top of the valley fill, modern sand dunes.

The sand, which forms two-thirds or more of the total fill, is fine grained and well sorted. It ranges from light brown (5*YR* 6/4) to dark yellowish orange (10*YR* 6/6), and is composed mostly of grains of quartz and chert. In some places it contains abundant carbon fragments and plant remains. Generally the sand is even bedded, but locally is finely crossbedded. It is partly consolidated with a carbonate cement.

The clay beds, which have a characteristic vertical jointing, consist of even layers of poorly sorted silty clay rich in organic materials. The clay is plastic and sticky when wet, and very hard and brittle when dry. The beds range in thickness from 1 inch or less to 3 feet or more, and generally are pale to moderate brown (5*YR* 5/2–4/4), although parts that are near abundant carbon fragments are bleached to greenish gray (5*GY* 6/1). The clay beds contain veinlets and small nodules of white caliche and plant remains including stems, roots, and leaves. Some layers also have abundant gastropods and very small pelecypod shells.

The valley fill extends the full length of Montezuma Canyon from about 2 miles north of Verdure Creek to the San Juan River beyond the south boundary of the mapped area. Along the tributary streams the fill is restricted to the lower 2 or 3 miles of the canyons near their mouths. The thickness of the valley fill ranges from 1 foot or less toward the heads of the canyons to 50 feet or more in the middle part of Montezuma Canyon. The height of the alluvial terrace along Montezuma Creek indicates that the fill thickens from 20 to 30 feet thick in the upper part of Montezuma Canyon to 50 feet thick in the middle part near Long Canyon. From there it probably thins gradually southward; it is about 40 feet thick near Devil Canyon and about 20 feet thick south of the area near the mouth of Cross Canyon.

The valley fill represents material deposited in the canyons by aggrading streams. The sandy facies was probably deposited in the stream channel and the silty clay layers in swamps or lakes on the neighboring flood plain.

No direct evidence for dating the valley fill has been found. Throughout the upper part of Montezuma Canyon many pueblo ruins dot the surface of the valley fill. These sites contain abundant pottery shards, but no pottery has been found in place more than 4 feet below the top of the fill. Most of the fill therefore is "prepottery" in age and was deposited before A.D. 600 to 1200. Fossils collected 7 to 8 feet beneath the surface of alluvium along Alkali Wash (USGS Cenozoic locality 21704) which have been identified by D. W. Taylor (written commun., 1959), include the fresh-water clam *Pisidium casertanum* (Poli), the fresh-water snail *Fossaria dalli* (Baker), and the land snails *Pupilla* sp., *Vertigo modesta corpulenta* (Morse), *Vallonia cyclophorella* Sterki, cf. *Succinea*, *Discus cronkhitei* (Newcomb), *Hawaiia minuscula* (Binney), and *Zontioides arboreus* (Say). All these species are still living but generally under conditions slightly more moist than those of the present environment. The valley fill is probably Wisconsin and early Recent in age. It is probably correlative with the Tsegi Formation (Quaternary) of the Navajo country (Hack, 1942, p. 62, 68) and with the earlier part of the Nakaibito Formation (Recent) near Gallup, N. Mex. (Leopold and Snyder, 1951, p. 9–12). It may also be in part correlative with the Jeddito Formation (Quaternary) of the Navajo Country (Hack, 1942, p. 61, 68) and the Gamerco Formation (Recent) of the Gallup area (Leopold and Snyder, 1951, p. 6–9).

Along the modern creek beds a thin discontinuous deposit of very recent alluvium, which consists mostly of reworked older alluvium, has been laid down during the formation of the deep arroyos in which the streams now flow. Arroyo formation in the area began some time between 1875 and 1900. Williams (1925, p. 202) stated that the arroyo in Montezuma Canyon started to form about 1900 and in 3 years had been cut the full length of the canyon. During the summer months flash floods in Montezuma, Verdure, Long, and Devil Creeks erode the arroyo walls and deposit thick banks of sand and gravel on the slipoff slopes of their meanders. These floods characteristically leave abundant armored mudballs in the creek bed as the water recedes. These armored mudballs are formed of clayey pieces of valley fill that are picked up by the floodwaters and rolled along the streambed where the balls receive their armor of pebbles. The recent mudballs formed in this manner are identical with fossil mudballs found in the valley fill.

LOESS

The loess is an eolian deposit of light- to moderate-brown (5*YR* 6/4, 4/4, 5/6) silty sand which covers most of the upland surface. It is well sorted and consists of about half very fine sand, a quarter fine and medium sand, and the remainder mostly silt (table 3). This loess is coarser grained than much of the loess in the central part of the United States (Swineford and Frye, 1951, p. 311), but it is finer grained than most dune sands (Udden, 1914, p. 714–718). Although the loess described in table 3 shows only a slight regional variation in grain size, the samples from the more northern regions generally are a little finer grained.

The loess consists mostly of subangular to rounded frosted grains of quartz with a reddish coating of iron oxide. Zircon, tourmaline, garnet, magnetite, and ilmenite form about 1 percent of the material.

The loess is massive and virtually homogeneous. Most of it is unconsolidated but some of it is cemented with caliche in light-colored mottled and veined accumulations. Polygonal jointing such as that which characterizes loess in the Mississippi Valley is not present.

TABLE 3.—*Size distribution of typical loess samples from the Great Sage Plain, Colorado-Utah, compared with that of loess and dune sand from other areas*

Sample and location	Percent by weight for indicated size fractions (mm)					Median diameter (mm)	Coefficient of sorting
	1.0–0.5	0.5–0.25	0.25–0.125	0.125–0.0625	<0.0625		
Loess, near State Highway 47, 15 miles south of Blanding, Utah	0	4	18	60	18	0.086	1.30
Loess, on Alkali Point, 12 miles southeast of Blanding	0	5	25	57	13	.10	1.31
Loess, along McElmo Creek road 4 miles south of Hovenweep National Monument, Utah	0	7	27	52	14	.10	1.34
Loess, along U.S. Highway 160, 2 miles east of Monticello, Utah	0	5	19	46	30	.086	1.48
Loess, near Colorado-Utah State line on U.S. Highway 160	0	4	24	50	22	.092	1.41
New dune, near Colorado-Utah State line on U.S. Highway 160	0	3	23	65	9	.090	1.40
Loess, Finney County, Kans.[1]	0	2.2	21.4	19.5	57.0	.051	2.21
Loess, Stanton County, Kans.[1]	0	1.4	3.8	12.1	82.7	.028	1.83
No. 235 Dune sand, Alliance, Nebr.[2]	2.5	17.2	70.5	9.7	.1	.19	1.20
No. 245 Dune sand, Moline, Ill.[2]	2.1	10.7	71.9	12.5	3.3	.18	1.20
No. 260 Lee sand, Lindsborg, Kans.[2]	.7	1.3	14.4	65.2	17.1	.085	1.27

[1] Swineford and Frye (1951, p. 311).
[2] Udden (1914, p. 682–683, 716–717, 719).

Loess is thickest and most widely distributed on the upland surface but it also covers parts of the topographic benches composed of the Brushy Basin and Westwater Canyon Members. Its thickness ranges from less than an inch along the edge of the upland to more than 20 feet in several of the highway roadcuts east of Monticello. In general, the loess is thickest in the central part of the upland areas and thins toward the cliff of Dakota and Burro Canyon that rims the upland. Thickness of the loess is also related to local topography. This is particularly noticeable south of Monticello where loess blankets the north sides but not the south sides of hills, and east of Monticello where it blankets the northeast sides of knobs of Dakota Sandstone. Loess is shown on the geologic map only where it forms a continuous cover at least several feet thick.

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No mature-soil horizon comparable to the paleosol is present within the loess. Layers of irregular caliche accumulation at various levels within the loess probably represent immature soil horizons. The most systematic horizon of caliche accumulation in the loess is about 1.5 to 2.5 feet beneath the land surface, and consists of a slight cementing of the loess by carbonate in light-colored mottled and veined areas. The loess above is entirely unconsolidated and contains no carbonate. The Pacific Northwest pipeline trench excavated near Dove Creek, Colo., in 1956, uncovered several pit houses dug in the loess by the Basketmaker III people about A.D. 600. These pit houses cut the near-surface caliche horizon, but the disturbed loess has no caliche accumulation, indicating that caliche accumulation during the last 1,300 years has been negligible.

The loess of the Montezuma Canyon area is of unquestionable eolian origin as indicated by its distribution and by its uniform composition, unrelated to the bedrock lithology. The material probably came from the extensive desert areas south and southwest of Montezuma Canyon where reddish-brown very fine grained sandstones and mudstones of Permian, Triassic, and Jurassic age are exposed in extensive outcrop areas (Gregory, 1938, p. 21). Silt and sand transported by the prevailing south and southwesterly winds from this desert area continue to be deposited on the vegetation-covered Great Sage Plain during dust storms.

The presence of several caliche zones and the continued movement of loess during droughts suggest that loessal deposition occurred during several periods—much of it during an arid period which interrupted the long more humid period during which the paleosol formed. Although the loess of the Great Sage Plain may be pre-Wisconsin (Hunt, 1956, p. 38), much of it probably is Wisconsin or Recent in age. The near-surface caliche accumulation in the loess may correlate with the Brady Soil (middle Wisconsin) of the Kansas-Nebraska-Iowa area.

Throughout the upland in the Montezuma Canyon area and on the main part of the Great Sage Plain to the east the loessal soil is suitable for dry farming. Much of this area, once covered by pinyon pine, juniper, and sage, has been cleared, and large crops of wheat and pinto beans are harvested in years of sufficient moisture. During the dry windy spring of 1956 the soil was considerably damaged by wind erosion. The loess was deposited by wind and, during droughts, may be carried away by the wind. Rows of trees to serve as windbreaks—and other conservation measures—can protect this valuable resource.

STRUCTURE

The structure of the Montezuma Canyon area is comparatively simple. The dips are low, the folds broad and shallow, and the few faults small in throw. The steepest dip, 1¾°, is south of Verdure. In much of the area the dips generally are 1° or less. The low dips and simple structure of this area contrast sharply with pronounced structural features such as the Monument upwarp, to the west and the laccolithic bodies to the southeast, west, and north.

Regionally, the Montezuma Canyon area is part of what Gregory called the Sage Plain downwarp (1938, p. 85). This downwarp has also been called the Paradox Basin (Shoemaker, 1956, fig. 27) and the Blanding Basin (Kelley, 1956, fig. 33). The eastward-trending zone of faulting which crosses the Montezuma Canyon area is possibly related to the Paradox Fold and Fault Belt to the north (Kelley, 1956, fig. 33).

The low dips and lack of a good datum in the stratigraphic column make structural mapping in the area difficult. The base of the Dakota Sandstone, being the best available, is used as a structural datum in this report. This contact occurs throughout the area and is distinctive; however, it is an unconformity with a perceptible local relief. The base of the Summerville Formation is remarkably flat and uniform and except for its narrow outcrop area would make an excellent structural datum. Contours drawn on the base of the Summerville Formation correspond in general with contours drawn on the base of the Dakota Sandstone, in middle Montezuma Canyon (pl. 3), but differ considerably in detail. Several broad shallow channels at the base of the Dakota in middle Montezuma Canyon have a local relief of 30 feet or more. Similar channels are present throughout the area. Such irregularities in the structural datum cause lateral shifting of the structure contours of one-third mile or more where the regional dips are less than 1°. For this reason the structure contours shown on the accompanying geologic map (pl. 1) convey an incomplete picture of the structure.

There are no large folds completely within the Montezuma Canyon area. The easterly dips in the northwest part of the area near Monticello are a reflection of the Abajo dome which lies immediately west of the area. This structural rise extends eastward as a very gentle nose across the upper part of Pearsons Canyon to the vicinity of Eastland. This fold may connect with a westward extension of the low Dove Creek anticline which lies south of the town of Dove Creek near Cross and Big Cahone Canyons, Colo., about 15 miles east of the Montezuma Canyon area (Finley, 1951). This fold is south of and roughly parallel to the well-defined Dolores anticline (Stokes and Phoenix, 1948).

In the southern part of the area, south of the fault zone, the prevailing dip is southward about 1°. A low noselike ridge extending southeastward along Alkali Point is the only feature of note.

No evidence was found in the area to date the folding. The Sage Plain downwarp may have developed about the same time as the Monument upwarp to the west and the Dolores anticline to the north. According to Hunt (1956, p. 73) the Monument upwarp probably formed during the early Tertiary. Major folding of the Dolores anticline also occurred during the early Teritary (Cater, 1955a). Hunt (1956, p. 82) suggested a middle Miocene age for the laccolithic intrusions such as the Abajo Mountains. The structural flank of the Abajo dome within the Montezuma Canyon area must date from the time of this intrusion.

The local structures may have been formed in part prior to the Tertiary Period. Some mapping by the authors in Cross Canyon 15 miles east of the Montezuma Canyon area suggests a thinning of the Burro Canyon Formation across the axis of the Dove Creek anticline. If so, this structure may have been active in the Early Cretaceous as were the Dolores and Gypsum Valley salt anticlines to the north (Cater, 1955a). No thinning of the formations across the axis of this fold in Montezuma Canyon was noted, but the fold is so gentle in this area that such thinning would be slight and difficult to determine.

An east-west zone of block faulting that contains several grabens and sets of in echelon normal faults extends across the Montezuma Canyon area (pl. 1). In the southern part of the Verdure 2 SE quadrangle, the largest of these grabens forms much of the valley of Verdure Creek and is here called the Verdure graben. A second prominent graben on Dodge Point about 1½ miles south of the Verdure graben is named the Dodge Point graben. Many of these faults can be observed clearly from the road along the bottom of Montezuma Canyon.

The Verdure graben is about ½ mile wide and about 25 miles long. The north Verdure fault, bounding the graben's north side, extends from Cottonwood Canyon near Elk Ridge (Lewis, 1958, p. 82) eastward along the southern border of the Abajo Mountains and across the entire Montezuma Canyon area; it dies out to the east somewhere near the head of Coal Bed Canyon a few miles southwest of Dove Creek, Colo., a total distance of more than 40 miles. The fault on the south side of the graben, the south Verdure fault, extends from just east of Cottonwood Canyon across the southern border of the Abajo Mountains to about a mile west of Montezuma Canyon, a total distance of nearly 25 miles. The maximum measured throw on the north Verdure fault is 182 feet in Montezuma Canyon. At the eastern edge of the map area near the head of Horsehead Canyon, this same fault has a throw of only 15 to 20 feet. The throw of the south Verdure fault ranges from a few feet, where the fault dies out near Montezuma Canyon, to about 160 feet near the western edge of the map area. The north Verdure fault dips about 70°–80° S. where it crosses Montezuma Canyon (fig. 10). Elsewhere the faults have equally high or higher dips. Both of these faults are normal; that is, they dip toward the downthrown or graben block.

The Dodge Point graben extends eastward from Dodge Point on the west side of Montezuma Canyon to Horsehead Point on the east side of Horsehead Canyon. The fault on the north side of the graben can be traced from a mile or so beyond the west edge of the mapped area to well beyond the east edge. It probably connects with a fault across the head of Monument Canyon southwest of Dove Creek, Colo.,

FIGURE 10.—North Verdure fault at Frost's Ranch, near mouth of Verdure Canyon. This fault has a throw here of 182 feet and dips about 75° S. (South is to the left.)

about 10 miles east of the Montezuma Canyon area. The fault on the south side of the graben extends 7 miles eastward from Dodge Point to Horsehead Point. In Montezuma Canyon the north fault has a maximum measured throw of 102 feet, the south fault, 80 feet; the north fault dips about 80° S., whereas the south fault is nearly vertical; both are normal faults, like those of the Verdure graben.

At least one small graben lies north of the Verdure graben and can be traced from Montezuma Canyon eastward to the head of Pearsons Canyon. Several small grabens and isolated vertical faults are also present south of the Dodge Point graben on Pearsons and Horsehead Points. In general these structures are similar to the ones described except that they are smaller and have throws of less than 50 feet. Movement on all the faults apparently is dipslip and normal; no evidence of lateral displacement was found.

