Petrography of Sedimentary Rocks in the Slick Rock District, San Miguel and Dolores Counties, Colorado

GEOLOGICAL SURVEY PROFESSIONAL PAPER 576-B

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

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By DANIEL R. SHAWE

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

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Microscopic study of uranium- and vanadium-bearing and associated sedimentary units contributes to the understanding of the geologic events that formed the rocks: sedimentation, deep burial, mild deformation, and alteration

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PETROGRAPHY OF SEDIMENTARY ROCKS IN THE SLICK ROCK DISTRICT, SAN MIGUEL AND DOLORES COUNTIES, COLORADO

By Daniel R. Shawe

ABSTRACT

Petrographic studies, largely thin-section examinations, of rocks from the Chinle and Morrison Formations and adjacent strata in the Slick Rock district, supplement the stratigraphic studies of sedimentary rocks exposed in the district.

Sandstones investigated in strata above the Moss Back Member of the Chinle Formation generally contain about 50–80 percent quartz, 2–10 percent chert, 1–10 percent feldspar, 3–15 percent clay, 1–15 percent calcite, and minor amounts of other components. Some sandstone in the Moss Back Member contains abundant limestone grains, and sandstone in the underlying Cutler Formation is arkosic and contains about one-third feldspar. Siltstones are distinguished from sandstones principally by their finer grain size and higher proportion of clay; otherwise, they are mineralogically similar to sandstones. Mudstones contain about 25–30 percent quartz, 0.25–3.5 percent chert, 2–6 percent feldspar, 40–65 percent clay, 0–25 percent calcite, and minor amounts of other components. Silty claystones in the Burro Canyon Formation average about 80 percent clay and commensurately less of other components. Shale in the Mancos Shale consists of about 1 percent pyrite, 3 percent carbonaceous material, 5 percent detrital minerals, 25 percent calcite, and the remainder clay.

Mineral compositions of particular sedimentary rock types vary as much within individual formations as they do from one formation to another. Rocks whose constituent grains display a great range in size, degree of sorting, and rounding have no commensurate varations in mineral composition, other than generally higher clay and calcite content in poorer sorted and finer grained material.

The ore-bearing sandstone of the Salt Wash Member of the Morrison Formation is not unique in mineral composition, and its mineral composition probably did not influence uranium-vanadium deposition. The Brushy Basin Member of the Morrison Formation, commonly cited to contain abundant volcanic material, has unusual amounts only in its middle green unit, and even in that unit, material from nonvolcanic sources probably equals in amount that from volcanic sources.

Reddish-brown rocks of all types are characterized by numerous detrital black opaque mineral grains, films of hematite on other detrital grains, and dustlike hematite dispersed in matrix material. Light-colored rocks (commonly called bleached) contain virtually no hematite, either as detritals or grain coatings, but they do contain pyrite or marcasite, or limonite oxidized from these. Many of the light-colored rocks are altered equivalents of reddish-brown rocks and will be discussed in detail in a later chapter of this professional paper.

Silica is an abundant cement in most of the sedimentary rocks studied; it probably is a product of diagenesis. Calcite occurs as fine-grained interstitial blebs in reddish-brown rocks, and as larger patches enclosing detrital grains in light-colored rocks, suggesting epigenetic redistribution during alteration that developed the light colors. Other carbonate minerals, as well as barite, anatase, pyrite, marcasite, albite, and analcite, occur as well-formed authigenic crystals chiefly in altered rocks.

Some evidence indicates crystallization of authigenic (epigenetic) minerals when the strata were deeply buried and before they were extensively folded.

INTRODUCTION

The Slick Rock uranium-vanadium district occupies about 570 square miles in the western parts of San Miguel and Dolores Counties, Colo., (fig. 1). A generalized geologic map is given in figure 2. Sedimentary rocks cropping out in the district range in age from Permian to Cretaceous. Older sedimentary rocks that underlie these are known to rest on igneous and metamorphic rocks of a probable Precambrian basement. Maximum thickness of exposed sedimentary rocks in the district is about 4,700 feet, and the total section of sedimentary rocks underlying the district is about 13,000 feet. The exposed stratigraphic section is summarized in table 1.

The district lies in the Paradox Basin at the southeast end of the Paradox fold and fault belt (Kelley, 1958). Major folds in the district are broad and open, trend about N. 55° W., and are parallel to the collapsed Gypsum Valley salt anticline bounding the northeast edge of the district. The Dolores anticline is about 10 miles southwest of the Gypsum Valley anticline; the Disappointment syncline lies between the two anticlines.

TABLE 1.—*Generalized section of exposed consolidated sedimentary rocks*

Age	Formation and member		Thickness (feet)	Description
Late Cretaceous	Mancos Shale		1,600–2,300	Dark-gray carbonaceous calcareous marine mudstone and minor amounts of gray limestone, greenish-gray bentonitic shale, and light-buff sandstone. Contains abundant invertebrate fossils.
Late Cretaceous	Dakota Sandstone		120–180	Light-buff fine-grained quartzose marginal marine and fluvial sandstone, dark-gray carbonaceous shale, coal, and locally, light-buff conglomeratic sandstone.
	Unconformity			
Early Cretaceous	Burro Canyon Formation		40–400	Light-gray to light-buff fine-grained to conglomeratic quartzose fluvial sandstone, greenish-gray flood-plain shale and siltstone, and greenish-gray to gray lacustrine(?) limestone and chert.
Late Jurassic	Morrison Formation	Brushy Basin Member	300–700	Predominantly reddish-brown and greenish-gray bentonitic flood-plain mudstone and some light-reddish-brown, light-buff, and light-greenish-gray fluvial siltstone, sandstone, and conglomerate.
Late Jurassic	Morrison Formation	Salt Wash Member	275–400	Light-reddish-brown, light-buff, and light-gray quartzose fluvial sandstone and reddish-brown flood-plain mudstone. Sandstone lenses in top part are dominantly light buff or light gray and contain abundant carbonaceous plant material; lenses in lower part are mainly light reddish brown and contain sparse carbonaceous material.
Late Jurassic	Junction Creek Sandstone		20–150	Light-buff fine-grained quartzose sandstone with sweeping eolian crossbeds at south end of district. Changes northward to light-reddish-brown fine-grained tidal-flat(?) sandstone with horizontal beds; merges laterally with Summerville Formation.
Late Jurassic	Summerville Formation		80–160	Reddish-brown quartzose horizontally bedded marginal marine siltstone and fine-grained sandstone.
Late Jurassic	Entrada Sandstone	Slick Rock Member	70–120	Light-buff to light-reddish-brown fine-grained quartzose eolian sandstone.
Late Jurassic	Entrada Sandstone	Dewey Bridge Member	20–35	Reddish-brown very fine grained silty tidal-flat sandstone.
	Unconformity			
Jurassic and Triassic(?)	Navajo Sandstone		0–420	Light-buff and, locally, light-reddish-brown fine-grained quartzose eolian sandstone.
Late Triassic(?)	Kayenta Formation		160–200	Purplish-gray to purplish-red fluvial siltstone and sandstone, and locally, shale, mudstone, and conglomerate.
Late Triassic	Wingate Sandstone		200–400	Light-buff and light-reddish-brown very fine grained to fine-grained quartzose eolian sandstone.
Late Triassic	Chinle Formation	Church Rock Member	340–500	Reddish-brown, purplish-brown, and orangish-brown, mostly tidal-flat, horizontally bedded quartzose sandstone, siltstone, and mudstone, and a minor amount of dark-greenish-gray conglomerate.
Late Triassic	Chinle Formation	Petrified Forest(?) Member.	0–100	Greenish-gray fluvial and flood-plain mudstone, siltstone, and shale, and minor amounts of reddish-brown mudstone and greenish-gray sandstone and conglomerate.
Late Triassic	Chinle Formation	Moss Back Member	20–75	Light-greenish-gray limy arkosic and quartzose fluvial sandstone and gray to greenish-gray limy fluvial sandstone and conglomerate, containing abundant carbonaceous plant material, and minor amounts of greenish-gray and reddish-brown, mudstone, siltstone, and shale.
Middle(?) and Early Triassic	Moenkopi Formation		0–200 (none exposed)	Light-reddish-brown micaceous tidal-flat(?) siltstone and sandy siltstone.
Permian	Cutler Formation		1,500–3,000 (240 exposed)	Reddish-brown, orangish-brown, and light-buff arkosic fluvial and flood-plain sandstone, siltstone, mudstone, and shale.

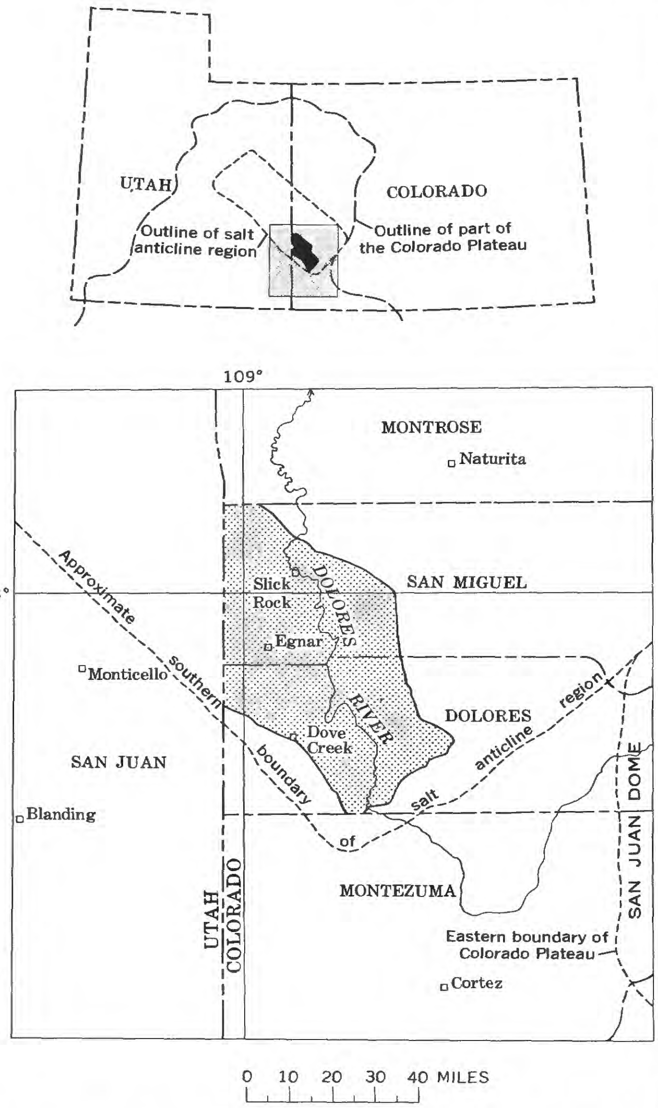

FIGURE 1.—Map showing location of the Slick Rock district (stippled).

A zone of faults bounds the southwest edge of the collapsed core of the Gypsum Valley salt anticline. The Dolores fault zone is about 2 miles northeast of, and parallel to, the axis of the Dolores anticline. A few faults form a conjugate set normal to the Dolores fault zone in the northern part of the district. The southern part of the district is cut by the Glade fault zone which trends about N. 80° E.

Geology and ore deposits of the district have been briefly summarized (Shawe and others, 1959), and details of the stratigraphy of the district and vicinity are in press (Shawe and others, 1968). Additional details of the geology of the district are being prepared in other reports on petrography of the sedimentary rocks (this report), structure, rock alteration, geologic history, and uranium-vanadium deposits. Although rock alteration is inevitably discussed in this report describing petrography, a much fuller treatment will be given in a later chapter of this professional paper, in which chemical and additional mineralogical facts are presented, and varieties of altered rock are dealt with in detail.

The Morrison Formation and the Moss Back Member of the Chinle Formation—the two known uranium-bearing horizons in the district—and associated strata, were studied chiefly by means of microscopic examination of more than 100 thin sections and by a few grain-size analyses. About two-thirds of the thin sections studied are from the Morrison Formation; this unit received the most attention because it has produced virtually all the uranium-vanadium ore mined in the district. Studies of the heavy-mineral content of nearly 100 samples from practically the same rock units herein discussed will be described in another report in this professional paper series on alteration of the rocks.

DEFINITIONS AND METHODS

ROCK NAMES

Rock names as applied in this report are generally those recommended by the Committee on Sedimentation, Division of Geology and Geography of the National Research Council (cited in Pettijohn, 1957, p. 17–19). Claystone is massive or structureless rock consisting dominantly of clay-sized material (<1/256 mm in diameter). Actually, all the claystones herein described have small amounts of silt-sized (1/256–1/16 mm) or sand-sized (1/16–2 mm) particles, arbitrarily set as up to 20 percent of the total rock. Siltstone and sandstone consist dominantly of silt-sized and sand-sized particles, respectively. Conglomerate consists dominantly of particles greater than 2 mm in size. Actually, any sandstone with more than 20 percent granule or larger particles is here considered conglomerate, and any with less than this, but still evident granule or pebble-sized material, is called conglomeratic sandstone. Shale is material of the grain size of claystone but has fissility; mudstone is argillaceous rock poorly fissile or lacking in fissility which contains less than 60 percent and more than 20 percent silt to coarse sand-sized particles. Limestone consists dominantly of calcite. Some detrital rocks that are dominantly calcite are called calcarenite in the sand-sized range and calcirudite in the granule and larger grain size.

TEXTURAL TERMS

Grain-size categories have already been alluded to in the descriptions of rock names above. Within sand-sized material, a further breakdown has been made in millimeters, as follows: Very fine sand, 1/16–1/8; fine, 1/8–1/4; medium, 1/4–1/2; coarse, 1/2–1; and very coarse,

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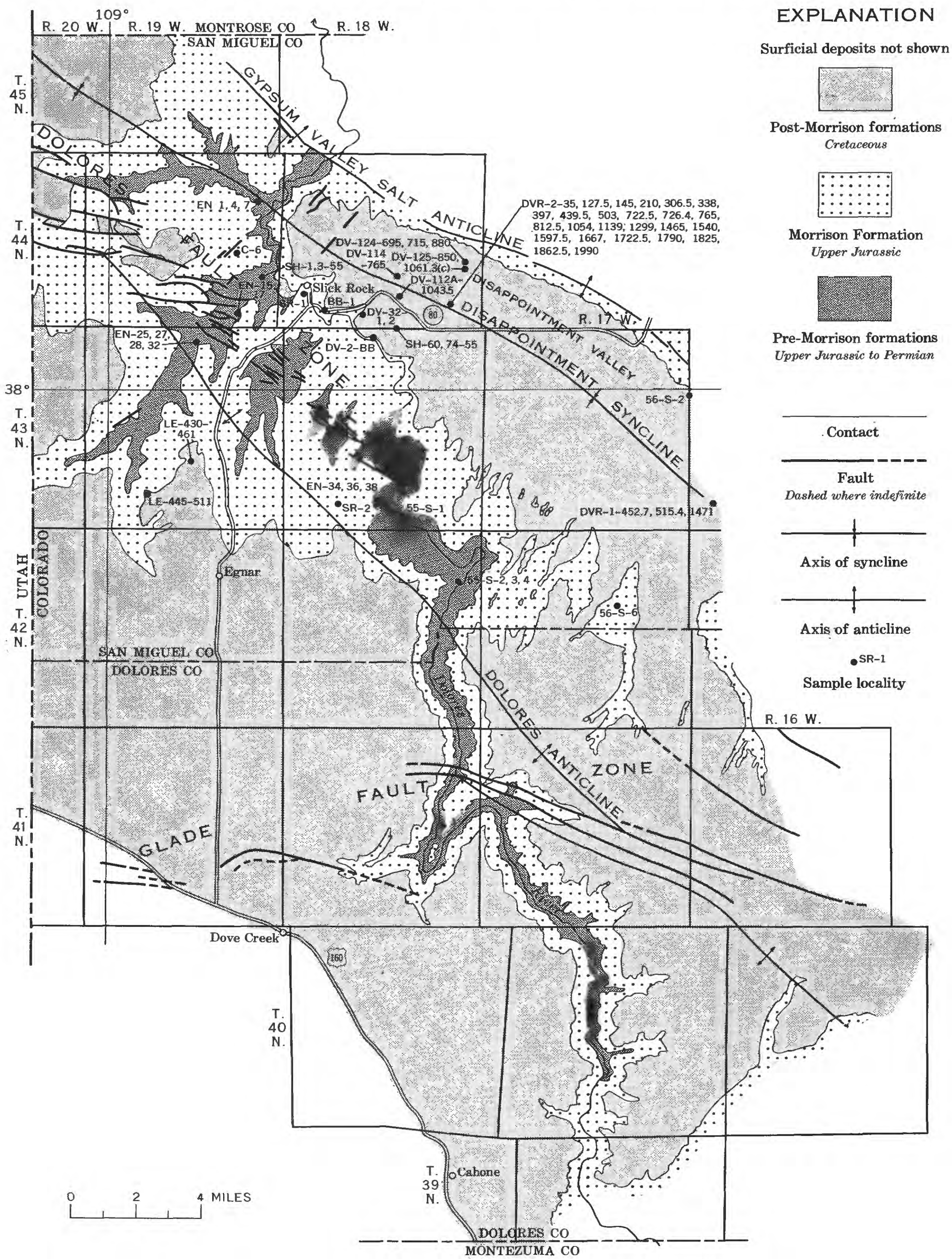


FIGURE 2.—Generalized geologic map of the Slick Rock district showing sample localities.

1–2. Granules range in size from 2 to 4 mm and pebbles from 4 to 64 mm.

Porosity—the percentage of pore space between particles making up a rock—was not systematically evaluated. Sandstones and conglomerates that are poorly cemented have as much as about 20 percent porosity, and those that are thoroughly cemented have virtually none. Siltstones, mudstones, shales, and claystones have lower porosities; porosity is at its lowest, 2.3 percent, in the Mancos Shale.

Sorting—the number of size grades—and the grain size frequency distribution in the detrital rocks were not measured except for a few rocks from the Entrada Sandstone and Summerville Formation. Sorting can be indicated by means of a coefficient of sorting, namely, the square root of the ratio of quartiles, the quartiles being the size value at the intersection of the 25- and 75-percent values of the cumulative frequency curve (Pettijohn, 1957, p. 37). Perfectly sorted sediment has a coefficient of sorting of 1; poorly sorted, that is, with many size grades, has a coefficient several times higher. Rocks examined in this study were, without any measurements, estimated to be well sorted if most of the particles were within one size grade; moderately sorted, if within two size grades; and poorly sorted, if within more than two size grades.

Roundness of detrital grains—the degree of curvature of angular edges of grains—also was not measured. Instead, this property was estimated by comparison with roundness in the roundness classes shown by Pettijohn (1957, fig. 28) and described by him as angular, subangular, subrounded, rounded, and well rounded.

Packing—the degree to which particles in the rock are fitted together—was not evaluated except in a few samples. Rocks containing particles fitted so that as little as possible interstitial space remains are called well packed, and those with particles poorly fitted and displaying relatively extensive unfilled interstitial space are called poorly packed.

Interstitial material between detrital grains in sedimentary rocks is termed either "matrix" or "cement" (Pettijohn, 1957, p. 284). Matrix is finely divided detrital material (silt and clay) usually deposited along with the coarser detritus. Cement consists of minerals precipitated in voids following deposition of sediment. This distinction is attempted in the descriptions of individual rocks that follow. In some rocks, however, matrix material was impregnated with cement or recrystallized, and distinction between matrix and cement was not always possible.

Some poorly sorted rocks that have a large proportion of fine-grained material, particularly that which is dark colored or opaque, are here termed "dirty" rocks. Well-sorted rocks and those rocks whose constituent grains are not clouded with dark finely dispersed material are referred to as "clean."

MODAL POINT COUNTS AND ESTIMATES

Modal point counts of mineral components were made of thin sections of about half the rocks described in this report. These counts were made using a click stage, and counting for most samples not more than 200 points per thin section in traverses 1 mm apart. Greater accuracy for individual thin sections could have been obtained by counting more than 200 points. However, it was visibly evident that chance compositional variations in rock layers only inches from the position of the sampled rock are much greater than statistical errors resulting from counting only 200 grains. This signifies the fruitlessness of more precise determinations of individual thin sections for this study.

Compositions of the remaining half of the thin sections were estimated. These modal estimates were based on extensive practice estimates of varying known percentages of filled space (shown as dark shapes of varying sizes) within a given area. Estimates were checked by point counting until proficiency was acquired. Validity of the estimates can be judged on the basis of the comparison of point counts and modal estimates of the composition of thin sections of Salt Wash Member sandstone given in table 5. The table suggests a slight tendency of the author to overestimate the abundance of minor components.

ROCK-FORMING MINERALS

Rock-forming minerals in the detrital rocks to be described are surprisingly similar in both kind and abundance in all the stratigraphic units above the Moss Back Member of the Chinle Formation. Permian and basal Triassic rocks include some arkosic (feldspar-rich) and calcite-rich detrital varieties; but overlying rocks are mostly quartz rich, and contain small amounts of chert and feldspar, and differ principally in clay and calcite content. Minor amounts of dolomite, siderite, barite, chlorite, analcite, hematite, other black opaque minerals, biotite, muscovite, leucoxene, anatase, limonite, pyrite, marcasite, tourmaline, or zircon are present in many of the rocks.

Quartz grains, making up 50–80 percent of the sandstones and 25–50 percent of siltstones and mudstones, are commonly unstrained and contain minor to abundant amounts of dustlike inclusions. Some quartz grains contain internal sutures, as if derived from quartzite; others are strained as evidenced by undulatory extinction. Quartz overgrowths, which constitute as much as 15 percent in some rocks, are faceted or are in contact with adjacent overgrowths along irregular boundaries. Some interstitial quartz consists of microscopic grains in mosaic aggregates, on the order of chert. Some quartz grains have been corroded by solutions, and locally, they interpenetrate where solution and compaction progressed simultaneously.

Chert grains, constituting 2–10 percent of sandstones and 0.25–6 percent of siltstones and mudstones, were recognized as mosaic aggregates of microscopic silica grains. Although some may be altered volcanic material, there is no evidence in most of them to suggest that they were not derived from a sedimentary chert source.

