Sedimentary Rock Alteration in the Slick Rock District, San Miguel and Dolores Counties, Colorado

GEOLOGICAL SURVEY PROFESSIONAL PAPER 576-D

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

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Epigenetic alteration of sedimentary rocks was
spatially and temporally related to deposition
of uranium-vanadium ores. Mineralogic and chemical
characteristics and distribution of altered rocks
suggest that uranium- and vanadium-bearing pore
waters that were expelled from compacted Upper
Cretaceous Mancos Shale in early Tertiary time
accounted for the alteration of sedimentary
rocks and formation of the ores in the
Upper Jurassic Morrison Formation

UNITED STATES DEPARTMENT OF THE INTERIOR

THOMAS S. KLEPPE, *Secretary*

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CONTENTS

ILLUSTRATIONS

TABLES

CONTENTS

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

SEDIMENTARY ROCK ALTERATION IN THE SLICK ROCK DISTRICT, SAN MIGUEL AND DOLORES COUNTIES, COLORADO

By Daniel R. Shawe

ABSTRACT

In the Slick Rock district, terrestrial red beds of Permian and Mesozoic age several thousand feet thick are overlain by Upper Cretaceous reduced rocks and underlain by Pennsylvanian reduced rocks, each mostly marine and a few thousand feet thick. The red beds, noteworthy for their contained uranium-vanadium ore deposits, are chiefly oxidized rocks, but locally they contain two facies of reduced rocks, one related to accumulations of abundant carbonized plant material and the other the result of epigenetic reducing alteration. Ore deposits occur in carbon facies rocks, but only where these rocks also have been epigenetically altered.

Red-beds-facies rocks formed in a near-surface, oxygenated environment shortly after deposition when sediments still lay above the water table. They are colored reddish brown by the contained hematite and they contain relatively abundant detrital black opaque heavy minerals and no pyrite. Black opaque minerals contain, in addition to major iron and titanium, significant amounts of chromium and vanadium. Silica cement occurs in some rocks; calcite cement is widespread and occurs mostly as interstitial patches less than 0.5 mm across; minor barite forms interstitial patches in places. Red-beds-facies rocks are widespread in the district, and are thousands of cubic miles in volume throughout the Colorado Plateau.

Carbon-facies rocks also formed near the surface shortly after deposition but in a reducing environment characterized by abundant carbonaceous material, and below the water table. These rocks, which contain no hematite, are light gray or greenish gray and contain only a moderate amount of detrital black opaque minerals and a small amount of pyrite. Silica, calcite, and barite cements are generally similar to those in red-beds-facies rocks. Chemical data suggest that carbon-facies and red-beds-facies rocks are compositionally similar. Where carbon-facies rocks are weathered near the surface, they are shades of buff or brown due to limonite formed from oxidized pyrite. Carbon-facies rocks occur mostly in the lower part (Moss Back Member) of the Upper Triassic Chinle Formation and the upper part (ore-bearing sandstone) of the Salt Wash Member of the Upper Jurassic Morrison Formation. Carbon-facies rocks are probably a few tens of cubic miles in volume throughout the Colorado Plateau.

Altered-facies rocks, like carbon-facies rocks, lack hematite coloring and are light gray or greenish gray but they contain only sparse detrital black opaque minerals and significant pyrite, and may or may not contain carbonaceous material. Metals present in pyrite in addition to major iron are manganese, silver, arsenic, cobalt, molybdenum, nickel, lead, selenium, and zinc. Chemical and radiometric data show that altered-facies rocks contain significantly more lead and uranium, and possibly more cobalt, nickel, vanadium, yttrium, and ytterbium, than do red-beds-facies rocks, and possibly less iron, magnesium, calcium, chromium, niobium, and zirconium, than do red-beds-facies rocks. Where altered-facies rocks have been weathered near the surface they, like carbon-facies rocks, are shades of buff or brown owing to limonite formed from oxidized pyrite. Altered-facies rocks occur in permeable strata of most of the Mesozoic red-beds formations, in the vicinity of faults and joints and in the axial region of the Dolores anticline extending southeastward through the Slick Rock district. The Lower Cretaceous Burro Canyon Formation at the top of the red-beds sequence is almost entirely of the altered facies; it contains virtually no carbonaceous material. The Upper Cretaceous Dakota Sandstone and Mancos Shale above the red-beds formations are classified as altered-facies rocks on the basis of mineralogic and chemical compositions; they contain abundant carbonaceous material. Altered-facies rocks in the red-beds formations are several hundreds of cubic miles in volume throughout the Colorado Plateau.

Confinement of altered-facies rocks to the vicinity of fractures, to permeable sandstone strata, and to selvages of argillaceous rocks surrounding altered permeable sandstone suggests that the rocks were consolidated at the time of alteration. Filling temperatures of fluid inclusions in barite and calcite from the Mancos Shale are 120° – 125° C, which if due to a normal geothermal gradient indicate development of the altered facies in the Mancos at a depth of burial of about 10,000 feet.

Chemical compositions of lithologic types throughout the stratigraphic section in the Slick Rock district, without reference to alteration or lack of it, are remarkably similar. Components that are consistently more abundant in argillaceous rocks than in arenaceous, because of higher clay and carbonate contents of the finer grained rocks, are Al_2O_3, MgO, CaO, CO_2, Na_2O, K_2O, boron, beryllium, cobalt, chromium, copper, gallium, nickel, scandium, strontium, vanadium, yttrium, and ytterbium. K_2O shows a decrease upward in the section from the Navajo Sandstone to the Dakota Sandstone reflecting a similar decrease in potassium

feldspar. Elements that are erratically distributed among formations and lithologic types are silver, arsenic, barium, lanthanum, molybdenum, niobium, lead, tin, and zirconium.

Carbonate and iron minerals were leached, recrystallized, and concentrated as a result of the action of altering solutions that caused the formation of altered-facies rocks. Detrital black opaque minerals were nearly all destroyed and some pyrite was deposited in their place; such elements as chromium and vanadium were thereby taken into the altering solution, and such elements as silver, arsenic, cobalt, molybdenum, lead, and selenium were thereby precipitated from solution. Calcite was recrystallized and as a result acquired substantial iron—largely iron that was liberated from black opaque minerals but not precipitated as pyrite—and some other elements. Iron and carbonate minerals both were concentrated near the borders of altered zones, or along fractures, and in these places the minerals tend to be enriched in vanadium, uranium, and lead. Concentrations of iron minerals near the borders of altered rocks commonly display roll-like forms characteristic of the uranium-vanadium ore deposits.

Epigenetic alteration was controlled by fractures that likely formed during the early Tertiary; younger fractures that postdate alteration formed during the late Tertiary and Quaternary. Several features suggest that alteration occurred when the sediments were deeply buried; maximum burial of about 10,000 feet occurred during the early Tertiary.

The large volume of epigenetically reduced rocks in the red-beds sequence, the obvious inadequacy of the red beds themselves to generate solutions capable of causing that alteration, and the addition of uranium and lead to altered-facies rocks indicate that the altering solutions, which were also responsible for introducing the uranium-vanadium ores, were derived outside the red-beds sequence. The Mancos Shale, because it was being compacted and was expelling pore fluids during deep burial, is a likely source of a large volume of chemically reducing water that would account for the alteration that occurred in early Tertiary time, appropriate to the inferred time of epigenetic alteration of red-beds strata.

The Mancos Shale is a thick marine black shale that when deposited as clay and silt contained abundant organic material, a large amount of calcite, and likely significant amounts of uranium and vanadium that characterize most black shales. Uranium and vanadium are now abnormally low in the Mancos Shale and perhaps much of the original amounts of these elements present was expelled during compaction. Undoubtedly, trapped seawater buried in the mud of the Mancos Shale had low Eh because of high organic content, was carbonated owing to high calcite content, contained abundant hydrogen sulfide and chlorine, and was alkaline. It was chemically ideal for carrying available uranium in solution as uranyl dicarbonate and tricarbonate complexes and as organic complexes, and for carrying vanadium as complex ions. It was chemically capable of reducing red beds, forming authigenic minerals such as albite, analcite, and barite, and leaching or precipitating various minerals and elements in altered-facies rocks.

Upon compaction to about a third to a tenth of its original water-saturated volume, the mud of the Mancos Shale throughout the Colorado Plateau expelled several tens of thousands of cubic miles of pore water. Most of the water moved upward into younger sediments, but much moved into lower porous strata, along faults that formed at the time, because of relatively high water density and abnormally high fluid pressures. Epigenetic alteration occurred wherever the water flowed, and uranium-vanadium ore deposits were formed where the water encountered strong concentrations of humic acid in the vicinity of abundant carbonaceous material, particularly in the ore-bearing sandstone of the Salt Wash Member.

INTRODUCTION

Altered sedimentary rocks that are the subject of this report are of particular interest for their contained uranium-vanadium deposits in the Slick Rock district and throughout the Colorado Plateau. They are part of strata that comprise a terrestrial "red-beds" section of Permian and Mesozoic age several thousand feet in thickness and thousands of cubic miles in volume. Above the red-beds section the Dakota Sandstone and Mancos Shale of Late Cretaceous age aggregate about 2,000 feet or more in thickness; these formations are terrestrial and marginal marine sandstone and mudstone, and marine black shale, respectively. Underlying the red-beds section the Pennsylvanian Hermosa Formation—which consists of evaporites, carbonate rocks, and black shale—and other older carbonate and arenaceous rocks, all of which are marine, total a few thousand feet in thickness.

The red beds are chiefly oxidized rocks that contain abundant hematite, whereas the strata of Late Cretaceous age above and of Pennsylvanian age below the red-beds section are chiefly reduced rocks that contain abundant carbonaceous material and pyrite, and are grayish colored. Locally within the red-beds sequence are reduced rocks of two types. One type consists of relatively minor amounts of carbonaceous strata in economically significant layers such as the lower part of the Chinle Formation of Late Triassic age and parts of the Morrison Formation of Late Jurassic age. These layers, although they total perhaps only a few tens of cubic miles in volume throughout the Colorado Plateau, contain numerous widespread large deposits of uranium minerals that constitute the chief uranium ore resource of the United States. The second type of reduced rock in the red-beds sequence consists of relatively large amounts of noncarbonaceous strata in which alteration, in part structurally controlled, has formed a reduced rock from once oxidized rock of red-beds type, and a small amount of originally carbonaceous strata that was modified by reducing alteration. The volume of this second type of reduced rock is significant, measuring probably several hundreds of cubic miles throughout the Colorado Plateau.

Sedimentary rocks in the Slick Rock district thus show color differences, reflecting alteration, that are related both to the position of the uranium-vanadium deposits and to structural features. The color differences were studied in order to elucidate the possible genetic relation of alteration to ore deposition, and the possible structural control of ore deposition. From almost the beginning of mining in

the Morrision Formation "bleached" sandstone and "altered" shale were noted to be associated with the ore deposits (Coffin, 1921, p. 153, 156, 187, 188; Fischer, 1942, p. 376, 390), and "bleached" areas in some sandstone formations were recognized to have structural control (Coffin, 1921, p. 73). More recently during intense study of the uranium deposits of the Colorado Plateau in the decade of the 1950's, some geologists have called attention to the association of deposits and "altered" sedimentary rocks (Fischer and Hilpert, 1952, p. 12; Weir, 1952, p. 18–21; Shawe, 1956b; Shawe and others, 1959, p. 404–405) and the relationship of "bleached" sandstone to faults and joints (Trites and others, 1956, p. 281; McKeown and Hawley, 1955, p. 47; Shawe and others, 1959, p. 405).

Despite recognition of the relationship between rock alteration and uranium-vanadium deposits, its importance in understanding origin of the deposits generally has not been emphasized, even in more recent studies of the chemistry of ore formation (for example, Hostetler and Garrels, 1962) and in summaries of Colorado Plateau uranium deposits (Fischer, 1968). Further, processes besides those that formed the ores also may have caused alteration, and this fact has discouraged attempts to understand the relationship between alteration and ores. This report describes rock alteration and presents data showing some geologic, mineralogic, and geochemical characteristics of the alteration that pertain to the origin of the ores. The report is the fourth in a series describing geologic investigations in the Slick Rock district. The first three reports covered stratigraphy of the district and vicinity (Shawe and others, 1968), petrography of sedimentary rocks (Shawe, 1968), and structure (Shawe, 1970). An earlier report (Shawe and others, 1959) briefly summarized geology and ore deposits of the district. Altered sedimentary rocks have been described briefly in three previous reports (Shawe, 1956b; Shawe and others, 1959; Bowers and Shawe, 1961).