There are several possible explanations for the faulting in the Montezuma Canyon area. It may be due to collapse along an incipient salt anticline that occurred when the compressional stresses that produced the folding relaxed or possibly when salt was removed by solution, similar to the cause suggested by Cater (1955b, p. 129) for the faulting in the Gypsum Valley and Dolores anticlines. The faulting also may be due to the intrusion of the Abajo laccoliths and may represent the slightly arcuate fault pattern associated with many domal structures as shown by Parker and McDowell (1951). Within the area there is no evidence to support one hypothesis more than another. The juxtaposition of the Verdure graben and the Abajo Mountains strongly suggests a close tectonic interrelation, and two dikes along the south Verdure fault in the Abajo Mountains (Witkind, 1958, p. 64–65) suggest that the graben is at least as old as the igneous intrusions.

Jointing is common in the sandstone of the Montezuma Canyon area. During erosion the sandstone beds commonly break away from the cliff face in large joint blocks leaving joint surfaces as the cliff face. Many of these joints are virtually parallel to the cliff and may have formed, since the development of the canyons, from subsidence of weaker rocks underneath. Near the faults many prominent joints are parallel to and related to the faults.

All joints in the ore-bearing sandstone lens of the Salt Wash in middle Montezuma Canyon are nearly vertical. Mine maps of the Lucky Boy, Strawberry, and Verdure mines (pls. 6, 7; fig. 14) show that at each mine the joints are in two sets approximately perpendicular to each other. The joints in general are parallel to or perpendicular to the trend of the sinuous sandstone lens near these mines (pl. 3). Such joints probably are related to compaction of the strata and therefore are sedimentary rather than tectonic in origin. Other joints, believed to be related to sedimentary structures, have been described as being responsible for the biscuitlike weathering surface of the Entrada Sandstone (p. 14–15).

In summary, most joints present appear to be related to physiographic and sedimentary structures. Only those related to the faulting appear to be of unquestionable tectonic origin.

GEOMORPHOLOGY

The Montezuma Canyon area is in the southern part of the Canyon Lands section of the Colorado Plateau physiographic province (Fenneman, 1931, pl. 1, p. 306–307). The area includes two major geomorphic features: the broad nearly horizontal upland surface called the Great Sage Plain and the deeply incised canyon network of Montezuma Creek and its tributaries (fig. 2). These two features result in part from different erosion cycles and in part from differences in susceptibility of the rocks to erosion. The older or upland cycle, which formed the Great Sage Plain, is represented today by streams flowing in gentle valleys in the northern part of the upland. The younger, or canyon cycle, is slowly destroying the upland by headward-migrating canyons and cliff retreat.

The upland surface has an altitude of about 7,100 feet near Monticello and slopes gently to an altitude of 5,600 feet in the southern part of the area. Most of this surface is at or near the top of the Dakota Sandstone. In the northern part of the area however, this resistant formation is covered by several hundred feet of the overlying Mancos Shale and near Monticello by pediment gravels. Viewed from its surface the upland appears to be a smooth and regular plain broken only by the intrusive Ute, Abajo, and La Sal Mountains which rise above it (fig. 11). It is only when one views the canyons from the edge of the upland that he is aware of the deep dissection of this plain.

At least two hypotheses have been advanced for the origin of the Great Sage Plain. Gregory (1938, p. 92) described it as a stripped plain which was formed along the top of a resistant formation (Dakota Sandstone) by the removal of overlying nonresistant beds (Mancos Shale). Fenneman (1936, p. 181), however, described the upland surface as an uplifted peneplain, and contended that the area was reduced to a plain of low relief, or a peneplain, by subaerial erosion during a long period of crustal stability, followed by a regional uplift which caused a rejuvenation of the streams and the second cycle of erosion. It seems likely that both hypotheses partly apply to the area. The close correlation of the upland surface with the top of the Dakota Sandstone strongly suggests a stripped plain, but such a plain

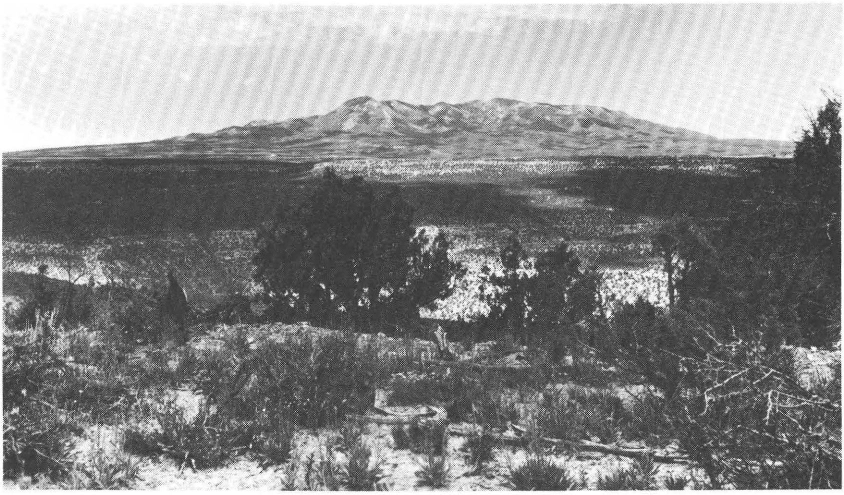

FIGURE 11.—View across head of Pearsons Canyon showing upland surface at foot of Abajo Mountains.

probably developed at a time when the area was at a lower altitude, so that it could also be described in part as a peneplain.

When the upland cycle began is known only within broad limits. The youngest bedrock in the area is the Mancos Shale of Late Cretaceous age. Only the lowermost few hundred feet of this formation are present in the Great Sage Plain but several thousand feet of Mancos and younger Cretaceous and Tertiary formations are present in surrounding areas. The last major structural activity in the area was probably the intrusion of igneous rocks forming the Abajo and Ute Mountains in Miocene(?) time (Hunt, 1956, p. 82). Hunt (1956, figs. 61–62) suggested that through drainage in the Great Sage Plain area may have been established in the late Pliocene. The formation of the upland surface would have begun then. This surface was well developed by the time the pediment gravels were deposited near the Abajo Mountains, some time during the Pleistocene.

The paleosol on the upland surface near Monticello is also an indication of low relief and of a long time of development. Although this paleosol is most prominent on the pediment gravel, the same zone of intense weathering can be recognized on the Mancos Shale and on the Dakota Sandstone beyond the limits of the pediment gravel at the same general altitude. The depth and nature of the soil indicate extensive chemical weathering uninterrupted by mechanical erosion. It seems reasonable to hypothesize, therefore, that the region remained a surface of low relief long after the pediment gravel was deposited.

The second major cycle of erosion affecting the Great Sage Plain area has produced the extensive canyon system along Montezuma

Creek and its tributaries. Montezuma Canyon extends the full length of the area. In the northern part of the area 3 miles east of Monticello, Montezuma Creek flows at an altitude of 6,670 feet in a valley 80 feet deep and a quarter of a mile wide; 4 miles to the south the creek flows at an altitude of 5,800 feet in a canyon 1,000 feet deep and over a mile wide. Toward the southern part of the area Montezuma Creek has an altitude of 4,870 feet and flows in a canyon only 700 feet deep but several miles wide. In that area the upland surface has been reduced to long narrow points and isolated buttes by the formation of numerous tributary canyons.

Unlike most of the major rivers on the Colorado Plateau which are superposed or antecedent to the regional structure, Montezuma Creek and its tributaries tend to flow down the regional dip and appear to be well adjusted to structure. Direct structural control is illustrated by Verdure Creek which follows the Verdure graben to within 2 miles of its mouth.

Parts of Montezuma and its tributary canyons have deeply entrenched meanders, indicating that prior to the canyon-cutting cycle these streams had a comparatively large discharge and flowed on a plain of low relief. The presence of these entrenched meanders plus the steep heads of the present canyons indicate that rejuvenation of the streams and subsequent canyon growth was rapid in comparison with time required for forming the upland surface (fig. 12).

Following the initial canyon cutting the destruction of the upland was mainly a process of cliff retreat. The Montezuma Canyon area illustrates two contrasting types of this process in an arid climate. In formations with alternating resistant and nonresistant beds, such as the Morrison, Burro Canyon, and Dakota, cliff retreat is a discontinuous process involving isolated rockfalls. Such cliffs consist of weathered joint surfaces where joint blocks of sandstone have fallen when undermined by the removal or subsidence of underlying weak shale beds (Koons, 1955). The steplike cliffs formed in this manner have large joint blocks that move by creep across sloping rubble-covered mudstone slopes. Isolated rockfalls occur occasionally; such a one occurred in 1957 when a sandstone block of Salt Wash 15 feet long tumbled several hundred feet to the road surface at the bottom of Montezuma Canyon.

In contrast to this discontinuous process, the massive generally homogeneous sandstone of the Entrada forms cliffs which retreat primarily by the continuous removal of individual sand grains. Slight variations in cementing are accentuated by removal of the sand. Crossbeds are thus etched in relief and natural arches and caves hollowed out of the cliff.

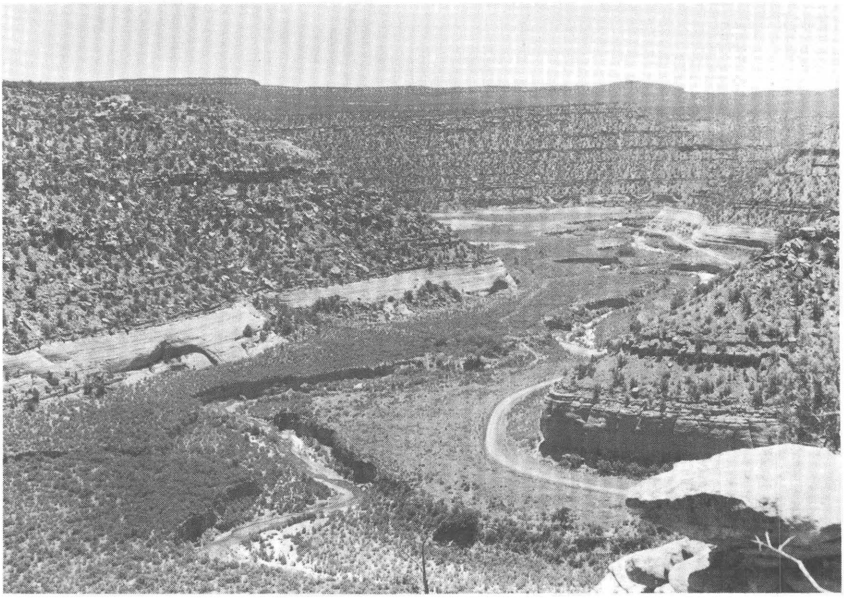

FIGURE 12.—View south from the Strawberry mine showing entrenched meanders of Montezuma Canyon and partly dissected alluvial fill.

Exactly when the canyon cycle began is not known. Quite possibly the present cycle began in remote parts of the Colorado Plateau following the epeirogenic uplift during late Miocene time (Hunt, 1956, p. 65). The canyon cycle did not reach the Montezuma area until after much of the upland surface had been formed. Remnants of pediment gravel on Long and Dodge Points suggest that the canyon cycle reached the area near Monticello after the formation of the pediment and the deposition of the gravel—sometime during the Pleistocene. The canyons still are advancing headward near Monticello.

At the present, Montezuma Creek and its tributaries flow in meandering arroyos 15 to 50 feet deep cut in the thick valley fill along the floor of the canyons. The presence of the valley fill indicates a local change in stream regimen from the degrading canyon cycle to an aggrading cycle. This change apparently took place during the Pleistocene and early Recent. The smaller meanders of the present streams within the larger meanders of the canyons suggest that the present streams are underfit, or are smaller than earlier streams. The original canyon cutting possibly was done by a larger flow of water in a more humid climate. A change in the climate brought about aggradation and deposition of the valley fill.

The ancient landsliding on the bench of Brushy Basin also occurred during the later stages of canyon cutting and probably during a period of higher precipitation. These landslide masses are all quite old and are modified by some erosion. The present-day climate seems to be too arid for their formation.

The present arroyo cutting began about 1900 (Williams, 1925, p. 202). Photographs by W. H. Jackson taken in Montezuma Canyon near the mouth of Coal Bed Canyon in 1875 show no dissection of the valley floor where an arroyo 35 feet deep is present today. Arroyo cutting, which is common now throughout much of the Colorado Plateau, may have had both natural and artificial causes. Climatic change, overgrazing, timbercutting, and even removal of beavers from the streams are some of the many possible causes. Deep channels in the valley fill now filled with alluvium indicate previous periods of arroyo cutting. Such channel fillings even contain fossil armored mudballs similar to those formed today during flash floods. Similar conditions of early arroyo cutting in other canyons on the plateau have been described by Bailey (1935).

ECONOMIC GEOLOGY

OIL AND GAS

Although the Montezuma Canyon area presently (1961) has no producing oil or gas wells, the chances of eventual production seem favorable. The recent discovery and development of the Aneth field just to the south of the area has greatly stimulated exploration for oil and gas in the region. From 1955 to early 1961 at least 18 wells were drilled in the Montezuma Canyon area (table 4), but of these only the Coal Bed Canyon 1 had any production. This production, which consisted of 7,970,000 cubic feet of gas and 148 barrels of condensate per day before the well was shut in, came from the Paradox Member of the Hermosa Formation of Middle Pennsylvanian age. Production in both the Aneth field to the south and the Dove Creek field to the east is also from this member.

There are no obvious oil-bearing structures in the Montezuma Canyon area. In the Aneth field the Paradox reservoirs are of the reef type (Turnbow, 1955, p. 66), and the lack of structural closures in the Montezuma Canyon area should not be considered unfavorable for the occurrence of oil and gas. If the economic possibilities of oil and gas in this area had been recognized and if oil-well logs and samples had been available while field investigations were in progress this subject would have been studied in greater detail.

TABLE 4.—*Chronological list of oil wells drilled in the Montezuma Canyon area*

No. on pl. 1	Name	Company	Date completed	Depth (feet)
1	Boulder Knoll	Boulder Knoll	6–12–30	8, 680
2	Redd 1	Western Natural Gas	2– 4–48	8, 677
3	Calgram 1	Southern Union	9– 9–48	2, 640
4	Coal Bed Canyon 1	Gulf	1–11–56	5, 912
5	Coal Bed Canyon 3	Gulf	3–17–56	5, 850
6	Frost 1	White Canyon Mining	11– 8–56	5, 935
7	Gulf-Aztec-Blanding- Federal 1.	Gulf	5– 7–57	4, 982
8	Montezuma Canyon 1	Pan American	6– 5–57	6, 545
9	Coal Bed Canyon 4	Pan American	6– 9–57	6, 454
10	Gulf-Aztec-Montezuma-Federal 1.	Gulf	7–28–57	6, 190
11	Gulf-Aztec-Montezuma-Federal 2.	Gulf	4–21–58	5, 629
12	Federal Friedman 1	Sinclair	6– 2–58	5, 937
13	Montezuma Creek 2	Kingwood	7– 2–58	6, 222
14	Ramsey-State 1	Ramsey	8– 1–58	5, 978
15	Coal Bed Canyon 6	Kern County Land	9–28–58	5, 863
16	Deadman Canyon 1	Pan American	12–10–58	5, 797
17	Bug Canyon 1	Lion	5–14–59	5, 706
18	Deadman Canyon 2	Pan American	7– 9–59	6, 107
19	Honolulu-Gulf-Federal 1	Honolulu	9–27–59	5, 885
20	Dalton 1	Lion	12–31–59	5, 276
21	Howard Crittenden 1	Tenneco	1– 8–61	6, 632

WATER

Water supplies are limited within the Montezuma Canyon area. Monticello obtains an adequate supply of water for domestic use from creeks in the Abajo Mountains but not enough is available to supply the increasing demand of the Monticello uranium mill. Efforts to increase the mill water supply by a series of wells have been only partly successful.