Content of orthoclase grains averages 12.5 percent in Permian sandstone, ranges lower, 0.25–6.5 percent in younger standstones, and is 1–4 percent in siltstones and mudstones in the Slick Rock district. Orthoclase is commonly clouded with dustlike alteration products.

Microcline grains are abundant, 20 percent, only in Permian sandstone; in younger sandstones they are 0.25–6 percent and in siltstones and mudstones, 0–3 percent. Grains are clear in some rocks and clouded with alteration products in others.

Plagioclase, making up 0.25–5 percent of sandstones and 0–4 percent of siltstones and mudstones, is either clear and unaltered or clouded with alteration products. It is detrital, and also not uncommonly occurs as an authigenic mineral, either as overgrowth cement or as small interstitial laths. It ranges in composition from nearly pure albite where authigenic to more calcic albite and oligoclase in detrital grains.

Clay makes up 0–15 percent of sandstones, 20–70 percent of siltstones and mudstones, and about 80 percent of claystones. Compositionally, it is montmorillonite, kaolinite, or hydrous mica, or mixtures of these (Shawe and others, 1968). Some argillaceous and coarser clastic rocks contain both mineral clay and clay-sized detritus. Most argillaceous rocks contain predominantly mineral clay in this size grade, but some contain distinguishable clay-sized detritus of other minerals, principally quartz and feldspar. Matrix in coarser clastic rocks is both mineral clay and clay- or silt-sized detritus.

Calcite occurs as detrital grains, matrix material impregnating clay-sized material, and cement interstitial to sand and silt grains. As detritus, it is the major component only in sandstone of the Moss Back Member of the Chinle Formation. In younger sandstones, largely in the form of cement, it ranges from 0.5 to 25 percent; in siltstones, mudstones, and shales, both in cement and matrix, it occurs in similar amounts. In limestones, calcite of course constitutes more than half the components of the rocks.

Dolomite, siderite, barite, hematite, analcite, anatase, limonite, pyrite, and marcasite are minor authigenic minerals. They occur either as metacrysts in clay-rich rocks or interstitially in coarser detrital rocks. Hematite occurs commonly as grain coatings, cement, and dispersions of dustlike material. Chlorite appears to be mostly a minor alteration product of earlier mafic minerals. Black opaque detrital grains consist largely of hematite resulting probably from diagenetic oxidation of original magnetite and ilmenite. Some magnetite and ilmenite remains in a small part of the black opaque detrital grains. Leucoxene, perhaps largely altered from ilmenite through diagenetic oxidation, is a minor but common component and may be originally detrital in part. Tourmaline and zircon are minor but common detrital components.

All identifications were made optically under the petrographic microscope with the exception of those for clay minerals, and for hematite in black opaque detrital grains, which were verified by X-ray diffraction.

PRE-MORRISON ROCKS

The rocks are divided into three groups, pre-Morrison, Morrison, and post-Morrison for convenience of petrographic description. Pre-Morrison rocks include examples from the Cutler Formation of Permian age, the Moss Back Member and so-called Black Ledge of the Church Rock Member of the Chinle Formation of Late Triassic age, the Dewey Bridge and Slick Rock Members of the Entrada Sandstone of Late Jurassic age, and the Summerville Formation of Late Jurassic age. Morrison rocks include examples from the Salt Wash and Brushy Basin Members of the Morrison Formation of Late Jurassic age. Post-Morrison rocks include examples from the Burro Canyon Formation of Early Cretaceous age and the Dakota Sandstone and Mancos Shale of Late Cretaceous age.

CUTLER FORMATION

The Cutler Formation, consisting of arkosic sandstone, siltstone, and mudstone, was sampled at the United Uranium mine adit in the Dolores River canyon, SW¼ sec. 12, T. 42 N., R. 18 W. Two samples of limy sandstone were collected 2 and 3 feet below the contact between the Cutler and overlying sandstone of the Moss Back Member of the Chinle Formation. The average mineral composition of thin sections of the samples is shown in table 2.

Sample 55–S–4, the lower of the two, is reddish-brown medium- to fine-grained arkosic sandstone composed of angular detrital grains—chiefly quartz and feldspar, and minor mica and accessory minerals in a matrix of calcite and clay (fig. 3). Microcline and plagioclase grains are largely clear; orthoclase is in part perthitic and myrmekitic. Minor chlorite is mostly a replacement

TABLE 2.—*Average mineral composition, in percent, of sandstones from some Permian and Mesozoic formations in the Slick Rock district, Colorado*

[Based on modal point counts (200 points) and modal estimates of thin sections. "Minor" generally indicates less than 0.25 percent]

Component	Cutler Formation	Chinle Formation: Moss Back Member	Chinle Formation: Church Rock Member	Entrada Sandstone: Dewey Bridge Member (siltstone)	Entrada Sandstone: Slick Rock Member	Summerville Formation	Morrison Formation: Salt Wash Member	Morrison Formation: Brushy Basin Member	Burro Canyon Formation	Dakota Sandstone
Quartz grains and overgrowths	28	12	52	81.5	71	47	76.6	64.5	83	61.5
Chert	-------	1	10	1.5	3.5	5	5.7	8	3	10
Orthoclase	12.5	5	Minor	6.5	5	2	3.0	4	1.5	3
Microcline	20	6	Minor	.5	3.5	2	1.0	.5	Minor	-------
Plagioclase	5	Minor	1	1	3	2	.8	3	Minor	1.5
Rock fragments and mineral aggregates	-------	-------	5	-------	Minor	Minor	Minor	1.5	-------	Minor
Clay (mineral clay and clay-sized detritus)	15	-------	15	6	6	15	2.5	6	3	12
Calcite and (or) dolomite	14	[1] 75	15	.5	6.5	25	8.4	11	6	6
Barite	-------	Minor	-------	-------	Minor	-------	Minor	Minor	1	Minor
Chlorite	3.25	Minor	Minor	-------	Minor	Minor	Minor	.5	Minor	.5
Hematite and other black opaque minerals	.75	-------	.5	1.5	[2] Minor	1	Minor	.5	Minor	Minor
Biotite	.5	Minor	-------	-------	Minor	Minor	Minor	Minor	-------	1
Muscovite	.75	Minor	1	.5	Minor	Minor	Minor	Minor	Minor	Minor
Leucoxene	.25	Minor	Minor	Minor	Minor	Minor	Minor	Minor	Minor	.5
Limonite	-------	-------	-------	-------	[2] Minor	-------	Minor	-------	1	Minor
Pyrite	-------	.5	-------	Minor	[2] Minor	-------	Minor	-------	-------	Minor
Carbonaceous material	-------	-------	-------	-------	-------	-------	-------	-------	-------	3.5
Number of samples	2	1	1	1	7	1	38	13	6	4

[1] Largely rock fragments. [2] Total 0.5 percent.

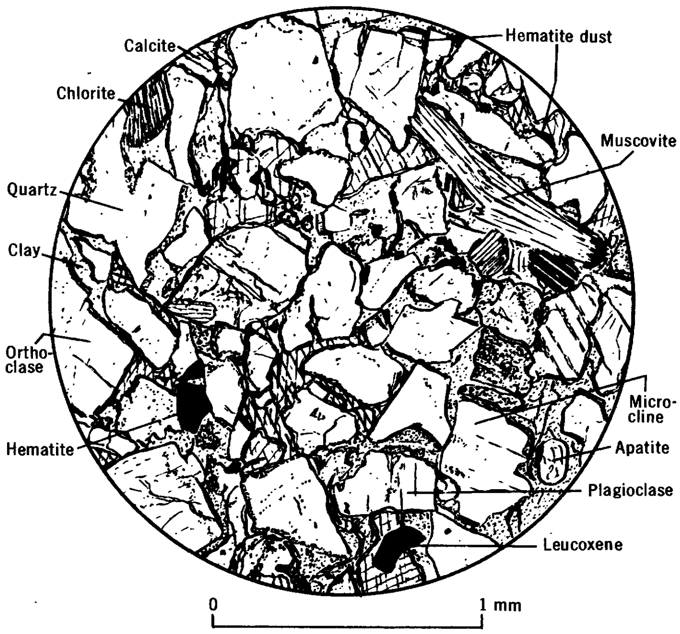


FIGURE 3.—Reddish-brown medium- to fine-grained limy arkosic sandstone of the Cutler Formation. Angularity characterizes most grains; matrix is largely calcite and clay; hematite dust coats all grains. Sample 55–S–4, Dolores River Canyon.

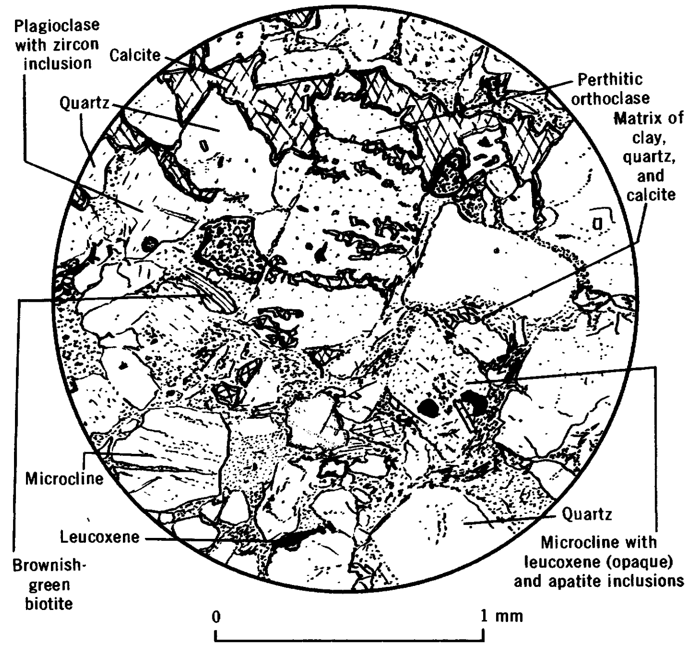


FIGURE 4.—Light-brownish-gray medium-grained arkosic sandstone of the Cutler Formation. Angularity of grains is characteristic; opaque dust and opaque grains are largely leucoxene; calcite that is optically continuous with adjoining matrix calcite partly replaces perthitic orthoclase. Sample 55–S–3, Dolores River Canyon.

of biotite or some other ferromagnesian mineral. Interstitial matrix makes up about a third of the rock. Calcite commonly occurs as optically continuous patches less than a millimeter in diameter, some of which enclose two or three grains of detrital minerals. Hematite occurs as a fine-grained dustlike material dispersed in the clay matrix and as films coating all the detrital grains.

Numerous detrital grains of black opaque minerals are present and are included with hematite in table 2.

The second sample, 55–S–3, collected 1 foot stratigraphically higher than sample 55–S–4, is light-brownish-gray medium-grained arkosic sandstone, composed of angular to subrounded detrital grains chiefly of quartz and feldspar, and minor mica and accessory minerals in a matrix of clay, calcite, quartz, and chlorite (fig. 4). Some perthitic orthoclase in this rock is partly replaced by calcite; a few grains of plagioclase that is albite to oligoclase in composition are dusty looking as though partly altered. Sparse indeterminate rock fragments appear to be largely altered, although some contain small relict feldspar laths. Matrix is about one-fourth of the rock and consists largely of clay; interstitial patches of clay and calcite give way locally to aggregates of microscopic clay, chlorite, quartz, and calcite. Hematite is absent, both as detrital grains and as films on other grains.

Sharp angularity of many mineral grains, as well as the abundance of feldspars and micas, suggests that these rocks were derived from the nearby Uncompahgre highland.

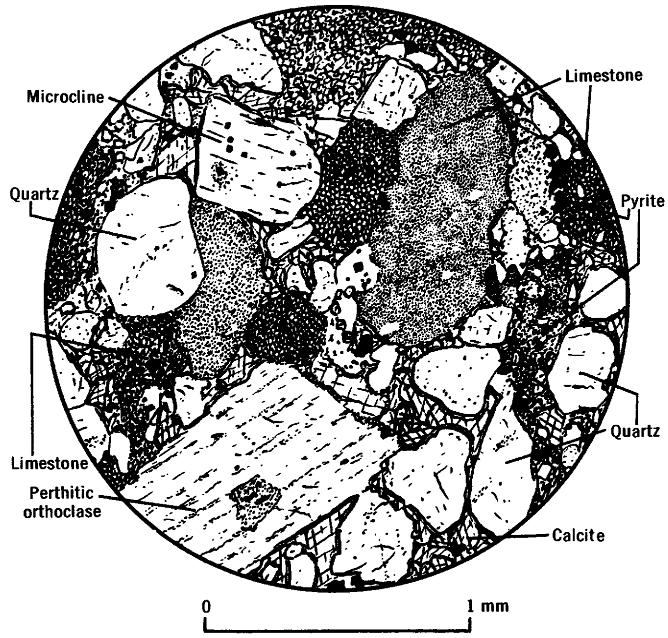


FIGURE 5.—Light-gray coarse-grained calcarenitic sandstone of the Moss Back Member. Illustration shows a higher proportion of quartz and feldspar than is typical of most of the rock. Sample 55–S–2, Dolores River Canyon.

CHINLE FORMATION

The Moss Back Member of the Chinle Formation, consisting of limy arkosic and quartzose sandstone, calcarenite, calcirudite, mudstone, siltstone, and shale, was sampled at the United Uranium mine adit in the Dolores River Canyon, SW¼ sec. 12, T. 42 N., R. 18 W., about 3 feet above the base of the member. Here, the member consists of a common type of gray (*N*5) coarse-grained sandstone and conglomerate containing nearly two-thirds limestone fragments. The poor sorting of the rock, angularity of grains suggesting a close source area, and tendency to contain abundant calcite cement are shown in figure 5, which illustrates a rock with more quartz grains than is typical. The mineral composition of a thin section of the rock (sample 55–S–2) is given in table 2. Some limestone grains contain considerable clastic quartz and some chlorite and pyrite. Chlorite occurs as sheaves in small altered mineral grains. Chalcedony grains (included with chert in table 2) contain concentric colloform structures. Calcite cement of the rock (about 10 percent) is coarse to fine grained and locally merges with limestone grains, indicating these to be the likely source of this cementing material. Most of the pyrite of the rock, as cubes and anhedra, occurs in calcite cement. Parts of the interiors of some large limestone grains are recrystallized and composed of coarse calcite, locally showing polysynthetic twins. Bedding of the rock is manifested by thin layers which appear to have had some shearing along them.

The so-called Black Ledge of the Church Rock Member of the Chinle Formation (Stewart and others, 1959, p. 518), made up of sandstone, siltstone, and minor conglomerate, was sampled in the Dolores River Canyon. This sample (55–S–1) is of the upper sandstone layer of the Black Ledge, a very fine grained thinly and horizontally laminated sandstone in which muscovite flakes and clay are conspicuous on some bedding planes. A thin section of this rock shows poorly sorted largely angular to flakelike grains in a clay and calcite matrix contaminated by dustlike indeterminate material (fig. 6). Mineral composition of the thin section is given in table 2. Some clay, calcite, and chlorite may be altered ferromagnesian minerals. In the rock matrix is some very fine grained to medium-grained interlocking secondary quartz, but none as overgrowths, and minor chlorite and probably anatase as dustlike material. Hematite is thoroughly dispersed in the matrix and coats most detrital grains; it occurs also as detrital black opaque grains. Calcite cement, more or less evenly distributed through the rock, is in optically continuous patches, as much as 0.5 mm in diameter, which enclose several detrital grains. The rock may be largely volcanic material, as the sharp flakelike fragments show no evidence of abrasion by water transport; furthermore, the even, fine horizontal stratification suggests deposition of this material by air fall into quiet water or onto

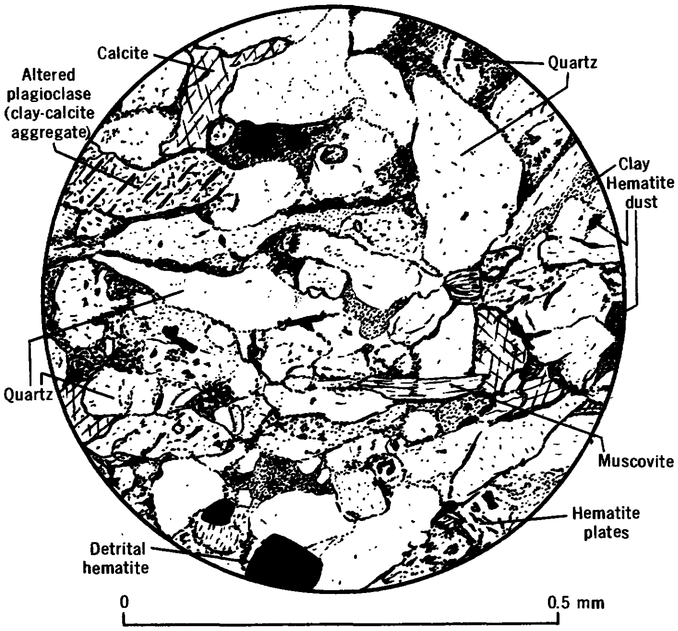


FIGURE 6.—Reddish-brown very fine grained sandstone from the so-called Black Ledge of the Church Rock Member. Angular and flakelike grains suggest a crystal tuff origin of the rock. Sample 55–S–1, Dolores River Canyon.

land. Some water-borne detritus is present, however, as evidenced by scattered well-rounded grains in the rocks. Probably original glass devitrified, and constitutes much of the clay, silica, and perhaps calcite, in the matrix.

ENTRADA SANDSTONE

Sandstone and siltstone of the Dewey Bridge Member of the Entrada Sandstone are quartzose and are cemented by variable amounts of clay and in small spots by carbonate and barite. Muscovite or biotite is visible in places. Mineral composition of a thin section of typical reddish-brown siltstone from 10 feet below the top of the member (sample DVR–2–1990) collected from a deep diamond-drill hole drilled by the U.S. Geological Survey in Disappointment Valley, sec. 36, T. 44 N., R. 18 W., is given in table 2. Hematite content shown in the table includes numerous detrital black opaque minerals. The rock is cemented with mostly clay, some hematite as films on quartz grains and finely dispersed in clay, and a small amount of carbonate. Some of the carbonate, in small scattered blebs, is probably calcite, and some, as rhombs, may be dolomite. The rock is poorly sorted and well packed, with angular to well-rounded silt-sized detritus containing rare medium-sized quartz and chert grains.

The Slick Rock Member of the Entrada Sandstone consists of very fine grained to fine-grained sandstone in three units, a lower massive unit, middle crossbedded unit, and an upper horizontally bedded unit. The average mineral composition of the member as judged from the average composition of seven thin sections is shown in table 2. Five of the seven samples of the Slick Rock are light reddish brown and contain hematite as grain coatings, finely dispersed materials, and detrital black opaque minerals, whereas the other two samples are light brown and contain no hematite. The mineral compositions of samples from the three subdivisions of the Slick Rock Member are given in table 3. A typical sample of the massive unit (SH–3–55) was collected near its top at the north side of Poverty Flat. A thin section of this sample shows the rock to be moderately sorted, and most grains rounded (fig. 7). Scattered grains about 0.5 mm in diameter are known as Entrada berries (Wright and others, 1962, p. 2063). Although most of the Entrada berries are quartz, some are small rock fragments, or material that has been altered to clay; one colloform-banded chalcedony grain was observed. Minor chlorite occurs probably as an alteration product in some of the fine-grained detritus. Matrix makes up about 20 percent of the rock and is mostly clay and about one-fourth carbonate as small patches of optically continuous calcite as much as 0.5 mm across, and rare euhedral rhombs probably dolomite, between quartz grains. A small amount of dustlike hematite, and traces of minute euhedral anatase crystals and iron-rimmed carbonate rhombs that may be siderite, are scattered throughout the matrix.

Grain-size analyses of two samples of the massive unit of the Slick Rock Member (EN–32 and EN–38)

TABLE 3.—*Average mineral composition, in percent, of sandstones from the Slick Rock Member of the Entrada Sandstone*

[Based on modal point counts (200 points) and modal estimates of thin sections. "Minor" generally indicates less than 0.25 percent]

Component	Massive unit	Cross-bedded unit	Horizontally bedded unit
Quartz grains and overgrowths	76	67	75
Chert	3	3.5	5.5
Orthoclase	4	7	5.5
Microcline	1	3	4
Plagioclase	1.5	4	5
Rock fragments and mineral aggregates		Minor	Minor
Clay (mineral clay and clay-sized detritus)	9	5	3
Calcite and dolomite	5	9	1
Barite		Minor	Minor
Chlorite	Minor		Minor
Hematite and other black opaque minerals	Minor	Minor	Minor
Biotite	Minor		Minor
Muscovite	Minor		
Leucoxene and anatase	Minor	Minor	Minor
Limonite		Minor	
Pyrite		Minor	
Number of samples	2	4	1

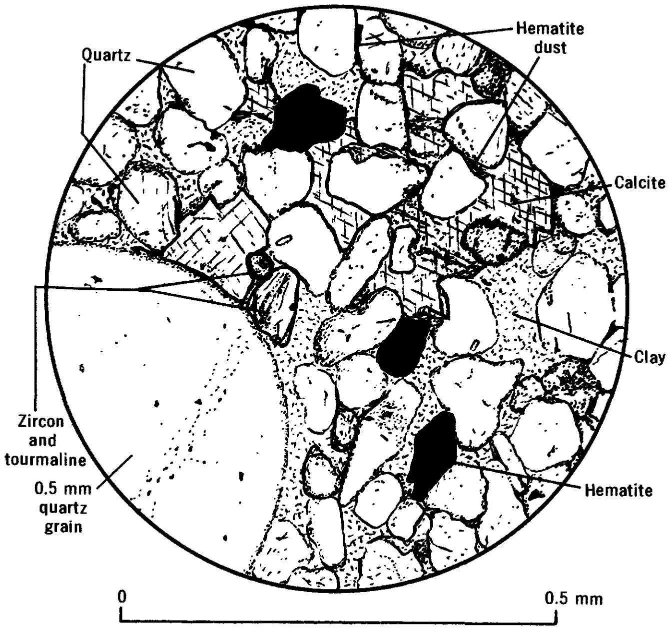
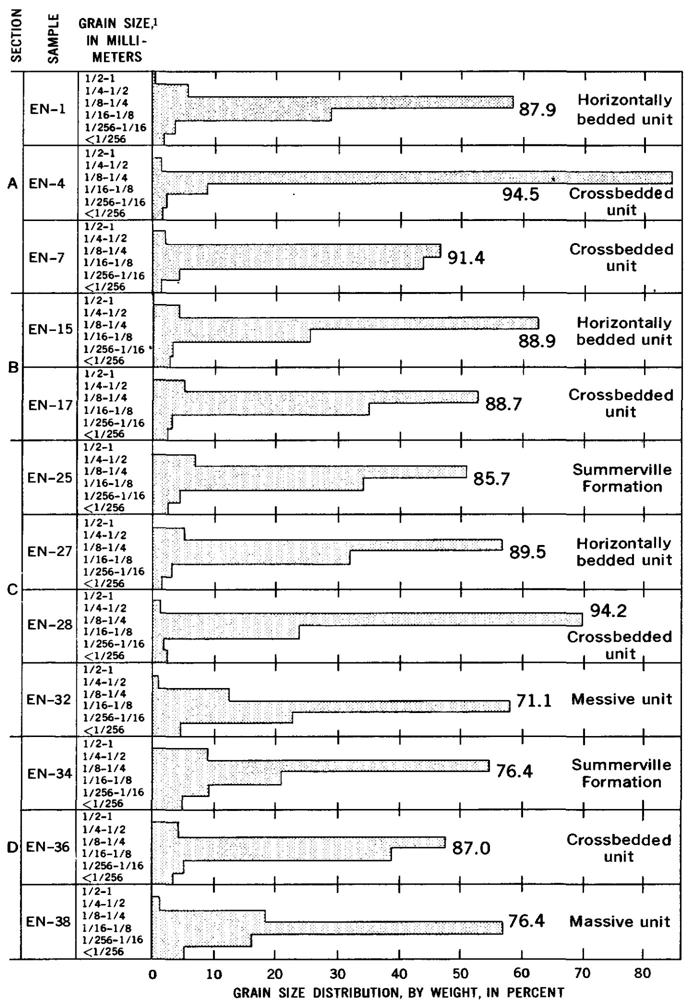


FIGURE 7.—Light-reddish-brown very fine grained sandstone from the massive unit of the Slick Rock Member. Clay and calcite form matrix; detrital hematite grains are abundant and most sand grains are coated with hematite dust; relatively large grain in lower left quadrant is typical Entrada berry. Sample SH–3–55, near the top of the unit at the north side of Poverty Flat.

are shown in figure 8. The 1/16–1/8 mm and 1/8–1/4 mm size fractions together average 73.8 percent. Percent of grains in the two dominant size fractions is here used merely as an index for comparison with other samples of Entrada Sandstone. In terms of all the size fractions in the rock, the massive unit consists of less than 1 percent coarse sand, about 1 percent medium sand, 16 percent fine sand, 58 percent very fine sand, 19 percent silt, and 5 percent clay.