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

In the district uranium deposits are known in the Moss Back Member of the Chinle Formation (Upper
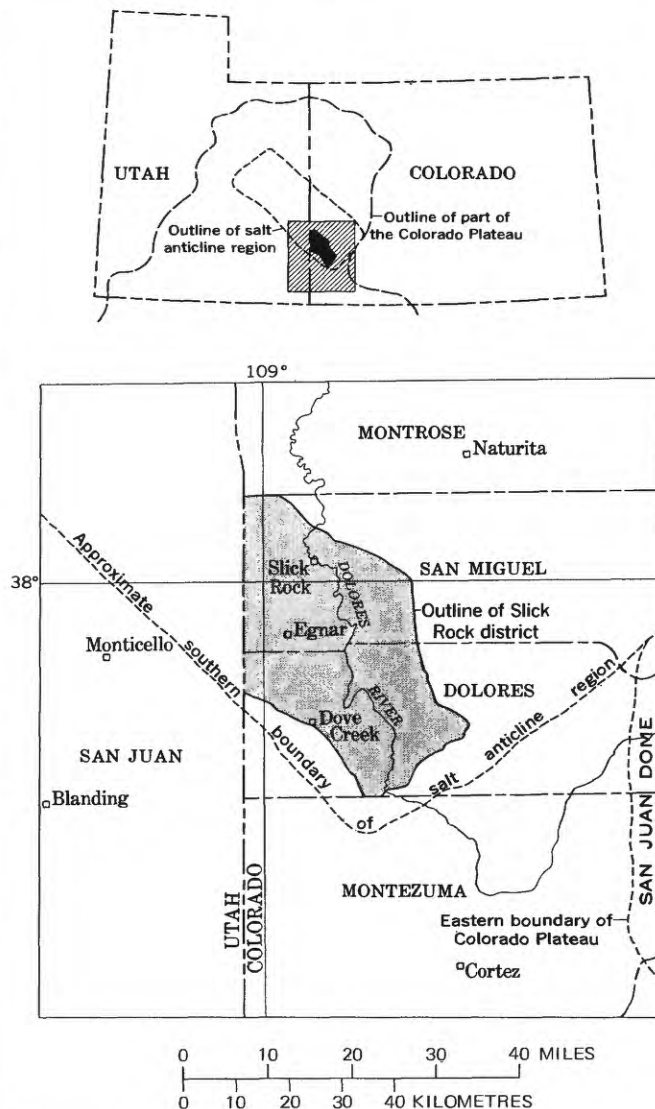
FIGURE 1.—Location of the Slick Rock district (stippled).

Triassic) and throughout the Morrison Formation (Upper Jurassic); important production has come mainly from the top sandstone unit or so-called "ore-bearing sandstone" of the Salt Wash Member of the Morrison.

The district is 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.

A zone of faults bounds the southwest edge of the collapsed core of the Gypsum Valley salt anticline. A second zone, the Dolores, is about 2 miles northeast
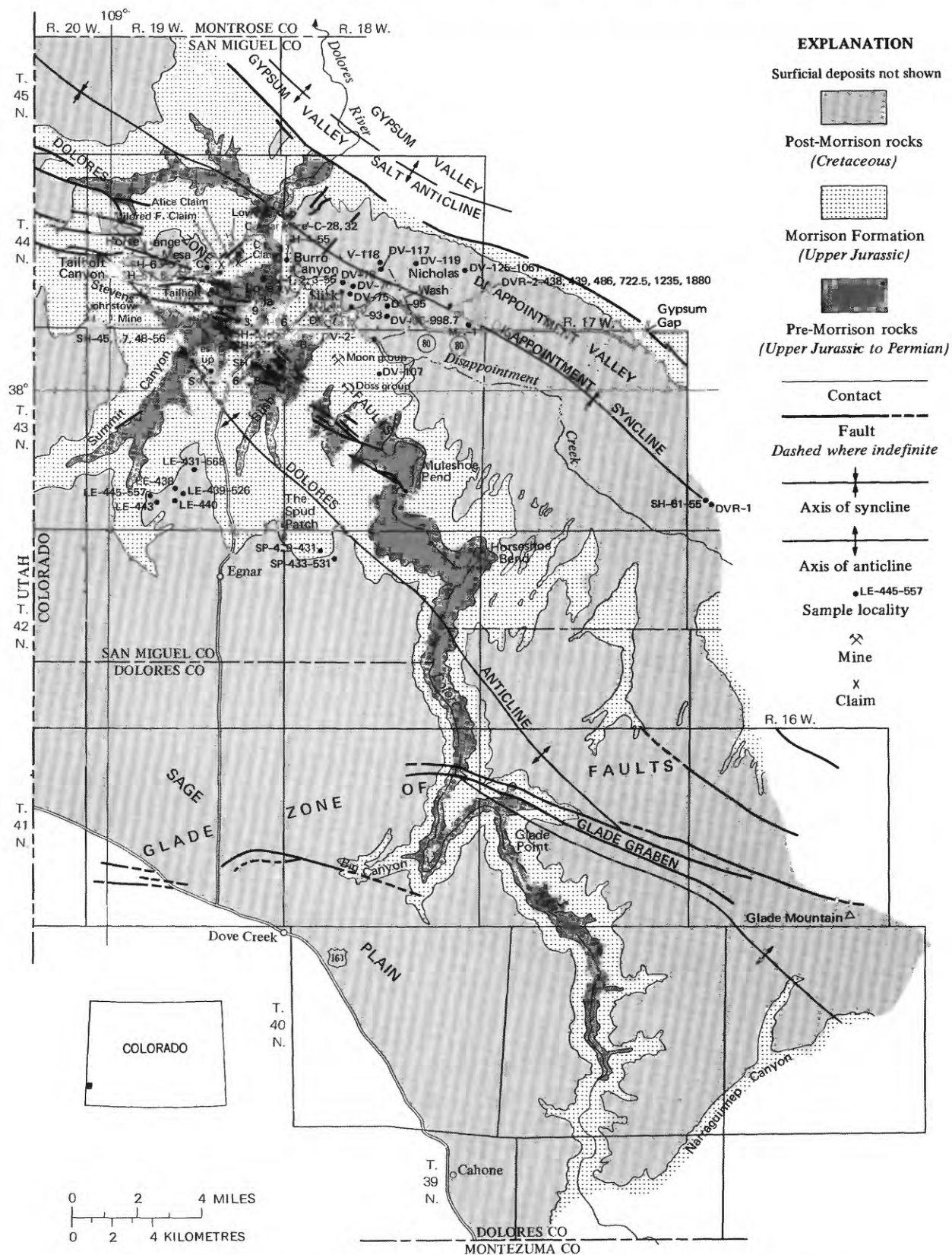
FIGURE 2.—Generalized geologic map of the Slick Rock district showing sample localities.

TABLE 1.—*Summary of consolidated sedimentary rocks in the Slick Rock district*

Age	Formation and member	Thickness (feet)	Description
Late Cretaceous	Mancos Shale	1, 600–2, 300	Dark-gray carbonaceous, calcareous shale.
	Dakota Sandstone	120–180	Light-buff sandstone and conglomeratic sandstone, dark-gray carbonaceous shale, and coal.
Early Cretaceous	Burro Canyon Formation	40–400	Light-gray to light-buff sandstone and conglomeratic sandstone; greenish-gray and gray shale, siltstone, limestone, and chert.
Late Jurassic	Morrison Formation, Brushy Basin Member	300–700	Reddish-brown and greenish-gray mudstone, siltstone, sandstone, and conglomerate.
	Morrison Formation, Salt Wash Member	275–400	Light-reddish-brown, light-buff, and light-gray sandstone and reddish-brown mudstone.
	Junction Creek Sandstone	20–150	Light-buff sandstone.
	Summerville Formation	80–160	Reddish-brown siltstone and sandstone.
	Entrada Sandstone, Slick Rock Member	70–120	Light-buff to light-reddish-brown sandstone.
	Entrada Sandstone, Dewey Bridge Member	20–35	Reddish-brown silty sandstone.
Jurassic and Triassic(?)	Navajo Sandstone	0–420	Light-buff and light-reddish-brown sandstone.
Late Triassic(?)	Kayenta Formation	160–200	Purplish-gray to purplish-red siltstone, sandstone, shale, mudstone, and conglomerate.
Late Triassic	Wingate Sandstone	200–400	Light-buff and light-reddish-brown sandstone.
	Chinle Formation, Church Rock Member	340–500	Reddish-brown, purplish-brown, and orangish-brown sandstone, siltstone, and mudstone; dark-greenish-gray conglomerate.
	Chinle Formation, Petrified Forest(?) Member	0–100	Greenish-gray mudstone, siltstone, shale, sandstone, and conglomerate.
	Chinle Formation, Moss Back Member.	20–75	Light-greenish-gray and gray sandstone and conglomerate; minor greenish-gray and reddish-brown mudstone, siltstone, and shale.
Middle(?) and Early Triassic	Moenkopi Formation	0–200	Light-reddish-brown siltstone and sandy siltstone.
Early Permian	Cutler Formation	1, 500–3, 000	Reddish-brown, orangish-brown, and light-buff sandstone, siltstone, mudstone, and shale.
Late and Middle Pennsylvanian	Rico Formation	130–240	Transitional between Cutler and Hermosa Formations.
Middle Pennsylvanian	Hermosa Formation, upper limestone member	1, 000–1, 800	Light- to dark-gray limestone; gray, greenish-gray, and reddish-gray shale and sandstone.
	Hermosa Formation, Paradox Member	3, 250–4, 850	Upper and lower units gray dolomite, limestone, and dark-gray shale interbedded with evaporites; middle unit halite and minor gypsum, anyhdrite, dolomite, limestone, and black shale.
	Hermosa Formation, lower limestone member	100–150	Medium-gray limestone, dark-gray shale.
Early Pennsylvanian and Mississippian	Molas Formation	100	Reddish-brown, dark-gray, and greenish-gray shale and silty shale and gray limestone.
Mississippian	Leadville Limestone	240	Medium-gray limestone and dolomite.
Devonian	Name not assigned	250–550	Gray sandy dolomite and limestone and grayish-green and reddish sandy shale.
Cambrian	Name not assigned	500–700	Light-gray to pinkish conglomeratic sandstone, sandstone, siltstone, shale, and dolomite.
Precambrian	Name not assigned	--------------	Granitic to amphibolitic gneisses and schists, and granite.

of, and parallel to, the axis of the Dolores anticline. A few faults form a conjugate set normal to the Dolores zone of faults in the north part of the district. The south part of the district is cut by the Glade zone of faults which trends about N. 80° E. Prominent joint sets, mostly parallel to individual faults in all the zones of faults, are widespread throughout the district.

Most of the uranium-vanadium deposits in the Slick Rock district are in a broad northwesterly oriented zone centered on the Dolores zone of faults and referred to as the Dolores ore zone.

The red beds and grayish-colored rocks present in the Slick Rock district, in accord with their oxidized and reduced characters, have been grouped into two diagenetically formed types, "red-beds facies" and "carbon facies," and one epigenetically altered type, which for convenience is called simply "altered facies" in this report. These three types of rocks are essentially the same as the three types of sandstone in the Morrison Formation described previously by Shawe (1956b) by Shawe, Archbold, and Simmons (1959, p. 404–405), and by Bowers and Shawe (1961, p. 175–178).

Rocks of the three facies have many similarities that will not be described in detail here. Detrital components with the exception of black opaque minerals are virtually the same in the three facies. These have been described previously (Shawe, 1968). Mineralogical distinctions among the facies, in addition to variations in black opaque mineral content, are principally differences in the form, abundance, and distribution of epigenetic or authigenic minerals; the following discussions of mineralogic variations among the facies will indicate chiefly these differences. Commensurate chemical differences among the facies also will be described.

Figure 3 shows diagrammatically the relations among the three facies. The diagram is not to scale; for example, altered-facies rocks generally extend outward from fractures no more than a few feet, but in some permeable strata they may extend several thousand feet.

Some details of the alteration effects differ from formation to formation, as well as within formations, although the foregoing generalizations appear to be widely applicable.

Semiquantitative spectrographic data presented in this paper are based on their identity with geometric brackets whose boundaries are 1.0, 0.46, 0.22, 0.10 percent, and so forth; the data were originally reported arbitrarily as midpoints of these brackets, 0.7, 0.3, and 0.15 percent, respectively. Comparisons of this type of semiquantitative results with data
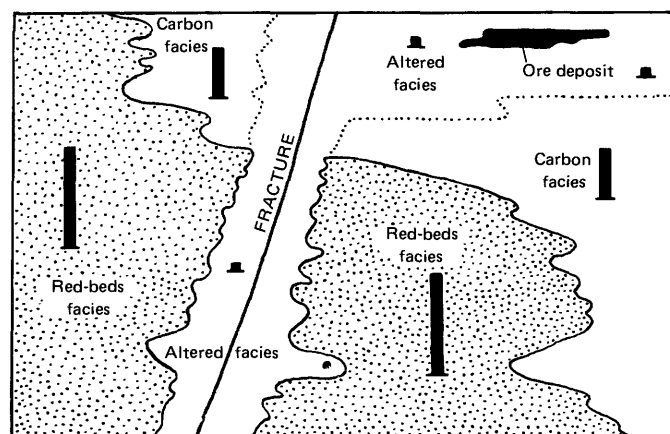
FIGURE 3.—Diagrammatic section (not to scale) showing relationships among three facies of sandstone. Red-beds facies is light-reddish-brown sandstone; carbon facies and altered facies are light-gray to light-brown sandstone. Height of vertical bars in the different facies suggests relative abundance of black opaque minerals.

obtained by quantitative methods, either chemical or spectrographic, show that about 60 percent of the assigned groups include the quantitative value. Most of the results reported in this paper, however, are arithmetic averages of two or more analyses and the reported numbers therefore do not necessarily coincide with the midpoints of the brackets indicated above.