Most of the creeks in the area are dry during the summer. Flow usually is continuous along upper Montezuma Creek but this water, which contains effluent from the Monticello mill, is of poor quality when the discharge is low.

On the uplands, water supplies adequate for domestic and farm use commonly are obtained from drilled wells 100 to 200 feet deep. These wells produce water from saturated sandstone at the base of the Burro Canyon Formation. The underlying Morrison Formation contains no good aquifers and without excessive pumping costs good supplies cannot be anticipated from wells drilled beneath the base of the Burro Canyon. At the Monticello uranium mill several wells were drilled through the Morrison Formation into the Entrada Sandstone where fair supplies were obtained at a considerable depth.

Springs are not numerous in the area but there are some which provide valuable water supplies. Most of the springs discharge ground water from the saturated sandstone at the base of the Burro Canyon Formation where this horizon crops out at the head of canyons.

In a small area in lower Montezuma Canyon conditions are satisfactory for artesian water supplies. The Bonnie Dalton well at the mouth of Bug Canyon and the Max Dalton well near the mouth of Tank Canyon are artesian wells which tap ground water under pressure in the Entrada Sandstone about 800 feet beneath the land surface. Over most of the area the Entrada Sandstone is too deep to serve as a source of ground water without excessive drilling and pumping costs.

CONSTRUCTION MATERIALS

Abundant supplies of sand and gravel for construction purposes are found in the pediment gravel deposits. Gravel from one large pit 2 miles east of Monticello and from others along the Blanding road south of Monticello has been used locally for both concrete aggregate and road metal. The gravel consists of sand and weathered pebbles and boulders of igneous rock. Both the size and the hardness of the weathered fragments vary from place to place.

The Dakota and Burro Canyon Formations can serve as a source of sand. During 1954, rock from a quarry in the Dakota Sandstone about 2 miles east of Monticello was used along with gravel from a nearby gravel pit to obtain road metal for paving the Monticello-Cortez road. The sandstone and gravel were mixed during crushing and the desired size fractions obtained by screening. Reserves of sand and gravel are adequate for any foreseeable demand.

Good dimension stone is available in the area but is little used because of the high cost of quarrying. The San Juan County Courthouse in Monticello is constructed of dimension sandstone cut from sandstone ledges of Salt Wash in Bradford Canyon.

COAL

The Dakota Sandstone in the Montezuma Canyon area contains lenticular low-rank coal beds as much as 2 feet thick. These beds, which grade laterally into carbonaceous claystones, occur throughout the formation as shown by the measured section of the Dakota (section 6, p. 94). Most of this coaly material is too impure for commercial use and because of the lenticular nature, small size, and poor exposures no reserves can be estimated. Several small coal mines and prospects, however, were found during the geologic mapping. The largest of these, on Pearsons Point (sec. 35, T. 34 S., R. 25 E.) has a drift 200 feet long exploring 1½ feet of bituminous(?) coal overlain by 1½ feet of carbonaceous mudstone. About 50 tons of coal is estimated to have been mined.

URANIUM-VANADIUM DEPOSITS

The present investigation was made principally to aid the discovery of new uranium-vanadium deposits. Each of the known mines and prospects was visited and its location plotted on the geologic map (pl. 1). Geologic information concerning the most important ore deposits was obtained by detailed examination, mapping, and study. Geochemical information concerning them was obtained by collecting and analyzing rock samples for uranium and associated ore metals. Together, the geological and geochemical information permit some statements concerning the origin of these deposits and provide prospecting guides which will be useful in the search for additional deposits.

HISTORY AND PRODUCTION

Prospecting and ore production in the Montezuma Canyon area have been intermittent during the last 50 years. The three main periods of prospecting correspond in general to economic interest in three different metals: radium prospecting, 1910–24; vanadium prospecting, 1935–44; and uranium prospecting, 1948–57. The total production of the Montezuma Canyon area is small in comparison with that of some areas on the Colorado Plateau. Only a few mines here have had a total production exceeding 1,000 tons of ore. During 1955 to 1957, when fieldwork for this investigation was in progress, several of the mines were active.

As the ore production has been small, the grade will be described only in very general terms. The earliest production included small quantities of very rich ore obtained from the outcrops of carboniferous fossil logs replaced in large part by carnotite. Ore produced later contained from 0.10 to 0.20 percent U_3O_8, from 1 to 2 percent V_2O_5, and from 10 to 15 percent $CaCO_3$. Metallurgically, the ore is classified as a high-vanadium high-carbonate ore.

GEOLOGIC FEATURES

GENERAL DESCRIPTION

In the Montezuma Canyon area all the known uranium-vanadium deposits are in the Salt Wash Member of the Morrison Formation. However, about 8 miles to the south near Hatch's Trading Post several uranium-vanadium deposits have been discovered in the Brushy Basin Member of the Morrison. The Moss Back and Shinarump Members of the Chinle Formation, which produce rich ore in the Lisbon Valley area and elsewhere on the Colorado Plateau, are not exposed in the Montezuma Canyon area and have not been explored except where penetrated by a few oil wells.

The uranium-vanadium ore bodies which are found only in the thick prominent sandstone lenses in the Salt Wash Member (fig. 13), are typically local concentrations of ore elongated parallel to the bedding. Most of the ore bodies are from 3 to 6 feet thick, 20 to 50 feet wide, and from 50 to 100 feet long. An ore body may have one or more ore layers separated by barren rock. Locally the ore layers curve upward or downward crossing the stratification to form "ore rolls." High-grade ore generally is associated with conglomeratic or "trashy" zones of clay galls, clay seams, and carbonaceous material.

Near the ore bodies the red mudstone and sandstone of the Salt Wash are bleached or altered; effects of this alteration are most conspicuous where the red mudstone has been bleached to a light greenish gray along contacts with permeable sandstone. Although the alteration features are widespread throughout the Salt Wash Member, they are most intense near the uranium-vanadium deposits.

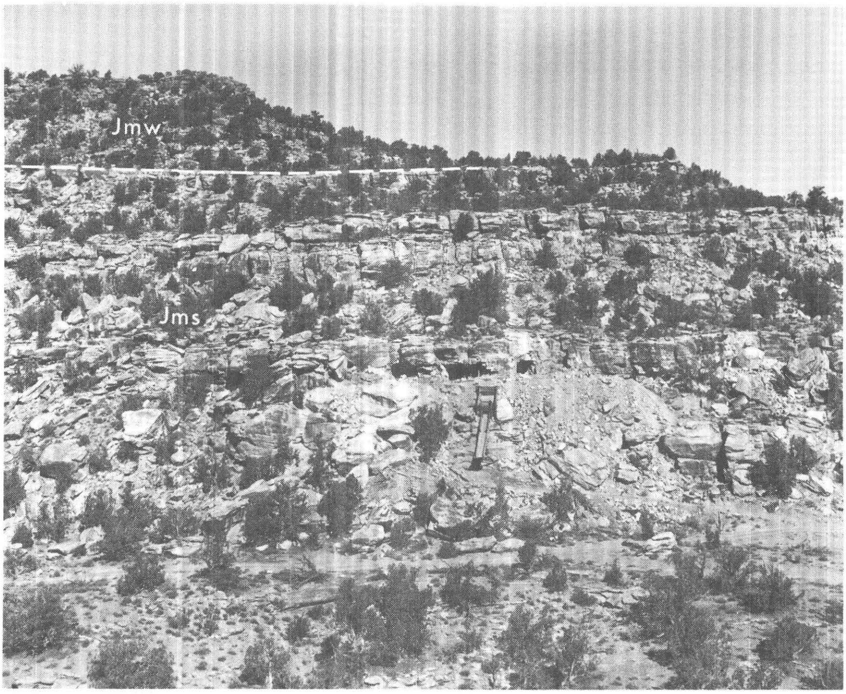

FIGURE 13.—Leo J. mine, formerly North Star mine, in Bradford Canyon, showing typical occurrence of a uranium-vanadium deposit in a prominent sandstone lens of the Salt Wash Member of the Morrison Formation (Jms). Westwater Canyon Member of the Morrison (Jmw) shown to left at top of photograph.

The ore minerals consist chiefly of the black or dark-gray vanadium micas which impregnate and cement sandstone. Cement fragments, separated from sand grains by ultrasonic vibration and hand picking from ore from the Strawberry mine, were identified by X-ray diffraction analysis as a mixture of roscoelite and chlorite. Carnotite or metatyuyamunite, both bright-yellow uranium vanadates, commonly coat joint surfaces and fill cavities in the richest ore. Specimens of carnotite from the Pay Day, L. E. May, and Rim Rock mines were identified by X-ray diffraction analyses as were specimens of metatyuyamunite from the Strawberry and Horsehead mines and the calcium vanadates metarossite and simplotite from the Horsehead mine. Other ore minerals such as tyuyamunite, pascoite, volborthite, and calciovolborthite have been reported (V. R. Chamberlain, written comm., 1946) and additional study probably would reveal more. The common gangue minerals are calcite and goethite. Thin layers of pink cryptocrystalline barite and similar layers of white powdery alunite are present locally along stratification seams near the ore. Aragonite and jarosite have been reported in the ore (V. R. Chamberlain, written comm., 1946).

The sand grains, where protected by a tight cement of the ore minerals, are well rounded and show no solution effects; where not so protected, the grains in part are etched or corroded, and those in contact have sutured or interlocking grain boundaries The ore generally has a lower carbonate content than unmineralized rock, and some of the calcite originally present was replaced in part by vanadium minerals. Abundant carbonized plant fragments are found in the ore in some of the deposits.

In general, the ore minerals of the Montezuma Canyon area are of the secondary, or oxidized, type. Exploration at depth in other parts of the Colorado Plateau has revealed uraninite, coffinite, montroseite, pyrite, and other primary minerals beneath the surficial zone of oxidation (Botinelly and Weeks, 1957). Similar primary uranium-vanadium minerals probably are present in deeply buried areas of the Salt Wash in the Montezuma Canyon area but they have not yet been observed.

ORE-DEPOSIT ZONING

Many of the ore deposits in the Montezuma Canyon area have three distinct zones called here the ore zone, the brown zone, and the gray zone. The ore zone is the olive-gray sandstone impregnated with uranium-vanadium minerals, just described. The brown zone is an iron-stained porous sandstone commonly containing abundant carbonaceous material or abundant plant fragments. The gray zone is a light-gray sandstone tightly cemented with carbonate and commonly freckled with limonitic specks. These zones are most easily recognized in deposits that range from 10 to 20 feet in length.

In homogeneous well-sorted sandstone the ore zone typically is a continuous smoothly curved rounded or ellipsoidal layer or "shell," that completely envelops the brown zone and is in turn completely enveloped by the gray zone (Huff and Lesure, 1962, figs. 1, 2). The rounded ends or sides of the ore zone form the characteristic ore rolls that have been described elsewhere on the Colorado Plateau (Fischer, 1942, p. 383–385; Shawe, 1956). Mudstone layers, logs, and concentrations of organic debris create local irregularities in the shape of the ore zone. The ore layer commonly is from ¼ to 2 feet thick. It is thinnest at the top or bottom of the shell and is particularly thin where close to a mudstone bed. It is thickest where it forms the side or margin of the ore shell. The boundary between the ore zone and the inner brown zone is sharp, but the boundary between the ore zone and the outer gray zone is gradational.

Samples of the ore zone, the brown zone, and the gray zone were collected from 13 typical mines. Analyses of samples of the ore zone from these 13 deposits ranged from 0.001 to 1.54 percent U_3O_8 and from 0.5 to 7.35 percent V_2O_5.

The brown zone, which is inside the ore layer or shell, is a limonite-stained porous sandstone, ranging from grayish orange to moderate brown depending on the iron content. Most of the quartz sand grains in the brown zone are etched or corroded; some have discontinuous authigenic quartz overgrowths. In most of the deposits the carbonate content of the brown zone is very low. The brown zone commonly has a high organic content consisting of carbonized plants or many iron-stained molds of tiny plant fragments. Chemical analyses of samples of the brown zone from the 13 deposits indicate a range in U_3O_8 content of 0.001 to 0.024 percent and in V_2O_5 content of 0.015 to 0.55 percent.

The gray zone, which is outside the ore layer or shell, is a gray sandstone tightly cemented with calcite. It is generally a very light gray or white and characteristically has abundant small limonite spots or freckles. Where the quartz sand grains are in contact, they generally are etched and have sutured grain boundaries; where not in contact many grains have authigenic quartz overgrowths. Calcite, which commonly fills all interstices in the sandstone, locally forms single skeleton crystals 3 to 5 inches in diameter. Carbonized plant fragments are present in some of the deposits in the gray zone. The gray zone has a gradational boundary with the ore zone, and grades imperceptibly into the country rock. Chemical analyses of samples of the gray zone from the 13 deposits indicate a range in

757-270 O—65——5

U_3O_8 content of <0.001 to 0.058 percent and in V_2O_5 content of 0.06 to 0.54 percent.

The three zones can be identified and mapped within many of the uranium-vanadium deposits. At the Lucky Boy mine (fig. 14) the ore shell is a single flattened northwest-trending ellipsoid more than 120 feet long and about 40 feet wide. In some of the other large mines, however, the zonal pattern is not as simple. In the Strawberry mine at least four ore shells enclosing separate brown zones locally coalesce forming a complicated intergrowth of zones. Nowhere, however, does one zone occur without the corresponding other two zones. These more complicated patterns may represent overlapping of the zones during mineralization.

STRATIGRAPHIC CONTROLS

Stratigraphic controls of ore occurrence were studied in detail in the part of Montezuma Canyon that includes most of the important uranium deposits (pl. 3).

In this area all the important mines are in one large lens of sandstone in the middle of the Salt Wash Member. This sinuous asymmetric lens has a maximum thickness of 152 feet and a width of 5,100 feet. At both sides the lens grades into thinner sandstones separated by tongues of mudstone.

The sandstone lens apparently is the fill within a deep meandering channel cut into the underlying more thinly bedded sandstones and mudstones. The cut banks of the meander can be identified by the abrupt thickening of the sandstone fill; the slip-off slopes are characterized by the interbedding of mudstone lenses in the sandstone (pl. 3, section *A–A′*).

No obvious relation between the location of the ore deposits and the shape of the sandstone lens was found but most of the ore deposits seem to be close to the edge of the sandstone. Only the Strawberry deposit is near the middle of the sandstone lens. Several deposits, like the Cottonwood, the Lucky Boy, the Rainbow, and the Coyote No. 1, are near the pinchouts of mudstones along the slip-off slopes where probably there were original concentrations of organic material.