Sandstone of the crossbedded unit of the Slick Rock Member (table 3) consists of quartz and lesser K-feldspar and plagioclase grains in a clay and calcite matrix. Sparse well-rounded quartzite fragments are present. Orthoclase is both untwinned and carlsbad twinned; plagioclase shows albite and pericline twins. This rock is well sorted and has rounded to well-rounded grains. A few bedding planes contain very fine sand or silt-sized sharply angular detrital grains that may be of crystal tuff origin. Part of a thin section (SH–1–55) from a sample collected near the base of the crossbedded unit at the north side of Poverty Flat is shown in figure 9.

Grain-size analyses of five samples of the crossbedded unit (En–4, 7, 17, 28, 36, fig. 8) show that the 1/16–1/8 mm and 1/8–1/4 mm size fractions together average 91.2 percent. In terms of all the size fractions in the rock, the crossbedded unit consists of less than 1 percent coarse sand, about 3 percent medium sand, 60 percent fine sand, 30 percent very fine sand, 3 percent silt, and 3 percent clay. These values show that the crossbedded unit is considerably better sorted than the underlying massive unit (average index 73.8), and corroborate the conclusion, on grounds of bedding characteristics, that the crossbedded unit is dominantly of eolian origin.



[1] 1/2–1 (>500 microns) = coarse sand
1/4–1/2 (<500>250 microns) = medium sand
1/8–1/4 (<250>125 microns) = fine sand
1/16–1/8 (<125>62 microns) = very fine sand
1/265–1/16 = silt
1/265 = clay

FIGURE 8.—Histograms of grain-size distribution for samples from the Slick Rock Member of the Entrada Sandstone and lower part of the Summerville formation (2 samples). Figure at end of each histogram is percent of sample in size fractions 1/8–1/4 mm and 1/16–1/8 mm, combined.

Modal estimates of mineral composition of four thin sections of samples from the crossbedded unit (table 3) indicate a higher content of cementing material than is indicated by the grain-size analyses and by the data on average calcite and solubles content to be presented in a later chapter of this professional paper series on

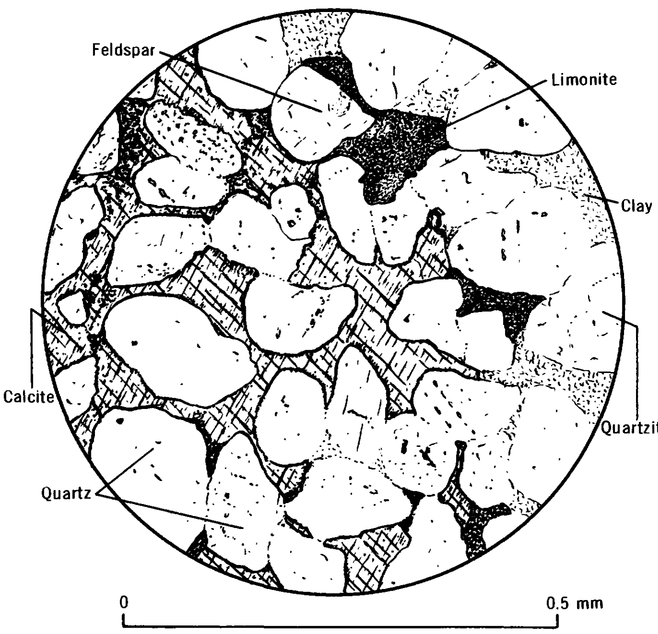


FIGURE 9.—Buff very fine grained sandstone from the crossbedded unit of the Slick Rock Member. Patch of optically continuous calcite bordered by spots of limonite forms a local cement around sand grains; clay is the principal matrix in most of the rock; individual sand grains are quite clean. Sample SH–1–55, near the base of the unit at the north side of Poverty Flat.

rock alteration. Two of the samples examined in thin sections were collected near the base of the crossbedded unit; these samples average about 25 percent cement that is principally calcite. They are not typical of the crossbedded unit in this respect, and may be from a part of the unit that is transitional into the massive unit below.

A sample from 7 feet below the top of the horizontally bedded unit (DVR–2–1862.5) was collected from drill core from the deep diamond-drill hole in Disappointment Valley, sec. 36, T. 44 N., R. 18 W. The mineral composition of a thin section of this sample is given in table 3. The rock is light reddish brown, moderately sorted, and contains rounded to well-rounded very fine sand. Sparse Entrada berries are present. Interstitial material consists of clay, locally only as grain coatings, and small patches of calcite. Sparse authigenic dolomite rhombs occur within clay.

Grain-size analyses of three samples (EN–1, 15, 27, fig. 8) show that the $\frac{1}{16}$–$\frac{1}{8}$ mm and $\frac{1}{8}$–$\frac{1}{4}$ mm size fractions together average 88.8 percent. In terms of all the size fractions in the rock, the horizontally bedded unit consists of less than 1 percent coarse sand, about 5 percent medium sand, 60 percent fine sand, 29 percent very fine sand, 3 percent silt, and 2 percent clay. Although the average percentage of size fractions in the horizontally bedded and crossbedded units are almost identical, the range for individual size fractions in the crossbedded unit is great and in the horizontally bedded unit rather narrow. This fact suggests that, if the horizontally bedded unit was reworked from the crossbedded unit, as is likely, the various reworked parts of the crossbedded unit were thoroughly mixed in the process.

SUMMERVILLE FORMATION

The Summerville Formation consists of mudstone, siltstone, and very fine grained to fine-grained sandstone that make up a lower transitional unit, an argillaceous unit above this, a sandstone "marker bed" above this, and an argillaceous unit at the top. A reddish-brown argillaceous sandy layer of the transitional unit of the Summerville was collected from drill core from the drill hole in sec. 36, T. 44 N., R. 18 W., Disappointment Valley. The sample (DVR–2–1825) consists of poorly sorted fine-grained sand of sharply angular to very well rounded detritus and an extremely fine-grained interstitial mixture of calcite, clay, and hematite. The sample contains thin layers of mudstone and siltstone; parts of these layers are shown in figure 10. Sparse medium to coarse grains in finer grained detritus suggest kinship to the underlying Entrada. This sample is suggestive of the small-scale heterogeneity that is characteristic of the Summerville. Although abundance of mineral constituents ranges widely in different parts of the transitional unit, a modal estimate of the composition of the thin section from the illustrated sample indicates the general mineralogy, and is given in table 2. Rounded detrital black opaque minerals are included in table 2 with hematite. About 25 percent calcite as irregular granular patches and 15 percent clay, both as clay-sized detritus and clay minerals, that contain perhaps half a percent of dustlike hematite make up the matrix of the rock. Abundance of sharply angular fragments of detritus suggest possible admixture of airborne volcanic material in the rock.

Grain-size analyses of two samples of the transitional unit (EN–25 and EN–34, fig. 8) show that the 1/16–1/8 mm and 1/8–1/4 mm size fractions combined average 81.1 percent. In terms of all the size fractions in the rock, the samples average less than 1 percent coarse sand, about 8 percent medium sand, 53 percent fine sand, 28 percent very fine sand, 7 percent silt, and 4 percent clay. These samples are better sorted than most of the Summerville, and in this respect are more like the underlying Entrada Sandstone.

Probably typical of the mudstone and siltstone layers in the upper argillaceous part of the Summerville Formation is a sample (DVR–2–1790) collected from drill

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TABLE 4.—*Average mineral composition, in percent, of siltstones, mudstones, and shales from some Mesozoic formations in the Slick Rock district, Colorado*

[Based on modal point counts (200 points) and modal estimates of thin sections. "Minor" generally indicates less than 0.25 percent]

Component	Summerville Formation	Morrison Formation				Burro Canyon Formation	Dakota Sandstone	Mancos Shale	
		Salt Wash Member		Brushy Basin Member					
	Siltstone	Siltstone	Mudstone	Siltstone	Mudstone	Claystone	Mudstone	Mudstone	Shale
Quartz detritus and secondary quartz	51	50	27.5	61	28	9.5	25	29.5	5
Chert	1	4	3.5	6	.25	1	(1)	3	
Orthoclase	4	4	2.5	3	2.5	1	2	2.5	
Microcline	3	1	.5	1	Minor	.25			
Plagioclase	4	1.5	1	2.5	3.5	.5		.5	
Rock fragments and mineral aggregates					Minor			2.5	
Clay (mineral clay and clay-sized detritus)	30	20	40	17.5	56	82	67	(2) 56.5	73.5
Calcite and dolomite	5	18.5	23.5	7.5	3.5	4.5		1.5	17.5
Barite				Minor	1			Minor	
Chlorite	Minor	Minor		Minor	2.5	Minor	Minor		
Hematite and other black opaque minerals	1	Minor	.5	.5	.25	.25			
Biotite	Minor	Minor	Minor	Minor	.25	.25	Minor	.5	
Muscovite	.5	Minor	Minor	Minor	.5		Minor	.5	
Leucoxene and anatase	Minor	Minor	Minor	Minor	Minor	Minor	Minor	Minor	
Limonite		Minor			Minor		Minor	Minor	
Pyrite			Minor		Minor	Minor	Minor	.75	1
Analcite					1				
Carbonaceous material			.5		.5	.5	5	1.5	3
Number of samples	1	4	2	4	13	4	1	2	2

[1] Included with quartz. [2] In one sample, clay includes about 10 percent clay-chlorite aggregates.

core obtained from the deep diamond-drill hole in Disappointment Valley. A modal estimate of the mineral composition of a thin section of this clayey siltstone is given in table 4. Numerous detrital black opaque grains are included in the table with hematite. About 30 percent clay, consisting of both clay mineral and clay-sized detritus, 5 percent calcite, for the most part extremely fine grained and in scattered patches, and a trace of authigenic yellow anatase crystals and perhaps a small amount of dustlike hematite, make up the matrix. Some calcite occurs as sparse detrital limestone grains.

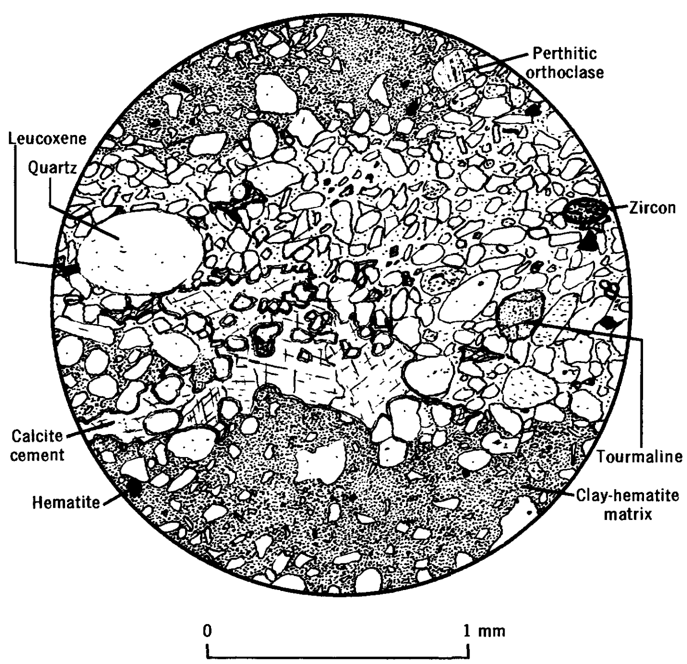

FIGURE 10.—Poorly sorted reddish-brown sandstone with thin siltstone and mudstone layers (shown here) from the lower part of the Summerville Formation. Sample DVR–2–1825, Disappointment Valley.

MORRISON FORMATION ROCKS

SALT WASH MEMBER

The Salt Wash Member of the Morrison Formation consists of interbedded fine-grained fluvial sandstone, siltstone, and flood-plain mudstone strata comprising (1) a lower sandstone unit, (2) a middle mudstone unit, and (3) an upper or "ore-bearing" sandstone unit. The average mineral composition of 38 samples of sandstone from the member is given in table 2. A comparison is made in table 5 of the average mineral composition of thin sections of 19 of these samples based on 200-point counts, of thin sections of 19 different samples based on modal estimates, and of 202 samples of the Salt Wash Member from the whole Colorado Plateau as analyzed by R. A. Cadigan (in Craig and others, 1955, p. 147–148). This comparison shows that the analyses of Slick Rock samples by point counting and by estimating are close, and that the average composition of Slick Rock samples is close to the average for the whole Colorado Plateau.

A sample (DVR–2–1667) of light-reddish-brown very fine grained sandstone from the upper part of the lower unit was collected from drill core from the deep diamond-drill hole in Disappointment Valley. An estimate

TABLE 5.—*Comparison of average mineral composition of sandstones from the Salt Wash Member, Slick Rock district, with that of sandstones from the Salt Wash Member throughout the Colorado Plateau*

Component	Slick Rock district			Colorado Plateau [1]
	Point counts	Modal estimates	Average	
Quartz	72.3	71.7	72.0	71.4
Quartz overgrowths	4.3	4.3	4.3	4
Chert	4.8	6.4	5.6	5.8
K-feldspar	2.7	5.3	4.0	5.8
Plagioclase	.6	.9	.8	
Calcite	8.2	8.5	8.3	13
Clay	2.1	2.9	2.5	--------
Other	5.0	--------	2.5	--------
Number of samples	19	19	38	202

[1] Analyzed by R. A. Cadigan, calculated from data of Craig and others, (1955 p. 147–148).

of the mineral composition of a thin section of this rock is given in table 6. Hematite in table 6 includes detrital black opaque grains. Detrital grains are rounded to well rounded and moderately sorted. About 15 percent silica as overgrowth on detrital grains constitutes most of the rock cement. Some overgrowths are faceted, but most are joined to adjacent overgrowths along sutured or irregular borders. A small amount of calcite as irregular small interstitial blebs, dustlike hematite and grain coatings, and a trace of barite make up the remainder of the matrix. A few detrital grains are limestone, some of which are surrounded by calcite cement that is also molded around adjacent quartz and feldspar grains.

Modal estimates of the mineral content of thin sections of three samples of sandstone from the middle unit of the Salt Wash Member are averaged in table 6. Hematite is present in two of the thin sections—both light-reddish-brown sandstone—and pyrite is present in one—a light-gray sandstone containing carbonaceous material. Detrital grains in the samples are angular to well rounded, poorly to moderately sorted, of chiefly very fine grain size, ranging from silt to medium-fine grain size. Light-reddish-brown sandstone has either minor thin ragged silica overgrowths on a few quartz grains, or abundant overgrowths, largely irregular and a few faceted, more in some parts of the rock than in others. A sample of light-reddish-brown sandstone (SR–1) illustrated in figure 11 has abundant overgrowths on quartz grains and shows some solution of quartz grains, suggesting a local origin of matrix silica. Light-gray sandstone has some etched quartz grains and a minor amount of overgrowth silica, also possibly indicating only local movement of silica in solution.

Modal estimates and point counts of the mineral content of 14 thin sections of sandstone from the upper unit (ore-bearing sandstone) of the Salt Wash Member are averaged in table 6. Several of these samples were collected close to uranium-vanadium deposits and contain much greater-than-average amounts of calcite as determined for the ore-bearing sandstone by Archbold

TABLE 6.—*Average mineral composition, in percent, of sandstones from the Salt Wash Member of the Morrison Formation*

[Based on modal point counts (200 points) and modal estimates of thin sections. "Minor" generally indicates less than 0.25 percent]

Component	Lower unit	Middle unit	Upper unit
Quartz grains and overgrowths	76	77.5	75
Chert	7	2	6.5
Orthoclase	10	3.5	4.5
Microcline	1	.5	.5
Plagioclase	1	1	1
Rock fragments and mineral aggregates	2	Minor	Minor
Clay (mineral clay and clay-sized detritus)	Minor	1	2
Calcite and dolomite	2	13	9
Barite	Minor	--------	Minor
Chlorite	Minor	Minor	Minor
Hematite and other black opaque minerals	Minor	.5	Minor
Biotite		Minor	Minor
Muscovite			Minor
Leucoxene and anatase	Minor	Minor	Minor
Limonite			Minor
Pyrite		Minor	--------
Number of samples	1	3	14

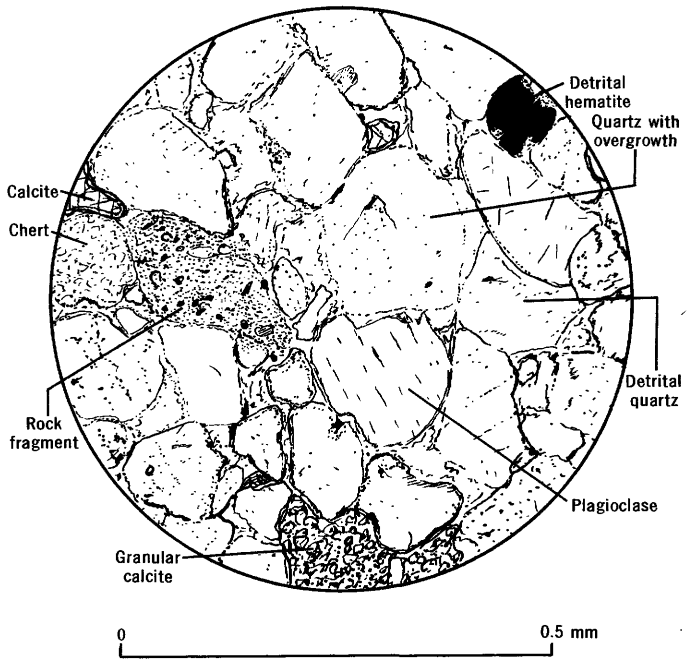

FIGURE 11.—Light-reddish-brown fine-grained sandstone from the middle unit of the Salt Wash Member. Detrital quartz grain to the right of quartz with overgrowth fits against a partly rounded detrital quartz grain possibly because of partial solution under pressure; many grains have thin dusty hematite coatings. Sample SR–1, north of the Middle Group mines at Slick Rock.

(1959). For this reason the average calcite content of the 14 samples is about three times that of the ore-bearing sandstone as a whole. Most of the samples are of light-brown sandstone and only a few of light-reddish-brown, which accounts for a greater number containing limonite (after pyrite or marcasite) rather than hematite. Detrital black opaque minerals occur along with hematite films and dustlike material in the reddish-brown rocks.

Sandstone of the upper unit is generally fine to very fine grained and moderately to well sorted, and has grains that are angular to well rounded (fig. 12). Commonly, the sandstone is cemented by calcite, though in most places not so thoroughly as shown in figure 12, and by silica. Calcite cement more or less permeates sandstone in places that are close to ore deposits (as in fig. 12) and adjacent to mudstone layers (Archbold, 1959). Elsewhere in the upper unit, calcite occurs as patches enclosing a few sand grains, and where sparser, as isolated interstitial blebs. Many of the patches of calcite show polysynthetic twins (fig. 12), possibly indicating stressing of the sandstone after calcite deposition. Silica cement ranges from almost none to about 15 percent of the rock. It occurs as overgrowths, commonly irregular, which join adjacent overgrowths at sutured contacts, but which in many places are faceted. Perhaps faceted overgrowths are more abundant in more porous sandstone. Some sandstone has little or no silica overgrowths on grains, but the grains are tightly held together by their own interpenetration at places of contact, as though some silica went into solution at a time when the rock was under pressure. An example is shown in figure 13, a sandstone that also contains probably more than average limonite cement (after pyrite or marcasite). The limonite occurs as isolated patches in the sandstone, one of which is shown in figure 13.

Replacement textures are evident in the sandstone of the upper unit and are shown mainly by calcite as irregular penetrations around the periphery of quartz grains and between grain and silica overgrowth, and by the selective replacement of plagioclase, illustrated in figure 12. In places microcline and orthoclase are replaced by clay minerals.