The tables in this report that present semiquantitative spectrographic data list all values determined as below the limit of detectability as "O." These values for the elements concerned are as follows:

Element	Weight percent	Element	Weight percent	Element	Weight percent
Ag-----	0.00001	Hg-----	0.08	Rh-----	0.004
Al-----	.0001	Ho-----	.001	Ru-----	.008
As-----	.01	In-----	.0004	Sb-----	.01
Au-----	.001	Ir-----	.03	Sc-----	.001
B------	.005	K*-----	.005 (0.3)	Si-----	.005
Ba-----	.001	La-----	.003	Sm-----	.008
Be-----	.00005	Li*----	.00003 (0.04)	Sn-----	.004
Bi-----	.005	Lu-----	.005	Sr-----	.001
Ca-----	.01	Mg-----	.00003	Ta-----	.1
Cd-----	.005	Mn-----	.0007	Tb-----	.01
Ce-----	.03	Mo-----	.0005	Te-----	.08
Co-----	.008	Na*----	.0003 (0.01)	Th-----	.08
Cr-----	.0006	Nb-----	.001	Ti-----	.0005
Cs*----	.01 (0.8)	Nd-----	.006	Tl-----	.04
Cu-----	.00005	Ni-----	.005	Tm-----	.001
Dy-----	.006	Os-----	.1	U------	.08
Er-----	.003	P------	.07	V------	.001
Eu-----	.003	Pb-----	.001	W------	.07
Fe-----	.0008	Pd-----	.003	Y------	.003
Ga-----	.004	Pr-----	.01	Yb-----	.0003
Gd-----	.006	Pt-----	.003	Zn-----	.008
Ge-----	.001	Rb*----	.007 (7.)	Zr-----	.0008
Hf-----	.03	Re-----	.04		

*A second exposure is required for the high sensitivity listed.

In calculations of arithmetic average values, any value listed as "O" (below limit of detectability) is

arbitrarily given a value of half that listed in the preceding table of limits.

In following pages where semiquantitative spectrographic data for various groups of rocks or of individual rocks are compared, the differences in content of elements among the rocks may not appear to be significant. However, generally most of the samples in the groups are lithologically similar and were analyzed concurrently by one analyst, and amounts of elements were determined from the same film. Because the recorded differences of element content were based on differences of spectrum line intensity, the differences in element content probably are real, though they are not quantitatively accurate.

Data on heavy minerals were obtained by the late H. E. Bowers of the U.S. Geological Survey and me by counting grains in mounts mostly of the -150 mesh size fractions (grain size $\cong$ 0.03 – 0.1 mm), using a petrographic microscope chiefly with a medium-power (16 mm) objective, a mechanical stage, and a cell counter. Each grain mount was traversed at 1-mm intervals until at least 200 heavy-mineral grains in each mount were counted. Preparation of mounts was described by Bowers and Shawe (1961, p. 180 – 181). Considerable help in the preparation of samples for study was given by G. C. Simmons, W. B. Rogers, N. L. Archbold, the late O. T. Marsh, E. L. Boudette, and W. B. Gazdik, all of the U.S. Geological Survey.

All heavy minerals except carbonate minerals were counted. Because the range of density of carbonate minerals in the rock samples brackets the density of bromoform used in the separations, carbonate minerals were not consistently brought down in the bromoform separations.

Separations of several rock samples to obtain concentrations of pyrite and calcite for analyses used in this report were made by R. G. Coleman of the U.S. Geological Survey. I made separations of several samples to obtain pyrite, calcite, and black opaque mineral concentrations for additional analyses.

Although some of the data and relations described in this report may be susceptible to interpretations other than those I propose, the interpretations presented here are favored because I believe they accord best with the general mechanism of alteration that I think is demanded by the grosser relationships that will be described in later pages. I acknowledge that additional data will be required to resolve many of these problems and the possible discrepancies, and I urge that new work be applied toward that end.

RED-BEDS-FACIES ROCKS

Red-beds-facies rocks are the dominant type in the Mesozoic red-beds sequence in the Slick Rock district and throughout the entire Colorado Plateau. Generalized outcrop distribution of the facies in the Morrison Formation in the north part of the district is indicated in figure 4, and detailed distribution of the facies in the Morrison Formation in this area is shown in Shawe, Simmons, and Archbold (1968, pl. 7), where red beds are mapped as "unaltered" rocks.

Red-beds-facies sandstone is light reddish brown, and is characterized by relatively abundant black opaque heavy minerals. No apparent change in color or composition has occurred in red-beds-facies sandstone where it has been exposed to weathering. Siltstone and mudstone of the red-beds facies are reddish brown, darker than sandstone. They are mineralogically and chemically akin to red-beds-facies sandstone, and they differ from sandstone principally in smaller grain size and higher clay content.

The reddish-brown rocks, or rocks with variations of this color, which constitute the red beds, in addition to containing abundant black opaque minerals, are characterized by films of hematite on detrital grains and by dustlike hematite dispersed in matrix material. This characterization is true regardless of the type 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. In places abundant detrital black opaque minerals occur in some bedding layers in reddish-brown sandstone of the Salt Wash Member. Reddish-brown stain due to hematite films on quartz grains is noticeably most intense in and near layers of abundant black opaque minerals. This relation suggests that iron in the hematite stain was derived from the detrital black opaque minerals. Most of the black opaque minerals in red-beds-facies rocks, all clearly showing rounded detrital forms, were probably originally magnetite and ilmenite, but now are reddish black and are composed chiefly of hematite (Bowers and Shawe, 1961, p. 182 – 184). In mineral separations, a hand magnet invariably removed some ferromagnetic material that is inferred to consist chiefly of magnetite. Frantz isodynamic separator paramagnetic fractions that showed high titanium content are inferred to be ilmenite in part. Most detrital black opaque mineral material was identified as hematite by X-ray diffraction studies. The black opaque mineral grains are readily crushed with a needle point and seem to be porous. The porous black opaque mineral grains and hematite-coated detrital grains could not have been transported to their site of deposition in their present form, so it is evident that their present character developed in place. The red beds thus came into being through diagenetic processes that removed

EXPLANATION

MORRISON FORMATION

Upper part – Includes the Brushy Basin Member and the ore-bearing sandstone of the Salt Wash Member

Lower part – Includes approximately the lower three-fourths of the Salt Wash Member. Sandstone in the lower part of the Morrison Formation outside areas of altered-facies sandstone is red-beds facies

Altered-facies sandstone – Shown only in the lower part of the Morrison Formation in the area of detailed mapping

————— Contact

————— Fault

—⊢—⊢— Axis of anticline

—⊢—⊢— Axis of syncline

Nearly vertical joint bounded by altered-facies sandstone

● Deposit of iron minerals

○ Location of joint lined with calcite

————— Outline of area in which joints were mapped

FIGURE 4.—Map of the north part of the Slick Rock district showing distribution of altered-facies sandstone in outcrops of the lower part of the Morrison Formation, and distribution of other alteration phenomena in the Morrison Formation.

iron from oxidizing black opaque detrital minerals (and possibly other iron-bearing minerals such as pyroxenes and amphiboles that are no longer present) and deposited it nearby as hematite films on other detrital grains and as finely dispersed hematite in matrix.

Clay minerals in red-beds-facies rocks are kaolinite, illite, montmorillonite, and chlorite (Keller, 1959); montmorillonite and mixed-layer derivatives appear to dominate in the Brushy Basin Member and illite (hydromica) and mixed-layer derivatives in the Salt Wash Member (data of A. D. Weeks in Waters and Granger, 1953, p. 4; Keller, 1962, pl. 1; p. 39).

Silica as a cement is a widespread but irregularly distributed minor component of red-beds-facies rocks. Many reddish-brown sandstones contain no silica cement (Shawe, 1968, figs. 3, 7, 10, and 17); only a few contain as much as 15 percent silica that forms overgrowths on quartz grains adjacent to interpenetrating quartz grains, suggesting local solution and redeposition of quartz (Shawe, 1968, figs. 6, 11). Most quartz overgrowths join at sutured or irregular boundaries and few are faceted. Some interstitial silica occurs as very small interlocking quartz crystals in the manner of chalcedony.

Carbonate minerals, mostly calcite, range greatly in abundance in different rocks of the red-beds facies, tending to be more abundant in finer grained rocks. Within specific rock types, however, carbonate tends to be rather evenly distributed, where it occurs mostly as small interstitial blebs and patches less than 0.5 mm across (Shawe, 1968, figs. 3, 6, 7, 10, 11, 17). Locally small segregations of calcite occur in mudstone and siltstone of the red-beds facies (Shawe, 1968, fig. 24), but they are not numerous. Detrital grains of calcite (and dolomite?) are common in rocks of the red-beds facies and in some places make up a few percent of the rock.

Carbonate (dominantly calcite) content of red-beds-facies rocks is given in table 2. According to the data, in the Brushy Basin Member of the Morrison Formation red-beds-facies mudstone contains less calcite than does red-beds-facies sandstone; the reverse is true in the Salt Wash Member. Calcite is appreciably less abundant in both sandstone and mudstone of the red-beds facies in the ore-bearing sandstone than it is in similar rocks in the remainder of the Salt Wash Member.

According to an analysis by James A. Thomas of the U.S. Geological Survey one reddish-brown mudstone sample from the lower part of the Brushy Basin Member collected from diamond-drill hole LE-438 in

TABLE 2.—*Average calcite content, in percent, of red-beds-facies and altered-facies rocks in some Mesozoic Formations in the Slick Rock district, Colorado*

[Based on chemical analyses by N. L. Archbold (method described in Archbold (1959)) and modal point counts and estimates by Shawe (1968). Number of samples given in parentheses]

	Red-bed facies		Altered facies	
	Sandstone	Mudstone	Sandstone	Mudstone
Mancos Shale				18 (9)
Dakota Sandstone			6 (4)	--------
Burro Canyon Formation			6 (6)	--------
Morrison Formation:				
Brushy Basin Member	12 (10)	8 (27)	9 (3)	4 (7)
Salt Wash Member	10 (4)	15 (10)	9 (14)	--------
Ore-bearing sandstone	[1]2.5(47)	[1]7.2(47)	[1]2.5(238)	[1]4.1(47)
Entrada Sandstone	3 (16)	--------	4 (18)	--------

[1]Archbold (1959, fig. 3); dominantly samples from the ore-bearing sandstone, but includes samples from above and below ore-bearing sandstone.

the Legin area contained by weight 13.5 percent carbonate mineral, 5.4 percent calcium, and only a trace magnesium, indicating nearly pure calcite. Another analysis by Thomas of a reddish-brown mudstone sample from the upper part of the Brushy Basin Member collected from diamond-drill hole LE-440 in the Legin area contained by weight 55.3 percent carbonate mineral, 22.1 percent calcium, and only a trace magnesium, again indicating nearly pure calcite.

The chemical composition of calcite separated from red-beds-facies rocks, based on semiquantitative spectrographic analyses of two samples from the Salt Wash Member—one of calcite from grayish-red sandstone and the other of calcite from reddish-brown interlayered mudstone and siltstone—is presented in table 3.

In the analyses given in table 3, presence and relative amounts of silicon, aluminum, sodium, potassium, titanium, boron, barium, zirconium, and perhaps a few other elements, indicate mostly the presence and relative amounts of impurities such as quartz, clay minerals, feldspars, titanium oxides, tourmaline, barite, zircon, and other detrital and diagenetic minerals. Iron, magnesium, manganese, strontium, and of course calcium, likely reside chiefly in the calcite structure; other elements such as silver, chromium, copper, gallium, lanthanum, nickel, lead, scandium, vanadium, yttrium, and ytterbium, may or may not be present in the calcite structure.

Heavy mineral content of red-beds-facies sandstone is summarized in table 4. Dominance of black opaque minerals in this facies is evident. Chemical composition of black opaque minerals separated from sandstone samples of the red-beds facies is given in table 5. Presence of some pyrite, particularly in samples of the Entrada Sandstone, is anomalous;

TABLE 3.—*Semiquantitative spectrographic analyses, in weight percent, of nine samples of calcite from red-beds-facies, carbon-facies, and altered-facies rocks of the Morrison Formation, Burro Canyon Formation, and Mancos Shale, Slick Rock district*

[Analyses by Joseph Haffty (5 samples) and Katherine V. Hazel (4 samples). 0, looked for but not found (below limit of detectability). Also looked for but not found: P, As, Au, Be, Bi, Cd, Ce, Co, Cs, Dy, Er, Eu, Gd, Ge, Hf, Hg, Ho, In, Ir, Li, Lu, Mo, Nb, Nd, Os, Pd, Pr, Pt, Rb, Re, Rh, Ru, Sb, Sm, Sn, Ta, Tb, Te, Th, Tl, Tm, U, W, Zn]

| Sample No--- | Red-beds facies | | | Carbon facies | Altered facies | | | | | | |
	1	2	Average	3	4	5	6	7	8	9	Average
Si----------	3	0.03	1.5	3	3	3	0.3	10	10	0.003	4.4
Al----------	.3	.003	.15	1	1	1	.03	3	1	.003	1.0
Fe----------	.3	.3	.3	1	3	3	.03	1	1	.7	1.5
Mg----------	.3	.3	.3	.3	1	.3	.03	.3	.3	.3	.4
Ca----------	>10	>10	>10	>10	>10	>10	>10	>10	>10	>10	>10
Na----------	.01	.005	.008	.03	.03	.03	.005	.1	.1	.005	.05
K-----------	.1	0	<.1	.1	.1	.3	.05	1	.3	0	.3
Ti----------	.01	0	<.01	.03	.03	.1	0	.1	.1	0	.06
Mn----------	.03	.3	.17	.01	.03	.01	.07	.1	.1	.3	.10
Ag----------	.0001	.00003	.00007	.0001	.0001	.0001	0	.00003	.00001	.00003	.00005
B-----------	0	0	0	0	0	.003	0	0	0	0	<.003
Ba----------	.01	.003	.007	.01	.03	.03	0	.01	.01	0	.015
Cr----------	.0003	0	<.0003	.0003	.003	.003	0	.001	.003	0	.002
Cu----------	.001	.0003	.0007	.001	.01	.003	.0007	.001	.0003	.003	.003
Ga----------	0	0	0	0	0	0	0	.001	.001	0	<.001
La----------	0	.03	<.03	0	0	0	0	.01	0	0	<.01
Ni----------	.003	0	<.003	.001	.001	.001	0	0	0	0	<.001
Pb----------	.001	0	<.001	0	.001	.001	0	0	0	0	<.001
Sc----------	0	0	0	0	0	.001	0	.001	.001	0	<.001
Sr----------	.01	.03	.02	.03	.03	.03	.003	.03	.1	.03	.04
V-----------	0	0	0	.001	.001	.001	0	.003	.003	0	.0015
Y-----------	0	0	0	.001	.001	.001	0	.03	.01	0	.007
Yb----------	0	0	0	.0001	.0001	.0001	0	.003	.0003	0	.0006
Zr----------	.003	0	<.003	.001	.001	.001	0	.003	.003	0	.0015