STRUCTURAL CONTROLS

No evidence was found for tectonic control of the uranium-vanadium deposits in the Montezuma Canyon area. In the area of detailed mapping, the base of the Summerville Formation and the base of the Dakota Sandstone were both contoured at an interval of 20 feet (pl. 3). The base of the Summerville, which is a very flat surface and easy to recognize from a distance, shows an even gentle dip of about ½° SE., and no apparent interruption by local structures. The base of the Dakota is not a flat surface. This horizon includes shallow channels

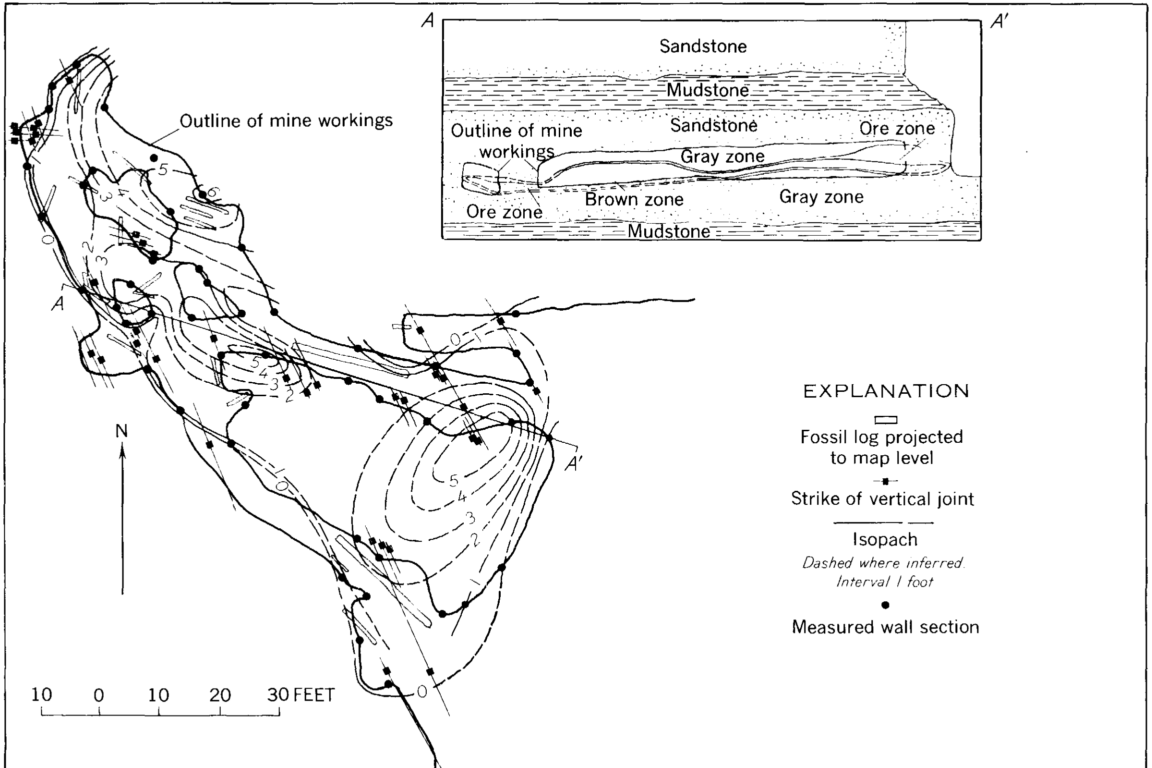

FIGURE 14.—Geologic map and section of the Lucky Boy mine, Montezuma Canyon, San Juan County, Utah. Isopachs show thickness of mineralized shell or combined ore zone and brown zone. Mapped by F. G. Lesure and A. J. Froelich, July 1956.

with 20 or 30 feet of local relief causing local irregularities in the 20-foot-interval structure contours. In general, however, the two horizons are parallel and neither indicates local folding.

The middle Montezuma Canyon area has no faults. Systematic joint sets were mapped in mines in this area, but joints are no more well developed there than elsewhere. There is no apparent relation between the joints and the present position of the ore bodies. In upper Montezuma Canyon, where some mines like the Rim Rock are close to major faults, there is no relation apparent between the ore and the faults.

GEOCHEMICAL STUDIES

The geochemical studies were designed to investigate geochemical methods of prospecting and geochemical facts of significance in origin of the ore. Both ore and barren rock contain a high proportion of quartz, feldspar, and clay minerals; accordingly their main chemical constituents must be silicon, aluminum, calcium, magnesium, potassium, and sodium. Of more interest to this investigation is the distribution of the ore metals uranium and vanadium and of metals like copper, lead, and zinc which may be associated with the ore metals. The geochemical studies were confined to the distribution of the ore and associated metals in three groups of samples: (1) samples of all sedimentary formations present, (2) samples of different lithologic types at various distances from ore in the Salt Wash Member, and (3) samples of the different zones in the ore deposits. All the samples are of oxidized, partly weathered rock so that there is some chance that their original composition may have been changed by subsequent oxidation and weathering.

TRACE ELEMENTS IN THE SEDIMENTARY FORMATIONS

Samples collected during the measurement of stratigraphic sections were analyzed by methods devised for geochemical prospecting. The uranium test (Thompson and Lakin, 1957) and the vanadium test (Ward and Marranzino, 1953; Ward and others, 1963, p. 89–91) are specific for these metals. The total heavy-metal test (Huff, 1951) is a group test designed to identify any samples containing abnormal amounts of copper, lead, or zinc.

Most of the samples analyzed have a uranium content less than 4 ppm (parts per million), a vanadium content less than 60 ppm, and a total heavy-metal content of less than 55 ppm (table 5). These values are much like those of 1 ppm uranium, 10 ppm vanadium, and 60 ppm total heavy metal obtained for unmineralized Salt Wash sandstone (Shoemaker and others, 1959, pp. 31–32). In comparison, the earth's crust contains about 4 ppm uranium, 150 ppm vanadium, and 170 ppm total heavy metal calculated as zinc equivalents (Huff, 1951; Mason, 1952, p. 41). Sedimentary rocks contain 1.2 ppm uranium (Evans and Goodman, 1941) and from 20 ppm vanadium in sandstone to 120 ppm in shale (Jost, 1932).

TABLE 5.—*Uranium, vanadium, and total heavy-metal content of samples from various geologic formations of the Montezuma Canyon area*

[Analyses by H. E. Crowe, A. P. Marranzino, and C. E. Thompson]

Formation	Number of samples having composition indicated											
	Uranium (ppm)				Vanadium (ppm)				Total heavy metal (ppm)			
	<4	4	8	>8	<60	60	100 to 240	>300	<50	50	100	>100
Surficial deposits:												
Alluvium	99	0	0	1	96	4	0	0	80	16	4	0
Loess and pediment gravel	15	0	0	0	11	1	0	3	11	3	1	0
Mancos Shale	10	0	0	0	3	6	1	0	5	2	2	1
Dakota Sandstone	21	1	1	0	12	9	2	0	13	5	4	1
Burro Canyon Formation	15	1	0	1	9	2	6	0	11	4	2	0
Morrison Formation:												
Brushy Basin Member	16	0	0	0	[1] 6	[1] 6	[1] 4	0	12	4	0	0
Westwater Canyon Member	12	0	0	0	10	2	0	0	6	5	1	0
Salt Wash Member	89	8	9	2	[2] 38	[2] 19	[2] 21	12	73	27	6	2
Summerville Formation	20	0	0	0	14	2	0	2	15	3	2	0
Entrada, Carmel(?), and Navajo Formations	16	0	0	0	11	[3] 4	0	1	15	0	1	0

[1] Includes 3 reported as <300.
[2] Includes 12 reported as <300.
[3] Reported as <300.

Most of the samples containing abnormal amounts of the investigated trace elements are from the Salt Wash Member (table 5). Of the 108 samples collected from the Salt Wash Member, 19 have 4 ppm or more uranium in comparison with 5 of 233 samples from the other formations having 4 ppm or more. Most of the samples containing the abnormal amounts of trace elements come from near the Rim Rock uranium mine. If these samples were omitted the results would show no significant difference of trace elements between the various formations. Except for these samples from near the Rim Rock uranium mine, the sedimentary rocks in the Montezuma Canyon area appear to have just a normal content of the ore metals. Evidently the presence of ore deposits here is not explainable to any degree by a local abundance of the ore metals in these rocks.

TRACE ELEMENTS IN THE SALT WASH MEMBER

The distribution of uranium, vanadium, and heavy metals—as affected by lithology, alteration, and proximity to ore—within the Salt Wash Member was studied in samples collected from both altered and unaltered sandstone and mudstone, mostly in the middle Montezuma Canyon area but partly in the northern part of Montezuma Canyon and in Bradford Canyon. The unaltered sandstone in the Salt Wash has a reddish cast; the altered is white. The unaltered mudstone is red; the altered is gray or green. Sample sites were chosen in or at the bases of ore-bearing sandstone lenses and in or at the bases of sandstone lenses both above and below ore-bearing lenses. All sample sites were spaced less than 50 feet, from 50 to 500 feet, and more than 500 feet horizontally from an ore deposit. A total of 216 samples were collected; of these 72 samples were duplicates used to evaluate reproducibility of the measurements.

Although variations in uranium, vanadium, and total heavy-metal content among the samples are small, lithologic character has a perceptible influence. The total heavy-metal content is highest in the mudstone samples; over three times as many mudstones as sandstones have a total heavy-metal content of 20 ppm (table 6). The vanadium content is highest in the altered rocks, particularly in the altered mudstones. The uranium content may be slightly higher in the mudstones than in the sandstones but appears to be unrelated to alteration.

TABLE 6.—*Uranium, vanadium, and total heavy-metal content of samples from the Salt Wash Member*

[Analyses by E. F. Cooley, H. E. Crowe, E. A. Smith, and C. E. Thompson]

Description	Number of samples having composition indicated												
	Uranium (ppm)				Vanadium (ppm)				Total heavy-metal (ppm)				
	<4	4	8	>8	<50	50	80 to 100	>100	<20	20	50	100	>100
Rock type:													
Unaltered sandstone	71	0	1	0	69	2	0	1	64	7	1	0	0
Unaltered mudstone	64	5	1	2	56	8	7	1	34	33	2	2	1
Altered sandstone	69	2	0	1	57	4	3	8	61	9	2	0	0
Altered mudstone	61	6	3	2	41	8	13	10	39	26	4	1	2
Stratigraphic proximity to ore:													
Above ore interval	71	1	0	0	66	2	2	2	50	17	3	0	2
Ore interval	67	2	1	2	52	9	8	3	45	22	3	1	1
Ore interval (duplicate set)	60	7	3	2	50	6	9	7	47	22	2	1	0
Below ore interval	67	3	1	1	57	5	5	5	58	13	0	1	0
Lateral distance from ore:													
<50 ft	84	6	2	4	72	6	8	10	63	30	1	0	2
50–500 ft	86	7	3	0	79	4	7	6	68	19	5	3	1
>500 ft	95	0	0	1	73	12	7	4	68	26	2	0	0

The proximity to ore seems to have even less effect upon the trace-metal content of the samples than the lithologic character. Of the 96 samples collected less than 50 feet laterally from ore only 12 have a uranium content of 4 ppm or more. Many of these samples were collected within only 10 or 15 feet of ore where much higher values were anticipated. Some samples collected only a few feet directly below ore contain less than 4 ppm uranium. No evidence was found of any downward leaching of the ore metals from the deposits.

In the Montezuma Canyon area abnormal uranium and vanadium concentrations appear to be limited to the immediate vicinity of the ore. Other investigations on the Colorado Plateau show no detectable uranium at short vertical distances above uranium ore—30 feet above ore in several places (Holland and others, 1958) and 10 feet above ore in another (Huff, 1955, p. 251). Uranium is detectable at greater distances laterally from ore along the bedding but the distribution of the uranium is somewhat erratic and the value of such anomalies for geochemical prospecting has not been established.

Two botanical methods of prospecting for uranium deposits on the Colorado Plateau have been developed (Cannon and Kleinhampl, 1956): (a) analyzing plant ash for traces of uranium; and (b) mapping the distribution of *Astragalus pattersoni*, *A. confertiflorus*, and other "indicator plants" which grow preferentially near uranium deposits. These methods were investigated briefly on Salt Wash exposures in the Montezuma Canyon area, but there the uranium deposits are too deeply buried for the plant analysis method to be applicable, and *Astragalus pattersoni*, the most useful indicator plant on the Colorado Plateau, was not identified.

Some indicator plants, however, are present near the Montezuma Canyon uranium deposits. During a botanical reconnaissance of representative mines, Helen L. Cannon collected and identified *Atriplex confertifolia* (shad scale), *Eriogonum*, and *Astragalus confertiflorus*. *Astragalus confertiflorus* indicates the presence of selenium in clay soils. As selenium is present in the ore, its occurrence in the soil may be considered to indicate the presence of ore.

GEOCHEMISTRY OF THE ORE DEPOSITS

The geochemical studies of the ore deposits were confined to chemical studies of the three zones which make up the typical zoned ore bodies. Sample sites were selected where the brown, ore, and gray zones could be sampled within a few feet of each other. Samples of each of these three zones were collected from 15 sites representing 13 zoned ore bodies. These 45 samples were analyzed chemically for uranium and vanadium, radiometrically for equivalent uranium, and spectrographically for 65 other chemical elements. The percentages of the elements having the greatest range in concentration were plotted as histograms for each zone (pl. 4) to show significant differences in composition among the zones.

The differences are most marked for the uranium and vanadium. The U_3O_8 content ranges from 1.54 percent in one ore-zone sample to 0.001 percent in several of the gray-zone samples. The averages are more revealing in indicating systematic differences than individual values. The average U_3O_8 content of the brown zone is 0.005, of the ore 0.191, and of the gray zone 0.010 percent. Corresponding averages for V_2O_5 are 0.226, 3.46, and 0.291, respectively. The average ore is thus over ten times as rich in both uranium and vanadium as the brown or the gray zone nearby.

The equivalent uranium is in approximate agreement with the uranium determined chemically. Among the 45 samples the equivalent uranium exceeds the uranium in 21 and the uranium the equivalent uranium in 16 but only 4 samples had more than a twofold difference. Considering possible analytical errors, there is not enough difference between the equivalent uranium and the uranium to demonstrate differential leaching during weathering of either the uranium or the radioactive daughter products.

Like uranium and vanadium, magnesium is more abundant in the ore than in the brown or gray zones; this abundance probably is related to the presence of chlorite in the ore. Iron, titanium, silver, cobalt, molybdenum, nickel, zirconium, and yttrium, and possibly strontium, lead, and copper are more abundant in both the brown and ore zones than in the gray zone. In general, these accessory elements abundant in the brown zone or in the ore are those known from other investigations (Shoemaker and others, 1959) to be present in Salt Wash uranium ore throughout the Colorado Plateau.

Of the various geochemical comparisons made in Montezuma Canyon the contrast is quantitatively largest between the uranium and the vanadium in the ore and that in the adjoining rock. This contrast reflects the sharp outer limit of the ore bodies which for many years has been recognized as characteristic of Salt Wash ore deposits and which hampers exploration for the ore; a drift or a drill hole may come within a few feet of ore and give no indication of the ore nearby. The same sharp outer limit of the ore hampers geochemical prospecting for the ore; geochemical prospecting is of questionable value except where the ore-metal content in the materials sampled increases gradually from background values several hundred feet or more from the ore body to a maximum as the ore is approached.

ORIGIN

The uranium-vanadium deposits of the Colorado Plateau have been studied for many years but their origin still is not fully understood. Geologists agree in general that deposition of the primary ore minerals near organic materials and the later changes in ore mineralogy are explainable as chemical processes of oxidation and reduction. There is no such general agreement concerning related subjects such as the source of the uranium and vanadium and the means by which these metals were transported to their present location. New data obtained during the present study indicate that the zoning may result from the slow diffusion of uranium and vanadium in a nearly stagnant fluid just prior to deposition. Diffusion as a process in the origin of Colorado Plateau ore deposits has received little or no attention previously; it is suggested here and in greater detail in a companion article

(Huff and Lesure, 1962) as the cause of "ore rolls" of sandstone-type ore.

In brief, the diffusion hypothesis is that the ore bodies developed by a process of solute diffusion to and chemical precipitation in a zone of reaction between two nearly static solutions of different composition. Uranium and vanadium ions were present in the relatively static solution which saturated the sandstone. Slowly these ions diffused toward local pockets of the second, but reducing, solution where reducing chemical reactions precipitated low-valent minerals such as uraninite, coffinite, and montroseite. Reduction and precipitation of these minerals along the interface between the two solutions produced the ore shell and other zoned features.

The following problems are involved in this hypothesis: What were the primary ore minerals? What was the source of the uranium and vanadium? Can the chemical and physical conditions at the time of ore deposition be determined? How were the elements precipitated as the various ore minerals? How were the uranium and vanadium introduced? Are diffusion mechanisms capable of transporting these elements in significant quantities? Answers to these questions resulting from previous investigations require discussion before the diffusion hypothesis can be described in detail.