A typical reddish-brown siltstone was collected near the top of the lower unit in Disappointment Valley (sample DVR–2–1597.5). A modal estimate of the mineral composition of a thin section of the rock is given in table 7. Some hematite is detrital as indicated by subrounded to rounded forms, and some occurs finely dispersed in clay; traces of chlorite are found in a few detrital minerals. Detritus is sharply angular to

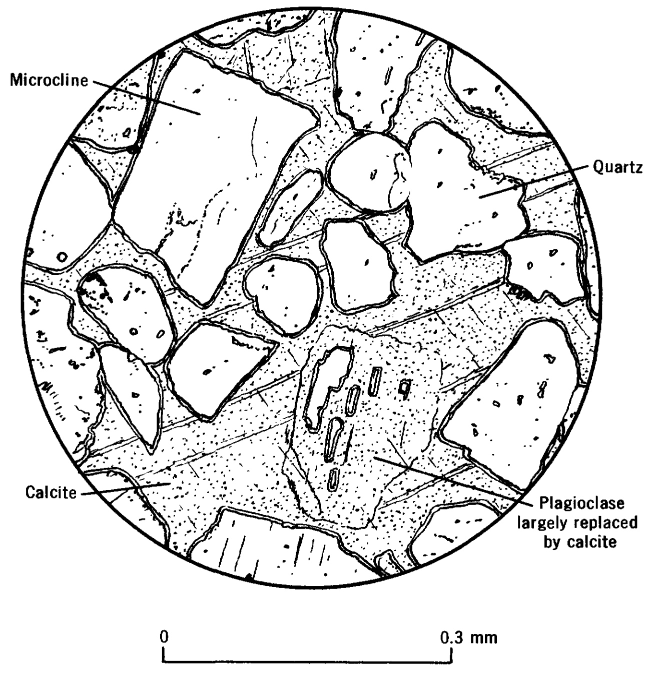

FIGURE 12.—Very light brown very fine grained standstone from the upper unit of the Salt Wash Member, cemented by calcite. Calcite that has almost completely replaced a plagioclase grain is optically continuous with surrounding calcite, but polysynthetic twinning in the interstitial calcite does not extend into the replaced grain; slightly mineralized rock is within a few millimeters of the area shown. Sample C–6, Cougar mine.

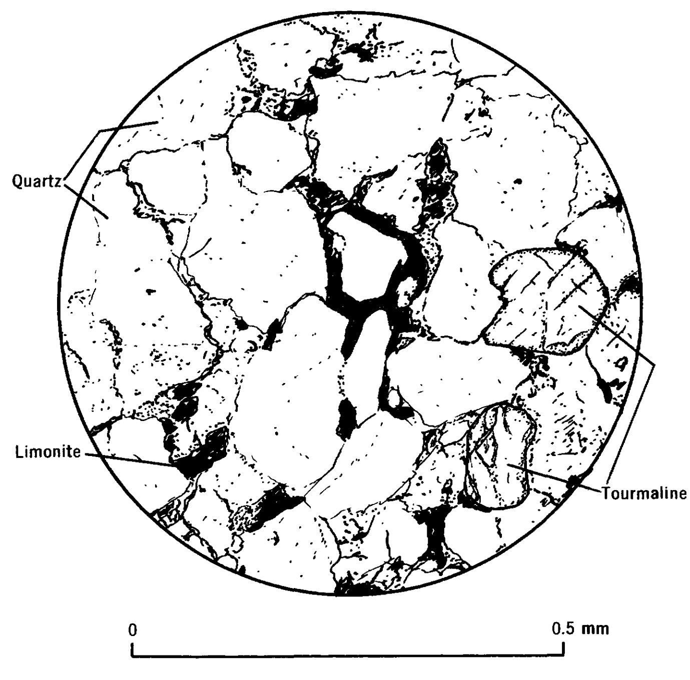

FIGURE 13.—Very light brown very fine grained sandstone from the upper unit of the Salt Wash Member. Sutured contacts between some quartz grains suggest solution of silica under pressure; opaque mineral is limonite altered from pyrite or marcasite; upper tourmaline is dichroic in shades of blue; lower, in shades of yellow. Sample SR–2, Lone Peak 1 claim, Spud Patch group of mines.

TABLE 7.—*Average mineral composition, in percent, of siltstones from the Salt Wash Member of the Morrison Formation*

[Based on modal point counts (200 points) and modal estimates of thin sections. "Mi ıor" generally indicates less than 0.25 percent]

Component	Lower unit	Middle unit	Upper unit
Quartz grains and overgrowths	50	45	52. 5
Chert	5	5	3. 5
Orthoclase	5	5	3
Microcline	1	2	. 5
Plagioclase	3	2	. 5
Clay (mineral clay and clay-sized detritus)	25	30	12
Calcite	10	10	27
Chlorite	Minor	Minor	Minor
Hematite and other black opaque minerals	Minor	Minor	--------
Biotite			Minor
Muscovite	Minor	--------	Minor
Leucoxene	Minor	Minor	Minor
Limonite			Minor
Number of samples	1	1	2

rounded, poorly sorted, silt sized; a minor amount is fine sand sized. Clay is concentrated in laminae that represent bedding layers, and these are mashed and distorted probably by slumping of the rock before consolidation. Calcite occurs interstitial to detrital grains, as well as in blebs in clay. Some detrital grains are wholly calcite and some only partly calcite, as though replaced by it. A few devitrified glass shards are evident in clay, and these, together with sharply angular detritus, suggest that some airborne volcanic material is present. Probably ash-fall material is mixed with water-transported material.

A modal estimate of the mineral composition of a siltstone sample (DVR–2–1540) that is probably typical of siltstone from the middle unit of the Salt Wash Member is given in table 7. Hematite occurs as detrital grains, and hematite and chlorite are present in trace amounts disseminated in the matrix, and in or coating detrital grains. Detrital grains in the sample are chiefly silt sized and in small part sand sized; they range from sharply angular to well rounded and are chiefly poorly rounded, embedded in clay matrix. Amounts of matrix vary in different bedding layers.

Thin sections of two samples of siltstone from the ore-bearing sandstone have the average composition given in table 7. Grains are sharply angular to rounded and poorly sorted. One of the samples contains angular clay fragments as much as 1 cm in length. Siltstone in the ore-bearing sandstone seems to be intermediate between mudstone and sandstone in most of its properties. Calcite is more abundant than in either of the other types, however, although the samples studied may be atypical in this respect.

The lower part of the lower unit of the Salt Wash Member in the vicinity of the drill hole in Disappointment Valley is not typical, consisting of a carbonaceous mudstone layer about 50 feet thick not known elsewhere in the district. A sample (DVR–2–1722.5) of the carbonaceous mudstone collected from the drill hole was examined in thin section, and a modal estimate of the mineral composition of the thin section is given in table 8. Clay is strongly birefringent and may be in large part hydrous mica. A small amount of calcite and a trace of pyrite and minute rhombs of dolomite occur as visible authigenic minerals scattered throughout clay. Some calcite is detrital. The rock is well bedded, and carbonaceous material is largely concentrated along bedding planes. A pen-and-ink drawing of part of the thin section is shown in figure 14.

A modal estimate of the mineral composition of a thin section of a mudstone sample (DVR–2–1465) collected near the top of the middle unit of the Salt Wash in Disappointment Valley is given in table 8. Hematite occurs as detrital grains and as coatings on quartz and other minerals; it also is finely dispersed throughout the rock matrix. Detritus, sharply angular to rounded, is chiefly silt sized and is embedded in a matrix of clay and chiefly clay-sized calcite detritus. Some calcite occurs as silt-sized detrital grains. Bedding laminae, manifested by alternating clay-rich and detritus-rich parts, are contorted, propably by preconsolidation slumping.

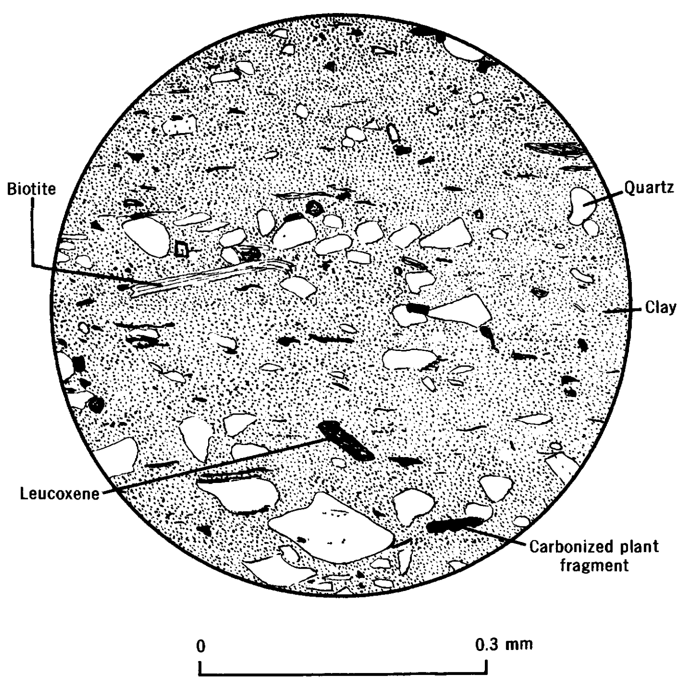

FIGURE 14.—Dark-gray carbonaceous mudstone from the lower part of the lower unit of the Salt Wash Member. Almost all the black particles are carbonized plant fragments. Sample DVR–2–1722.5, Disappointment Valley.

TABLE 8.—*Mineral composition, in percent, of mudstones from the Salt Wash Member of the Morrison Formation*

[Based on modal estimates of thin sections. "Minor" generally indicates less than 0.25 percent]

Component	Lower unit	Middle unit
Quartz grains and overgrowths	26	30
Chert	3	4
Orthoclase	2	3
Microcline	--	1
Plagioclase	1	1
Clay	65	15
Calcite and dolomite	2	45
Hematite and other black opaque minerals	------	1
Biotite	Minor	--------
Muscovite	Minor	Minor
Leucoxene	Minor	Minor
Pyrite	Minor	--------
Carbonaceous material	1	--------
Number of samples	1	1

BRUSHY BASIN MEMBER

The Brushy Basin Member of the Morrison Formation is bentonitic flood-plain mudstone interbedded with lesser amounts of sandstone and conglomerate and a minor amount of thin limestone layers. These rocks comprise a lower brown unit, a middle green unit, and an upper brown unit. The average mineral composition of 13 thin sections of sandstone from the Brushy Basin Member is given in table 2. Modal point counts and estimates of the mineral content of seven thin sections of drill cores of fine-grained to very fine grained sandstone from the lower brown unit are averaged in table 9. Similarity to composition of sandstone in the underlying ore-bearing sandstone of the Salt Wash (table 6) is evident. Sandstone of the lower brown unit of the Brushy Basin is poorly to moderately sorted. Silica cement in these rocks, included with quartz in table 9, ranges from none to almost 10 percent, and probably averages less than 5 percent. It occurs in places as almost complete filling of pore spaces (fig. 15), as sutured interpenetrating overgrowths, and where pore spaces are incompletely filled, as faceted overgrowths. Calcite is present principally as cement, although detrital limestone grains are locally fairly abundant. Calcite occurs as isolated small blebs, illustrated in figure 15, as larger patches that enclose several detritial grains, and as extensive zones of cement, commonly at the tops and bottoms of sandstone layers. Figure 16 shows optically continuous calcite cement in a tightly cemented zone near the base of a sandstone layer 45 feet thick at the top of the lower brown unit. Calcite cement and detrital grains are locally polysynthetically twinned. Parts of sandstone layers in the unit are well cemented with clay, or mixtures of clay, very fine grained calcite, and finely disseminated hematite, as shown in figure 17. Hematite occurs in all reddish-brown sandstone in the unit, commonly as detritus and as films coating other detrital grains (figs. 16, 17), as well as dispersed in the matrix (fig. 17). Barite in reddish-brown sandstone is typically irregularly shaped and is probably chiefly a matrix mineral; some fragments from heavy-mineral separates show crenate outlines that suggest the original shape of a barite-filled space between rounded detrital grains. In light-gray or light-buff sandstone, barite commonly has replaced quartz grains (fig. 15), or forms euhedral crystals between detrital grains and in places penetrates into detrital grains. Anatase appears locally along with calcite and hematite, finely disseminated in a clay matrix.

The average mineral content of thin sections of three very fine grained sandstone samples from the middle green unit is shown in table 9. Barite amounting to less than one-half percent has replaced chert locally in one rock. Figure 18 shows the general dirty character of these sandstones; this rock from the Legin area, sample LE–430–461, contains minute segregations of marcasite, one of which is shown here. The intimate association of calcite and marcasite may indicate their segregation in interstitial patches simultaneously, when the rock was cemented. In sandstone of the middle green unit erratic solution and deposition of silica has caused scattered development of corroded quartz grains and silica overgrowths. Calcite appears to have replaced small patches of silt- and clay-sized particles in the sandstone. Clay and calcite replacement of feldspars has occurred in places. The very fine grained sandstone is composed of poorly sorted sharply angular to well-rounded detrital

TABLE 9.—*Average mineral composition, in percent, of sandstones from the Brushy Basin Member of the Morrison Formation*

[Based on modal point counts (200 points) and modal estimates of thin sections. "Minor" generally indicates less than 0.25 percent]

Component	Lower brown unit	Middle green unit	Upper brown unit
Quartz and overgrowths	74	60	46.5
Chert	6	7	14
Orthoclase	2	6	7
Microcline	1	.5	Minor
Plagioclase	2	1.5	6
Rock fragments and mineral aggregates	1	1	5
Clay (mineral clay and clay-sized detritus)	2.5	14	6.5
Calcite and dolomite	11	9	13
Barite	Minor	Minor	Minor
Chlorite	Minor	1	1
Hematite and other black opaque minerals	Minor	Minor	Minor
Biotite	Minor	Minor	Minor
Muscovite	Minor	Minor	--------
Leucoxene and anatase	Minor	Minor	Minor
Pyrite and marcasite	------	Minor	--------
Number of samples	7	3	3

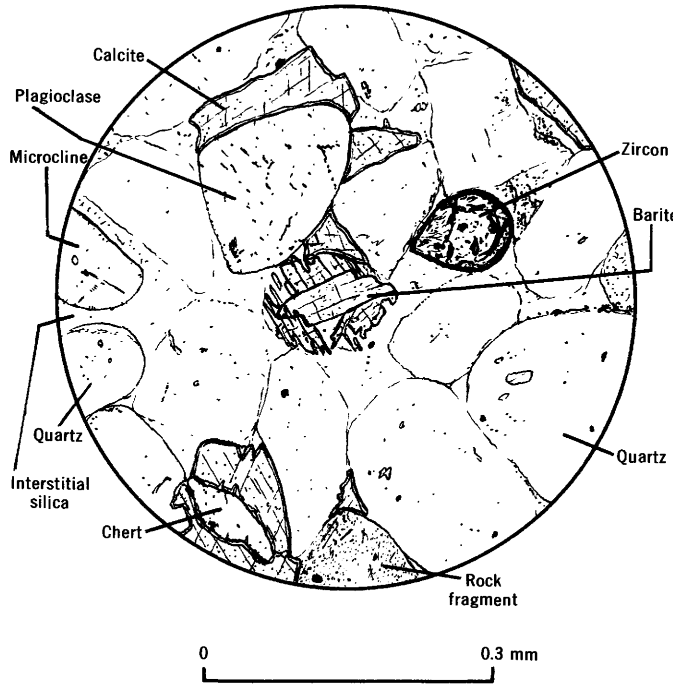

FIGURE 15.—Light-gray very fine grained sandstone from the lower brown unit of the Brushy Basin Member. Pore spaces are almost completely filled with silica and calcite; quartz grain below microcline shows remnant of earlier cycle silica overgrowth; detrital quartz grain at center of field is almost wholly replaced by barite. Sample DVR–2–1299, Disappointment Valley.

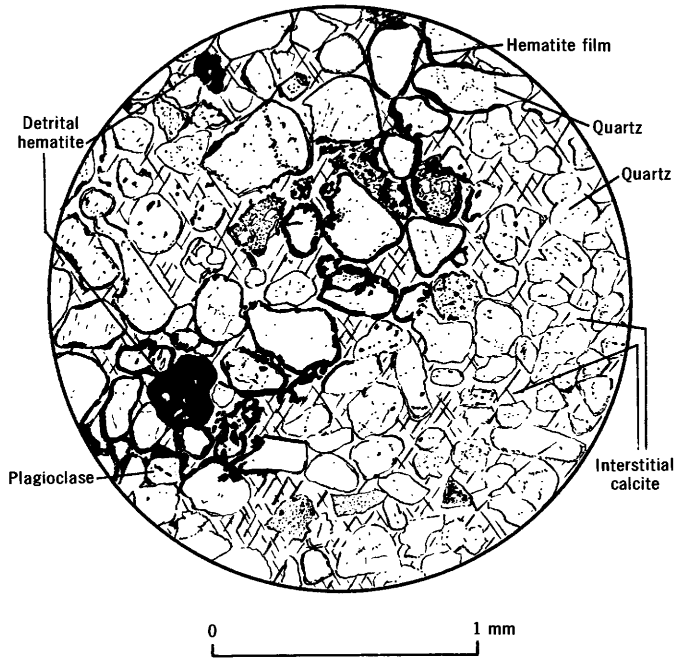

FIGURE 16.—Very fine grained light-brown to very light reddish brown sandstone from the lower brown unit of the Brushy Basin Member. Zone of hematite-coated grains is part of a ring surrounding light-brown sandstone partly shown at upper left; calcite is optically continuous throughout the field of view; section cut almost parallel to sandstone bedding. Sample DV–125–1061.3(C), Disappointment Valley.

grains. A few thin layers and pebbles of clay in the sandstone show faint outlines of shards. Part of the rock is of volcanic origin, but most of it appears to have been derived from clastic sedimentary rocks.

Modal point counts and estimates of the mineral content of three thin sections of samples of sandstone from the lower half of the upper brown unit, taken from drill cores from hole DVR–2 in Disappointment Valley, have an average composition shown in table 9. This average is notably different from the averages of sandstone from the middle green and lower brown units, being appreciably lower in quartz and higher in chert and feldspar (especially plagioclase). A larger proportion of volcanic material is indicated, but likely much of it was waterborne from a volcanic source, rather than being deposited from the air as ash.

Individually, the three sandstones whose mineral contents are averaged in table 9 vary considerably. One sample near the base of the unit is clean and well sorted, and firmly cemented with silica (fig. 19). The silica cement in this light-gray quartzite (sample DVR–2–1139) consists of a very fine grained mosaic, chertlike in places, that makes up about 15 percent of the rock. In one bedding layer where detrital leucoxene is abundant, anatase has formed authigenic clusters around quartz

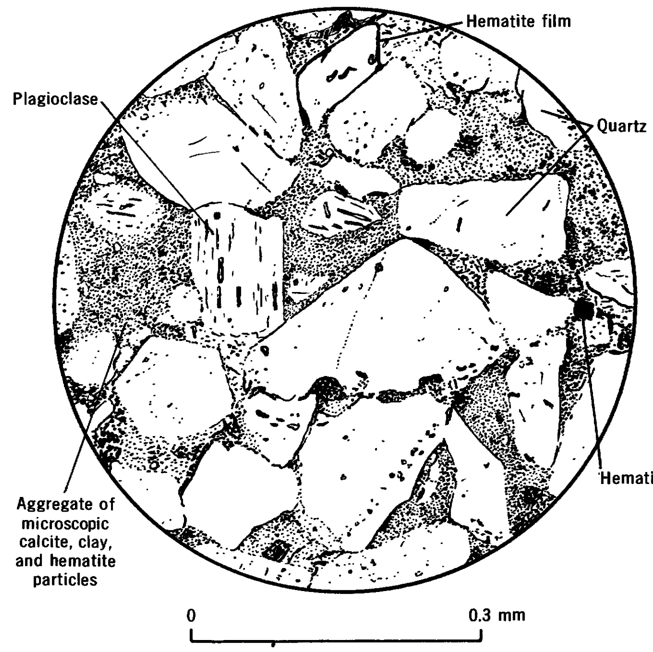

FIGURE 17.—Light-reddish-brown very fine grained sandstone from the lower brown unit of the Brushy Basin Member. Largely quartz grains in calcite-clay-hematite matrix. Sample DV–112A–1043.5, Disappointment Valley.

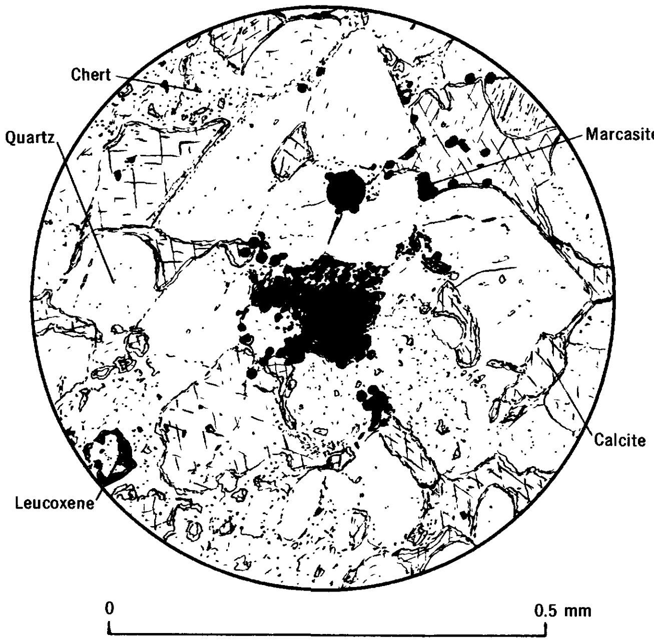

FIGURE 18.—Very fine grained light-brownish-gray sandstone from the middle green unit of the Brushy Basin Member. Marcasite is interstitial aggregates of minute spheres, in part enclosed in calcite. Sample LE–430–461, Legin group area.