SAMPLE DESCRIPTIONS

Sample No.	Field No.	Description
1-----	SP-429-431---	Calcite from grayish-red sandstone, Salt Wash Member.
2-----	DV-96-998.7--	Thin calcite layer in reddish-brown mudstone, Salt Wash Member.
3-----	SP-433-531---	Calcite from light-brown carbonaceous sandstone, Salt Wash Member.
4-----	LE-439-526---	Calcite from light-gray sandstone, Salt Wash Member.
5-----	LE-445-557---	Calcite from light-brown sandstone, Salt Wash Member.
6-----	DVR-2-438----	Thin calcite layer in grayish-green mudstone, Burro Canyon Formation.
7-----	DVR-2-439----	Calcite-rich grayish-green mudstone, Burro Canyon Formation.
8-----	DVR-2-486----	Light-greenish-gray limestone, Burro Canyon Formation
9-----	MA-1---------	Calcite from septarian nodule, lower part of the Mancos Shale.

TABLE 4.—*Average volume percent of heavy minerals in the heavy fraction and average weight percent of heavy fraction from samples of sandstone of the red-beds facies from one Permian and several Jurassic units*

[Number of samples shown in parentheses. m, minor, indicates less than 0.5 percent; leaders (--) indicate not detected]

	Cutler Formation	Entrada Formation		Morrison Formation					Average volume percent of heavy-mineral fraction	Average weight percent of total rock
		Dewey Bridge Member	Slick Rock Member	Salt Wash Member			Brushy Basin Member			
				Lower unit	Middle unit	Upper unit[1]	Lower brown unit[1]	Middle green unit		
	(1)	(1)	(5)	(12)	(17)	(66)	(24)	(3)	(129)	
	Average volume percent of heavy minerals in heavy fraction									
Black opaque minerals-----	30.5	71	56	63.5	66	59	64	71	61	0.20
Zircon---------	5	20	9	9	12.5	14.5	13	9	13	.043
Tourmaline-----	m	1	5.5	6.5	4	4	2	1	4	.013
Apatite--------	.5	.5	2	1	1	1.5	1	1	1.5	.005
Rutile---------	.5	1	1.5	m	1	1	.5	.5	1	.003
Garnet---------	.5	----	----	m	m	m	m	----	----	----
Leucoxene------	9	4	11.5	9.5	6.5	6.5	4.5	3	6.5	.021
Barite---------	49.5	----	8.5	7	6.5	12	13.5	12.5	10	.033
Anatase--------	----	----	1	2	.5	1	1	1	1	.003
Spinel---------	----	----	----	.5	----	m	m	----	----	----
Pyrite---------	----	2	4.5	----	.5	m	m	----	----	----
Other minerals-	5.5	.5	.5	1	1.5	.5	.5	----	2	.007
	Average weight percent of heavy fraction									
Total sample---	0.58	0.35	0.14	0.32	0.30	0.31	0.38	0.8	0.33	----

[1]From Bowers and Shawe (1961, tables 5 and 6).

TABLE 5.—*Semiquantitative spectrographic analyses, in weight percent, of four samples of paramagnetic black opaque heavy minerals from red-beds-facies sandstone in the Morrison Formation, Slick Rock district*

[Analyses by Nancy M. Conklin. 0, looked for but not found (below limit of detectability). Also looked for but not found: K, P, Ag, As, Au, B, Be, Bi, Cd, Ce, Co, Dy, Er, Eu, Ga, Gd, Ge, Hf, Hg, Ho, In, Ir, La, Li, Lu, Mo, Nd, Os, Pd, Pr, Pt, Re, Rh, Ru, Sb, Se, Sm, Sn, Ta, Tb, Te, Th, Tl, Tm, U, W, Y, Yb, Zn. Elements not looked for: Na, Cs, F, Rb]

Field No---	[1]SH-4-55.a	[2]SH-4-55.b	[3]LE-431-568	[4]LE-431-586	Average
Si---------	0.7	0.7	0.7	0.7	0.7
Al---------	1.5	1.5	1.5	1.5	1.5
Fe---------	>10	>10	>10	>10	>10
Mg---------	1.5	1.5	.7	.7	1.1
Ca---------	.3	.3	.3	.3	.3
Ti---------	>10	7	7	7	>7
Mn---------	.7	.7	.3	.3	.5
Ba---------	.015	.015	.007	.015	.013
Cr---------	.15	.03	.07	.7	.24
Cu---------	.007	.015	.03	.015	.017
Nb---------	.03	.015	.015	.015	.019
Ni---------	.007	.007	.003	.007	.006
Pb---------	0	0	0	.015	<.015
Sc---------	.007	0	0	0	<.007
Sr---------	.0015	.0015	.007	.007	.004
V----------	.15	.15	.07	.15	.13
Zr---------	.3	.15	.3	.07	.21

[1]Sandstone sample from sandstone unit below ore-bearing sandstone, Salt Wash Member, Veta Mad area. Hematite concentrate, -200 mesh, -0.06 ampere Frantz separator fraction.
[2]Sandstone sample from sandstone unit below ore-bearing sandstone, Salt Wash Member, Veta Mad area. Hematite concentrate, -200 mesh, +0.06-0.15 ampere Frantz separator fraction.
[3]Sandstone sample from ore-bearing sandstone, Salt Wash Member, Legin area. Hematite concentrate, -200 mesh, +0.10-0.15 ampere Frantz separator fraction.
[4]Sandstone sample from ore-bearing sandstone, Salt Wash Member, Legin area. Hematite concentrate, -150+200 mesh, +0.25-0.35 ampere Frantz separator fraction.

perhaps these samples have been partly altered from their presumed oxidized condition as red-beds facies.

Heavy mineral content of siltstones and mudstones of the red-beds facies is presented in table 6. From the table it is plain that the relative abundances of heavy minerals are similar to those in sandstones of the red-beds facies (table 4).

TABLE 6.—*Average volume percent of heavy minerals in heavy fraction and average weight percent of heavy fraction from samples of mudstone and claystone of the red-beds facies, carbon facies, and altered facies from the Morrison Formation and Mancos Shale*

Number of samples shown in parentheses. m, minor, indicates less than 0.5 percent; leaders (--) indicate not detected]

	Morrison Formation						Mancos Shale
	Salt Wash Member			Brushy Basin Member			
	Red-beds facies (9)	Carbon facies (1)	Altered facies (2)	Red-beds facies (6)	Carbon facies (6)	Altered facies (1)	Altered facies (9)
Average volume percent of heavy minerals in heavy fraction							
Black opaque minerals----	56.5	40.5	3	53	51	1.5	m
Zircon--------	17.5	14.5	42	13	12.5	35.5	4.5
Tourmaline----	4	11.5	7.5	3.5	3	5.5	1
Apatite-------	2	5.5	2.5	1.5	2.5	3	3
Rutile--------	1.5	2.5	2	1	1	1	.5
Garnet--------	.5	1.5	m	1	1.5	.5	m
Leucoxene-----	9	20	13	7.5	11	13.5	3.5
Barite--------	5.5	m	21	18.5	17	33.5	1
Anatase-------	.5	----	3	m	.5	5.5	m
Spinel--------	----	----	.5	m	----	----	----
Pyrite--------	1	1	5	m	m	----	77
Other minerals	2	3	.5	1	----	.5	9.5
Average weight percent of heavy fraction							
Total sample--	0.17	0.03	0.06	0.20	0.17	0.17	1.2

Barite is a ubiquitous minor component in reddish-brown detrital rocks, where it occurs mostly as irregular white patches interstitial to detrital grains, and commonly is crowded with dustlike inclusions (leucoxene?) that impart a cloudy appearance to the barite. Among barite grains separated in heavy mineral fractions of the rocks, some crenate outlines suggest the original shape of a barite-filled space between rounded detrital grains of other minerals. In mudstone and siltstone of the red-beds facies an occasional crystal of authigenic barite is found (Shawe, 1968, fig. 24).

Anatase in reddish-brown sedimentary rocks of the Slick Rock district tends to be subhedral and generally interstitial to detrital grains. In places in these rocks anatase forms sparse minute euhedra.

The average chemical composition based on semiquantitative spectrographic analyses of 21 samples of red-beds-facies sandstone from some Mesozoic formations in the Slick Rock district is presented in table 7. Similarly, table 8 shows the average chemical composition of seven samples of red-beds-facies siltstones and mudstones. Most elements appear to be significantly more abundant in siltstones and mudstones than in sandstones, reflecting the greater abundance of carbonate and clay minerals in the finer grained sedimentary rocks. Of the elements detected, only magnesium, manganese, arsenic, barium, beryllium, and vanadium show comparable average abundances in the different grain-size variants.

Additional data on the vanadium content of red-beds rocks, and estimates of the uranium content of red-beds rocks, are presented and discussed in a later section describing relationships among rocks of the different facies.

CARBON-FACIES ROCKS

Carbon-facies rocks are widespread in the Slick Rock district, but only in the lower part of the Chinle Formation (Moss Back Member) and the upper part (ore-bearing sandstone) of the Salt Wash Member of the Morrison Formation. Outcrop distribution of the carbon facies is not shown in figure 4 inasmuch as it is megascopically indistinguishable from altered facies, but it can be inferred in part from plate 7 of Shawe, Simmons, and Archbold (1968). Sandstone in the upper part of the Salt Wash Member that is shown on that map as "altered", other than in the vicinity of ore deposits, is generally carbon facies. In addition parts of the ore-bearing sandstone of the Salt Wash Member below the surface in the northwestern part of Disappointment Valley, northwest of Horse Range Mesa, and west and southwest of Egnar on the Sage

TABLE 7.—*Average chemical composition, in weight percent, of sandstones of the red-beds facies in the Slick Rock district*

[Based on semiquantitative spectrographic analyses by Nancy M. Conklin (13 samples) and Joseph Haffty (8 samples). M, major; Tr, trace; 0, looked for but not found (below limit of detectability). Also looked for but not found: P, Au, Bi, Cd, Ce, Dy, Er, Eu, Gd, Ge, Hf, Hg, Ho, In, Ir, La, Li, Lu, Nd, Os, Pd, Pr, Pt, Rb, Re, Rh, Ru, Sb, Sm, Ta, Tb, Te, Th, Tl, Tm, U, W, Zn. Number of samples in parentheses]

	Navajo Sandstone (1)	Entrada Sandstone		Morrison Formation		Average (21)
		Dewey Bridge Member (3)	Slick Rock Member (5)	Salt Wash Member (7)	Brushy Basin Member (5)	
Si--------	>10	>10	>10	M	M	>10
Al--------	3	3	2.2	1.7	1.6	2
Fe--------	.7	1.3	.9	.8	.7	.9
Mg--------	1.5	1.6	.5	.5	.6	.7
Ca--------	3	2.1	1.1	2.3	1.4	1.8
Na--------	.15	.5	.4	.2	.6	.4
K---------	3	2.3	1.8	.9	.9	1.4
Ti--------	.15	.3	.12	.11	.08	.13
Mn--------	.07	.05	.008	.02	.03	.03
Ag--------	0	0	0	0	0	0
As--------	0	0	<.01	0	<.01	<.01
B---------	.003	.008	.003	.003	<.003	.003
Ba--------	.03	.03	.03	.04	.1	.06
Be--------	0	<.00015	0	0	0	<.00015
Co--------	Tr	<.0008	0	0	<.0007	<.0008
Cr--------	.003	.0048	.0016	.003	.002	.003
Cu--------	.0015	.0025	.0012	.002	.002	.0019
Ga--------	Tr	.0006	<.001	<.001	0	<.001
Mo--------	0	0	0	0	0	0
Nb--------	.0015	<.001	<.0015	<.0015	0	<.0015
Ni--------	.0007	.0022	<.001	.0005	<.001	.0009
Pb--------	Tr	.0013	<.0013	0	Tr	<.0013
Sc--------	0	.0008	0	0	0	<.0008
Sn--------	0	0	0	0	0	0
Sr--------	.007	.008	.004	.007	.01	.008
V---------	.003	.002	<.009	.005	.005	.004
Y---------	.0015	.003	<.0013	<.0015	<.0015	.0013
Yb--------	.00015	.0003	<.00018	<.00015	<.00015	.00014
Zr--------	.03	.03	.027	.012	.009	.018

Plain, and some other horizons in the Morrison and Chinle Formations elsewhere, are identified as carbon facies on the basis of drill logs and heavy-mineral studies of drill cores. None of the carbon-facies rocks studied in drill cores were collected closer than several hundreds of feet horizontally or several tens of feet vertically from mineralized layers in the same sandstone unit.