PRIMARY ORE MINERALS

Although the uranium-vanadium ores exposed in the Montezuma Canyon area are fully oxidized, mining elsewhere on the Colorado Plateau has shown that the primary ore, particularly that found beneath the water table, consists of low-valent unoxidized minerals. In ore with high vanadium-uranium ratios (3:1 to 15:1) the uraninite, coffinite, montroseite, and pyrite of the primary ores oxidize to carnotite, hewettite, tyuyamunite, and vanadium clay (Botinelly and Weeks, 1957). Probably if mining in the Montezuma Canyon area were carried on below the zone of oxidation primary unoxidized ores of this type would be found.

SOURCE OF THE URANIUM AND VANADIUM

The uranium and vanadium deposits of the Colorado Plateau area are clearly epigenetic. Age determinations of primary uranium minerals from other areas on the Colorado Plateau indicate that the ores are of Late Cretaceous or early Tertiary age (Stieff and others, 1953). More recent workers, although obtaining a wide spread of ages, suggested that the ores may be as young as Pliocene (Miller and Kulp, 1958). The age determinations plus such textural relations as ore layers crosscutting primary sedimentary features indicate that the ores were deposited long after the enclosing Jurassic sedimentary rocks.

Possible sources for these metals might be either sedimentary or magmatic; the possible sedimentary sources can be further subdivided into (a) parts of the Salt Wash outside the present ore bodies, (b) sedimentary rocks rich in volcanic ash such as the Brushy Basin Member of the Morrison Formation, or (c) sedimentary rocks rich in organic material such as plant fossils (McKelvey and others, 1955, p. 492–510; Gruner, 1956a).

Most proponents of a sedimentary source believe that the uranium and vanadium might have been transported by heated ground water or by connate water. Proponents of a magmatic source believe that these ores were deposited by hydrothermal solutions possibly related in some way to the laccolithic intrusions of the Colorado Plateau. Possibly the vanadium was introduced from one source, such as ground water, and the uranium from another, such as hypogene solutions. During the present study no new data were obtained concerning the original source of either the uranium or the vanadium.

CHEMICAL AND PHYSICAL CONTROLS OF ORE DEPOSITION

The reduced state of the primary ore minerals indicates that chemical processes of oxidation and reduction were important in ore deposition. Although the exact chemical and physical conditions that existed at the time of deposition are unknown, some of these conditions can be inferred. When the ore was deposited, the sandstone of the Salt Wash in the Montezuma Canyon area probably was buried at a depth of a mile or more. At such a depth any connate or ground water under the high hydrostatic pressure and at a temperature, due to the geothermal gradient, of 70°C to 110°C (Coleman, 1957) would behave very much like a low-temperature magmatic solution. Whatever its source, circulation of this solution probably was slow and reaction with sediments of different composition produced local differences in solution composition. Comparisons with ground water in recent sediments indicate that the solution around trashy zones, buried logs, and accumulations of macerated plant material probably was acid (low pH) and reducing (low Eh, oxidation potential). This solution would contain water-soluble organic compounds such as alcohols and aldehydes or hydrogen sulfide liberated from the slowly decaying organic matter by the action of anaerobic bacteria and by the increasing thermal gradient. The solution in nearby clean sandstone or mudstone would probably be alkaline (high pH) and possibly oxidizing (high Eh). Such local differences in composition of the water would provide opportunity for oxidation-reduction reactions.

One of the principal reactions which took place was the reduction of ferric compounds. In the Montezuma Canyon area most of the sandstone and much of the mudstone of the Salt Wash—both in the main ore horizon and also where in contact with coarse-grained sandstone—have been bleached. The original red ferric oxide grain coating was reduced and dissolved. The reducing capacity of carbonaceous materials is large (Garrels and Pommer, 1959, p. 164) and adequate enough to explain all the bleaching (Smith and others, 1963). The association of altered or bleached red beds with uranium ore is well established throughout the Colorado Plateau (Weir, 1952). In the Montezuma Canyon area the bleached areas are widespread and clearly related to the permeability of the sediments and to the distribution of organic matter.

Another important reaction was the reduction and precipitation of uranium and vanadium as the primary ore minerals. The close association of ore minerals with carbonaceous material and the replacement, locally, of carbonaceous material by ore minerals has long been recognized on the Colorado Plateau (Gruner, 1956b, p. 502). In many areas where mining activity has extended beneath the zone of oxidation the chemically reduced minerals which comprise the primary ore can be observed clearly as a cell-by-cell replacement of woody structure in the carbonaceous material (Gross, 1956).

Locally the ore minerals are deposited as a cement in clean sandstone and as joint fillings, but all ore commonly is not more than 10 feet from traces of carbonaceous material. Thus, it seems very likely that the reduction and precipitation of the ore elements was caused by oxidation of the organic compounds (Garrels and Pommer, 1959).

DIFFUSION HYPOTHESIS

Because of the probable slow circulation of water in the Salt Wash at the time of ore deposition some of the movement of the uranium and vanadium ions may have been by diffusion. The evidence of diffusion appears to be particularly prominent in the Montezuma Canyon area. The sharp boundary and smooth surface between ore and brown zones in the zoned deposits suggests reaction along an interface between two liquids of generally different composition. The zoned deposits in the Montezuma Canyon area are closed shells; this suggests that precipitation took place from the addition of uranium and vanadium from all sides. The shape of the ore shell in the zoned deposit is analogous to that of geodes, concretions, and liesegang rings, all of which can be explained by diffusion of solutes in a relatively stagnant solvent.

In a fluid that is not homogeneous throughout, material in solution concentrated at one point will diffuse toward areas of lower concentration until the fluid becomes homogeneous. This difference in concentration is commonly called a concentration gradient. If a solute is removed by precipitation at one point of a system the concentration at that point is reduced. More solute will diffuse toward the site of precipitation. If two fluids of different composition are involved, diffusion of the reacting solutes may take place toward their area of reaction and the precipitates formed will accumulate in this area. The zoned deposits may have formed in this way.

The chemical processes responsible for the deposition of the uranium and vanadium minerals probably were oxidation of soluble organic compounds or hydrogen sulfide and reduction of uranium, vanadium, and iron. The substances formed would be carbonate, water, sulfate, uraninite, coffinite, montroseite, and pyrite. The organic compounds and hydrogen sulfide came from the plant remains in the sandstones of the Salt Wash and the iron from the ferric oxide grain coatings. Only uranium and vanadium were not of local origin.

According to the diffusion hypothesis, soluble organic compounds such as alcohols, aldehydes, or possibly hydrogen sulfide formed from plant accumulations in the brown zone of the ore deposits. These reducing compounds diffused outward and reaction and precipitation took place where they encountered inward-diffusing uranium and vanadium ions. This precipitation formed the ore shell and by hindering additional diffusion tended to keep the interface between the two solutions in the original position.

If the plant fragments had yielded soluble reductants which diffused outward, then the ore could have been precipitated at some distance from the insoluble plant remains. Under such conditions the plant remains would be associated with ore, but not replaced by it. This explains why in some places carbonaceous material can be found which contains no ore and in other places ore can be found in clean sandstone with no carbonaceous material.

Quantitative studies show that diffusion could easily be significant through several hundred feet of saturated sandstone (Garrels and others, 1949). Under static hydrologic conditions and at elevated temperatures caused by deep burial, diffusion should be particularly effective.

To test the efficiency of diffusion, several laboratory experiments were made using reddish Salt Wash sandstone and mudstone mixed with various organic materials and water. Both carbonized wood from a typical Montezuma Canyon uranium deposit and peat from a recent peat bog in the Rocky Mountains were used. All experiments were performed in test tubes with a stagnant solution so that the only movement of solutes would be by diffusion. In each test tube a layer of crushed and sieved sandstone or mudstone was placed at the bottom. A layer of organic matter was added on top and then water added. In some test tubes organic matter was placed within the sediments. Both tap water and distilled water were used.

Results of these experiments are as follows:

1. Normal red sand in contact with peat and saturated with either distilled or tap water will be discolored after several weeks. The discoloration begins close to the peat and gradually spreads throughout the sand. Microchemical tests show that the discoloration involves a loss of iron from the sand, presumably the solution of some of the ferric oxide grain coating.
2. Normal red mud has a similar but much slower reaction.
3. Peat in either distilled or tap water will remove after a few days traces of uranium in solution added as uranium nitrate. Neither the normal red sand nor normal red mud will extract uranium from solution. Uranium determinations to test removal of uranium from solution were made by the fluorescent bead test.
4. Similar experiments using carbonized wood in place of peat produced no visible effects either of bleaching sediments or of extracting uranium.

In another experiment, clean white quartz sand was placed in a plastic box and saturated with water. A solution of thioacetamide which releases hydrogen sulfide was added to the sand in the center of the box by means of a glass tube inserted into the sand. A solution of lead nitrate was added to the sand along the outer edges of the box, also through glass tubes. Because the sand was fully saturated with water, no solution flow was possible. A black precipitate of lead sulfide, however, formed a continuous curved band around the thioacetamide solution near the center of the box indicating that lead ions diffused inward and sulfide ions diffused outward. This "zoned mineral deposit" formed by diffusion is analogous to the zoned uranium-vanadium deposits of the Montezuma Canyon area.

The size of the ore body formed by the diffusion process would depend upon the rate of uranium-vanadium introduction and upon the duration of the diffusion. Continual deposition of the ore would cause continuous diffusion of uranium and vanadium toward the center of reduction. Continued oxidation of organic material would continue the deposition of the ore. An ore body would thus continue to develop and the ore layer to thicken until all the uranium and vanadium had been deposited or all the soluble organic matter oxidized. After the soluble organic matter was oxidized, ore minerals might in part replace insoluble organic matter.

The grade and thickness of the ore shell depend in part upon position of the shell in the enclosing sandstone. In general the shell is best developed and the ore layer thickest and richest on the side of the shell facing the greatest mass of sandstone. The shell is least developed where close to an impermeable mudstone (Huff and Lesure, 1962, figs. 1 and 2). In terms of the diffusion hypothesis the massive sandstone simply permitted more diffusion of the ore metals toward the ore body.

ROLL-TYPE ORE BODIES

In many places on the Colorado Plateau roll ore bodies have been found and described as layered deposits that cut across sandstone bedding in curved forms (Fischer, 1942; Shawe, 1956, p. 239). These deposits have been explained as effects of sedimentary features, joints, and flowing fluids upon ore deposition (McKelvey and others, 1955, p. 494; Shawe, 1956). The roll ore bodies are similar in shape to one end of a zoned deposit like those of the Montezuma Canyon area. The similarity between the concentric layering of some rolls and liesegang rings is striking. Possibly these rolls also originated partly from diffusion.

Some of the larger ore bodies in the Montezuma Canyon area could be described as roll-type or as complexly zoned bodies with several zoned areas overlapping. The simple diffusion hypothesis is not completely applicable to such deposits. Where several zones overlap, some solution flow and mixing may have taken place producing a series of ore layers and possibly dividing a large mass of reducing solution into several smaller ones. Formation of zoned deposits around these small centers would produce a complex pattern as found at the Strawberry mine.

Large uranium deposits elsewhere on the Colorado Plateau have "ore rolls" which only in part can be attributed to diffusion. Evidently, then, considerable solution flow must be called upon to explain the extraordinary concentrations of uranium ore. The Montezuma Canyon area may have been ideal for the development of diffusion features and simple zoned deposits because of its long period of tectonic stability.

OXIDATION OF ZONED URANIUM-VANADIUM DEPOSITS

The ore deposits of the Montezuma Canyon area are fully oxidized. Following ore deposition, uplift and erosion in the area brought the deposits into the zone of oxidation. Pyrite deposited in the brown zone was oxidized and partly dissolved, and the iron oxide was precipitated as the characteristic ferruginous brown stain coloring the sandstone. In the gray zone the high carbonate content prevented the solution of iron; the disseminated pyrite grains oxidized in place to goethite producing the characteristic freckling of the sandstone. In the ore zone little migration of uranium took place during oxidation because of the low solubility of uranium vanadates (R. M. Garrels and C. L. Christ, written commun., 1956). Most of the ore oxidized in place or moved only a few feet into open spaces and along joints in the sandstone. The uranium and some of the vanadium formed uranium vanadates such as carnotite and metatyuyamunite; the excess vanadium formed vanadium minerals such as metarossite, simplotite, and vanadium clays. Some of these oxidized ore minerals were formed after jointing of the sandstone and coat the joint surfaces within the ore zone.

GUIDES FOR PROSPECTING

Only a small part of the Salt Wash Member in the Montezuma Canyon area is mineralized. One mine or prospect has been discovered for about every 2 linear miles of outcrop. This mineralized ground amounts to less than 0.1 percent of the outcrop length. To date (1961) more than 55 percent of the ore production has come from within 50 feet of the outcrop. This production has been in less than 0.00001 percent of the total area of Salt Wash sandstone preserved in the Montezuma Canyon area and the conclusion is made that only a small part of the ore present has been discovered and mined.

The principal reason for the low rate of discovery in this area is that the deposits are small and have sharp outer boundaries. Sandstone only a few feet from ore contains only trace amounts of uranium and vanadium. The obvious prospecting guides, such as the presence of bright-yellow uranium minerals or dark-gray vanadium minerals and abnormal radioactivity, are limited to finding ore bodies that crop out. Less direct indications of ore are the presence of carbonaceous material and extensive alteration or bleaching in sandstone or mudstone. However, carbonaceous materials and evidence of bleaching are so abundant that these indications of ore are of value only as a broad-scale prospecting guide.

Study of the known deposits indicates that in this area thick sandstone lenses from 100 to 200 feet below the top of the Salt Wash are more favorable for ore deposits than sandstone lenses at the top or the bottom of the member. Exploration in the thicker lenses, and especially on the slip-off slopes of meandering lenses, might be successful. Even though many uranium deposits in Triassic rocks are in channel sandstone (Wood and Grundy, 1956), there seems to be no particular advantage to exploring the base of channels in sandstone lenses in the Salt Wash.

For reasons not completely understood many of the Salt Wash deposits in the Colorado Plateau lie roughly within broad belts like the Uravan mineral belt (Fischer and Hilpert, 1952). When the deposits of middle Montezuma Canyon, in Horsehead Canyon, and in Monument Canyon are plotted on a regional map they line up crudely with mines west of Blanding, and possibly indicate a mineral belt.

Another possible mineral belt may extend through the deposits in Bradford and Devils Canyon. Prospecting within these belts may be more likely to lead to the discovery of new deposits than prospecting outside of them.

Study of the zoning in the ore and adjoining rock may be helpful in developing some of the deposits. The presence of abundant organic matter and brown iron oxide staining suggests the brown zone of a zoned deposit and nearness to the corresponding ore zone. Exploration should be extended by mining or by closely spaced drilling toward the center of the sandstone lens but not beyond the contact with the gray zone. The ore, if present, should separate the brown and gray zones. Because neither uranium nor vanadium migrated during oxidation no successful geochemical method of exploration was found during the present study.

In summary, many small deposits that cropped out in the area have been found and mined, but many similar deposits probably are present which do not crop out. No systematic method of exploration other than drilling near known areas of ore occurrence has yet been developed.

MINE DESCRIPTIONS

Names of mines and prospects in the Montezuma Canyon area have had many changes. None of the claims have been patented, and all of them have to be kept valid by annual assessment work. If assessment work lapses the claims can be restaked under a new claim name by another party. During the three prospecting periods—radium (1910–24), vanadium (1935–44), and uranium (1948–57)—most of these claims were staked and worked several times under different names. The names used in this report are those which were in use at the time of our examination. Most of these differ from those in use when the claims were examined in 1946 by the Union Mines Development Co., and probably there will be many future changes in the claim names.

The production and the grade information given with the mine descriptions were provided by the U.S. Atomic Energy Commission from their records of mill shipments during the 10 years prior to July 1, 1955, and are published with permission. Detailed information concerning production, grade, and reserves has not been released by the U.S. Atomic Energy Commission. Reserve estimates in this area would be of questionable value because of the spotty distribution of the ore.

The detailed mine descriptions given here are for what are considered the most significant deposits—those which have a total production of over 1,000 tons, those which consist of a network of passageways giving good three-dimensional exposures of the ore body, or those which have features of particular geologic interest. The mines and prospects are described according to the geographic clusters or groups in which they occur.