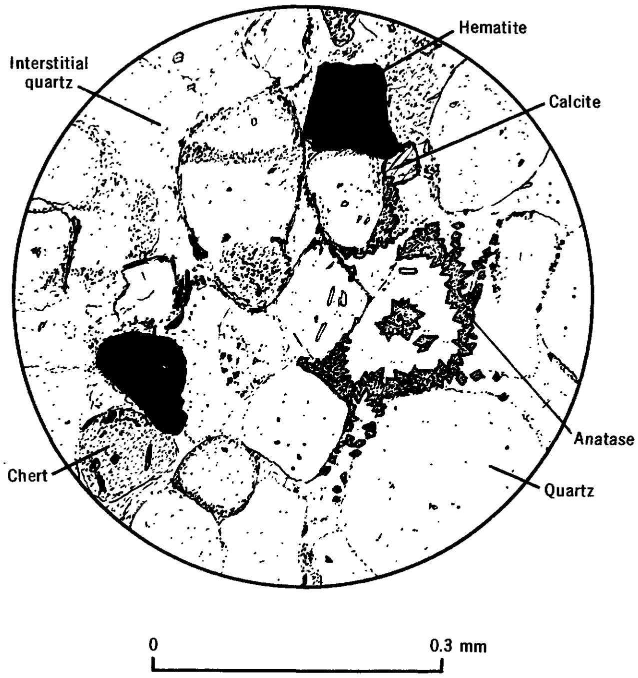

FIGURE 19.—Light-gray fine-grained quartzitic sandstone from the upper brown unit of the Brushy Basin Member. Most of the space between detrital grains is filled with small irregular interlocking patches of silica; anatase almost completely surrounds one quartz grain (anatase that appears to be enclosed in this grain actually lies on the side of the grain toward the observer and is part of the rim of anatase covering the grain); most of the opaque dust is leucoxene (microcrystalline anastase). Sample DVR–2–1139, Disappointment Valley.

grains (fig. 19), possibly at the time the rock became cemented with silica. A second sample (DVR–2–1054) of sandstone from higher in the unit is poorly sorted and dirty with abundant clay and mudstone fragments (20 percent of the rock), volcanic rock fragments (5 percent), and silt-sized detritus (fig. 20). The rock contains a few detrital limestone grains. In hand specimen the rock is seen to consist of interbedded coarse-grained poorly sorted sandstone and siltstone. The third sample, from still higher in the unit, is light red in color, well sorted with well-rounded grains, and almost completely cemented with about 20 percent interstitial silica overgrowths that join along sutured contacts but in places are faceted. Barite is common in the rock, chiefly as euhedral colorless crystals replacing the abundant chert grains; a small amount of barite occurs as anhedral interstitial material; and some detrital black opaque grains are present.

Modal point counts and estimates of the mineral composition of four thin sections of conglomerate and conglomeratic sandstone from the Brushy Basin Member are averaged in table 10. Two thin sections of coarse-grained conglomeratic sandstones from the middle

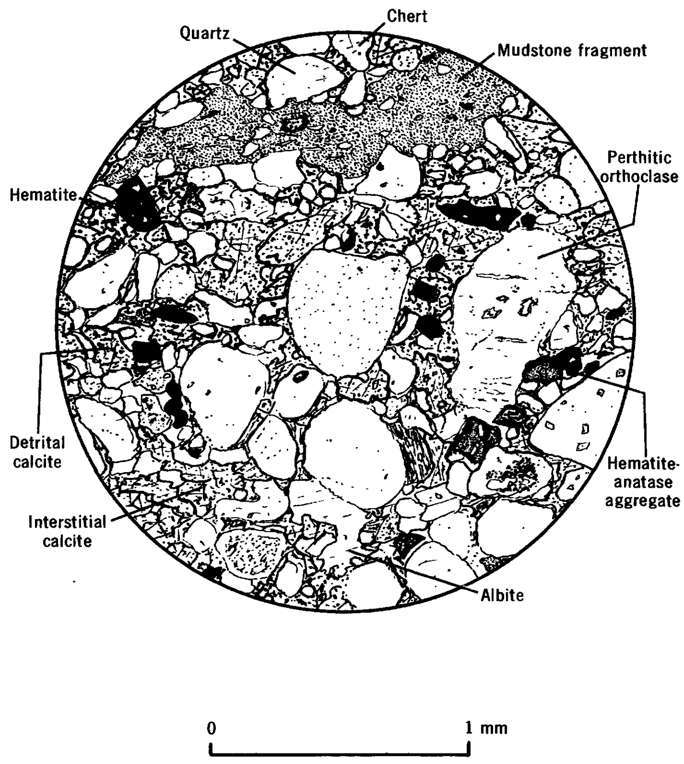

FIGURE 20.—Coarse-grained poorly sorted mottled light-gray and reddish-brown sandstone from the upper brown unit of the Brushy Basin Member. Matrix is largely calcite; mudstone fragment contains dustlike hematite; a few nearby fragments, not shown, are devoid of hematite; area shown is part of layer interbedded with reddish-brown siltstone laminae. Sample DVR–2–1054, Disappointment Valley.

green unit have the average composition given in table 10. Some of the chert in the rocks shows colloform structure. Calcite occurs both as cement and as detrital grains. These rocks are poorly sorted and contain subangular to well-rounded clasts. Rock fragments in one of the rocks are almost all siltstone, and only in small part are volcanic rocks, now thoroughly altered. Silica cement is abundant in the rocks. In the other sandstone, rock particles are dominantly of volcanic origin among which are altered and hematite-charged fragments, some of welded tuff origin; a few particles are clay and silt containing a few grains of coarser clasts. This rock (sample 56–S–6) is shown in figure 21. Plagioclase is abundant in this sample; parts of the sample contain abundant authigenic plagioclase possibly derived locally from solution of detrital plagioclase. The authigenic plagioclase occurs chiefly as overgrowths on detrital albite (fig. 22). The overgrowths are unusual in that they are almost completely albite twinned, whereas the detrital albite is untwinned or shows only a few twins. The overgrowths, probably nearly pure albite, have twinning slightly inclined to that in the detritals. Locally where detrital albite lies against chert grains, minute laths of authigenic albite with two or three albite twins have developed in interstitial spaces. The rock contains virtually no silica cement; some quartz grains are enclosed in authigenic albite that surrounds detrital albite (fig. 22). Even though many of the rock fragments and much of the abundant plagioclase and clay in the rocks must have come from volcanic sources, probably more than half the material in these rocks is derived from sedimentary rocks.

TABLE 10.—*Average mineral composition, in percent, of conglomerate and conglomeratic sandstones from the Brushy Basin Member of the Morrison Formation*

[Based on modal point counts (200 points) and modal estimates of thin sections. "Minor" generally indicates less than 0.25 percent]

Component	Member (Middle green and upper brown units combined)	Middle green unit	Upper brown unit
Quartz and quartz overgrowths	54	50	58.5
Chert	14	13	15
Orthoclase	1	.5	1.5
Plagioclase	4.5	7.5	1
Rock fragments and mineral aggregates	19.5	21.5	17
Clay (mineral clay and clay-sized detritus)	5	5	5
Calcite and dolomite	1	2	Minor
Barite	Minor	--------	Minor
Chlorite	.5	--------	1
Hematite and other black opaque minerals	.25	.5	Minor
Muscovite	Minor	--------	Minor
Leucoxene and anatase	Minor	Minor	Minor
Number of samples	4	2	2

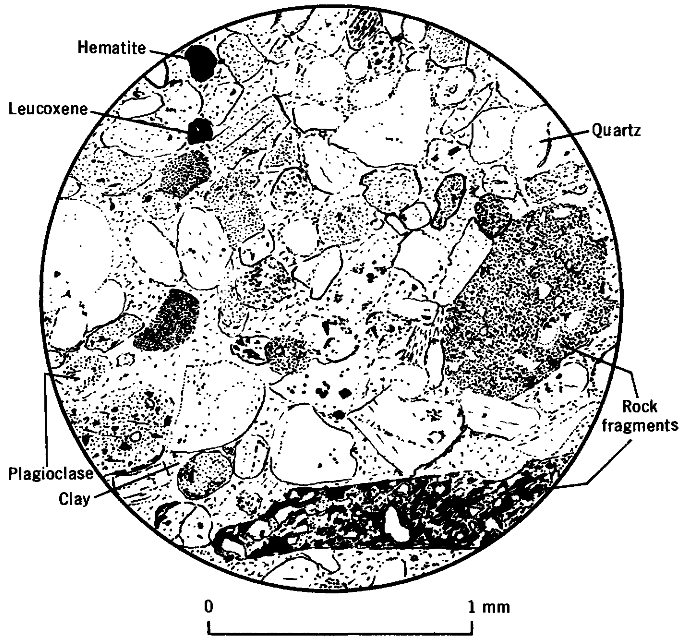

FIGURE 21.—Light-brown coarse-grained conglomeratic sandstone from the middle green unit of the Brushy Basin Member. Numerous grains 1 mm or more long are hematite-impregnated rock fragments. Sample 56–S–6, sec. 15, T. 42 N., R. 17 W.

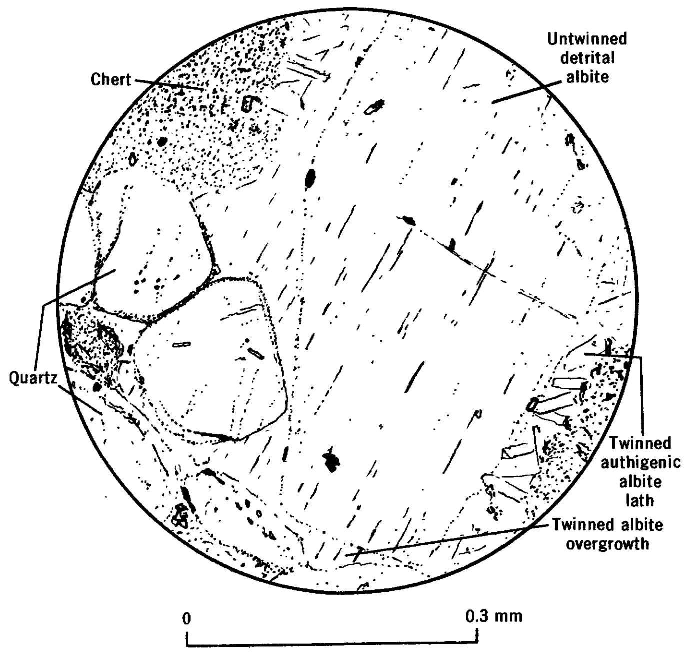

FIGURE 22.—Coarse-grained conglomeratic sandstone from the middle green unit of the Brushy Basin Member. Large untwinned detrital albite grain has twinned albite overgrowth and is partly surrounded by tiny authigenic albite laths. Sample 56–S–6, sec. 15, T. 42 N., R. 17 W.

The average of estimates of the composition of two thin sections of conglomerate and conglomeratic sandstone 70 and 80 feet below the top of the upper brown unit where the rocks are largely greenish gray is given in table 10. The conglomerate contains a higher proportion of chert and rock fragments and fewer quartz grains than the conglomeratic sandstone. Rock fragments in the conglomerate are of a wide variety, chiefly altered fine-grained volcanic rocks (some showing original flow structure), siltstone, mudstone, and sparse oolites. Some orthoclase and plagioclase in the conglomerate (sample DVR–2–765) appears as bunches of bladed laths, as though authigenic (fig. 23). The conglomeratic sandstone is unusually porous, pore space accounting for 15–20 percent of the rock volume; pebbles 1 cm in diameter and larger are scattered among sand grains that are about 0.5 mm in size; silt-sized detritus locally fills the space between sand grains. Both rocks contain detrital grains that were crushed in place, especially those grains in contact with pebbles. The crushing may have taken place during compaction of the rock, but also may have occurred as a result of compression or bending of the strata during regional folding.

The average mineral composition of four thin sections of siltstone from the Brushy Basin Member is given in table 4. A typical siltstone of the middle green unit taken from drill core (sample LE–445–511) from the Legin area is light greenish gray mottled with reddish brown. Composition of a thin section of the rock is given in table 11. Cement of the rock is calcite, occurring as minute interstitial blebs and patches, and clay. Detrital grains are rounded to sharply angular and flakelike, the latter possibly airborne volcanic material. Three samples of siltstone (DVR–2–722.5, DVR–2–726.4, DVR–2–812.5) from different horizons in the upper part of the upper brown unit where most of the rocks are greenish gray were collected from drill core from Disappointment Valley. The average of modal estimates of the mineral content of thin sections of these rocks is given in table 11. Detritus is chiefly silt sized, but some sand-sized grains are present, and in some layers, clay matrix makes up more than 50 percent of the rock. Some irregular patches of calcite show polysynthetic twins. In one reddish-brown siltstone (sample DVR–2–812.5) euhedral barite crystals as much as 1 mm in length have been surrounded and partly replaced by calcite (fig. 24). Silt-sized detritus as well as clay

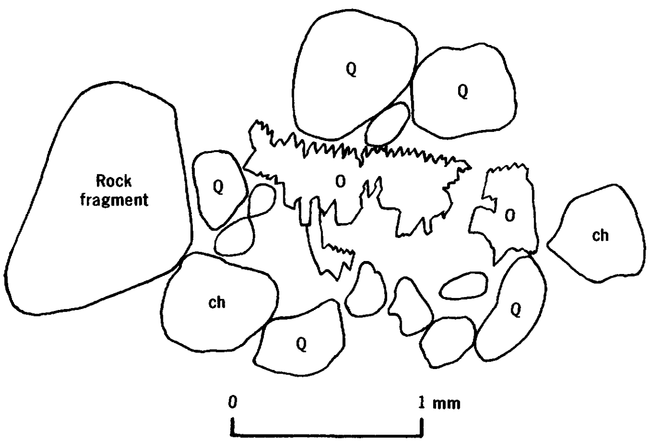

FIGURE 23.—Light-gray conglomerate from the upper part of the upper brown unit of the Brushy Basin Member showing outlines of bunches of bladed laths of authigenic orthoclase. O, orthoclase; Q, quartz; ch, chert. Sample DVR–2–765, Disappointment Valley.

TABLE 11.—*Average mineral composition, in percent, of siltstones from the Brushy Basin Member of the Morrison Formation*

[Based on modal estimates of thin sections. "Minor" generally indicated less than 0.25 percent]

Component	Middle green unit	Upper brown unit
Quartz and quartz overgrowths	50	64
Chert		8.5
Orthoclase	4	3
Microcline	1	1
Plagioclase	4	2
Clay (mineral clay and clay-sized detritus)	15	18.5
Calcite and dolomite	25	1.5
Barite		Minor
Chlorite	Minor	Minor
Hematite and other black opaque minerals	1	.5
Biotite	Minor	Minor
Muscovite	Minor	Minor
Leucoxene and anatase	Minor	Minor
Number of samples	1	3

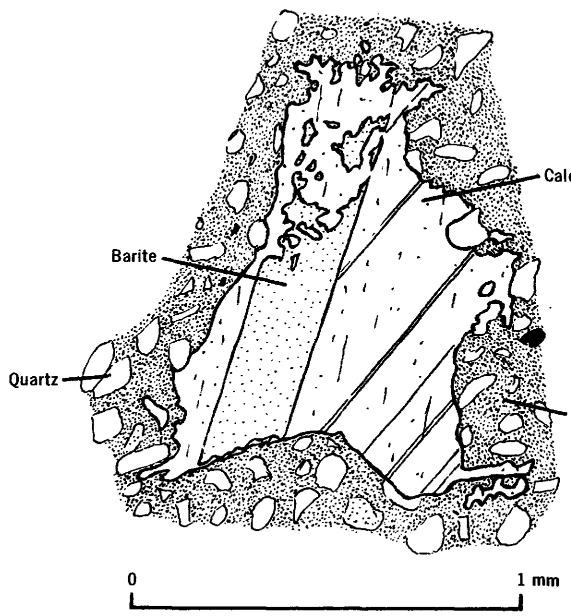

FIGURE 24.—Light-reddish-brown siltstone from the upper brown unit of the Brushy Basin Member. Illustration shows part of a clay-rich layer of the rock; euhedral barite crystal is surrounded and partly replaced by calcite; barite and calcite completely replace clay- and silt-sized detritus that originally occupied the space. Sample DVR–2–812.5, Disappointment Valley.

matrix was replaced by both barite and calcite. Here, it appears that barite formed first in the rock and later served as a locus for precipitation of calcite.

Modal point counts and estimates of the mineral content of 13 thin sections of Brushy Basin mudstone are averaged in table 4. Analyses of three samples of mudstone from the Brushy Basin by Robert F. Gantnier, of the Geological Survey, indicate an average specific gravity (bulk density) of 2.56, an average grain density of 2.61, and an average porosity of 3.3 percent. Modal point counts and estimates of seven thin sections of mudstone from the middle green unit are averaged in table 12. About one-half percent of carbonaceous material was seen in one thin section. Dilute hydrochloric acid tests of hundreds of feet of core from the middle green unit, calibrated by numerous chemical determinations of calcite content by N. L. Archbold, show most of the mudstone to contain less than about 5 percent calcite. Some thin layers contain much more, however, and indeed are argillaceous limestone locally; but these higher concentrations probably do not raise the average calcite content of the unit appreciably.

Barite and calcite are common metacrysts, or authigenic minerals, in greenish-gray mudstone of the middle unit. In places, barite crystals more than 1 cm long have grown in mudstone (sample DV–124–715) that is composed chiefly of devitrified volcanic ash containing some volcanic crystals and detrital sedimentary grains (fig. 25). A detailed part of figure 25 is shown in figure 26. Ghosts of devitrified shards are abundant in clay which contains crystals of volcanic origin as well as a few detrital sedimentary grains. Barite has tended to assume its crystal form, which is partly modified where pre-

TABLE 12.—*Average mineral composition, in percent, of mudstones from the Brushy Basin Member of the Morrison Formation*

[Based on modal point counts (200 points) and modal estimates of thin sections. "Minor" generally indicates less than 0.25 percent]

Component	Middle green unit	Upper brown unit
Quartz	28	28.5
Chert	--------	.5
Orthoclase	2	3
Microcline	Minor	--------
Plagioclase	2	5
Rock fragments and mineral agregates	--------	Minor
Clay (mineral clay and clay-sized detritus)	60	52
Calcite	4	2.5
Barite	2	Minot
Chlorite	--------	5
Hematite and other black opaque minerals	Minor	.5
Biotite	Minor	.5
Muscovite (green mica in upper brown unit)	Minor	1
Leucoxene and anatase	Minor	Minor
Limonite	Minor	--------
Pyrite	Minor	Minor
Analcite	1.5	--------
Carbonaceous material	Minor	1
Number of samples	7	6

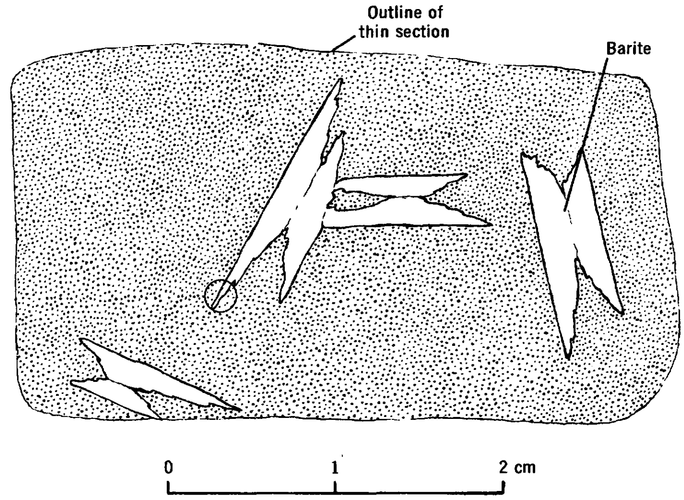

FIGURE 25.—Light-greenish-gray mudstone (devitrified volcanic tuff) from the middle green unit of the Brushy Basin Member. Where barite metacrysts have formed, all the minerals of the mudstone have been replaced. Sample DV–124–715, Disappointment Valley. Circle indicates area shown in figure 26.