Carbon-facies sandstone is light gray or locally light buff to light brown. Black opaque minerals are moderately abundant in carbon-facies sandstones (35 percent of the average heavy-mineral content compared to 2.5 percent in altered facies sandstone and 61 percent in red-beds-facies sandstone), but hematite is absent in the matrix or coating sand grains of these rocks. The detrital black opaque minerals are inferred to be largely magnetite and ilmenite, although no analytical data are available to show what species are present. Some of the detrital black opaque minerals are ferromagnetic. Pyrite (1 percent of the average heavy-mineral content) is more abundant than in red-beds-facies rocks (about 0.5 percent) and less abundant than in altered-facies rocks (9.5 percent). The light-gray color of carbon facies sandstone probably formed diagenetically under reducing conditions associated with local accumulations of carbonaceous material, and the local buff or brown colors are formed by near-surface oxidation of pyrite to limonite. The rock may have lost some black opaque minerals by action of (probably) connate solutions, by which released iron formed pyrite, but no hematite formed as coatings on other detrital grains as it did in red-beds-facies sandstone. Siltstone and mudstone of the carbon facies are gray to greenish gray. They too are mineralogically similar to, and by inference probably also akin chemically to, sandstone of the carbon facies, and differ from sandstone principally in smaller grain size and higher clay content.

Clay minerals in carbon-facies rocks are probably similar to those in red-beds-facies rocks which are

TABLE 8.—*Average chemical composition, in weight percent, of siltstones and mudstones of the red-beds facies in the Slick Rock district*

[Based on semiquantitative spectrographic analyses by Joseph Haffty. M, major; 0, looked for but not found (below limit of detectability). Also looked for but not found: P, Au, Bi, Cd, Ce, Dy, Er, Eu, Gd, Ge, Hf, Hg, Ho, In, Ir, Li, Lu, Nd, Os, Pd, Pr, Pt, Rb, Re, Rh, Ru, Sb, Sm, Ta, Tb, Te, Th, Tl, Tm, U, W, Zn. Number of samples in parentheses]

| | Morrison Formation | | Burro Canyon Formation | Average |
	Salt Wash Member (3)	Brushy Basin Member (3)	(1)	(7)
Si-----	M	M	M	M
Al-----	3	10	10	7
Fe-----	1	3	3	2
Mg-----	.5	1	1	.8
Ca-----	10	.3	3	5
Na-----	1	1	1	1
K------	3	2	3	3
Ti-----	.2	.3	.3	.3
Mn-----	.03	.03	.01	.03
Ag-----	0	0	0	0
As-----	0	<.01	0	<.01
B------	.005	.008	.01	.007
Ba-----	.03	.05	.01	.04
Be-----	0	<.0001	.0001	<.0001
Co-----	.001	.002	.003	.002
Cr-----	.008	.01	.01	.009
Cu-----	.003	.003	.003	.003
Ga-----	.001	.003	.003	.002
La-----	0	<.01	0	<.01
Mo-----	0	0	0	0
Nb-----	0	0	0	0
Ni-----	.003	.003	.003	.003
Pb-----	0	.001	0	<.001
Sc-----	.002	.003	.003	.002
Sn-----	0	0	0	0
Sr-----	.03	.03	.03	.03
V------	.005	.002	.001	.003
Y------	.003	.003	.003	.003
Yb-----	.0002	.0003	.0003	.0003
Zr-----	.02	.03	.03	.03

kaolinite, illite, montmorillonite, and chlorite.

Silica cement is common in sandstones of the carbon facies, generally making up about 10 percent of the rock. Much of it forms overgrowths with irregular, sutured boundaries on detrital quartz grains; well-formed facets on overgrowths are not abundant (Shawe, 1968, figs. 15, 19). Some interstitial silica occurs as very small interlocking quartz crystals in the manner of chalcedony.

Calcite varies considerably in abundance in rocks of the carbon facies. It commonly occurs in sandstones as small scattered and isolated blebs although in a few places it may constitute as much as 20 percent of the rock (Shawe, 1968, figs. 15, 19, 20). No data are available for the average contents of carbonate minerals in sandstones, siltstones, and mudstones of the carbon facies, but they may be close to those given for red-beds-facies rocks as shown in table 2. Chemical composition of calcite separated from light-brown carbon facies sandstone of the Salt Wash Member is given in table 3.

Carbonate that occurs as detrital grains does not appear to be as abundant in carbon-facies rocks as in red-beds-facies rocks, although in parts of the Moss Back Member of the Chinle Formation some calcarenites of the carbon facies of course contain abundant carbonate detritus.

Calcite metacrysts in carbonaceous claystone collected from a rare layer of what is likely carbon-facies rock near the middle of the Burro Canyon Formation from drill core of diamond-drill hole DVR-2 in Disappointment Valley probably formed during extreme compaction at the time of maximum burial of the rocks (Shawe, 1968, p. B26, and fig. 36).

Heavy-mineral content of carbon facies sandstone is summarized in table 9.

Barite is a common and widespread white mineral in carbon-facies rocks in which it is more than twice as abundant as in red-beds-facies rocks. Much of it in sandstones is subhedral to euhedral, showing multiple crystal facets, although large well-shaped crystals are rare. The barite is generally crowded with numerous dustlike inclusions that are likely leucoxene (or microcrystalline anatase). Crystals occur interstitially to detrital grains of other minerals, and also have partly replaced quartz, chert, and plagioclase detrital grains (Shawe, 1968, fig. 15).

Anatase like barite is common and widespread in carbon-facies rocks and is more than twice as abundant in these than in red-beds-facies rocks. It occurs mostly as subhedral to euhedral crystals interstitial to and rimming detrital grains of other minerals and as aggregates of minute crystals replacing other minerals (Shawe, 1968, figs. 19, 20). Anatase commonly occurs as tiny euhedra perched on leucoxene grains.

Pyrite is sparse and is distributed erratically in carbon-facies rocks. It forms anhedral to euhedral crystals interstitial to or replacing other minerals and, commonly, blebs filling cell spaces in carbonized wood fragments, or replacing such fragments.

The average chemical composition based on semiquantitative spectrographic analyses of only four samples of carbon facies sandstone from the Morrison Formation in the Slick Rock district is presented in table 10. No data are available to indicate chemical composition of siltstones and mudstones of the carbon facies.

ALTERED-FACIES ROCKS

Generalized outcrop distribution of altered-facies rocks in the Morrison Formation in the north part of the Slick Rock district is indicated in figure 4. Additional details of distribution are shown on plate 7 of Shawe, Simmons, and Archbold (1968); on that map most of the rocks mapped as "altered" below the top sandstone unit (ore-bearing sandstone) of the Salt Wash Member, and most of the top sandstone unit in the vicinity of uranium-vanadium deposits, are altered facies in the sense described here. As stated in the introduction to this report, virtually all of the Burro

TABLE 9.—*Average volume percent of heavy minerals in the heavy fraction and average weight percent of heavy fraction from samples of sandstone of the carbon facies from some Mesozoic units*

[Number of samples shown in parentheses. m, minor, indicates less than 0.5 percent; leaders (--) indicate not detected]

	Chinle Formation	Morrison Formation			Average volume percent of heavy-fractions	Average weight percent of total rock
	Petrified Forest(?) Member	Salt Wash Member		Brushy Basin Member		
		Middle unit	Upper unit[1]	Lower brown unit[1]		
	(2)	(7)	(32)	(32)	(73)	
Average volume percent of heavy minerals in heavy fraction						
Black opaque minerals----	40	32	42	29	35	0.10
Zircon--------	12	17.5	20	16.5	18	.050
Tourmaline----	2.5	2.5	6	5	5	.014
Apatite-------	5	1	1.5	1.5	1.5	.004
Rutile--------	4	1.5	1	.5	1	.003
Garnet--------	8	.5	m	.5	----	----
Leucoxene-----	12	8	9	8	8.5	.024
Barite--------	3	34	18	34	26	.073
Anatase-------	4	1	1.5	3.5	2.5	.007
Spinel--------	----	----	m	m	----	----
Pyrite--------	6.5	.5	1	1	1	.003
Other minerals	3	1.5	m	.5	1.5	.004
Average weight percent of heavy fraction						
Total sample--	0.06	0.15	0.16	0.45	0.28	----

[1]From Bowers and Shawe (1961, tables 5 and 6).

TABLE 10.—*Average chemical composition, in weight percent, of sandstones of the carbon facies in the Slick Rock district*

[Based on semiquantitative spectrographic analyses by M, major; 0, looked for but not found (below limit of detectability). Also looked for but not found: P, Au, Bi, Cd, Ce, Dy, Er, Eu, Gd, Ge, Hf, Hg, Ho, In, Ir, Li, Lu, Nd, Os, Pd, Pr, Pt, Rb, Re, Rh, Ru, Sb, Sm,·Ta, Tb, Te, Th, Tl, Tm, U, W, Zn. Number of samples in parentheses]

	Morrison Formation				Morrison Formation		
	Salt Wash Member (1)	Brushy Basin Member (3)	Average (4)		Salt Wash Member (1)	Brushy Basin Member (3)	Average (4)
Si---	M	M	M	Cr---	0.001	0.002	0.002
Al---	1	2	2	Cu---		.003	.002
Fe---	1	2	2	Ga	0	.001	<.001
Mg---	.1	.2	.15	La---	0	0	0
Ca---	.3	5	4	Mo---	0	0	0
Na---	.1	1	1	Nb---	0	0	0
K----	0	.7	.6	Ni---	.001	.001	.001
Ti---	.01	.14	.11	Pb---	.003	<.001	.001
Mb---	.01	.12	.09	Sc---	0	.001	.001
Ag---	0	<.00001	<.00001	Sn---	.01	0	<.01
As---	0	0	0	Sr---	.03	.05	.05
B----	0	0	0	V----		.001	.001
Ba---	.03	.12	.10	Y----	0	.001	.001
Be---	0	0	0	Yb---	0	.0001	.0001
Co---	0	<.001	<.001	Zr---	.01	.01	.01

Canyon Formation, the Dakota Sandstone, and the Mancos Shale appear to be altered-facies rocks, a fact to receive considerable attention in following pages because the Burro Canyon Formation contains practically no indigenous carbonaceous material but the Dakota Sandstone and Mancos Shale do contain indigenous carbonaceous material, and all are virtually devoid of uranium-vanadium deposits.

Altered-facies rock samples that were studied for heavy-mineral content and analyzed spectrographically for chemical composition were collected either from strata where grayish colors are clearly the result of alteration controlled by fractures, or from strata in which grayish colors formed in the axial region of the Dolores anticline, or from strata of grayish color within several hundreds of feet horizontally or several tens of feet vertically of mineralized layers in the same sandstone unit. In addition most of the samples collected from the formations of Cretaceous age (Burro Canyon, Dakota, Mancos) are considered to be of the altered facies as will be demonstrated in later pages.

Altered-facies sandstone is light gray or, where weathered, also light buff to light brown. It contains only a small amount of black opaque heavy minerals and some pyrite, and may or may not contain carbonaceous material. Uranium-vanadium deposits in the Morrison Formation, and probably in the Chinle Formation, occur in altered-facies sandstone, but only where the altered facies was developed in earlier carbon-facies sandstone. Altered-facies sandstone, although it initially may have been either light gray in the vicinity of carbonaceous material or light reddish brown elsewhere, appears to have originated from the action of introduced solutions that were largely

confined in zones of faults, in the axial region of the Dolores anticline, or in laterally extensive permeable sandstone units. The solutions leached most of the black opaque minerals from the sandstone, and where the sandstone was originally reddish, they also bleached the sandstone by destruction of hematite. No color change occurred where leaching of black opaque minerals took place in rock that was initially light gray. The light-buff to light-brown colors are imparted by limonite formed from oxidation of pyrite in weathered rock. Of the altered facies samples examined in this study, those collected below the water table contained pyrite and those collected above the water table contained limonite pseudomorphs after pyrite. Siltstone and mudstone of the altered facies are gray to greenish gray and are mineralogically and chemically akin to sandstone of the facies except for smaller grain size and higher clay content. They are found mainly as selvages against sandstone of the altered facies.

Altered-facies rocks are probably gradational to both red-beds- and carbon-facies types. Altered- and carbon-facies rocks may be difficult to distinguish in some places.

Clay minerals in altered-facies rocks, as in red-beds-facies rocks, are kaolinite, illite, montmorillonite, and chlorite (Keller, 1959); montmorillonite and mixed-layer derivatives appear to dominate in the Brushy Basin Member and illite (hydromica) and mixed-layer derivatives in the Salt Wash Member (data of A. D. Weeks, *in* Waters and Granger, 1953, p. 4; Keller, 1962, pl. 1; p. 39). The apparent similarity between clay minerals in red-beds-facies rocks and altered-facies rocks discouraged any additional studies of clays in sedimentary rocks in the Slick Rock district. Keller (1962, p. 62) pointed out that sedimentary rocks dominated by illitic clays signify derivation from a sedimentary-rock source and sedimentary rocks dominated by montmorillonitic clays signify derivation from a volcanic-rock (chiefly air-fall ash) source. Keller also suggested that kaolinite in the sedimentary rocks indicated an environment of leaching, perhaps by either ground water or hydrothermal solutions, but no data were acquired in the Slick Rock district to evaluate this possibility.