UPPER MONTEZUMA CANYON GROUP

Six mines and prospects have been opened in Montezuma Canyon north of the Dodge Point graben. Production of the group has been less than 50 tons of ore which has a grade of 0.05 to 0.15 percent U_3O_8 and 1.5 to 2 percent V_2O_5. The largest of the mines, the Rim Rock, is on the point between Montezuma and Boulder Canyons. It has two adits and about 160 feet of drift. The ore horizon is near the base of a prominent sandstone cliff formed by a 28.5-foot-thick sandstone lens in about the middle of the Salt Wash Member (section 2, p. 86). Neither this deposit nor the others of this group appear to be influenced by the faults nearby.

LONG CANYON GROUP

Six small mines and prospects form a group in Long Canyon. Total recorded production for the group is less than 50 tons of which the largest shipment contained 0.1 to 0.2 percent U_3O_8 and 1 to 2 percent V_2O_5. The largest mine, the Slum mine, is in a prominent sandstone bed about 30 feet thick in about the middle of the Salt Wash Member. It consists of two adits and about 150 feet of workings. The other five mines and prospects in this group have less extensive workings and have yielded less ore.

HORSEHEAD CANYON GROUP

Horsehead Canyon contains 5 mines and prospects of which the Titus No. 3 is the largest and has had the greatest production. The workings of the Titus No. 3 consist of 2 adits totaling 205 feet, plus some rim stripping. Most production from this mine was prior to 1942 and no grade data are available. Small shipments from the Last Chance No. 1 and from the Yellow Cake No. 4 contained 0.1 to 0.2 percent U_3O_8 and 1 to 2 percent V_2O_5.

MIDDLE MONTEZUMA CANYON GROUP

The mines and claims in Montezuma Canyon between the mouths of Long and Horsehead Canyons are the largest and most productive mines of the area. Several of the mines have produced from 3,000 to 6,000 tons of ore with a grade of 0.1 to 0.2 percent U_3O_8 and 1 to 2 percent V_2O_5. These mines are all within the uncommonly thick sandstone lens in the middle of the Salt Wash Member, which has been described previously and which is illustrated on plate 3.

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COTTONWOOD MINE

The Cottonwood mine, which is on the west side of Montezuma Canyon about 1½ miles south of Long Canyon, was located in 1940 by H. and L. Shumway, who in 1954 still owned the claim, but later sold it to a subsidiary of the Atlas Corp. The mine has extensive workings and has had about the largest production of any mine in the Montezuma Canyon area; the production was chiefly between 1940 and 1944.

This deposit is on the south edge of the main ore-bearing sandstone of middle Montezuma Canyon. It is on the slip-off slope of the meander near the wedge edges of two prominent mudstones interbedded with the sandstone. The ore sandstone is 57 feet thick at the mine and the ore body is from 10 to 18 feet beneath the top. One prominent mudstone at about the same altitude as the ore is interbedded in the main sandstone lens about 200 to 300 feet northwest of the main or northeast adit. Another prominent mudstone at about the same altitude is interbedded with tongues of the ore-bearing sandstone about 400 feet south of the main adit. These prominent mudstones do not extend into the mine workings but may be related to the thin mudstones found in the workings.

The ore is typically an olive-gray sandstone cemented with roscoelite. Cavities and joint surfaces are coated with carnotite. Some ore forms nearly horizontal bands or layers cementing massive sandstone and some ore is localized around clay seams, carbonaceous zones, and trash pockets. Some ore layers curve across bedding structures to form ore rolls. The ore layer or zone separates the brown zone and the gray zone as in other mines of the area.

The Cottonwood mine has 4 adits, almost 1,700 feet of drifts, as well as some small stopes. A map of this mine made by the Union Mines Development Corp. is reproduced here (pl. 5). As indicated by this map the workings follow several elongate ore bodies in a mineralized zone 350 feet long and 250 feet wide. Mineralized sandstone in the workings ranges from 0.1 to 3 feet in thickness. One ore seam about 1 to 2 feet thick was followed in the main adit for 240 feet before the ore zone broke up into several thin seams. Eight samples from this mine analyzed by the Union Mines Development Corp. contained from 0.001 to 0.39 percent U_3O_8 and 0.29 to 5.75 percent V_2O_5.

Drilling by the Atomic Energy Commission did not indicate ore very far beyond the mine workings (pl. 3). In drill holes 265, 279, and 280—which are immediately west of the mine workings—the altitude of the main radioactive horizon is about 20 feet lower than that of the mine. The ore distribution probably was controlled by the distribution of both carbonaceous material and mudstone which served as permeability barriers. Further prospecting in the mine area should be directed near the wedge edge of mudstones and near more concentrations of carbonaceous materials. Prospecting might be directed in part to exploring the horizon 20 feet beneath the western part of the workings.

LUCKY BOY MINE

The Lucky Boy mine, on the west side of Montezuma Canyon about half a mile south of Long Canyon, was studied and mapped in detail because of its fresh workings. It can be reached by jeep road from the county road along Montezuma Canyon.

Stratigraphically this deposit is on the north edge of the main ore-bearing sandstone of middle Montezuma Canyon on the slip-off slope of the meander (pl. 3). Near this deposit the main sandstone is split by 7 feet of mudstone into 2 sandstone beds. The Lucky Boy deposit is in the lower of the 2 sandstones, which is 22 feet thick at the mine. The general relations are shown by the accompanying mine map and section (fig. 14).

The Lucky Boy mine was owned by H. and L. Shumway in 1954 but was sold later along with the Cottonwood mine to a subsidiary of the Atlas Corp. The mine has yielded some ore, mostly since 1953.

The sandstone at this mine is hard, white, and fine to medium grained; it is mostly in massive crossbedded units, although some is mixed with clay pellets and carbonaceous plant fragments in trashy zones which separate the cleaner sandstone units. Carbonaceous fossil logs are numerous in this mine, but many of these are not mineralized and are found above the main ore body. A prominent set of joints in this mine strikes N. 20° W. A secondary set of joints strikes N. 80° W.

The ore in the Lucky Boy mine is sandstone and trashy material cemented with dark-gray roscoelite. The ore body is well zoned, and the ore layer, several inches to several feet in thickness, forms a complete shell around the inner brown zone. The edges of this shell form curved roll-like surfaces in the sandstone, transecting the cross-bedding. Along the top and bottom of this ore shell the ore layer follows trashy lenses and other stratification features. The ore is richest in the trashy material and around some of the carbonaceous logs but has no apparent relation to the joints. In the richest ore, joints and cavities in the sandstone are coated with bright-yellow carnotite.

The best developed roll surface and the richest ore in the mine are along the southwestern tunnel. This rich ore is between the main mass of ore sandstone and the main concentrations of organic material where it might be expected according to the diffusion hypothesis.

Drilling by the Atomic Energy Commission located a relatively highly mineralized area southwest of the Lucky Boy mine (pl. 3). Exploratory drilling in this area has been along the trend of the main ore sandstone and also along its slip-off slope, both of which are factors considered favorable for prospecting. Many of the AEC drill holes in this area penetrated mineralized sandstone in horizons above that of the Lucky Boy mine. The possibility of ore at these higher levels should be considered during future exploration.

ROCK MINE

The Rock mine is on the west side of Montezuma Canyon just south of the Verdure mine and about 1 mile south of the mouth of Long Canyon. The origial Rock claim was staked by H. Shumway in 1940; the Atlas Corp. acquired the claim in 1954, and the Paramount Uranium Corp. acquired it in 1956. The Rock mine was operated from 1941 to 1943, but very little or no ore has been produced from the mine since then.

Eight adits, comprising 855 feet of drift, make up the Rock mine. These workings have exposed three irregular mineralized zones with discontinuous layers of ore up to 2 feet thick. The mineralized sandstone is in a nearly level zone 8 to 16 feet beneath the top of the main ore-bearing sandstone lens in middle Montezuma Canyon. The Rock mine is about in the center, horizontally, of this lens which is more than 100 feet thick near the mine. The sandstone at the mine is white, hard, well sorted, fine to medium grained, and similar to the sandstone throughout the lens. Locally the sandstone contains mudstone fragments and carbonaceous logs and plant fragments. Seams in the well-sorted sandstone are filled with plant fragments and clay galls forming the common trashy zones.

The ore is olive-gray sandstone cemented with roscoelite. Cavities and joint surfaces are coated with carnotite. As noted elsewhere, the richest ore is associated with carbonaceous trashy zones and carbonized logs. Ore layers follow the bedding and also cross it in roll-like curved surfaces. The barren brown zone and weakly mineralized gray zones described above are associated with the ore in the Rock mine, but zoned ore bodies were not mapped in detail.

STRAWBERRY MINE

The Strawberry mine is on a prominent topographic point on the east side of Montezuma Canyon. The mine can be reached along a jeep trail which connects the county road along Montezuma Canyon with another on Pearsons Point. The claim was staked originally by F. J. Ottley, V. Dalton, W. A. Keele, and B. Jensen in 1939. In 1942 it was worked by P. Shumway and a Mr. Robinet. The Union Carbide Nuclear Co. owned the claim in 1957 and has drilled in the area. The mine produced considerable ore from 1941 to 1943 but little or none since.

This mine is in the thickest part of the main ore sandstone of middle Montezuma Canyon. An unusual feature of the deposit is its considerable vertical range and its workings on two different levels. The main ore sandstone is about 110 feet thick near the mine. The lowest ore is about 27 feet above the base and the highest ore is 59 feet above the base. Thus, the ore occupies a vertical range of 32 feet (pl. 6).

The sandstone at the mine is hard, white, well sorted, and fine to medium grained in massive crossbedded units. Claystone in the mine area consists chiefly of small green pellets and broken fragments scattered in the sandstone; some of these claystone fragments are more than 1 foot long. Carbonaceous materials in the form of a few large fossil logs and many tiny macerated plant fragments are abundant in certain crossbed units in the mine. Some of the carbonaceous materials are intermixed with clay pellets and sand to form trashy layers interbedded with massive cross-stratified units of clean sandstone.

As in other mines in the area the ore consists chiefly of sandstone tightly cemented by gray roscoelite. The ore occurs as layers, from 1 inch to more than 1 foot thick, which locally form roll-like curved surfaces that transect the crossbedding and elsewhere follow the crossbedding or the contact between crossbed units. The ore commonly is richest near carbonaceous trash pockets and carbonized logs. A dinosaur bone about 4 feet long exposed on the upper level is very strongly mineralized. Where the ore is richest, joint surfaces and cavities are coated with bright-yellow carnotite.

The ore is associated with porous sandstone stained brown with limonite and with gray sandstone tightly cemented with calcite. These rock types correspond to those of the brown zone and the gray zone and are typical of smaller uranium deposits of the Montezuma Canyon area which were described previously. These zones were traced along with the ore zone throughout the mine (pl. 6). In general, the overall pattern is similar to the zonation of the small deposits, but the details are much more complex. At least five zone sequences are present and perhaps this deposit was formed by several separate periods of diffusion-type ore accumulation which resulted in separate and overlapping zonal systems.

The workings comprise eight adits on two different levels corresponding in all to about 535 feet of tunneling. The adit farthest to the northwest, which was mapped in 1942 by the Union Mines Development Corp., is caved and was not accessible in 1956. Most of the workings are in two levels which are connected by two small winzes. As shown by the accompanying section, the number of ore layers ranges from one to three on the upper level and from one to four on the lower. The ore layers curve around, split into two separate layers, converge into a single layer, and wedge out in a very complicated fashion. Single ore layers range in thickness from less than 0.1 to about 2.3 feet.

This ore deposit is unlike most of the Montezuma Canyon deposits in that it is at a considerable distance from any thick mudstone beds. Its location probably is related to a local abundance of carbonaceous materials. Core drill hole 122, drilled by the Atomic Energy Commission, cut mineralized ground about 600 feet northeast of the Strawberry mine. This trend for the most part parallels the axis of the main ore sandstone and is probably a good direction in which to prospect for more ore. The presence of ore on two different levels in the Strawberry mine indicates that the prospecting of horizons above and below that of known ore may be fruitful also for other deposits of the Montezuma Canyon area.

VERDURE MINE

The Verdure mine is on the west side of Montezuma Canyon about 1 mile south of Long Canyon and just north of the Rock mine. The mine workings consist of about 800 feet of drift in an area about 250 feet long and 80 feet wide. This mine was mapped and studied in considerable detail because it contains the most extensive system of new mine workings in the Montezuma Canyon area. The Verdure claim was staked by S. Shumway in 1940; it was owned by H. Shumway when it was sold in 1954 to the Atlas Corp., and it was purchased by the Paramount Uranium Corp. in 1956. The mine was worked extensively from 1944 to 1954 and intermittently during 1955 and 1956.

The Verdure mine is near the center horizontally and close to the top of the main ore-bearing sandstone lens of middle Montezuma Canyon (pl. 3). At the portal of the mine the lens is 65 feet thick but drill data show it to be more than 100 feet thick a few hundred feet to the west or to the south (pl. 7). The ore horizon, which is the same as that mined in the adjacent Rock mine, is nearly horizontal and 8 to 16 feet from the top of the sandstone.

Carbonaceous material and clay pellets in a few trashy zones and many large carbonaceous fossil logs are present in the mine, but no mudstone layers. The ore consists of mineralized logs and trashy zones, and clean well-sorted sandstone tightly cemented by roscoelite. Carnotite is present in cavities and along joint surfaces. Several roll-like curved ore layers transecting bedding are present in the massive sandstone. The brown and gray zones of the zoned deposits described previously are present but were not mapped in detail.

The most obvious geologic control of ore deposition revealed by geologic mapping is the close proximity of trashy zones and carbonized logs. Several prominent joint sets having a northeast trend are present, but no direct correlation between the joints and the mineralization could be determined. Ventilation in the mine was poor, though, and the irregular increase in radioactivity toward the face may have been caused by an increase in radon in the mine air rather than by an increase in uranium.

Throughout most of the mine the gray zone forms the floor of the drifts but no attempt was made to map geochemical zones. Locally the mapping of such zones might lead to additional ore. Most of the ore occurs just underneath carbonaceous material and between this material and the main mass of the sandstone lens—a distribution consistent with the diffusion hypothesis. The discovery of new ore would depend upon the discovery of additional trashy zones and log accumulations. The area southwest of *B* (pl. 7) would seem to be the most favorable.

COAL BED CANYON GROUP

Six mines and prospects form a group within 2 miles of each other in the middle of Coal Bed Canyon. The group has produced between 3,000 and 6,000 tons of ore that ranged in grade from 0.1 to 0.2 percent U_3O_8 and from 1 to 2 percent V_2O_5. The largest mine in the group is the West Cliff House No. 8. The East Cliff House No. 5 is about half as large, and the White House No. 1 and No. 2 are much smaller.

WEST CLIFF HOUSE NO. 8 CLAIM

The U.S. Vanadium Corp. staked the West Cliff House No. 8 claim in 1940 and still held the property in 1956. The mine produced considerable ore prior to 1943, but has produced none since (1957). No information concerning grade of ore is available.

The mine consists of 4 connected adits with several small branches in a mineralized zone about 200 feet long and 150 feet wide (pl. 8). The mineralized zone, which is nearly continuous throughout the mine, consists of several thin layers and seams of roscoelite-impregnated sandstone associated with mudstone seams and carbonaceous matter. Some local staining of pascoite and carnotite occurs throughout the mine.

DEVIL CANYON GROUP

In Devil Canyon the mines and prospects consist of three near the mouth of the canyon and six in the middle of the canyon. Except for the Dixie No. 1 all are small and have had little or no production. Total production for the group is probably less than 200 tons of ore; most shipments contained 0.1 to 0.2 percent U_3O_8 and 1 to 2 percent V_2O_5.

DIXIE NO. 1

The Dixie No. 1 claim was staked by the Climax Uranium Co. in 1953; it was staked previously under the names Sunny Day (1952) and Cloudy Day (1937). Some ore was produced from the mine in 1943 and between 1948 and 1954.