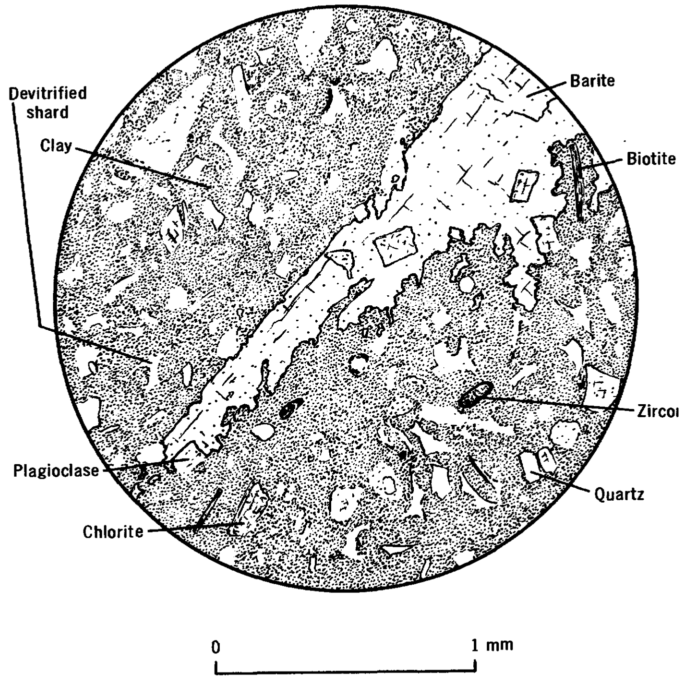

FIGURE 26.—Light-greenish-gray mudstone (devitrified volcanic tuff) from the middle green unit of the Brushy Basin Member; detail of figure 25. Devitrified shards are largely fine grained silica; barite metacryst has grown by replacing clay, devitrified shards, quartz, and feldspar, in that order. Sample DV–124–715, Disappointment Valley.

existing minerals were not replaced. Judged from the abundance of the various types of fragments still enclosed in barite, the order of susceptibility to replacement by barite was first clay, followed by devitrified shards, quartz, and finally plagioclase. Plagioclase thus appears to have been a relatively stable phase in the environment in which barite was precipitated. Calcite segregations are more numerous than barite in the mudstone of the middle green unit, but they generally show irregular boundaries rather than the euhedralism displayed commonly by barite. Figure 27 shows irregularly shaped calcite and barite together (sample DV–124–880). The relationships in this thin section suggest that as barite replaced calcareous clay and the enclosed detrital grains, calcite was segregated out of the clay to the periphery of growing barite patches. Chlorite is also locally concentrated at barite and calcite boundaries, and it too may be a segregation from the clay as a result of barite and calcite replacement. Analcite is another mineral commonly segregated in patches in mudstone of the unit. Figure 28 shows a clay-rich divitrified tuffaceous mudstone (sample DV–124–695) that contains about 10 percent detrital fragments. In places it contains visible shards, now altered to chlorite and radiating fibrous silica. Angular plagioclase fragments are abundant among the detrital fragments and probably are of volcanic origin. Analcite, nearly isotropic with refractive index of about 1.48, forms irregular patches which under crossed nicols are seen to consist of faint bladed forms as though crystals were lining the walls of vugs. Some of these crystals show faint polysynthetic

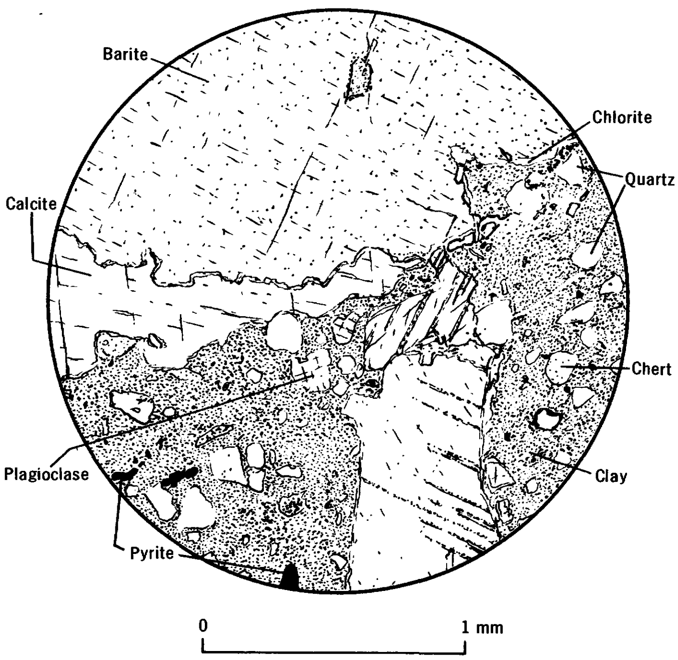

FIGURE 27.—Light-greenish-gray mudstone from the middle green unit of the Brushy Basin Member. Partly replaced by barite and calcite; barite is part of a crystal 3 mm in diameter that is rimmed with calcite and chlorite; lower calcite crystal is in a veinlet extending to another barite crystal. Sample DV–124–880, Disappointment Valley.

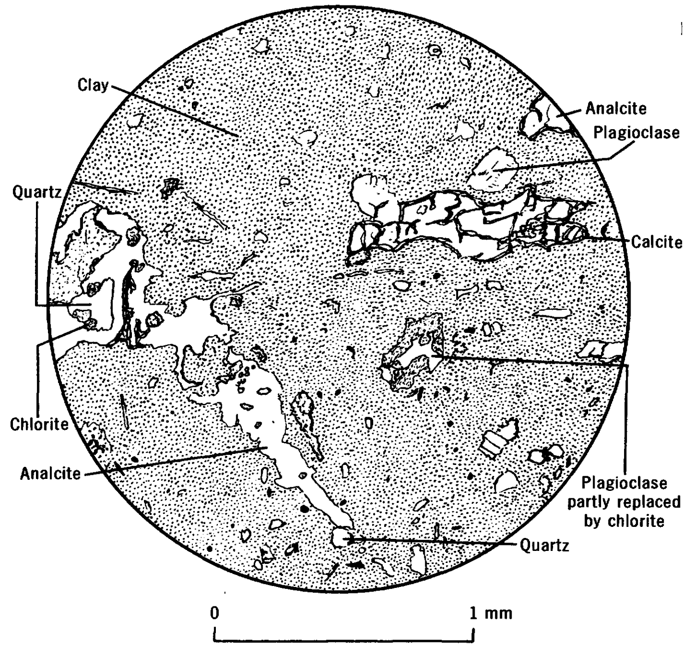

FIGURE 28.—Mottled light-reddish-gray and light-greenish-gray devitrified tuffaceous mudstone from the middle green unit of the Brushy Basin Member. Analcite, in places veined and rimmed with calcite, forms irregular elongate patches; one analcite patch contains secondary quartz; chlorite crystals lie in analcite or replace plagioclase; much of the fine-grained angular detritus in clay is plagioclase. Sample DV–124–695, Disppointment Valley.

twinning. Calcite rims and veins the analcite segregation and also occurs as patches away from the analcite. In a few places in the rock, chlorite has partly replaced plagioclase. The chlorite is optically (−), nearly uniaxial, has refractive index close to 1.60 and has very low birefringence; it is probably compositionally similar to either penninite or delessite.

Mineral-filled vugs are conspicuous locally in the mudstone. These vugs are small, generally not more than a few millimeters long, and are commonly lined with colloform calcite and barite and filled with chalcedonic silica. Possibly the vugs themselves formed as the result of solution movement through the middle green unit at the beginning of the stage of alteration that resulted in the mineral segregations. The colloform linings of calcite and barite are now optically continuous mineral, and no evidence of possible earlier growth layers survives. Probably the calcite and barite have recrystallized since initial deposition, although possibly they are merely replacements of an earlier colloform mineral, like chalcedony. Figure 29 shows a small vug partly lined with calcite and filled with chalcedonic quartz (sample DV–2–BB).

Modal estimates of the mineral content of thin sections of six mudstones from the upper brown unit have an

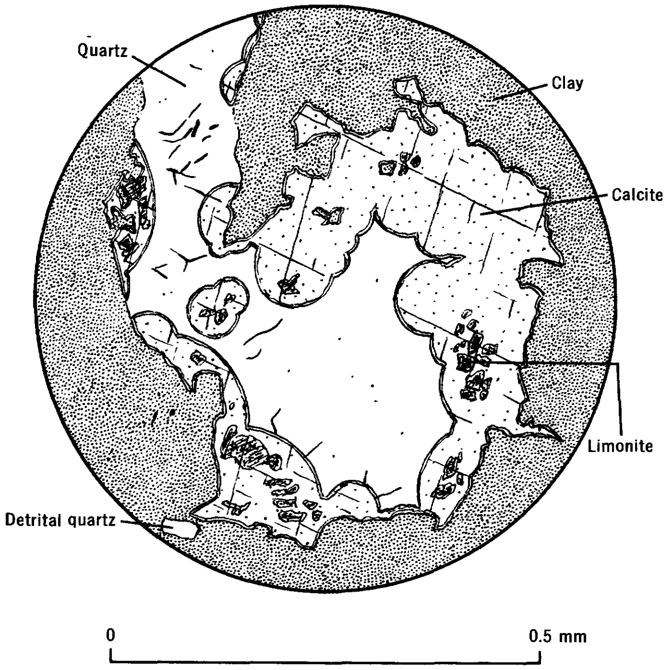

FIGURE 29.—Vug in light-greenish-gray mudstone from the middle green unit of the Brushy Basin Member, filled with calcite and chalcedonic quartz. Limonite forms bright-orange patches in calcite which appears recrystallized from colloform carbonate lining an irregular void; the center of the void is now filled with quartz. Sample DV–2–BB, Disappointment Valley.

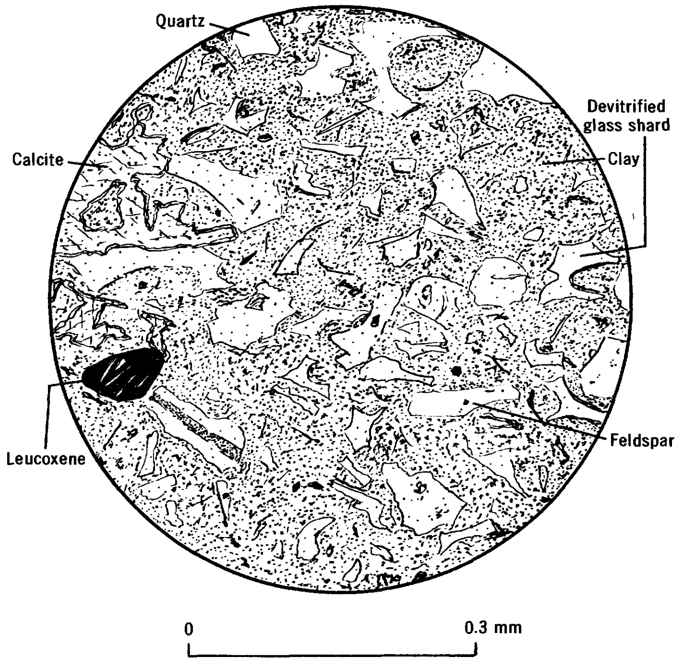

FIGURE 30.—Light-brownish-green mudstone from the upper brown unit of the Brushy Basin Member, a devitrified volcanic tuff. Glass shards have completely altered to clay minerals. Sample DV–114–765, Disappointment Valley.

average shown in table 12. One of the samples, greenish-gray mudstone from the upper part of the unit collected from drill hole DVR–2 in Disappointment Valley, contains about 5 percent carbonaceous material as minute specks and flakes flattened on prominent bedding planes. Detritus in the mudstone of the upper brown unit is chiefly silt sized and smaller and is commonly sharply angular, but an appreciable amount is rounded as though waterworn. Much of the clay is probably clay-sized detritus, including mostly comminuted quartz and feldspar. Clay that forms a uniform dense matrix is commonly partly recrystallized so that individual clay crystals are discernible.

Much of the clay in the mudstone shows shard structures, in some places quite faint but in many beds notably plain (fig. 30). Such a rock (sample DV–114–765) as illustrated in figure 30 may be almost wholly of volcanic origin and deposited from air, although sparse rounded particles such as leucoxene may have been water transported to the site of deposition, and there intermixed with volcanic material. Other mudstones contain devitrified shards and angular crystal fragments scattered in roughly equal amounts in clay matrix. Probably much of this clay is devitrified finely comminuted volcanic glass and is montmorillonitic.

A mudstone (sample DV–32–1) with probably less volcanic material is shown in figure 31. This rock contains only a very small amount of material that may represent devitrified volcanic glass particles. Most of the detritus is angular to well-rounded quartz and feldspar, probably in part of volcanic origin, but part at least shows considerable rounding from water transport. Hematite is abundant in this rock, and although it may be suggestive of oxidation accompanying volcanic extrusion, it is more likely similar in occurrence to hematite that coats grains, and forms extremely fine-grained dispersions in clay, in many of the other sedimentary rocks in the district. Probably most of the reddish-brown mudstone in the upper brown unit has considerably less volcanic material in it than the less abundant interlayered greenish-gray to brownish-gray varieties.

Metacrysts of barite and carbonate occur in mudstone of the upper brown unit. For example, bladelike crystals of siderite(?) as much as a centimeter in length have grown in light-brownish-green devitrified volcanic tuff (sample DV–114–765) as shown in figure 32. In this rock, part of which is shown in detail in figure 30, authigenic siderite(?) has developed locally where the rock contains patchy calcite.

A thin section from a sample (DV–32–2) of a reddish-brown argillaceous silty limestone layer in the lower brown unit collected from drill core from a

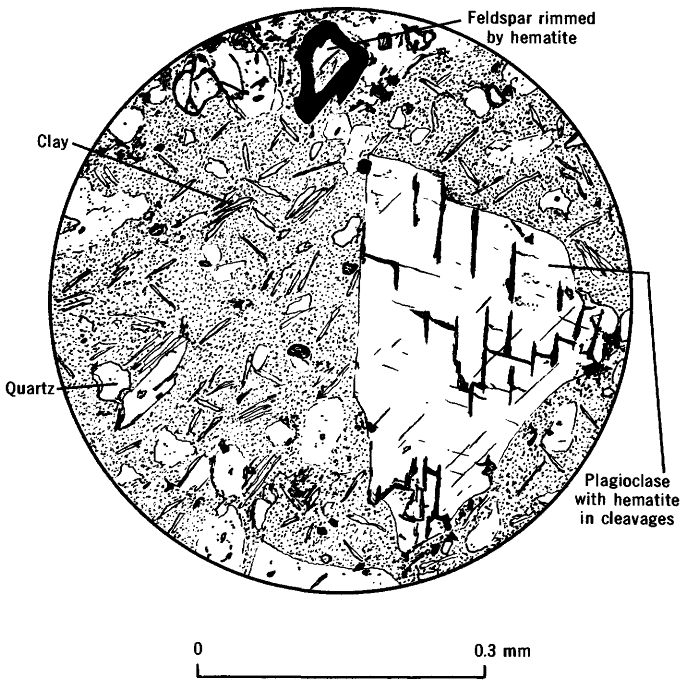

FIGURE 31.—Reddish-brown mudstone from the upper brown unit of the Brushy Basin Member. Poorly sorted detrital feldspar, quartz, hematite, and other minerals lie in a clay matrix; the matrix has partly recrystallized into individually visible clay crystals. Sample DV-32-1, Disappointment Valley.

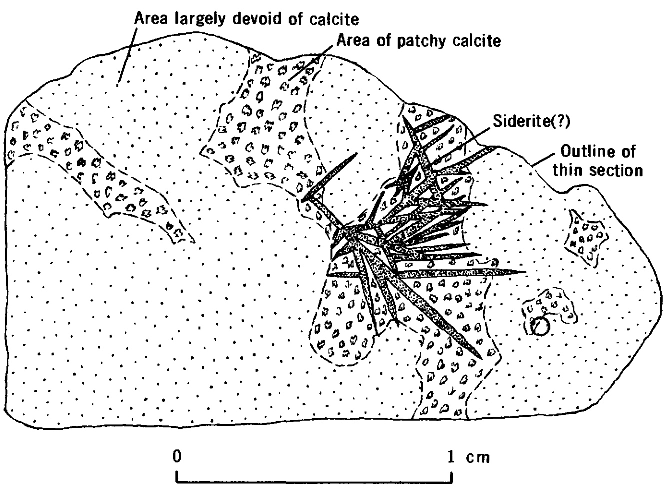

FIGURE 32.—Light-brownish-green mudstone from the upper brown unit of the Brushy Basin Member, a devitrified volcanic tuff. Authigenic siderate(?) has formed locally where the rock contains patchy calcite. Sample DV-114-765, Disappointment Valley. Circle indicates area of figure 30.

diamond-drill hole in Disappointment Valley contains about 70 percent calcite, 14 percent clay, 1 percent analcite, and 15 percent detrital grains. Calcite occurs in optically continuous patches, as much as 1 cm across, which join along cuspate boundaries. Some patches have a few polysynthetic twins. The calcite is filled with irregular small patches and wormlike blebs of clay. Detrital minerals, scattered through calcite, are about half quartz, with lesser, subequal amounts of K-feldspar, plagioclase, and chert, and minor amounts of hematite, leucoxene, green hornblende, and zircon.

One sample (DV-125-850) of reddish-brown limestone from the middle green unit of the Brushy Basin Member in the Disappointment Valley area, drill hole DV-125, contains thin interconnecting septa of clear white calcite as much as 3 cm long, mostly oriented nearly parallel and nearly normal to bedding, in a sort of boxwork. These septa are probably shrinkage cracks in impure limestone consisting of about 80 percent very fine grained calcite, 19 percent clay, 1 percent hematite as minute detritals and dustlike material in clay and calcite, and a trace of quartz as very small well-rounded detrital grains. A sample (BB-1) of greenish-gray limestone collected from the middle green unit near the mouth of Joe Davis Canyon comes from a layer of nodules that are as much as 6 inches in diameter. A thin section of this limestone consists of about 86 percent calcite, 10 percent detrital quartz and feldspar of silt size, 3 percent authigenic albite, and minor amounts of zircon, leucoxene, and limonite. Calcite is chiefly very fine grained, but in places it is coarsely crystallized in patches surrounded by dark medium-grained calcite containing limonite that probably has been altered from pyrite. The medium-grained calcite also contains abundant tiny laths of authigenic albite (fig. 33). Such laths

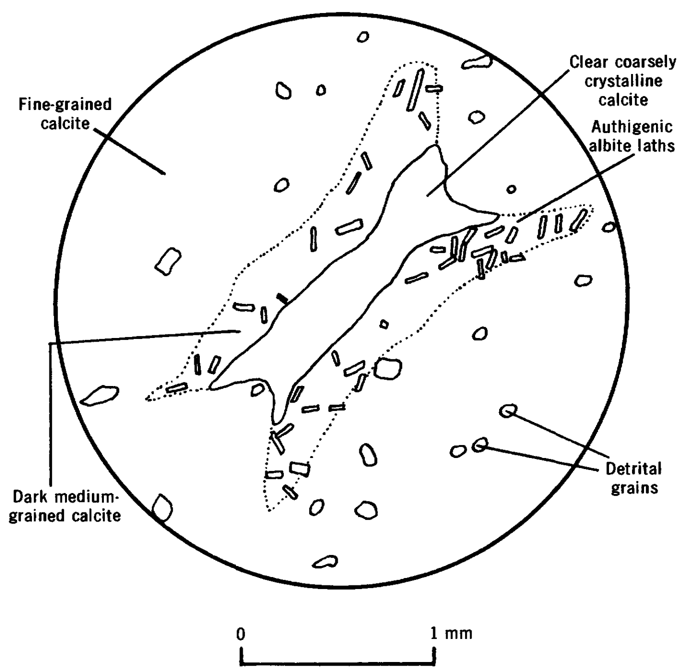

FIGURE 33.—Part of limestone nodule from the middle green unit of the Brushy Basin Member; authigenic albite is concentrated around patch of coarsely crystalline calcite. Sample BB-1, Joe Davis Canyon.

are scattered much more sparsely throughout the rest of the limestone; in places authigenic albite has overgrown detrital orthoclase. Apparently, constituents of the albite were introduced into the limestone at the time it was partly recrystallized, possibly during the stage of widescale alteration that affected the rest of the middle green unit. This possibility will be discussed again in a later chapter in this professional paper series on alteration of the sedimentary rocks.

One sample (DVR-1-1471) of reddish-brown clayey limestone from the upper brown unit collected from drill core from Disappointment Valley contains about 25 percent clay and about 5 percent of dustlike hematite and minute detrital grains. The rock has several anastomosing partly concentric calcite-filled veinlets, about 1 cm long, that are probably merely the original matrix calcite segregated into shrinkage cracks.

POST-MORRISON ROCKS

BURRO CANYON FORMATION

The Burro Canyon Formation is dominantly sandstone and conglomerate, interbedded with thin layers of mudstone. Locally, the formation has thin interbedded layers of mudstone, limestone, and chert in its upper part. Average mineral composition of sandstone from the Burro Canyon Formation, based on modal estimates and point counts of six thin sections, is shown in table 2. The sandstone has notably more quartz and less chert and feldspar than does that in the underlying Morrison Formation.

Quartz grains in the sandstone are poorly to well sorted and subangular to well rounded; most are clear but some show strain shadows or possess internal sutures. Some are embayed and interpenetrate where they are in contact. Many show silica overgrowths. Some overgrowths join along sutured boundaries; others project into pore spaces and are faceted. A few rounded grains show vestiges of earlier overgrowths on rounded grains formed during an earlier sedimentation cycle. In places, silica overgrowths are so extensive that the rock is a quartzite; generally the overgrowths make up from 0 to about 10 percent of the rock and probably average about 5 percent. Calcite is a widely distributed cement, filling pore spaces in irregular optically continuous patches which enclose a few to a score or more detrital grains. Calcite is commonly concentrated along bedding planes. Much of it is polysynthetically twinned. Locally where large patches of matrix calcite occur, detrital grains are poorly packed. Surrounding such areas, silica overgrowths may be abundant, and numerous quartz grains show solution embayment and interpenetration of adjacent grains, so that the detrital grains are better packed. These relationships suggest that calcite cement formed earlier than the silica cement and preserved the original packing of the sedimentary grains. Moreover, the common twinning of the calcite suggests that the calcite was desposited as a cement before any appreciable tectonic flexing of the strata—if the polysynthetic twinning can be attributed to such deformation. Minor amounts of clay form irregular small patches of matrix.

A typical well-cemented sandstone (sample SH-60-55) from the Burro Canyon in Disappointment Valley is shown in figure 34.

In places, layers of sandstone in the Burro Canyon Formation are compositionally like sandstone in the Brushy Basin Member of the Morrison Formation, especially where conglomeratic. One light-gray conglomerate layer containing red chert and greenish-gray mudstone pebbles was examined in thin section. The rock consists of only about 25 percent quartz; relatively large amounts of chert and rock fragments are present, about 25 percent each, which range from sand to pebble size. Rock fragments include mudstone, siltstone, and volcanic rock particles. About 5 percent K-feldspar is present. Interstitial material consists of about 15 percent calcite and 5 percent clay. Quartz overgrowths are sparse; in one place, small euhedral quartz prisms were

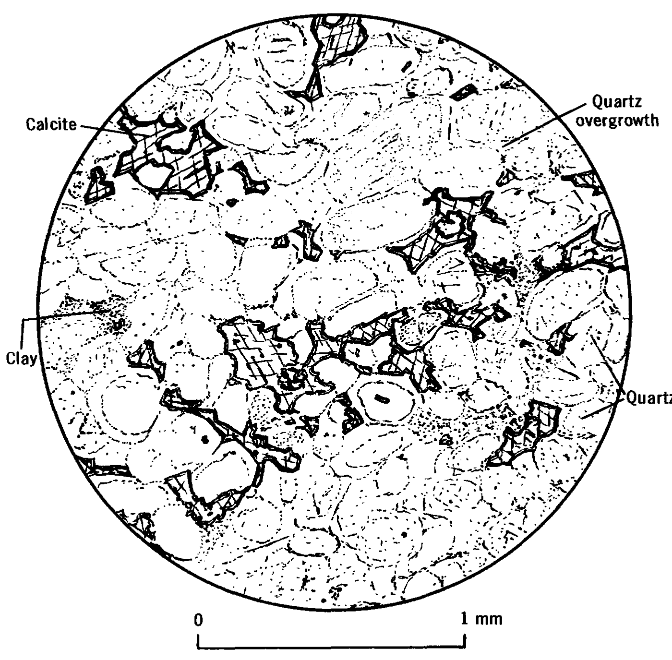

FIGURE 34.—Light-brownish-gray fine-grained quartzose sandstone from the Burro Canyon Formation. Almost all detrital grains are quartz and most have quartz overgrowths; characteristically, a thin clay film lies between grain and overgrowth; calcite fills most of the interstitial space not occupied by quartz; matrix clay is sparse. Sample SH-60-55, Disappointment Valley.

seen grown in crystallographic continuity on a rounded detrital quartz grain.