Keller (1962, p. 45 - 57) showed that the greenish colors of altered rocks are due mainly to the presence of iron-bearing clay minerals; in red-beds-facies rocks the greenish colors are masked by iron oxide.

Silica cement is widely distributed in sandstones of the altered facies and constitutes 5 - 15 percent of most rocks. Such secondary (authigenic) silica occurs chiefly as overgrowths on detrital quartz grains,

commonly joining adjacent overgrowths along irregular boundaries but also in many places displaying well-formed facets (fig. 5; Shawe, 1968, fig. 34). Some altered-facies rocks contain such numerous faceted overgrowths on quartz grains that the rocks glisten in sunlight. Locally silica overgrowths completely fill pore space between quartz grains so that the rock is a quartzite. A minor amount of interstitial silica is chalcedonic in character. The pore space in some carbonized cellular plant material has been filled with fine-grained silica.
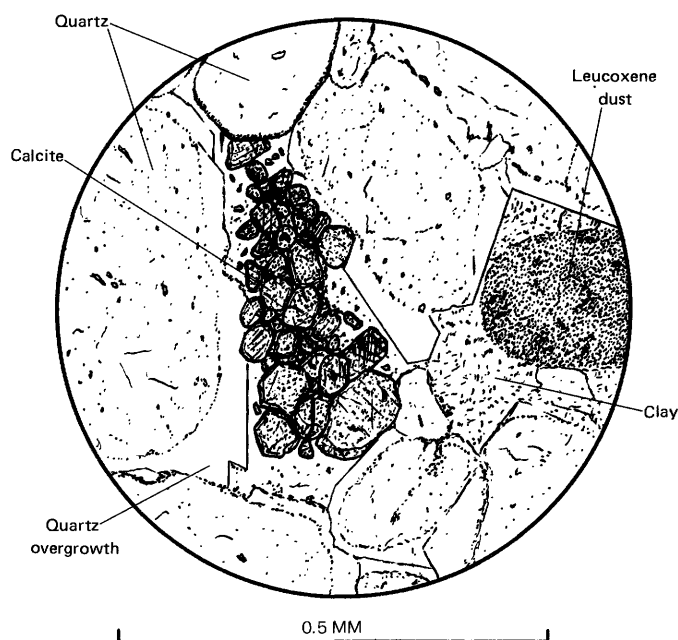
FIGURE 5.—Altered-facies sandstone from the top sandstone unit of the Salt Wash Member, showing faceted silica overgrowths on detrital quartz grains and authigenic interstitial euhedral calcite crystals. Sample C-32, 2 feet (0.6 m) from uranium-vanadium ore in the Cougar mine.

Solution effects on detrital quartz grains in the form of irregular embayments (Shawe, 1968, fig. 13) are widespread and abundant even in rocks where silica overgrowths are numerous, suggesting local derivation of much of the secondary silica. Some overgrowths themselves have been partly dissolved, indicating the likelihood of at least two stages of post-depositional silica solution and precipitation. Stylolites that formed where adjacent quartz grains mutually penetrate as a result of dissolution of silica show a common orientation normal to bedding, indicating that compression of the stylolites resulted from compaction of the sediments. It is thus inferred that such solution of quartz occurred when the rocks were deeply buried and under high load pressure.

Silica segregations are common in mudstone of the

altered facies, where they rim patches of barite and calcite, or as chalcedonic quartz they fill or line small vugs (fig. 6; Shawe, 1968, figs. 28, 29).

Carbonate minerals, mostly calcite, are widely but irregularly distributed in rocks of the altered facies; they are nearly absent in many rocks but constitute as much as 20 percent or more in some. Where present in sandstone, as seen in thin sections, calcite mostly forms optically continuous patches 0.5–3 mm in diameter that enclose numerous detrital grains (Shawe, 1968, figs. 4, 9, 12, 16, 34, 39, 40). In a few places calcite segregations are numerous, and are conspicuous in outcrops because of their resistance to weathering (fig. 7). Detrital carbonate grains are not numerous in altered-facies rocks.

Calcite commonly replaces detrital grains of minerals such as chert, quartz, potassium feldspar, and particularly plagioclase (Shawe, 1968, figs. 4, 12). Small authigenic calcite rhombs are visible on some detrital carbonate grains in altered-facies sandstone. In one thin section of altered-facies sandstone collected close to mineralized rock, calcite forms small clusters of euhedral crystals interstitial to quartz grains displaying faceted overgrowths (fig. 5). Calcite segregations and vug fillings are common in mudstones of the altered facies (fig. 6; Shawe, 1968, figs. 27, 28, 29, 30, 32, 36, 38), where calcite appears to have been reconstituted within lime-rich mudstone as a result of alteration. In some thin layers of carbonaceous material interbedded with sandstone and mudstone of the Morrison Formation and Dakota Sandstone small vertical veinlets, 1 mm or more wide, of calcite are common. Minute rhombs of dolomite have been observed in a thin section of dark-gray carbonaceous mudstone from the Salt Wash Member. Bladed crystals of (probably) siderite were observed in a thin section of altered-facies mudstone from the Brushy Basin Member (Shawe, 1968, fig. 32).

In places in altered-facies sandstone, calcite patches enclose detrital quartz grains that do not have quartz overgrowths even though surrounding quartz grains display numerous overgrowths. Sandstone grains outside the calcite patches also are better packed than those within the patches, and locally show evidence of solution, such as interpenetration of adjacent grains. Apparently the calcite protected the enclosed quartz grains from silica deposition, and hence the calcite was precipitated here earlier than was the secondary quartz; also the calcite inhibited compaction of enclosed grains while solution and redeposition of silica occurred concurrently nearby, and was accompanied by compaction. On the other hand, in other places matrix calcite is seen to surround quartz grains coated with overgrowths and locally even

embays faceted quartz overgrowths, showing that here secondary silica deposition preceded formation of matrix calcite.

Carbonate (dominantly calcite) content of altered-facies rocks is given in table 2. Average amounts of calcite in altered-facies rocks of the Morrison Formation are somewhat less than those in red-beds-facies rocks of the formation. Nevertheless, in altered-facies rocks, as in red-beds-facies rocks, calcite appears to be less abundant in mudstone than in sandstone of the Brushy Basin Member, whereas the reverse is true in the Salt Wash Member. Also, calcite is less abundant in both sandstone and mudstone in the ore-bearing sandstone than it is in similar rocks in higher and lower strata. The Mancos Shale, considered to be altered facies, averages much higher in calcite than other formations. Except for the interval of the Mancos equivalent to the lower part of the Carlile Shale (average about 2 percent calcite) most of the formation averages about 25 percent calcite.

The chemical composition of calcite separated from altered-facies rocks is presented in table 3. The composition is based on semiquantitative spectrographic analyses of six calcite samples: One in a septarian nodule from the Mancos Shale, two in grayish-green mudstone from the Burro Canyon Formation, one in light-gray limestone from the Burro Canyon Formation, and two in light-gray and light-brown sandstone from the Salt Wash Member.

Calcite (sample MA–1) collected from the core of a septarian nodule near the base of the Mancos Shale in the northwestern part of Disappointment Valley was studied by William Virgin of the U.S. Geological Survey in 1957 using a Kofler micro-hot-stage to determine homogenization temperatures of fluid inclusions. The temperature of disappearance of the vapor phase in several very small inclusions was approximately 120°C.

Authigenic potassium feldspar and albite occur locally in rocks of the altered facies. In places feldspars replace detrital mineral grains but more commonly they occur as subhedral to euhedral crystals growing in the interstices of detrital rocks or as overgrowths on detrital feldspars (Shawe, 1968, figs. 22, 23). Tiny authigenic albite laths occur in a limestone nodule within mudstone of the altered facies in the Brushy Basin Member (Shawe, 1968, fig. 33), and authigenic albite has overgrown detrital orthoclase grains in the limestone nodule. Potassium feldspar occurs as small authigenic euhedral crystals bordering barite crystals in altered-facies mudstone of the Brushy Basin Member.
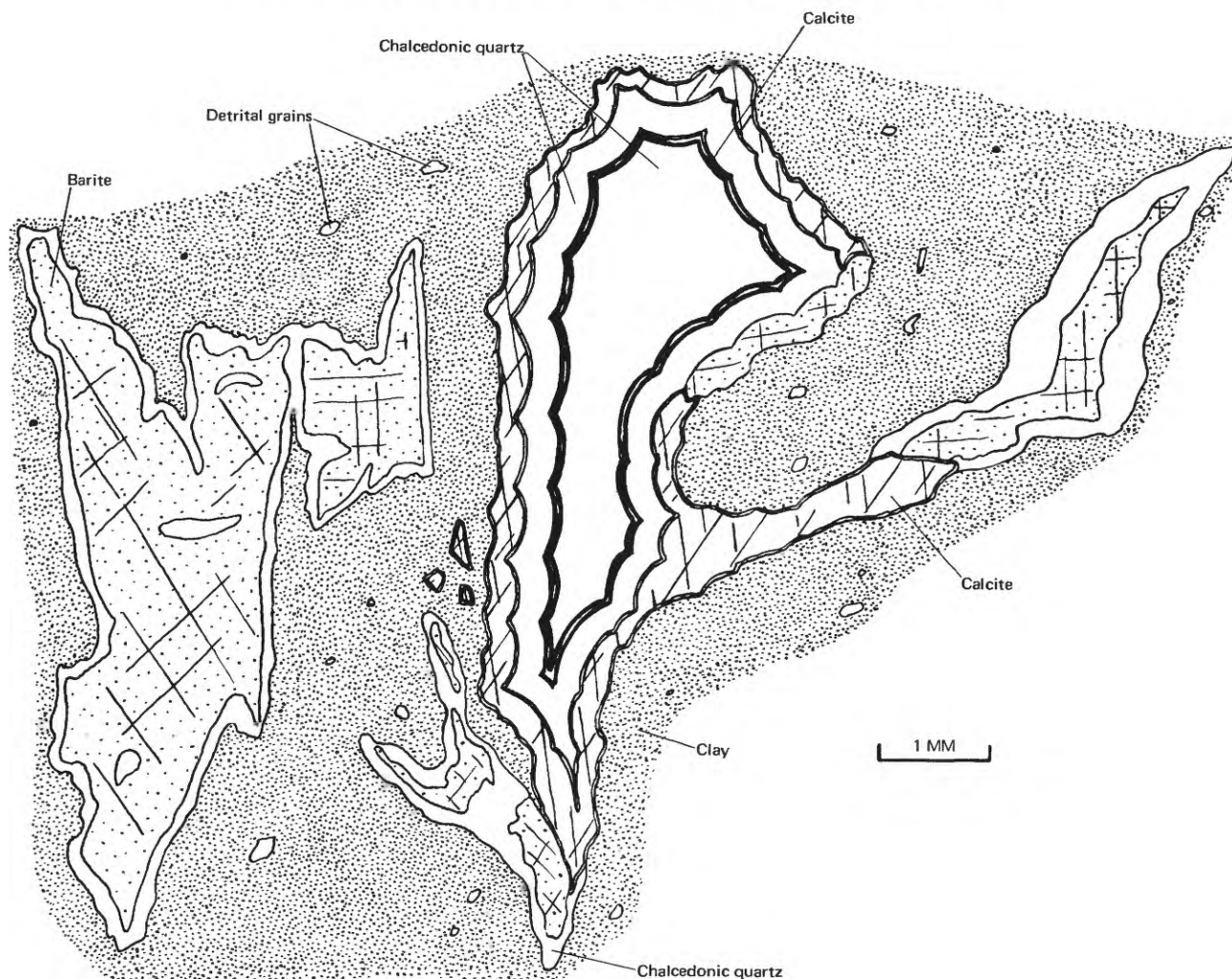
FIGURE 6.—Barite, calcite, and chalcedonic quartz segregations and vug fillings in light-greenish-gray altered-facies mudstone of the middle green unit of the Brushy Basin Member. Sample DV–2–BB, Disappointment Valley.

FIGURE 7.—Calcite segregations in altered-facies sandstone in the lower part of the Salt Wash Member, Summit Canyon.

Analcite is found as segregations in altered-facies mudstone (Shawe, 1968, fig. 28). Chlorite, in places constituting as much as 5 percent of the rock, occurs as authigenic segregations in mudstones associated with authigenic barite, calcite, and chalcedonic quartz (Shawe, 1968, figs. 27, 28) and in patches interstitial to detrital grains in coarser grained clastic rocks. An authigenic mica of unknown identity is a minor component of some carbonaceous sandstones of the altered facies in the Dakota Sandstone (Shawe, 1968, fig. 41).

Heavy-mineral content of altered-facies sandstone is summarized in table 11. Black opaque minerals, as detrital grains, probably chiefly magnetite, ilmenite, and hematite, are sparse in altered-facies sandstones (2.5 percent of the average heavy-mineral fraction compared to 35 percent in carbon-facies sandstone and 61 percent in red-beds-facies sandstone), and hematite is absent in the matrix or coating sand grains of these

rocks. Pyrite and pyrite pseudomorphs (9.5 percent of the average heavy-mineral fraction) is much more abundant than in carbon-facies sandstone (1 percent) and red-beds-facies sandstone (about 0.5 percent). This mineralogic distribution of iron, as in carbon-facies sandstone, accounts for the light-gray to light-greenish-gray colors of the rocks, or light-brown to light-yellowish-brown colors where weathered.