Mine workings on the Dixie No. 1 claim include 6 interconnected adits with an aggregate length of about 260 feet. The workings are located in a mineralized zone about 200 feet long and 50 feet or more wide. The ore in the individual adits is spotty and is usually associated with trashy zones containing clay pellets and sand intermixed with many small woody fragments. Layers of mineralized sandstone range in thickness from 0.1 to 1.5 feet. The ore is roscoelite-cemented sandstone with some carnotite stain.

MONUMENT CANYON GROUP

The Pure Luck mine has the most extensive workings and the largest production of the 14 mines and prospects scattered along Monument Canyon. The largest ore shipment from the group continued 0.1 to 0.2 percent U_3O_8 and 0.5 to 1 percent V_2O_5.

BRADFORD CANYON GROUP

Bradford Canyon contains 11 miles and prospects in 2 groups. The Bradford No. 5 mine, which has 10 interconnected adits and a total of 510 feet of workings, has the largest ore production of any mine in either group. Most ore produced from this and other mines in Bradford Canyon has a grade of 0.1 to 0.2 percent U_3O_8 and 1 to 2 percent V_2O_5. In this canyon the ore deposits are in a prominent sandstone bed about 30 feet thick in about the middle of the Salt Wash Member (fig. 13).

STRATIGRAPHIC SECTIONS

1. *San Rafael Group measured just north of a prominent fault on the west side of Montezuma Canyon about 2 miles north of Pearsons Canyon*

[NE¼NW¼ sec. 11, T. 35 S., R. 24 E.]

Jurassic.
Morrison Formation.
Salt Wash Member:
16. Sandstone, light-colored, medium-grained, firmly cemented; in thick massive crossbedded lens; stained dark brown to black on weathered surface; forms prominent cliff.

Unconformity.
San Rafael Group.

Summerville Formation:	*Feet*
15. Mudstone, moderate-reddish-orange (10*R* 5/6); silty, weakly cemented with a carbonate mineral, thin bedded, poorly exposed; forms slope	11.2
14. Sandstone, moderate-orange-pink (10*R* 7/4); weathers pale reddish brown (10*R* 5/4); very fine to fine grained, poorly sorted, silty; composed of angular to subrounded amber-stained quartz grains; minor dark accessory minerals; heavy carbonate cement; thin slightly irregular beds; interbedded with siltstone containing abundant mudcracks and ripple marks; forms cliff	16.0
13. Siltstone, moderate-reddish-brown (10*R* 5/6), poorly sorted, sandy; composed of subangular to rounded frosted and amber-stained quartz grains; minor black accessory minerals; weakly cemented with a carbonate mineral; regularly thin bedded; weathers to unconsolidated grains and carbonate-cemented concretionary masses; forms slope	8.1
12. Sandstone, grayish-orange (10*YR* 8/4); weathers pale yellowish brown (10*YR* 5/2); fine to medium grained, medium sorted; composed of subangular to rounded clear and frosted quartz grains; contains some dark accessory minerals and white fine-granular argillaceous matrix; well cemented with a carbonate mineral and silica; regularly bedded with obscure cross laminations; forms prominent cliff with rectangular jointing	15.8
11. Siltstone, like unit 13 but moderately well cemented with a carbonate mineral; poorly exposed; forms a covered slope	32.6
10. Sandstone, dark-yellowish-orange to pale-yellowish-orange (10*YR* 6/6–8/6), mottled; very fine to medium grained; medium sorted, silty; composed of clear subrounded quartz grains; well cemented with silica and iron oxide; forms massive ledge somewhat similar to Entrada Sandstone below	4.1

Jurassic—Continued	
San Rafael Group—Continued	
Summerville Formation—Continued	*Feet*
9. Siltstone, pale reddish-brown (10*R* 5/4), medium-sorted, sandy; composed of subangular to subrounded frosted and amber-stained quartz grains and some black accessory minerals; even bedded and laminated, poorly cemented; forms recess below unit 10	1.0
Total Summerville Formation	88.8
Entrada Sandstone:	
8. Sandstone, very pale orange (10*YR* 8/2); weathers pale yellowish brown (10*YR* 7/2); fine grained, well sorted; composed of subrounded to rounded clear and frosted quartz grains; contains some white very fine granular argillaceous matrix and is loosely cemented with a carbonate mineral and silica; has small scattered ferruginous spots; even medium bedded; obscure subaqueous cross laminations; weathers to a smooth steep cliff	17.8
7. Sandstone, grayish-orange (10*YR* 7/4), fine-grained, well-sorted; composed of subangular to rounded frosted quartz grains and some very fine granular argillaceous grains and matrix in scattered spots; loosely cemented with a carbonate mineral; in lenticular beds 1 to 20 feet thick; high angle, large-scale eolian-type crossbedding common; forms nearly vertical cliff	108.6
6. Sandstone, moderate reddish-orange (10*R* 5/6), fine-grained, well-sorted; composed of subangular to rounded amber-stained quartz grains, and some minor dark accessory minerals; loosely cemented with a carbonate mineral; thin evenly bedded; small-scale subaqueous crossbedding; forms smooth vertical cliff locally honeycombed with small cavities	25.1
5. Sandstone, moderate reddish-orange (10*R* 6/6), medium-grained, well-sorted; composed of rounded quartz grains; firmly cemented with a carbonate mineral; evenly thin to medium bedded; gently dipping subaqueous crossbedding; weathers in relief to form prominent ledge	3.0
Total Entrada Sandstone	154.5
Carmel(?) Formation:	
4. Siltstone, moderate-reddish-orange (10*R* 5/6), medium-sorted, very sandy; composed of angular to subrounded amber-stained quartz grains; contains a few scattered rounded and frosted quartz grains of medium to coarse sand; firmly cemented with a carbonate mineral; irregularly thin-bedded showing preconsolidation slumping and faulting; forms rounded blocks and knobs or "hoodoos" on weathered surface	16.2

Jurassic—Continued
San Rafael Group—Continued
Carmel(?) Formation—Continued *Feet*

3. Siltstone; similar to unit 4 but contains more abundant rounded and frosted quartz grains of medium to coarse sand; not as firmly cemented with a carbonate mineral; some blebs of crystalline calcite near top of unit; bedding obscured by preconsolidation deformation on small scale; forms smooth steep cliffs and covered slopes____ 19.8
2. Siltstone, moderate reddish-orange (10*R* 5/6), poorly sorted, very sandy; grades into silty, fine-grained sandstone; composed of angular to subrounded amber-stained quartz grains with some scattered rounded and frosted quartz grains of medium to coarse sand; moderately well cemented with a carbonate mineral; bedding indistinct; scattered light-colored spots as much as 0.5 inch in diameter contain clear to white quartz grains; overlies rough surface of Navajo Sandstone__________ 3.3

Total Carmel(?) Formation____________________ 39.3

Unconformity.
Jurassic and Triassic(?).
Navajo Sandstone (incomplete):

1. Sandstone, very pale orange (10*YR* 8/2); fine grained, medium sorted; composed of subangular to rounded clear and frosted quartz grains and many grains of black and red accessory minerals; loosely cemented with a carbonate mineral; thin to massive medium- to large-scale high-angle trough-type crossbedding; base not exposed______________________________________ 10.0

2. ***Salt Wash Member of the Morrison Formation measured near the Rim Rock mine on Boulder Point in upper Montezuma Canyon***

[NE¼NE¼ sec. 34, T. 34 S., R. 24 E.]

Jurassic:
Morrison Formation.
Brushy Basin Member (incomplete): *Feet*

13. Sandstone, very pale orange; speckled yellow, red, and green; poorly sorted, conglomeratic, lenticular; composed of angular to subrounded quartz grains of fine to coarse sand and red and green chert pebbles as much as 1 inch in length; abundant quartz overgrowths on sand grains; locally abundant carbonate cement; stained dark brown on weathered surface; grades into coarse sandstone with limonitic spots towards the top. Represents base of Brushy Basin according to Craig and others (1955, p. 156)_______________________________ 32.2
12. Mudstone, red and green; interbedded with thin beds of fine-grained greenish sandstone; forms slope, poorly exposed____ 30.1

Total Brushy Basin Member___________________ 62.3

Jurassic—Continued

Morrison Formation—Continued

Salt Wash Member: *Feet*

11. Sandstone, white with yellowish limonite freckles; medium grained, well sorted; composed of angular to subrounded grains of quartz and some plagioclase and chert; authigenic overgrowths on quartz grains common; some white argillaceous grains and granular matrix; permeable; well consolidated; moderate carbonate cement; forms ledge. This bed is the uppermost sandstone in the Salt Wash as mapped in this area____ 17.9
10. Mudstone, grayish-red (10*R* 4/2), very sandy; in thin layers alternating with thin beds, 1 to 3 feet thick, of fine-grained and very fine grained sandstone. Fine-grained sandstone is light colored with limonite freckles, moderate carbonate cement, permeable. Very fine grained sandstone is greenish-gray, tightly cemented with carbonate. Unit forms slope with a few thin sandstone ledges____ 46.3
9. Sandstone, yellowish-gray (5*Y* 8/1) with limonite freckles; fine grained, well sorted; composed of angular to subrounded grains of quartz, some plagioclase and chert, rare zircon and tourmaline, about 2 percent black accessory minerals, and some white argillaceous material; permeable; authigenic overgrowths on quartz grains common; well consolidated; lightly cemented with a carbonate mineral; massive ledge former with bedding poorly defined; some cross laminations apparent on weathered surfaces. Mudstone interval, 10 feet thick, toward middle of unit forms break in cliff______ 60.0
8. Mudstone, red; abundant carbonate cement; thin-bedded, alternating with greenish-gray fine-grained sandstone. Sandstone tightly cemented with a carbonate mineral; currentmarked, thin bedded (1–2 ft). Forms slope covered with talus blocks, poorly exposed____ 45.8
7. Sandstone; yellowish gray (5*Y* 7/1, 8/1) to light greenish gray (5*GY* 7/1) with limonitic freckles in lower part grading to pale red (10*R* 7/2) and pinkish gray in upper part; fine-grained, moderately well sorted; composition similar to unit 9; contains some plant fossils and mudstone pellets especially near the base; uranium-vanadium ore zone of Rim Rock mine near base of unit; forms massive cliff____ 28.5
6. Mudstone, red; interbedded with lenses of red and gray siltstone and very fine grained sandstone; shows alteration of red mudstone to gray near fine-grained sandstone lenses and in upper 2 feet of unit beneath overlying ore-bearing sandstone; forms slope, poorly exposed____ 29.1

Jurassic—Continued
Morrison Formation—Continued
Salt Wash Member—Continued

	Feet
5. Sandstone, grayish orange-pink (10*R* 8/2, 7/2); weathers to moderate reddish orange (10*R* 6/6); fine grained, medium sorted; composition similar to unit 9; well consolidated; moderate carbonate cement; red mudstone pellet conglomerate at base; some layers cross laminated; forms massive ledge	24.5
4. Mudstone, red; forms slope; mostly covered	14.3
3. Sandstone, pale-red (10*R* 6/2–5/2) to pale reddish-brown (10*R* 5/4), medium-grained, moderately well sorted; composed of angular to subrounded grains of amber-stained quartz with rare plagioclase, and tourmaline; abundant black accessory minerals; tightly cemented with a carbonate mineral; interbedded with some thin red mudstone lenses and mudstone-pellet conglomerates; massive cross-laminated sandstones form prominent ledges	34.2
2. Mudstone, grayish-red (10*R* 4/2) to reddish-brown (10*R* 4/4); in thin lenses interbedded with thin lenses of red siltstone; poorly exposed; forms narrow shelf separating two high sandstone cliffs	11.4
1. Sandstone, very pale orange to pale-yellowish-orange (10*YR* 8/2–8/6); weathers to grayish brown (5*YR* 3/2), light brown (5*YR* 6/4), and black; fine grained, well sorted; composition similar to unit 9; tightly cemented with calcite; stained in layers and on weathered surfaces with brown to black iron and manganese oxides; clay-pellet conglomerate locally at base; lenticular with fluviatile crossbedding; forms massive ledge; distinguished from underlying Summerville Formation by brownish color, lenticularity, and crossbedding	59.9
Total Salt Wash Member	371.9

Unconformity.
Summerville Formation.

3. ***Westwater Canyon and Salt Wash Members of the Morrison Formation measured near the Montezuma mine on the west side of Montezuma Canyon just north of the mouth of Coal Bed Canyon***

[Sec. 35, T. 36 S., R. 24 E.]

Jurassic:
Morrison Formation.
Brushy Basin Member:
29. Mudstone, red and green, poorly exposed.

Jurassic—Continued
Morrison Formation—Continued
Westwater Canyon Member:

	Feet
28. Sandstone, grayish-yellow-green (5*GY* 6/2) to yellowish-gray (5*Y* 7/2) with grayish-brown limonitic freckles; grayish orange to dark brown coating on weathered surfaces; fine grained, medium sorted; composed of angular to rounded grains of quartz and minor amounts of chert, plagioclase, and dark accessory minerals; tightly cemented by a fine-grained carbonate mineral and silica; forms ledge	6
27. Sandstone; very pale orange (10*YR* 8/2) with moderate-brown limonitic freckles locally; fine grained, well sorted; composed of subangular to rounded grains of quartz, minor amounts of magnetite, biotite, and plagioclase, and abundant white argillaceous material; upper part weakly cemented and friable, lower part well cemented by a carbonate mineral and silica, especially in outer "case-hardened" weathered layers	28
26. Sandstone, yellowish-green (5*GY* 6/2), fine-grained, medium-sorted; composed of angular to subrounded grains of quartz and some biotite, magnetite, and other dark accessory minerals; contains abundant white argillaceous grains; tightly cemented; forms resistant ledge	6
25. Sandstone, pale-greenish-yellow (10*Y* 7/2), grayish-yellow (5*Y* 8/4), and yellowish-gray (5*Y* 8/1); locally abundant moderate-brown limonitic freckles; weathers to dusky brown outer coating; fine-grained, medium to well sorted; composed of subangular to rounded grains of quartz, some plagioclase and chert, and minor amounts of dark accessory minerals; has abundant white argillaceous grains and matrix; lower part weakly cemented by a carbonate mineral, upper part tightly cemented by a carbonate mineral and silica especially in dark surficial "case-hardened" layers; bedding massive with some crossbedding; forms series of ledges	30.0
24. Covered interval	10.5
23. Sandstone, grayish-yellow-green (5*GY* 8/1); weathers light brown; has a surface coating of dusky brown in lower part; fine grained, well sorted; composed of subangular to rounded grains of quartz and minor amounts of black accessory minerals; has abundant white argillaceous grains and matrix; tightly cemented by a carbonate mineral and silica; massive; forms thick ledge	11.5
22. Covered interval	7.0