One unusual grayish-green siltstone (sample DVR-2-397) collected 17 feet below the top of the Burro Canyon, from drill core from hole DVR-2 in Disappointment Valley, may be of marine origin. It contains about 50 percent quartz, 35 percent chlorite, 10 percent calcite, 1 percent orthoclase, 0.5 percent each of microcline, plagioclase, and chert, and minor amounts of pyrite, zircon, tourmaline, and leucoxene. The chlorite is very pale greenish brown to light bright green, and occurs as rounded microcrystalline aggregates that may be glauconite or altered ferromagnesian minerals. Some well-rounded grains contain finely divided material that may be magnetite; some grains have concentric zones like oolites. Chlorite occurs also in the matrix of the rock. Most of the calcite occurs as isolated clear interstitial blebs; some is fine grained and speckled with impurities and may be recrystallized from detrital limestone grains. Part of a thin section of the rock is illustrated in figure 35. The siltstone is part of a sequence of interbedded greenish-gray mudstone and siltstone and minor silty limestone, evenly bedded, at the top of the Burro Canyon, that may have been deposited in a relatively shallow near-shore marine environment similar to that in the Baltic sea where reduced "gyttja" sediments are formed (see, for example, Manheim, 1961, p. 55-56).

The average mineral composition of four thin sections of samples of claystone from the Burro Canyon is shown in table 4. These rocks are notably more clay rich than mudstones in the Morrison and Summerville Formations. Clay averages about 80 percent of the rocks and commonly contains barely visible particles of reworked clay, shale, or mudstone. Some clay may have been authigenically recrystallized, for microscopically discernible crystals are seen lying parallel to bedding in some thin sections. Calcite, which averages about 5 percent, occurs commonly as irregular blebs, or dispersed in weblike forms in clay.

One unusual thin dark-gray carbonaceous claystone layer (sample DVR-2-503) near the middle of the Burro Canyon Formation in Disappointment Valley contains abundant authigenic crystals of calcite. A thin section of the rock shows very thin layers about a millimeter thick, with graded bedding; the bottom coarser part of each layer contains visible fine silt-sized detritus and particles of carbonaceous material that grade upward into homogeneous clay. Beadlike strings of calcite crystals have grown in almost vertical lines throughout the carbonaceous claystone. Locally along the vertical

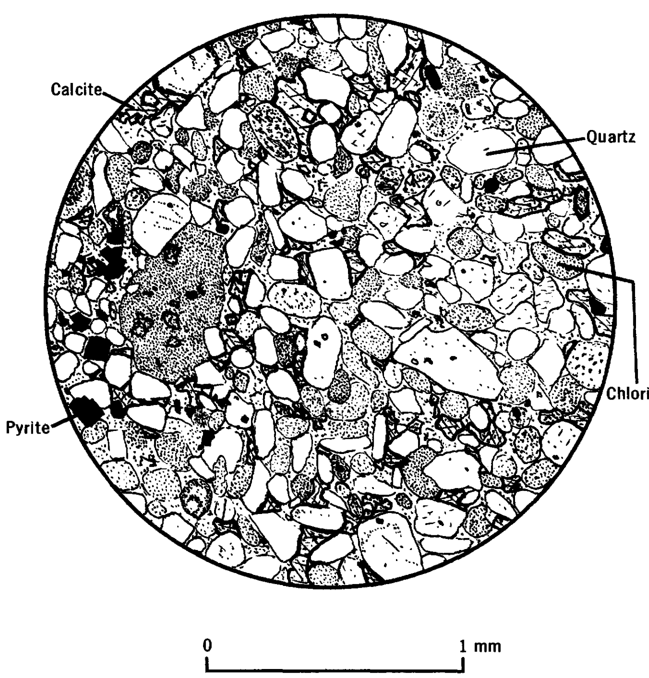

Figure 35.—Grayish-green sandy siltstone from a bed near the top of the Burro Canyon Formation. Rounded detrital grains that are almost wholly chlorite may be glauconite or altered ferromagnesian minerals; matrix is chlorite, calcite, pyrite, and leucoxene. Sample DVR-2-397, Disappointment Valley.

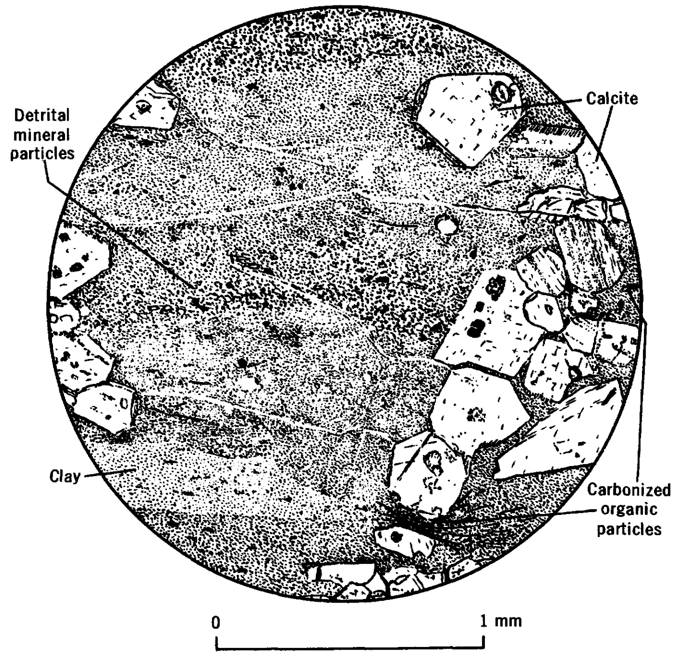

Figure 36.—Dark-gray carbonaceous claystone from the Burro Canyon Formation containing strings of calcite metacrysts. Crystals show a tendency to form beadlike strings approximately normal to bedding, and carbonaceous particles have accumulated near the extremities of strings possibly by mechanical pressure as the calcite crystals grew; nearly horizontal incipient fractures have controlled bleaching in thin zones. Sample DVR-2-503, Disappointment Valley.

strings of calcite crystals, carbonaceous material has been segregated by the pressure of crystal growth, much as micas or graphite are segregated at the extremities of chloritoid, ottrelite, or andalusite crystals in some metamorphic rocks (see, for example, Harker, 1932, fig. 175B). A drawing of part of a thin section of the rock is shown in figure 36. The calcite metacrysts seem to have grown under vertically directed pressure, because the carbonaceous material accumulations formed only at the upper and lower ends of segments of the nearly vertical strings of calcite crystals, and because the crystals may have grown in zones of tension nearly parallel to the direction of stress. It, therefore, seems probable that the sediments were deeply buried at the time the calcite metacrysts formed, for load pressure seems the only likely vertical force that could have been effective in the geologic environment of the Colorado Plateau sedimentary rocks.

In places, evenly bedded dark-greenish-gray claystone contains several thin layers of white to pale-gray calcite about half an inch thick. Locally, the layers consist of fibrous calcite oriented normal to the bedding; thin flakes of clay, parallel to and possibly remnants of bedding layers, occur imbedded in the fibrous calcite. In other nearby thin calcite layers (sample DVR-2-439.5), shears have developed at an oblique angle to the bedding, partly modifying the thin clay flakes that are parallel to bedding (fig. 37). Possibly the shearing resulted from differential stresses accompanying compaction of the beds. More likely it occurred after consolidation of the beds, for polysynthetic twins are concentrated where calcite is most intensely sheared; it could have occurred during folding of these beds, and as a result of the slipping of one bed over another as folding progressed.

In a few layers in the top part of the Burro Canyon in the Disappointment Valley area, mudstone or claystone and limestone are intimately mixed in a sort of microbreccia. Such layers are irregular and tend to be nodular in places. Nodules consisting of microbreccia are about an inch or more in diameter. As seen in thin section (sample SH-74-55), partly rounded fragments of mudstone and claystone as much as 2 mm across are imbedded in fine-grained calcite clouded by dustlike inclusions. Some of the argillaceous particles contain silt-sized detrital grains of quartz and other minerals. The mudstone and claystone particles are irregularly fractured and veined with clear calcite, and some of the larger calcite veins are continuous through matrix calcite, extending several millimeters through the rock. Locally, clay and calcite are intimately mixed in a fine-grained "mush." Minute specks of limonite, probably representing altered pyrite, are scattered throughout the rock; they are most abundant in mudstone. Part of a thin section of the rock is illustrated in figure 38. The

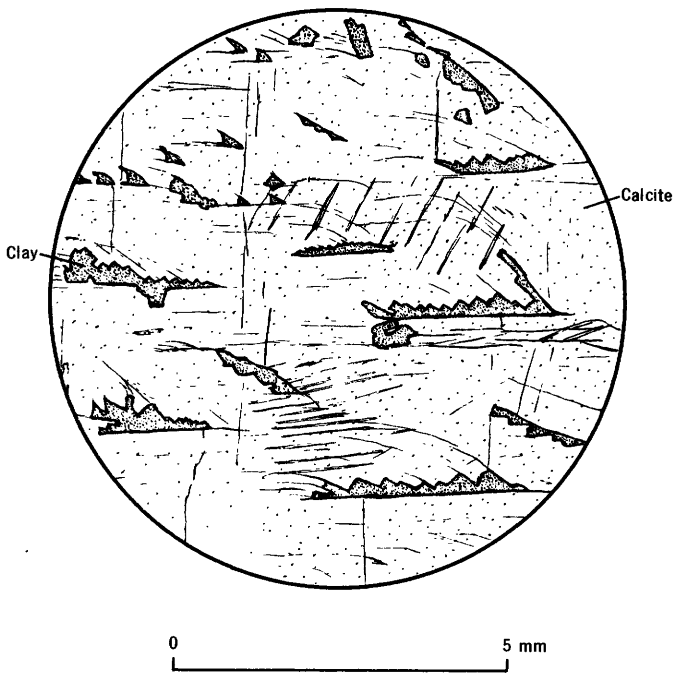

FIGURE 37.—Shear structures in calcite in a limy bed in greenish-gray claystone 60 feet below the top of the Burro Canyon Formation. Polysynthetic twinning crosses shears in places. Sample DVR-2-439.5, Disappointment Valley.

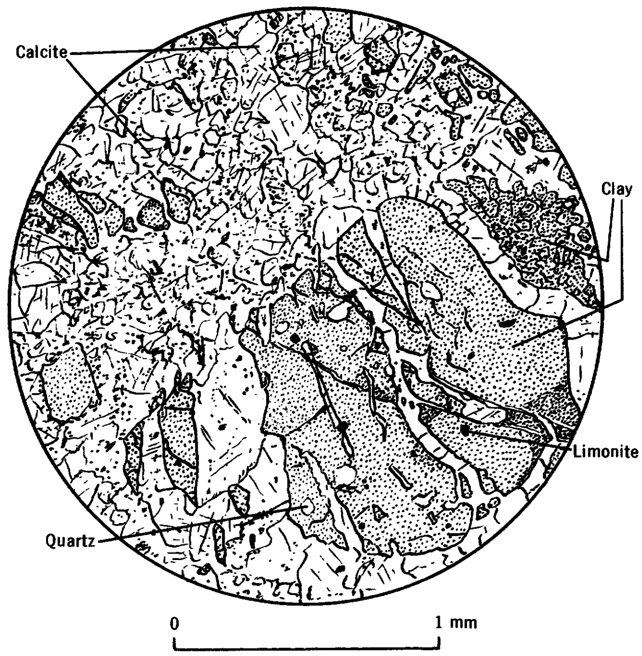

FIGURE 38.—Light-greenish-gray microbrecciated limy mudstone from the Burro Canyon Formation. Partly rounded mudstone fragment is fractured and veined with calcite; clearer calcite areas extend as veinlets several millimeters through the rock. Sample SH-74-55, Disappointment Valley.

character of the rock suggests that the rock was only partly consolidated when it became deformed and its clay and calcite became intermixed so thoroughly. Possibly, subaqueous slumping of beds took place before burial.

Limestone in the upper part of the Burro Canyon Formation appears to be nearly pure. Under the microscope the limestone is seen to consist of a high proportion of calcite, generally about 90 percent, and a small percentage of mineral clay and silt-sized detrital grains, chiefly quartz. Other detrital grains include traces of microcline, leucoxene, zircon, and tourmaline.

DAKOTA SANDSTONE

The Dakota Sandstone consists of fine- to medium-grained carbonaceous sandstone and minor amounts of conglomerate, carbonaceous shale and mudstone, and impure coal. The mineral composition of sandstone in the Dakota, based on modal estimates and point counts of four thin sections, is shown in table 2. Grains range from sharply angular to well rounded and are probably dominantly subrounded to rounded. Most of the sandstone is moderately sorted. On the basis of its mineral composition compared to that of older formations in the district, it is most like sandstone in the Brushy Basin Member of the Morrison Formation, except that it contains much more carbonaceous material. In addition, it probably contains more clay and less calcite than average sandstone in the Brushy Basin. The sandstone in the Dakota varies from slightly friable to firmly cemented with calcite, clay, and silica. Quartz grains, about 60 percent of the rock, commonly show thin silica overgrowths, and some well-rounded grains contain vestiges of overgrowths, indicating that these grains have gone through an earlier cycle of sedimentation. Some quartz grains contain internal sutures suggestive of quartzite.

A typical sandstone from the Dakota is shown in figure 39, which illustrates part of a thin section of a sample (56–S–2) collected near the top of the formation on the northeast side of Disappointment Valley. This moderately sorted sandstone with mostly rounded grains contains considerable clay, in both matrix and altered detrital mineral grains. Calcite occurs as isolated irregular interstitial patches, each showing uniform optical orientation; a few display fine polysynthetic twins. Biotite books, some completely altered to chlorite, have been mashed irregularly by other detrital grains probably during compaction of the rock accompanying burial. The fact that optically continuous patches of calcite locally are molded against the distorted biotite books suggests that calcite here was crystallized after

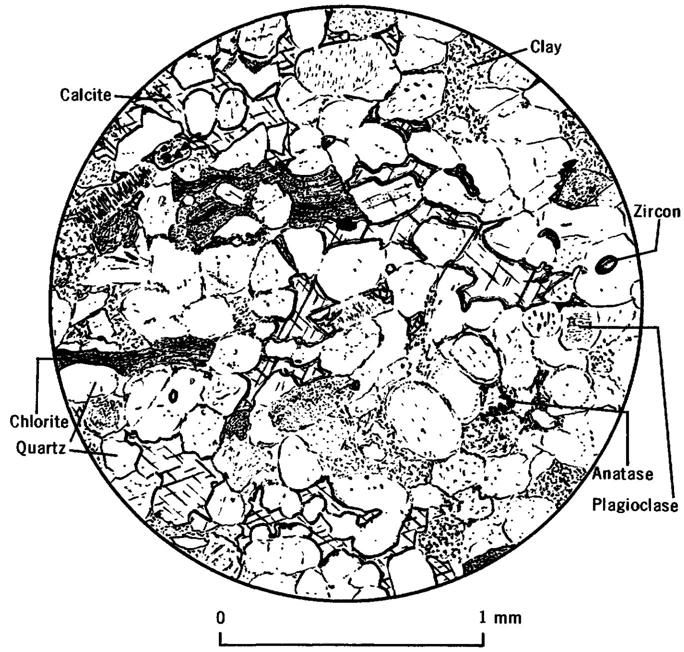

FIGURE 39.—Light-buff fine-grained quartzose sandstone from the Dakota Sandstone. Individual discontinuous calcite matrix patches, about 1 mm in diameter, have different optical orientations; a few quartz grains have thin quartz overgrowths; much of the opaque finely divided material is leucoxene and some is limonite altered from pyrite. Sample 56–S–2, near the top of the formation, Disappointment Valley.

compaction of the rock. Tiny pyrite crystals, some cubic, are mostly altered to limonite in this weathered sample. Considerable white opaque microlites throughout the matrix are probably leucoxene. Locally the microlites are coarse enough to be identified as anatase; occurrence of anatase in calcite cement is shown in figure 40. This relationship suggests that the components of the calcite and anatase may have been concurrently mobile in the sandstone. Further, the presence of polysynthetic twins in some calcite in the rock may indicate that deformation associated with the folding of the strata occurred mostly after calcite cement had become fixed in the sandstone.

In places, particularly in the middle part of the Dakota, sandstone is poorly sorted and contains abundant clay matrix and carbonized plant material. One such sample (DVR–2–306.5) is shown in figure 41, part of a thin section from drill core from Disappointment Valley. About 70 percent of detrital minerals comprise about 52 percent quartz and 6.5 percent chert; the remainder consists of minor amounts of other minerals and about 5 percent detrital minerals altered to clay. About 15 percent clay makes up the matrix, and the rock contains almost 15 percent carbonaceous plant debris.

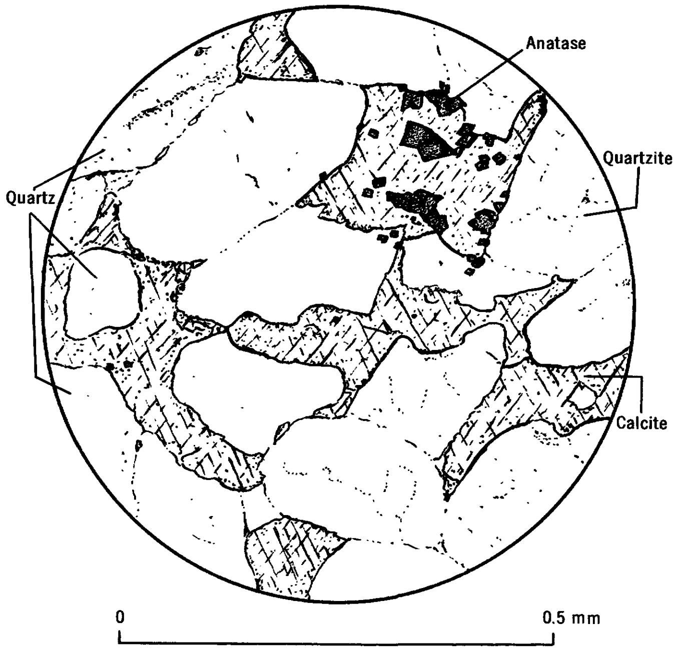

FIGURE 40.—Light-buff fine-grained quartzose sandstone from the Dakota Sandstone; a detail. Optically continuous patch of calcite with cluster of anatase crystals is typical; matrix in some parts of the rock is clay (not shown). Sample 56–S–2, near the top of the formation, Disappointment Valley.

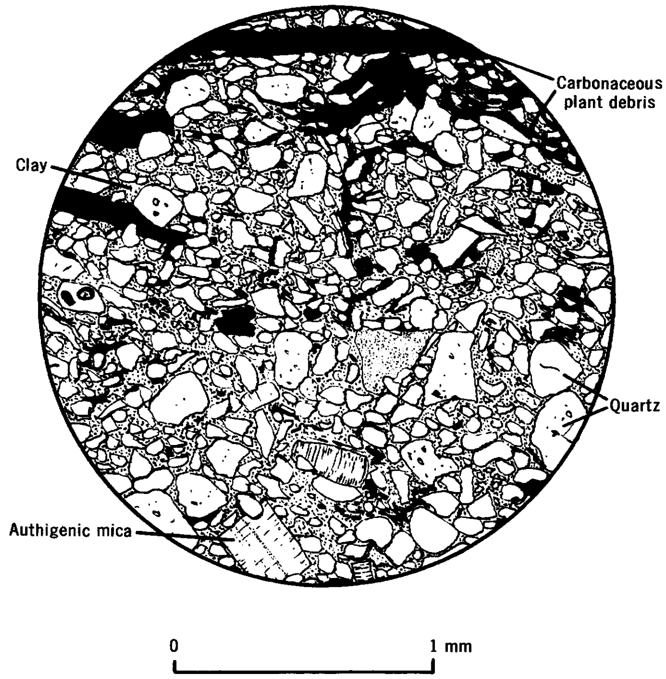

FIGURE 41.—Dark-gray carbonaceous very fine grained silty sandstone from the middle part of the Dakota Sandstone. Detritus is largely quartz; matrix is clay and clay-sized detritus. Sample DVR–2–306.5, Disappointment Valley.

Part of the carbonized wood shows cell structure, with pores filled with fine-grained silica, and part is replaced by pyrite. The sandstone is unique because of the presence of an unidentified authigenic mica, one euhedral crystal of which is illustrated at the bottom of the field in figure 41. The mica is biaxial $(-)$ with small $2V$, shows very weak birefringence, has refractive index near 1.59 and faintly mottled extinction and is weakly pleochroic in very pale yellowish brown colors. The mica books are generally greatly elongated parallel to c and length fast and display good basal cleavage. A few show lines of minute dark opaque inclusions parallel to c.

Detrital grains in the sandstone illustrated in figure 41 range from well rounded to sharply angular. Because of the abundance of sharp and flakelike grains and the relative abundance of altered grains, much of this rock may have been constituted from airborne volcanic material.

A sample (DVR–2–338) of gray mudstone collected about 40 feet above the base of the Dakota, from drill core obtained in Disappointment Valley, is probably typical for the formation. As seen in thin section, two-thirds of the rock consists of clay of low to moderate birefrigence and of generally uniform texture, except where clay wisps several millimeters long lie along bedding planes. Sharply angular to rounded silt-sized detritus is evenly distributed throughout the clay, except in the layers of clay wisps where detritus is absent. About a quarter of the rock is quartz, and minor amounts of feldspar, chert and other minerals are present. About 5 percent of the rock is carbonized plant fragments that tend to be equidimensional and very small in size. A modal estimate of the mineral composition of a thin section of this sample is given in table 4. Some other mudstone samples contain considerable large carbonized plant fragments and abundant pyrite.