Barite is widespread in altered-facies rocks in about the same abundance as in red-beds-facies rocks, but is commonly well crystallized or forms segregations several millimetres in size and rarely a few centimetres in size. In sandstone white barite tends to form euhedral crystals interstitial to or partly replacing detrital grains (fig. 8). In mudstone white barite forms anhedral to euhedral crystals, or segregations where it is associated with calcite and chalcedonic quartz (fig. 6; Shawe, 1968, figs. 25, 26, 27); barite in mudstone has replaced matrix clay and detrital minerals.

Barite (sample SH‑61‑55) collected from the Mancos Shale near drill-hole DVR‑1 in Disappointment Valley analyzed by the semiquantitative spectrographic method by Joseph Haffty of the U.S. Geological Survey contains major barium, 0.0003 percent aluminum, 0.0003 percent copper, and 0.07 percent strontium; no other elements were detected. Homogenization temperatures of very small fluid inclusions in this barite, determined by William Virgin of the U.S. Geological Survey in 1957 using a Kofler micro-hot-stage, ranged from 120° to 125°C. Larger fluid inclusions in the same material probably homogenized near 230°C, and this was the temperature of decrepitation of the crystal. A temperature of 230°C seems geologically improbable for the environment in which this barite is known to have resided since formation; perhaps leakage from the larger fluid inclusions accounted for the improbably high indicated temperature.

Anatase is a common authigenic mineral in altered-facies sandstone, where it has about the same average abundance as in red-beds-facies rocks. Locally in altered-facies sandstone near uranium-vanadium deposits are layers that contain much more than average amounts of anatase. In altered-facies sandstone, anatase is mostly euhedral and forms tiny crystals commonly embedded in authigenic matrix minerals such as calcite (Shawe, 1968, fig. 40).

Pyrite is moderately abundant and widely though erratically distributed in altered-facies rocks. In weathered rocks as observed in thin sections pyrite has been replaced by "limonite," but preservation of original pyrite crystal forms and lack of abundant limonite "wash" or dustlike limonite suggest that the forms of most limonite are indicative of the original
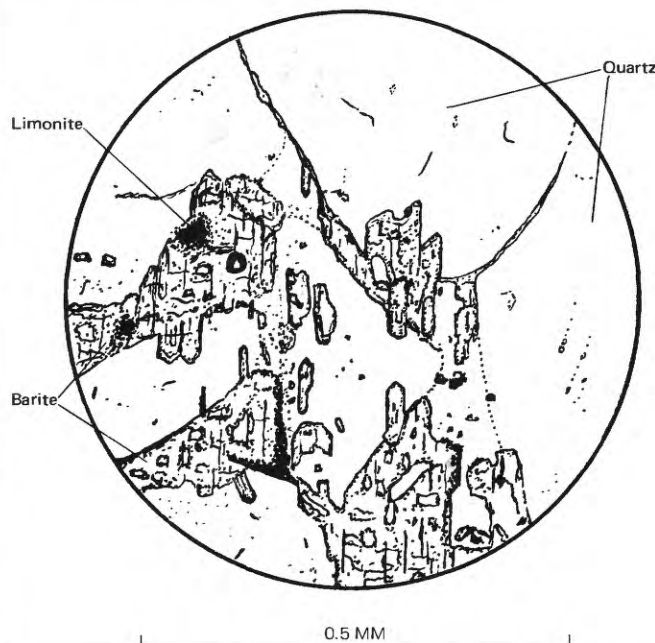
FIGURE 8.—Oriented barite crystals interstitial to and partly replacing quartz grains in altered-facies sandstone of the ore-bearing sandstone of the Salt Wash Member. Sample C‑28, 1 foot (0.3 m) from uranium-vanadium ore in the Cougar mine.

forms of pyrite before oxidation. Pyrite (or limonite) in sandstone occurs as isolated interstitial patches as much as 2 mm in diameter enclosing many detrital grains, or as cubes 1 mm across and smaller that are mainly interstitial but that also partly replace detrital grains (Shawe, 1968, figs. 9, 13, 35). In places altered-facies sandstone of the Salt Wash Member contains aggregates of minute tetrahedra of pyrite. Pyrite in altered-facies mudstone is found as tiny formless blebs (Shawe, 1968, figs. 27, 38, 42, 43, 44, 45), and as minute cubes, or aggregates of cubes as much as 5 x 10 mm in size. Locally pyrite cubes in Mancos Shale may be as large as 1 cm in size. Some cubes in Mancos Shale push aside bedding laminae, indicating the likelihood that pyrite formed here before sediment compaction, but many cubes do not appear to displace bedding laminae and they probably formed by replacement. Some pyrite has replaced foraminifera tests in Mancos Shale. Locally fractures in Mancos Shale that are filled with calcite are bordered by disseminated pyrite (for example, Shawe, 1968, p. B31 and fig. 46), showing that pyrite was deposited after consolidation of the shale. Some fractures in other formations have been filled with pyrite.

In addition to pyrite some marcasite is found in altered-facies rocks. In most cases the two are not distinguishable except by X-ray analysis; minute spherical forms in some mudstones and sandstones are probably marcasite (Shawe, 1968, fig. 18). Cockscomb-

TABLE 11.—*Average volume percent of heavy minerals in heavy fraction and average weight percent of heavy fraction from samples of sandstone of the altered facies from several Mesozoic units*

[Number of samples shown in parentheses. m, minor, indicates less than 0.5 percent: leaders (--) indicate not detected]

	Chinle Formation Moss Back Member (4)	Wingate Sandstone (1)	Entrada Sandstone Slick Rock Member (2)	Morrison Formation Salt Wash Member Lower unit (1)	Morrison Formation Salt Wash Member Upper unit[1] (74)	Burro Canyon Formation (7)	Dakota Sandstone (6)	Average volume percent of heavy-mineral fractions (95)	Average weight percent of total rock
			Average volume percent of heavy minerals in heavy fraction						
Black opaque minerals-----	4.5	4	1	2.5	2	6	5	2.5	0.003
Zircon---------	24	23	22	31	31	29	24.5	30	.036
Tourmaline-----	4	26	12	10	8	7.5	4	8	.010
Apatite--------	3.5	4	1	3	2	1.5	2	2	.002
Rutile---------	4	3	2	m	1	.5	.5	1	.001
Garnet---------	2.5	1	----	----	.5	m	m	----	----
Leucoxene------	21.5	20	16	19	13.5	17.5	14	14.5	.017
Barite---------	18	2	15	21.5	29.5	32	3	27	.032
Anatase--------	1.5	9	6	8.5	4	.5	2	3.5	.004
Spinel---------	----	2	----	2	m	----	----	----	----
Pyrite---------	14	[2]6	[2]15	----	7	2	44.5	9.5	.011
Other minerals-	2.5	----	1C	2.5	1.5	3.5	.5	2	.002
			Average weight percent of heavy fraction						
Total sample---	0.28	([3])	0.16	0.05	0.11	0.08	0.14	0.12	----

[1]From Bowers and Shawe (1961, table 5).
[2]Limonite pseudomorphs after cubic pyrite.
[3]Not determined.

shaped limonite pseudomorphs after marcasite have been recognized in vugs in altered-facies sandstone of the Burro Canyon Formation.

Chemical composition of pyrite separated from rocks of the altered facies is given in table 12.

In the analyses given in table 12, presence and relative amounts of silicon, aluminum, magnesium, calcium, sodium, titanium, barium, chromium, strontium, vanadium, zirconium, and perhaps other elements, indicate the presence and relative amounts of impurities not separated from the analyzed pyrites, such as quartz, clay minerals, carbonate minerals, feldspars, titanium oxides, barite, zircon, and other minerals. Iron, of course, is the principal metallic element of pyrite, and minor elements likely present in the pyrite structure are manganese, silver, arsenic, cobalt, molybdenum, nickel, lead, selenium, and zinc.

A composite sample of pyrite made up of eight samples (collected from diamond-drill hole DVR – 1) of pyrite separated from the lower part of the Mancos Shale (Greenhorn Limestone equivalent), analyzed by chemical methods in the U.S. Geological Survey's Washington laboratories, contained 0.003 percent lead and 0.0002 percent uranium (T. W. Stern, written commun., July 1963).

The average chemical composition based on semiquantitative spectrographic analyses of 35 samples of altered-facies sandstones from Mesozoic formations in the Slick Rock district is presented in table 13. A similar table (table 14) shows the average chemical composition of 14 samples of altered-facies siltstones, mudstones, and claystones. As in the comparison of element abundances of red-beds-facies sandstone to those of finer grained red-beds-facies rocks, altered-facies sandstone contains less of most elements than does altered-facies siltstone, mudstone, and claystone. A few elements, such as magnesium, manganese, barium, lead, and zirconium, show comparable average abundances among the grain-size variants.

Additional data on the vanadium content of altered-facies rocks and estimates of the uranium content of altered-facies rocks are presented and discussed in later pages dealing with relationships among rocks of the different facies.

The chemical compositions of three samples of sandstone, siltstone, and mudstone that appear to be only partly altered (on the basis of reddish-gray color compared to reddish-brown of red-beds-facies sandstone and light-gray or greenish-gray of altered-facies rocks) are shown in table 15.

RELATIONSHIPS AMONG RED-BEDS-, CARBON-, AND ALTERED-FACIES ROCKS

GENERAL RELATIONSHIPS

Whereas the carbon facies within the red-beds section is developed only in sedimentary rocks in

TABLE 12.—*Semiquantitative spectrographic analyses, in weight percent, of 17 samples of pyrite and 1 sample of goethite from altered-facies rocks of several Mesozoic formations, Slick Rock District*

[Analyses by Joseph Haffty (17 samples) and Nancy M. Conklin (1 sample). 0, looked for but not found (below limit of detectability). Also looked for but not found: K, P, B, Be, Bi, Cd, Ce, Cs, Dy, Er, Eu, Gd, Ge, Hf, Hg, Ho, In, Ir, La, Li, Lu, Nb, Nd, Os, Pd, Pr, Pt, Rb, Re, Rh, Ru, Sb, Sm, Ta, Tb, Te, Th, Tl, Tm, U, W. Number of samples in parentheses].

| | Chinle Formation | Morrison Formation | Burro Canyon | Mancos Shale | | | | |
| | Moss Back Member | Salt Wash Member | Formation | Greenhorn Limestone equiv. | Lower part, Carlile Shale equiv. | Upper part, Carlile Shale equiv. | Lower part, Niobrara Fm. equiv. | Average |
	(3)	(2)	¹(1)	(2)	(2)	(4)	(4)	(18)
Si-----	0.3	0.03	0.7	1.9	3	1.8	0.1	1.1
Al-----	.2	.2	.03	.3	.5	.4	.3	.3
Fe-----	>10	>10	>10	>10	>10	>10	>10	>10
Mg-----	.02	.005	.15	.03	.2	.1	.1	.09
Ca-----	<.07	.03	.07	.2	.03	.4	.8	.3
Na-----	0	0	0	0	.2	<.007	<.03	<.03
Ti-----	.1	.03	.003	.02	.2	.2	.02	.09
Mn-----	.002	.003	.03	.003	.02	.02	.01	.01
Ag-----	0	.00015	.0015	.00004	<.00003	.0008	<.00003	.0003
As-----	.03	.3	0	0	0	<.03	0	.02
Au-----	0	0	0	0	0	<.03	0	0
Ba-----	.21	.17	.007	.005	.007	.03	.09	.08
Co²----	<.001	0	.003	<.001	.001	.003	<.001	.001
Cr-----	.003	.0007	.0007	<.003	0	.003	.0005	.0015
Cu-----	.004	.003	.03	.02	.003	.09	.006	.03
Ga-----	0	0	<.001	0	0	0	0	0
Mo-----	.01	.03	.007	0	.03	.03	.02	.02
Ni²----	.001	<.001	.003	.005	.003	.02	.004	.006
Pb-----	<.007	.003	.03	.003	.003	.006	.03	.01
Se²----	.0035	.016	(³)	.0015	.001	.003	.016	.007
Sn-----	0	0	0	0	0	<.03	0	0
Sr-----	.004	<.003	.007	<.003	.003	<.005	.008	.004
V------	.004	0	<.003	0	0	<.003	0	<.003
Y------	0	0	.0015	0	0	.004	<.003	<.003
Yb-----	0	0	<.001	0	0	0	0	0
Zn-----	0	.03	.15	.015	0	.09	0	.03
Zr-----	<.007	.03	0	<.003	.003	.04	.02	.02

¹ Goethite after marcasite
² Colorimetric chemical analyses by Maryse Delevaux.
³ Not determined.

which carbonaceous material, particularly carbonized plant debris, is present, and the red-beds facies is generally present in sedimentary rocks devoid of carbonaceous material, the altered facies is commonly found in laterally extensive permeable sandstone layers, particularly in the upper parts of such sandstone layers, in the mudstone selvages of these layers, and also bordering fractures in the sandstone layers. The distribution of altered-facies rocks within the red-beds section thus is clearly related to permeable zones in the sedimentary rocks, and this distribution implies that alteration resulted from the flow of certain solutions through permeable zones after consolidation of the rocks. Carbon-facies and red-beds-facies rocks appear to exhibit indigenous traits reflecting the initial and early characters of the rocks, and altered-facies rocks possess the attributes of changes superimposed at a later time on the other two types.