Jurassic—Continued

Morrison Formation—Continued

Westwater Canyon Member—Continued	Feet
21. Sandstone, light-greenish-gray (5*GY* 8/1) to yellowish-gray (5*Y* 8/1), weathers light brown; fine grained, medium sorted; composed of angular to rounded grains of quartz with abundant plagioclase, dark accessory minerals, and white argillaceous material; well cemented by clay matrix and minor carbonate mineral; massive, forms ledge	8.5
20. Sandstone, grayish yellow-green (5*GY* 7/2); weathers moderate brown, conglomeratic near base and top; fine grained, medium to poorly sorted; composition similar to unit 23 but contains more grains of dark accessory minerals; has a few granules and small pebbles of chert and quartz scattered along crossbeds in lower and upper part of unit; generally well cemented with a carbonate mineral and silica, especially in outer "case-hardened" weathered layers; crossbedded, massive; forms ledge	6.2
19. Sandstone, grayish yellow-green, fine-grained; well-sorted; similar in composition to unit 21; lenticular bed; weathers to rounded cobbles and boulders	1.0
Total Westwater Canyon Member	114.7
Salt Wash Member:	
18. Sandstone, white to grayish-yellow-green (5*GY* 6/2), friable, clayey, fine-grained, poorly sorted; composed of subangular to rounded grains of quartz with minor amounts of dark accessory minerals. Weakly cemented with a carbonate mineral; grades into moderate-reddish-brown and grayish-yellow-green sandy mudstone at top. Unit as whole is thin bedded, poorly exposed; forms covered slope. May represent Salt Wash and Westwater Canyon transition zone	23.0
17. Sandstone, white, friable, fine-grained, medium-sorted; composed of angular to subrounded grains of quartz with some dark accessory minerals and white argillaceous material; some authigenic quartz overgrowths on sand grains; weakly cemented with a carbonate mineral; crossbedded; forms thin ledge	3.0
16. Mudstone, grayish-red; forms slope; poorly exposed and covered by sandstone blocks	31.0
15. Sandstone, white to pinkish-gray (5*YR* 8/1), weathers to light or moderate brown; fine-grained, medium-sorted; composition similar to unit 18 but also contains abundant white argillaceous grains; permeable; authigenic quartz overgrowths on sand grains; moderately cemented with a carbonate mineral; crossbedded; forms rounded ledges	26.8
14. Mudstone, grayish-red; forms slope; poorly exposed and covered by sandstone blocks	13.9

Jurassic—Continued	
Morrison Formation—Continued	
Salt Wash Member—Continued	*Feet*
13. Sandstone, grayish-orange (10*YR* 8/4) to pinkish-orange (5*YR* 8/1); brown limonite freckles locally; weathers to brownish gray (5*YR* 4/1); fine grained, medium to well sorted; composition similar to units 15 and 18; permeable; moderately cemented with a carbonate mineral; a few clay pellets concentrated along bedding planes locally; crossbedded; forms massive ledge	32.3
12. Covered interval; probably grayish-red mudstone	15.0
11. Sandstone, pinkish-gray (5*YR* 8/1) with small limonite freckles; weathers light brown; fine grained, medium sorted; similar in composition to unit 17; permeable; weakly cemented with a carbonate mineral; forms ledge	17.5
10. Covered interval, probably grayish-red mudstone	22.0
9. Sandstone, grayish orange-pink (5*YR* 7/2) with limonite freckles; weathers light brown (5*YR* 6/3); fine grained, well sorted; similar in composition to units 13, 15, and 18; authigenic quartz overgrowths common on sand grains; well cemented with a carbonate mineral; crossbedded; forms slope covered with platy rubble	5.2
8. Covered interval; mostly sandstone as above	5.5
7. Sandstone, white to pinkish-gray (5*YR* 8/1); light-brown limonitic freckles abundant near base but less common in upper part; weathers light brown; fine grained, medium to well sorted; similar in composition to units 9, 13, 15, and 18; permeable; authigenic quartz overgrowths common on quartz grains; light-greenish-gray (5*GY* 8/1) clay pellets common throughout; crossbedded; contains uranium-vanadium mineralized zone about 6 feet from base; forms massive cliff	43.0
6. Mudstone, grayish-red; forms slope covered with sandstone blocks	8.8
5. Mudstone, moderate-reddish-brown; interbedded with light-greenish-gray, grayish-orange-pink (10*R* 8/2) sandstone. Mudstone makes up three-fourths of unit, altered to light greenish gray near coarser sandstone beds. Sandstone is fine grained, well sorted; composed of subangular to rounded grains of quartz and some dark accessory minerals. Sandstones thin bedded, crossbedded, lenticular; generally friable, moderately cemented with a carbonate mineral; locally contain mudstone pellets; unit forms slope, lower part covered	28.0

Jurassic—Continued
Morrison Formation—Continued
Salt Wash Member—Continued *Feet*

4. Sandstone, pinkish-gray (5*YR* 8/1) to grayish-orange-pink (10*R* 7/2); weathers light brown; fine grained, medium to well sorted; composed of angular to rounded grains of quartz, minor dark accessory minerals, and white argillaceous material; authigenic quartz overgrowths common; white argillaceous and calcareous matrix common; friable with loose carbonate cement; locally firmly cemented with a carbonate mineral; some interbedded grayish-red (10*R* 4/2), silty layers; forms ledge; weathers into large blocks---------------- 35.2
3. Sandstone, grayish-orange (10*YR* 8/4) to grayish-orange-pink (10*R* 8/2); abundant brown limonite freckles in upper part; weathers light brown; fine grained, well sorted; composed of angular to rounded grains of quartz and minor amounts of black accessory minerals and white argillaceous material; weak to strong carbonate cement; authigenic quartz overgrowths common on sand grains; light-greenish-gray and grayish-red mudstone seams and pellets common throughout; thin lenticular bed of grayish-red mudstone with abundant quartz and mica sand grains near middle of unit; mudstone bed altered to light greenish gray (5*GY* 7/1) near sandstone. Sandstone beds crossbedded and lenticular; forms massive cliff---------------- 55.0
2. Mudstone, grayish-red (10*R* 4/2), altered to greenish gray (5*GY* 6/1); interbedded with thin lenses of pale-red (10*R* 6/2), grayish-red (10*R* 6/4), pale reddish-brown (10*R* 5/4), and light-brown (5*YR* 6/4) very fine grained sandstone. Sandstone composed of angular to subrounded grains of amber-stained quartz sand with minor amounts of dark accessory minerals and white argillaceous material; well cemented with a carbonate mineral; locally contains mudstone pellets; forms lenses 1 to 3 feet thick and 20 to 40 feet long. Unit forms partly covered slope---------------- 42.5
1. Sandstone, pale-red (10*R* 6/4) to moderate reddish orange (10*R* 5/6), altered to pinkish gray (5*YR* 8/1) and light greenish gray (5*G* 8/1) in spots and lenticular masses; very fine grained, well sorted; similar in composition to sandstone of unit 2; some authigenic quartz overgrowths on grains; firmly cemented with a carbonate mineral; poorly stratified in a thick lenticular bed; forms ledge. Unit unlike most basal sandstones of Salt Wash; it may represent local reworking of the Summerville rocks---------------- 46.0

Total Salt Wash Member---------------- 452.8

Unconformity.
Summerville Formation.

757-270 O—65——7

4. *Brushy Basin Member of the Morrison Formation measured on the west side of Montezuma Canyon near the mouth of Verdure Creek*

[Sec. 33, T. 34 S., R. 24 E.]

Cretaceous:
  Burro Canyon Formation:
    9. Sandstone, conglomeratic, in massive cliff.
Unconformity.
Jurassic:
  Morrison Formation.

Brushy Basin Member:	*Feet*
8. Claystone, red and greenish-gray interbedded, silty. Upper contact not well exposed, presumably base of cliff of Burro Canyon	24.1
7. Covered interval, probably claystone similar to unit 8	39.2
6. Claystone, pale-red (5*R* 6/2-10*R* 6/2), in part silty, plastic and bentonitic in part; interbedded with a few thin beds of unconsolidated silt and silicified claystone; poorly exposed	60.6
5. Claystone, light-olive-gray (5*Y* 6/1) to pale-red-purple (5*RP* 6/2), silicified, very hard; contains moderate-red (5*R* 4/6) veinlets of chert, scattered silt, very fine grains of angular quartz, and some oolites of chalcedony colored red by small silt-size hematite grains	5.6
4. Claystone, light-greenish-gray (5*G* 8/1) to pale-red (10*R* 6/2), silty, plastic, bentonitic; some carbonate mineral; bedding obscure; interbedded with some greenish silicified claystone; well exposed but disturbed somewhat by landsliding	104.4
3. Sandstone, grayish-yellow-green (5*GY* 7/2) to yellowish-gray (5*Y* 8/1), medium-grained; medium to poorly sorted; composed of angular to subrounded grains of quartz, minor amounts of biotite, plagioclase, chert, and dark accessory minerals; friable, poorly cemented; interbedded with minor amounts of plastic green and red mudstone near base and in upper middle of unit	57.5
2. Conglomerate, dusky-yellow (5*Y* 7/4), sandy, poorly sorted; dark surficial coating on weathered surfaces; composed of angular to rounded coarse sand and pebbles as much as ½ inch in diameter; pebbles mostly red, green, yellow, and black chert and silicified limestone, minor amounts of quartz and quartzite; sand grains mostly quartz, feldspar, and white argillaceous material; moderately cemented with a carbonate mineral; lenticularly bedded; base of unit irregular, filling scour in underlying mudstone; unit locally thickens to 20 feet, but in some places is absent. Represents base of Brushy Basin as described by Craig and others (1955, p. 156)	7.4

Jurassic—Continued

Morrison Formation—Continued

Brushy Basin Member—Continued *Feet*

1. Mudstone, red, unconsolidated, high carbonate content, in layers 1 to 4 feet thick; evenly bedded; interbedded with red claystone, green and purple mudstone, and hard jointed sandstone layers 1 to 3 feet thick; poorly exposed; forms slope ---- 49.4

Total Brushy Basin Member ---- 348.2

Salt Wash Member (not measured).

Sandstone, white, massive, forms cliff.

5. *Burro Canyon Formation measured on the southeast side of Pearsons Point*

[SW¼ sec. 30, T. 35 S., R. 25 E.]

Upper Cretaceous:

Dakota Sandstone (incomplete):

8. Sandstone, yellow, with some plant fossils.

Unconformity.

Lower Cretaceous:

Burro Canyon Formation: *Feet*

7. Sandstone, white, fine-grained, well-sorted; composed of quartz and minor dark accessory minerals; very hard, tightly cemented with silica forming thin quartzite beds; interbedded with light-green sandy siltstone; unit poorly exposed; forms slope ---- 21

6. Sandstone, white, conglomeratic, medium-grained, poorly sorted to well-sorted; composed of angular to rounded grains of quartz and minor dark accessory minerals; has white argillaceous matrix; small angular to rounded pebbles of white and gray chert concentrated in conglomeratic layers along crossbedding; lower part of unit friable, poorly cemented with a carbonate mineral, upper 3 feet firmly cemented with silica; crossbedded throughout; forms massive ledge ---- 24

5. Covered interval; probably very fine grained sandstone and mudstone as below ---- 12

4. Mudstone, grayish-yellow-green (*5GY* 7/2); weathers dark yellowish orange, very sandy, grades into clayey sandstone composed of subangular to rounded very fine to medium sand grains of quartz and greenish-gray clay matrix; a little carbonate cement; weathers hackly; forms slope ---- 11.5

3. Sandstone, white; weathers grayish orange; conglomeratic near base; upper part fine grained, well sorted; composed of subangular to rounded grains of quartz and rare dark accessory minerals; has minor white argillaceous matrix; interbedded with fine-grained chert-pebble conglomerate along crossbeds; contains small hard limonite-cemented concretionary masses of sandstone in upper part; forms ledge ---- 8

Lower Cretaceous—Continued

Burro Canyon Formation—Continued *Feet*

2. Sandstone, white, weathers grayish orange or brown, generally fine grained, poorly to well sorted; interbedded with fine-grained pebble-conglomerate and conglomeratic sandstone; sandstone composed of angular to rounded grains of quartz; has minor white argillaceous matrix; conglomerate composed of angular to rounded fine- to coarse-grained chert pebbles and a few small cobbles; chert colored red, white, yellow, black, gray, and brown; conglomerate beds locally firmly cemented with limonite and silica; most of unit weakly cemented with a carbonate mineral; contains a few thin lenticular masses of greenish-gray mudstone near base; unit massive, crossbedded, forms steep cliff---------- 42.5

Total Burro Canyon Formation---------- 119

Unconformity.

Jurassic:

Morrison Formation.

Brushy Basin Member:

1. Mudstone, medium-gray, noncalcareous, fractured, iron-stained; bedding obscure; forms slope below Burro Canyon Cliff; poorly exposed (not measured).

6. *Dakota Sandstone measured along the Pacific Northwest Pipeline ditch between Dove Creek and Cahone, Dolores County, Colo.*

[Sec. 21, T. 40 N., R. 18 W.]

Upper Cretaceous:

Dakota Sandstone. *Feet*

18. Sandstone, yellowish-gray (5*Y* 8/1); weathers yellowish orange (10*YR* 7/6); fine grained, well sorted; composed of quartz and minor dark accessory minerals; has abundant white argillaceous grains and matrix; firmly cemented with silica partly as authigenic overgrowths; massive, crossbedded; contains some worm tubes; forms prominent ledge that caps the hill; this is probably the top or near the top of the formation---------- 11.0
17. Claystone, light-gray (*N* 7), silty; contains ferruginous partings, several thin sandy layers, and scattered silt-size carbonaceous fragments---------- 9.7
16. Claystone, medium-dark-gray (*N* 4), very silty; contains abundant carbonaceous plant fragments; bedding thin and regular, alternating dark and light zones---------- 4.6
15. Siltstone, light-brownish-gray (5*YR* 7/1), very sandy and clayey; composed mostly of very fine grained sand and silt-size quartz grains and scattered carbonaceous plant remains; in thin regular beds from 0.5 to 1.0 foot thick with ferruginous and claystone partings---------- 12.2
14. Sandstone, grayish-yellow (5*Y* 7/4), fine-grained, poorly sorted; composed of quartz sand with white and yellow iron-stained argillaceous matrix; some scattered carbonaceous material; firmly cemented with silica, part as authigenic overgrowths; bedding obscure---------- 9.4

Upper Cretaceous—Continued

Dakota Sandstone—Continued *Feet*

13. Claystone, medium-light-gray (*N* 6); contains some scattered carbonaceous fragments; 0.9-foot ferruginous sandstone layer near base; unit shows faulting, swelling, and other effects of settling of blocks of overlying sandstone	5.6
12. Claystone, dark-gray (*N* 3); coaly, contains abundant carbonaceous plant fragments in several even beds separated by thin light-gray slightly carbonaceous claystones	2.7
11. Claystone, medium light-gray (*N* 6), silty; contains 0.4-foot iron-stained sandstone at base	5.0
10. Claystone, grayish-black (*N* 2); coaly, abundant carbonaceous fragments; even-bedded; gray claystone bed, 0.2-foot thick, near middle of unit contains well-preserved plant fossils	3.8
9. Claystone, very light gray (*N* 8), plastic, massive	2.1
8. Sandstone, pale-yellowish-orange (10*YR* 8/6), iron-stained, fine-grained, well-sorted; composed of quartz sand with a yellowish argillaceous matrix; even-bedded	0.9
7. Claystone, medium-gray (*N* 5); contains scattered carbonaceous fragments; massive	3.2
6. Sandstone, yellowish-gray (5*Y* 7/1), fine-grained, poorly sorted; composed of quartz, rare mica, and some dark accessory minerals; has yellowish argillaceous matrix; contains some interbedded claystone partings especially near base, and scattered carbonaceous fragments throughout; unit is in thin even beds, 2 to 4 inches thick	13.1
5. Sandstone, grayish-yellow (5*Y* 8/4), fine-grained, medium- to well-sorted; composed of angular to subrounded grains of quartz, and minor dark accessory minerals; has abundant white argillaceous grains and matrix; scattered limonitic spots common; firmly cemented with silica and minor carbonate mineral; some authigenic quartz overgrowths on grains; massive, crossbedded, forms ledge	17.8
4. Claystone, grayish-black (*N* 2), coaly; contains abundant carbonaceous plant material	1.4
3. Sandstone, medium-light-gray (*N* 6), fine grained, medium-sorted; composition similar to unit 5; some rounded granules of chert near base and scattered carbonaceous plant fragments throughout	5.3
Total Dakota Sandstone	107.8

Unconformity.

Lower Cretaceous:

Burro Canyon Formation (not complete):

2. Claystone, pale-green (5*G* 7/1), massive	2.2
1. Sandstone, greenish-yellow (10*Y* 7/4), very fine grained to coarse-grained, conglomeratic, poorly sorted; composed of angular to subrounded grains of quartz and some dark accessory minerals; has abundant yellow argillaceous matrix; locally contains small rounded pebbles and granules of chert, base not exposed	4.6

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INDEX

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