MANCOS SHALE

The Mancos Shale is composed chiefly of carbonaceous, calcareous shale, commonly silty and sandy (called mudstone), and minor amounts of thin layers of limestone, siltstone, sandstone, and bentonitic shale or claystone. The average mineral compositions of two thin sections of mudstone (samples DVR–2–35, DVR–2–210) and of two thin sections of shale (samples DVR–2–127.5, DVR–2–145) are given in table 4. The average composition of the mudstone samples is probably typical of the more silty parts, and of the lower part of the interval equivalent to the Carlile Shale (calcite analyses of three samples from the Carlile equivalent by N. L. Archbold show a range 0.6–2.8 percent). The average composition of the shale samples is probably typical of most of the rest of the Mancos, which likely is about two-thirds clay, one-quarter calcite (determinations on six samples by N. L. Archbold show a range 15.6–38.1 percent), and the remainder, detrital minerals, pyrite, and carbonized plant fragments. Calcite occurs largely as finely dispersed microscopic grains in clay, and locally is concentrated as strings of anhedral blebs along some bedding planes, as in sample DVR–2–127.5 shown in figure 42, and as scattered euhedra. Much of the carbonaceous material in the Mancos is translucent to nearly opaque, and dark brown; it, too, is illustrated in figure 40. Typically, it occurs as flattened particles less than a millimeter across lying in bedding planes, but some carbonaceous material that is black and opaque occurs as more equidimensional particles. The specific gravities of three samples of mudstone from the Mancos from drill hole DVR–1 are 2.53, 2.56, and 2.60 (avg, 2.56), as determined by Robert F. Gantnier, of the U.S. Geological Survey. Gantnier also determined the grain densities of these three samples, all of which are 2.63, and indicated an estimated porosity for the three samples, respectively, of 6.5, 4.5, and 2.3 percent. These low porosities suggest a depth of burial exceeding 10,000 feet (Athy, 1930).

A typical silty rock (sample DVR–2–35) is shown in figure 43. Most of the silt here is quartz, although in places silt-sized biotite or glauconite dominate. The silty mudstone in figure 43 contains about 60 percent mineral clay; the remainder is detritus except for minor amounts of pyrite and calcite. Detritus is chiefly quartz with a small amount of carbonized plant fragments, K-feldspar, plagioclase, chert, muscovite, biotite, and zircon.

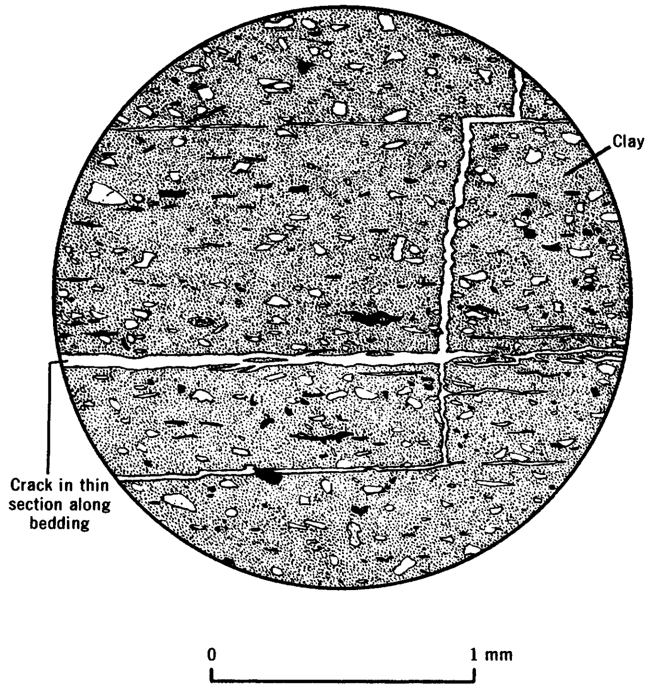

FIGURE 43.—Dark-gray silty carbonaceous mudstone from the Mancos Shale. Collected about 200 feet above the base of the formation; black particles are chiefly carbonized plant fragments; some of the smaller equidimensional black particles are pyrite; colorless detritus is largely quartz. Sample DVR–2–35, Disappointment Valley.

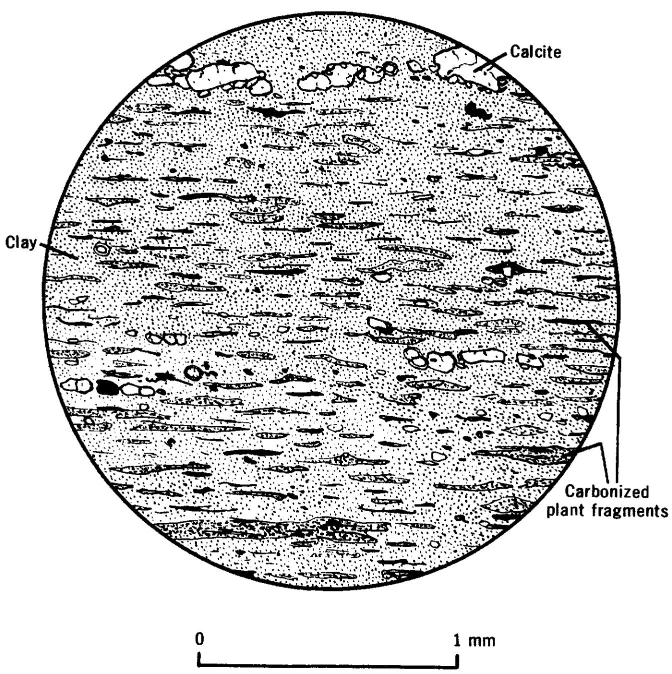

FIGURE 42.—Dark-gray carbonaceous shale from the Mancos Shale. Collected about 100 feet above the base of the formation; some of the smaller black particles are pyrite. Sample DVR–2–127.5, Disappointment Valley.

A sandy mudstone (sample DVR–2–210) from the basal Mancos is shown in figure 44. This rock is about half mineral clay and half detritus of sand, silt, and clay size, mostly sharply angular in the smaller sizes ranging to partly well rounded in the sand-sized material. Detritus is mostly quartz, but includes about 10 percent rounded clay-chlorite aggregates that are probably glauconite, about 5 percent chert, and 5 percent rock fragments largely of volcanic origin. Minor amounts of orthoclase, biotite. leucoxene, tourmaline, zircon, and hypersthene are also present. About 1 percent carbonized plant fragments, 1 percent pyrite, 1 percent calcite, and a trace of barite are scattered in clay.

Part of a thin section of a thin limestone layer (sample DVR–1–452.7) about 400 feet above the base of the Mancos is illustrated in figure 45. This rock consists of about 80 percent calcite, 15 percent pyrite, and 5 percent carbonaceous material as small irregular fragments and a few tiny fiberlike or stemlike fragments. A minor amount of silt- and clay-sized quartz detritus

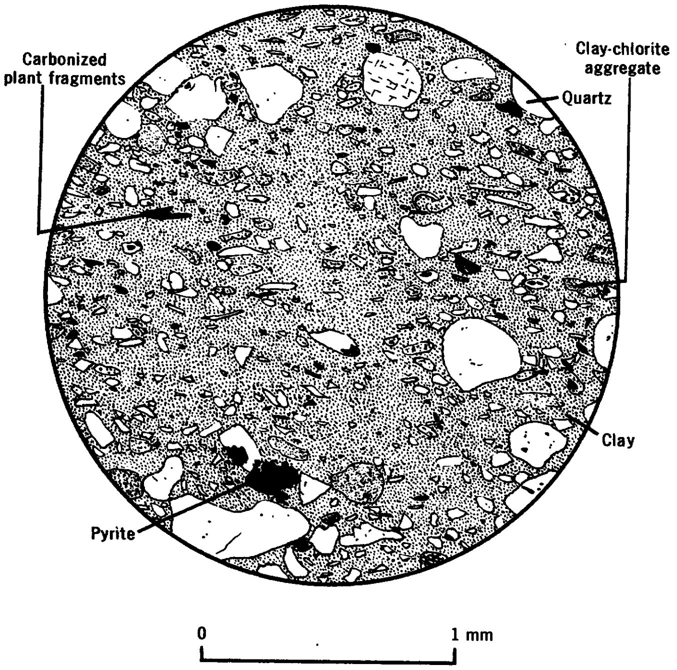

FIGURE 44.—Dark-gray sandy carbonaceous mudstone from the Mancos Shale. Collected about 30 feet above the base of the formation; black particles are chiefly carbonized plant fragments; colorless detritus is largely quartz. Sample DVR-2-210, Disappointment Valley.

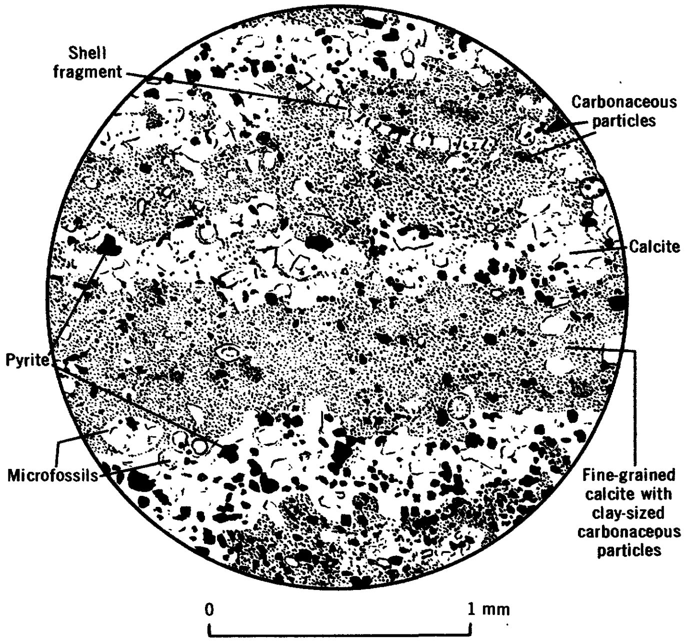

FIGURE 45.—Dark-gray carbonaceous limestone from the Mancos Shale containing abundant pyrite. Microfossils are abundant in some bedding layers. Sample DVR-1-452.7, Disappointment Valley.

occurs in some bedding layers. As figure 45 shows, microfossils, carbonaceous material, and pyrite tend to be concentrated in certain bedding layers.

The layering is shown at a smaller scale in figure 46, which also illustrates a segment of a small gash fracture in the limestone. The gash fracture is only a few centimeters long, terminating at points outside the area shown in figure 46 where bedding layers are not offset. Fracturing and minor flexing of the beds occurred after the sediment had acquired some rigidity following deposition, and at a time when the components of calcite and pyrite were still mobile in the rock, as attested by the occurrence of calcite within the fracture and the concentration of pyrite along the fracture. Probably, lateral secretion of calcite and pyrite to the gash fracture took place when the beds were deeply buried. A further conclusion to be drawn from the gash-fracture relationships is that calcite and pyrite components migrated into the isolated fracture merely because of pressure differential; the simple local opening of the fracture in beds far from any throughgoing structures could not have involved chemical disequilibrium resulting from introduction of a foreign solution differing in composition from that which already saturated the strata. Perhaps on a much larger scale this principle of pressure-induced lateral secretion could have wide application in problems dealing with metal concentrations, and may bear on the origin of uranium-vanadium ores in formations underlying the Mancos Shale in the Slick Rock district.

Part of a light-gray limestone nodule (sample DVR-1-515.4) collected from core about 340 feet above the base of the Mancos (unit 29 in the detailed section from DVR-1 of the lower part of the Mancos, Shawe and others, 1968) was examined in thin section and was seen to consist of about 80 percent calcite. About 2 percent pyrite as minute grains 0.02–0.04 mm across, mostly cubes, is sparsely distributed throughout most of the calcite but locally is concentrated in aggregates about 5–10 mm in size. The remainder of the rock consists of clay, partly dispersed in fine-grained calcite but mostly in broken and streaked fragments as much as 5 mm long irregularly distributed in fine-grained calcite. No carbonaceous material is evident. Small irregular fractures have been filled with coarse calcite. These relationships suggest that bedding in the layer in which the nodules formed was somewhat disrupted during the formation of the nodule. Some deformation occurred after the nodule acquired its full size.

Numerous thin bentonitic claystone layers in the lower part of the Mancos Shale probably represent volcanic ash falls. Biotite and quartz are the most abundant clastic constitutents in the claystone layers but are not evident in all layers. The layers commonly contain no calcite, and carbonaceous material appears to be ab-

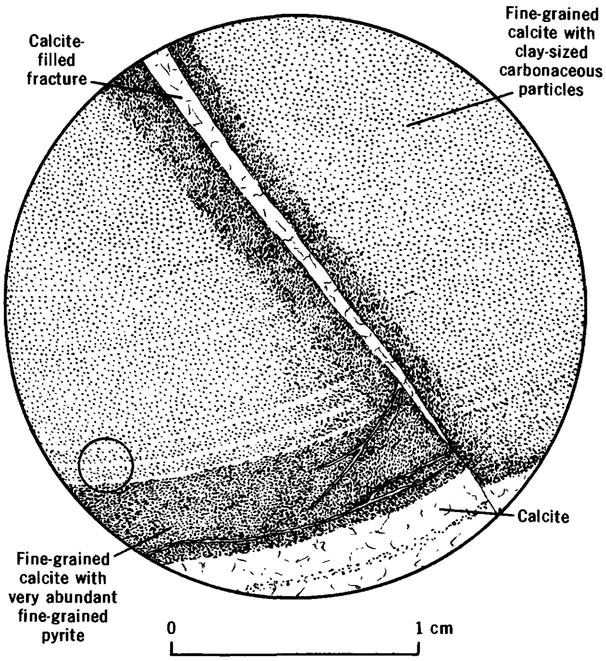

FIGURE 46.—Dark-gray carbonaceous limestone from the Mancos Shale, with calcite-filled fracture. Pyrite is abundant along the fracture and in a bedding layer adjacent to coarse-grained calcite. Sample DVR–1–452.7, Disappointment Valley. Circle shows area of figure 45.

sent from all of them, but pyrite is abundant in nearly all. Zircon and apatite, common heavy minerals in the claystone, are mostly sharply euhedral crystals, evidence that the material was dropped in place from the air rather than transported by water to the deposition site. Abundance of pyrite in the layers may indicate that iron was an important constituent of the ash, possibly being liberated by devitrification of glass and redeposited in diagenetic pyrite. Hydrogen sulfide was probably abundant in the organic-rich sediments accumulating at the bottom of the Mancos sea, and in addition, sulfur may have been especially abundant in the volcanic ash (see, for example, Fenner, 1933, p. 86–87, 92–95). Sudden deposition of individual ash layers accounts for the absence of carbonaceous material in these despite its notable abundance throughout the rest of the Mancos Shale. Possibly local reworking of the clay layers explains the presence of rounded quartz silt and sand grains in some of them.

GENERAL CONCLUSIONS

Mineral compositions of the investigated sandstones above the Moss Back Member of the Chinle Formation are surprisingly similar. Compositions of particular rock types vary as much within individual formations as they do from one formation to another. The sandstones generally contain about 50–80 percent quartz, 2–10 percent chert, 1–10 percent feldspar, 3–15 percent clay, 1–15 percent calcite, and minor amounts of other components. Sandstones in the Cutler Formation are much more arkosic, about one-third K-feldspar; this composition suggests their derivation from the nearby Uncompahgre highland to the east. Sandstones in the Moss Back, although recognized as quartzose in part, and likely compositionally similar to overlying rocks, are in part calcite rich; this content suggests derivation from carbonate rocks that were exposed in the Zuni highland to the southeast.

The ore-bearing sandstone of the Salt Wash Member of the Morrison Formation is not unique in mineral composition, and its mineral composition probably had little, if anything, to do with localization of uranium-vanadium deposits at this horizon. Sandstones in the Brushy Basin Member, a unit commonly cited as containing abundant volcanic material, contain probably only slightly more such components (chiefly some forms of chert, rock fragments, and plagioclase), than do many other sandstones exposed in the Slick Rock district. They are not rich enough in volcanic debris to distinguish them sharply from sandstones in underlying and overlying stratigraphic units. The Dakota, for example, contains sandstone composed partly of volcanic material, and bentonitic claystones are common in the Dakota and the Mancos Shale. Material in the sandstones other than that of volcanic origin may have come principally from clastic sedimentary formations in source areas, and ultimately thence from Precambrian igneous-metamorphic rock terranes.

Siltstones studied here, all from Jurassic formations, are distinguished from sandstones principally by their finer grain size and higher proportion of clay. They are otherwise mineralogically similar. Again, siltstones in the Brushy Basin Member, although containing volcanic materials, are not distinguished by unusual amounts of such material.

The mineral compositions of mudstones investigated, all from the Morrison Formation and Cretaceous units, are generally similar also. They contain about 25–30 percent quartz, 0.25–3.5 percent chert, 2–6 percent feldspar, 40–65 percent clay, 0–25 percent calcite, and minor amounts of other components. Burro Canyon Formation claystones contain on the average about 80 percent clay and commensurately less of other components. Mudstones in the Brushy Basin Member have an average content of 1 percent each of barite and analcite, principally because of large amounts in altered rocks, and in this respect are unique. In addition, mudstones in the Brushy Basin contain clay that is in large part derived from devitrification of volcanic ash; clay in the middle green unit of the member is chiefly of volcanic origin, but that in the upper and lower brown units is less so.

Shale that is the dominant rock type of the Mancos Shale contains about 1 percent pyrite, 3 percent carbonaceous material, 5 percent detrital minerals, 25 percent calcite, and the remainder clay.

Sedimentary rocks whose constituent grains display a great range in size, degree of sorting, and rounding have no commensurate variations in mineral composition, other than higher clay content in poorer sorted and finer grained material. Calcite cement also is greater in amount in finer grained rocks in general. Probably the mode of deposition, rather than difference among the rocks of the source areas—generally west or southwest of the Colorado Plateau for all the Jurassic and Cretaceous formations—determined the gross variations in mineral composition of these rocks. Differences in rock type in, and proximity to, source areas determined variations among some of the Triassic and Permian rocks.

Rocks which are reddish brown, or variations of this color, and which constitute the Colorado Plateau sedimentary strata that are termed "red beds," are characterized by content of numerous detrital black opaque mineral grains, films of hematite on other detrital grains, and dustlike hematite dispersed in matrix material. This is true regardless of the manner of deposition of the original sediment—fluvial, eolian, tidal flat, or flood plain. Hematite films and finely dispersed hematite impart the reddish-brown color that gives the rocks the name red beds. On grounds that the hematite-coated grains could not have been transported to the site of deposition without loss of the hematite films by abrasion, and that the detrital black opaque grains were oxidized in place following deposition (Bowers and Shawe, 1961, p. 175–176, 182–184, 212–213), it is evident that the red beds, as such, came into being through diagenetic processes that moved iron from the oxidizing detrital black opaques and deposited it nearby as finely dispersed hematite in matrix and as films on other detrital grains.

Rocks that are not reddish brown—the "bleached" rocks of the plateau—contain virtually no hematite, either as detritals or as grain coatings. They do contain pyrite or marcasite (where the rocks are deeply buried and are light gray) or limonite oxidized from iron sulfide (where the rocks are at or near the surface and are light buff or light yellowish brown). Such rocks contain either abundant carbonaceous material or none. These variations will be investigated in more detail and their significance discussed in a later chapter of this professional paper dealing with alteration of the sedimentary rocks.

The common evidence of distortion of rocks composed of clay-sized material suggests that slumping of water-saturated material shortly after deposition may have been extensive in Colorado Plateau sedimentary strata.

Silica is an abundant cement in most of the sedimentary rocks studied. It is present in both reddish-brown rocks and in "bleached" rocks. Commonly, silica cement and overgrowths occur very close to zones where silica has gone into solution from detrital quartz grains, indicating the local derivation of the matrix silica. Its ubiquitous occurrence in rocks regardless of color suggests it may have formed during diagenesis. The common interpenetration of quartz grains where solution has been extensive suggests high pressure at the time of solution, perhaps when the strata were deeply buried or undergoing folding. Silica as faceted overgrowths appears to be more abundant in light-gray or light-buff rocks, and may be a product of the alteration that bleached such rocks. In light-gray sandstone of the Burro Canyon Formation, silica overgrowths locally appear to have formed later than calcite, normally a constituent that has been extensively redistributed in altered rocks.

Calcite, on the average equally abundant in rocks of all colors, in reddish-brown sandstones occurs mostly as small interstitial blebs and patches less than 0.5 mm across, whereas in light-gray and light-buff sandstones it occurs commonly as larger optically continuous patches 0.5 mm or more in size, enclosing several detrital grains. In the light-gray and light-buff rocks, calcite is commonly intimately associated with euhedral crystals of authigenic minerals, such as anatase, pyrite, and marcasite (or limonite after pyrite and marcasite). These relationships indicate remobilization of calcite during the alteration that developed the light colors.

Calcite, dolomite, siderite(?), and barite occur as metacrysts (authigenic crystals) principally in rocks that are light colored, again suggesting that alteration related to the bleaching tended to induce crystallization of these minerals. Albite overgrowths in altered sandstone, albite microlites associated with recrystallized limestone, and analcite segregations in altered mudstone of the Brushy Basin, together with barite metacrysts, suggest that altering solutions may have been saline. Saline solutions have been proposed as the reason for growth of sodium-bearing minerals including albite and analcite, as well as barite in the Green River Formation in Utah (Milton, 1957, p. 143). Davidson (1965, p. 946), quoting Bogdanov (1962), remarks at the extensive albitization of copper-bearing red-bed arenites of Udokansk in eastern Siberia as a result of saline metamorphism.

Calcite metacrysts in the Burro Canyon Formation that apparently developed under pressure from the considerable load of overlying sediments show that calcite deposition occurred when these rocks were deeply buried.

The very low porosities of the argillaceous rocks suggest great depth of burial, in excess of 10,000 feet.

Common polysynthetic twins in calcite in many rock types, including those of light color, suggest that the rocks were stressed following the alteration that caused bleaching and redistribution of calcite. The most likely cause of stressing seems to be folding of the sedimentary strata. Other evidence of stress that may have been the result of folding of the rocks are shears parallel or subparallel to bedding and sand grains crushed against pebbles in conglomerate. In one rock from the Burro Canyon Formation shears subparallel to bedding are directly associated with polysynthetic twins in calcite. Formation of the folds in the district, and the time of their folding, will be considered in later chapters in this professional paper discussing structure and rock alteration.

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