Thick and laterally extensive sandstone formations are widely altered in their upper parts, especially in the axial region of the Dolores anticline where entire formations may consist of altered-facies sandstone. On the other hand, in the axial region of the Disappointment syncline, much of these formations is red-beds-facies sandstone. Although the Wingate sandstone consists of light-reddish-brown or light-orangish-brown (red-beds-facies) sandstone throughout most of the Slick Rock district, in places in the Dolores River canyon the top few feet consists of light-buff (altered-facies) sandstone. In parts of Summit Canyon more of the upper part appears to be light buff. These areas coincide with the axial region of the Dolores anticline.

The Navajo Sandstone is mostly light brown and is interpreted to be of the altered facies in most parts of the district, for example throughout Summit Canyon and most of the Dolores River canyon as far south as Big Canyon. Locally in Summit Canyon parts of the Navajo are light reddish brown between joints that are bordered by bleached rock (fig. 16). These fractures range in orientation from N. 88° E. to N. 72° W. Here alteration appears to have resulted from the flow of solutions along permeable joints and bedding layers. Where the entire Navajo is light brown, alteration may have resulted from pervasive flow of solutions where no open joints were present to channel the flow as in Summit Canyon.

Altered-facies rocks in the Dewey Bridge Member of the Entrada Sandstone seem to be confined largely

TABLE 13.—*Average chemical composition, in weight percent, of sandstones of the altered facies in the Slick Rock district*

[Based on semiquantitative spectrographic analyses by Nancy M. Conklin (24 samples) and Joseph Haffty (11 samples). M, major; Tr, trace; 0, looked for but not found (below limit of detectability). Also looked for but not found: P, Au, Bi, Cd, Ce, Dy, Er, Eu, Gd, Ge, Hf, Hg, Ho, In, Ir, Li, Lu, Nd, Os, Pd, Pr, Pt, Rb, Re, Rh, Ru, Sb, Sm, Ta, Tb, Te, Th, Tl, Tm, U, W, Zn. Number of samples in parentheses]

| | Navajo Sandstone (2) | Entrada Sandstone | | Morrison Formation | | Burro Canyon Formation [1] (3) | Dakota Sandstone (3) | Average (35) |
		Dewey Bridge Member (2)	Slick Rock Member (3)	Salt Wash Member (18)	Brushy Basin Member [1] (4)			
Si	>10	>10	>10	M	M	M	M	M
Al	2.3	3.0	2.0	1.5	1.5	.8	2.3	1.7
Fe	.9	1.1	.4	.5	1.3	1.0	2.3	.8
Mg	.2	2.6	1.2	.9	.5	.1	.2	.8
Ca	.5	3.0	1.7	2.5	1.8	1.1	.2	1.9
Na	.1	.2	.15	.3	.3	.1	.2	.2
K	2.3	3.0	2.0	.8	.5	0	0	1.0
Ti	.2	.2	.17	.10	.05	.02	.1	.10
Mn	.01	.07	.02	.02	.03	.02	.008	.02
Ag	0	0	0	0	0	<.00001	.00001	0
As	<.3	0	0	0	<.01	.01	.01	<.01
B	<.007	.007	<.005	.002	<.005	<.005	<.005	.003
Ba	.2	.03	.03	.03	.06	.03	.04	.04
Be	0	<.00015	0	0	0	0	0	0
Co	<.003	.0015	<.0007	<.0007	<.001	0	<.001	<.001
Cr	.0009	.002	.002	.001	.002	.002	.002	.001
Cu	.002	.0015	.0015	.002	.003	.002	.002	.002
Ga	Tr	.0005	Tr	<Tr	<.001	0	.001	<.001
La	0	0	0	0	<.01	0	0	0
Mo	0	0	0	<.0015	0	0	0	0
Nb	0	<.0015	0	<.0015	0	0	0	<.0015
Ni	.004	.004	<.0007	.0005	.001	.002	.002	.001
Pb	<.0015	.001	.001	.003	<Tr	0	<.001	.002
Sc	0	.0007	0	<.0007	<.001	0	.001	<.001
Sn	0	0	0	0	0	0	0	0
Sr	.003	.005	.006	.005	.007	.02	.005	.006
V	.005	.005	.007	.004	.004	.001	0	.004
Y	<.0015	.002	.001	.001	.001	.001	.001	.001
Yb	<.00015	.0003	.0002	.0001	.0001	.0001	.0001	.0001
Zr	.02	.03	.02	.02	.01	.01	.03	.02

[1] Includes one conglomerate.

to selvages along faulted and jointed rocks (fig. 17) apparently where altering solutions flowed. Abundant silt and clay in the rocks have made the Dewey Bridge Member relatively impermeable, probably accounting for the scarcity of alteration effects.

Locally in some red-beds stratigraphic units, such as the Dewey Bridge Member, light-buff to light-yellowish-brown spots up to a few inches in diameter are seen apparently randomly distributed in reddish-brown sandstone. These spots appear to be centered on small limonite nodules or specks that likely formed from oxidation of pyrite or marcasite. No carbonaceous material has been observed within the spots. The origin of these bleached spots is not known, nor is it clear that they are analogous to altered-facies sandstone.

Altered-facies sandstone in the Slick Rock Member of the Entrada Sandstone is clearly related to structural features. Near the axis of the Dolores anticline, as in the vicinity of The Spud Patch, practically the entire member is bleached; in much of Summit Canyon on the northeast limb of the fold only the upper half of the member is bleached; near the Dolores River along the axis of the Disappointment

syncline only the upper few feet of the member is bleached; and in Disappointment Valley where the axis of the syncline plunges to the southeast none of the Slick Rock Member is bleached. On the north side of Poverty Flat red-beds facies and altered facies of the Slick Rock Member of the Entrada are well exposed together. Figure 9 shows the two facies diagrammatically, and gives heavy-mineral data that demonstrate some of the differences between the two facies.

In places a selvage of altered-facies sandstone bounds faults that offset the Slick Rock Member, notably in the vicinity of Summit Canyon. In areas where faults cut the upper part of the Slick Rock Member, altered-facies sandstone along faults is indistinguishable from that which is widespread in the upper part of the member, and no contact is visible between the two. This relationship suggests that pervasive alteration in the transmissive upper part of the member occurred at the same time as alteration along the permeable fault zones; altering solutions extended to greater depths along the faults simply because the sandstone there was shattered and thus more permeable. Most of the fractures in the Slick

TABLE 14.—*Average chemical composition, in weight percent, of siltstones, mudstones, and claystones of the altered facies in the Slick Rock district*

[Based on semiquantitative spectrographic analyses by Joseph Haffty. M, major; 0, looked for but not found (below limit of detectability). Also looked for but not found: P, Au, Bi, Cd, Ce, Cs, Dy, Er, Eu, Gd, Ge, Hf, Hg, Ho, In, Ir, Li, Lu, Nd, Os, Pd, Pr, Pt, Rb, Re, Rh, Ru, Sb, Sm, Ta, Tb, Te, Th, Tl, Tm, U, W, Zn. Number of samples in parentheses]

| | Morrison Formation | | Burro Canyon Formation | Dakota Sandstone | Mancos Shale | Average |
| | Salt Wash Member | Brushy Basin Member | | | | |
	(2)	(3)	(4)	(1)	(4)	(14)
Si	M	M	M	M	M	M
Al	7	10	8	10	8	8
Fe	2	3	3	3	3	3
Mg	1	1	.8	1	1	1
Ca	7	1	3	.3	10?	5
Na	1	2	.8	1	1	1
K	3	3	3	3	1	2.4
Ti	.3	.3	.3	.3	.3	.3
Mn	.02	.02	.01	.003	.01	.01
Ag	<.00003	0	0	.00001	<.00001	<.00001
As	0	<.01	<.01	0	0	<.01
B	.01	.005	.01	.01	.01	.01
Ba	.03	.03	.03	.03	.03	.03
Be	0	.0001	.0001	.0001	.0001	.0001
Co	.001	.001	.001	.003	.003	.002
Cr	.01	.007	.007	.03	.02	.01
Cu	.017	.002	.002	.003	.003	.005
Ga	.002	.003	.003	.003	.003	.003
La	0	.01	0	.01	.01	<.01
Mo	0	0	0	0	<.003	0
Nb	0	0	0	0	0	0
Ni	.003	.002	.002	.01	.01	.005
Pb	.001	.004	<.001	.001	.001	.002
Sc	.003	.003	.003	.003	.003	.003
Sn	0	0	0	0	0	0
Sr	.03	.03	.03	.03	.03	.03
V	.002	.01	.01	.01	.01	.01
Y	.003	.003	.003	.01	.003	.003
Yb	.0003	.0003	.0003	.0003	.0003	.0003
Zr	.02	.02	.02	.03	.02	.02

Rock Member that have controlled alteration are oriented between N. 45° W. and N. 80° W., the prevailing orientation of the Dolores zone of faults. A fracture oriented N. 47° E. in the lower part of the Slick Rock on the north side of the mouth of Stevens Canyon (sec. 34, T. 44 N., R. 19 W.) is the only alteration-bounded fracture observed that shows a disparate orientation.

In Summit Canyon, in the Dolores zone of faults, the reddish-brown lower part of the Summerville Formation (transitional into the underlying Entrada Sandstone) locally has been fractured and altered (fig. 10). At the base of the Summerville a reddish-brown mudstone layer is altered to greenish gray for a few inches just above the contact with light-buff sandstone of the Entrada.

Altered-facies rocks in the Salt Wash Member are mostly sandstones, widespread in the ore-bearing sandstone at the top of the member, and confined largely to the Dolores zone of faults and the zone of faults that bounds Gypsum Valley farther northeast. Altered-facies rocks in the Brushy Basin Member include a significant amount of mudstones in addition to sandstones and conglomerates. These rocks occur principally in the middle green unit of the member, which is not present everywhere in the district but is well defined between the Horseshoe and Muleshoe Bends of the Dolores River on the east side of the river canyon, near and west of Slick Rock (Shawe and others, 1968, pl. 7), and in the area of deep diamond drilling in Disappointment Valley (Shawe and others, 1968, pls. 12, 14). The middle green unit is thickest in Burro Canyon and vicinity and eastward across Disappointment Valley. Outside this area it appears to thin in all directions, or is absent. If the middle green unit were as thick in the area of Bush and Summit

TABLE 15.—*Semiquantitative spectrographic analyses, in weight percent, of three samples of rocks that may be partly altered red-beds-facies rocks in the Slick Rock district*

[Analyses by Joseph Haffty. M, major; 0, looked for but not found (below limit of detectability). Also looked for but not found: P, Au, Bi, Cd, Ce, Dy, Er, Eu, Gd, Ge, Hf, Hg, Ho, In, Ir, Li, Lu, Nd, Os, Pd, Pr, Pt, Rb, Re, Rh, Ru, Sb, Sm, Ta, Tb, Te, Th, Tl, Tm, U, W, Zn]

Sample No---	1	2	3	Sample No---	1	2	3
Si---------	>10	M	M	Cr---------	0.001	0.01	0.003
Al---------	1	3	10	Cu---------	.001	.003	.003
Fe---------	.3	3	3	Ga---------	<.001	.001	.003
Mg---------	.1	1	1	La---------	0	0	0
Ca---------	.1	1	1	Mo---------	0	0	0
Na---------	.3	1	1	Nb---------	0	0	0
K---------	1	1	3	Ni---------	.001	.003	.003
Ti---------	.01	.3	.3	Pb---------	.003	0	0
Mn---------	.003	.03	.01	Sc---------	0	.001	.003
Ag---------	.00001	0	0	Sn---------	0	0	0
As---------	0	0	0	Sr---------	.003	.03	.03
B---------	<.005	<.005	<.005	V---------	0	.001	.001
Ba---------	.03	.03	.1	Y---------	0	.003	.003
Be---------	0	0	.0001	Yb---------	0	.0003	.0003
Co---------	0	.003	.001	Zr---------	.003	.03	.03

SAMPLE DESCRIPTIONS

Sample No.	Field No.	Description
1----	DVR-2-1880	Light-reddish-gray sandstone, Slick Rock Member, Entrada Sandstone.
2----	DVR-2-722.5	Reddish-gray siltstone, Brushy Basin Member, Morrison Formation.
3----	DVR-2-1235	Brownish-gray mudstone, Brushy Basin Member, Morrison Formation

Canyons, where it is absent owing to Quaternary(?) erosion there, as it is in the Burro Canyon area, the zone of thick middle green unit would be roughly concident with the Dolores zone of faults and the zone of uranium-vanadium deposits in the Salt Wash Member. Alteration of the middle green unit and deposition of ore deposits both appear to have been most prevalent near the Dolores zone of faults.

The Burro Canyon Formation is unusual among the sedimentary rocks in the Slick rock district because it is largely "bleached," containing mainly light-gray and light-brown sandstone and conglomerate layers and light-greenish-gray mudstone, siltstone, and clay-stone layers, yet it contains no visible carbonaceous material except in a few very thin beds of restricted distribution. The formation contains only a few isolated layers of light-reddish-brown sandstone and conglomerate, and reddish-brown mudstone, silt-stone, and claystone. Where red beds are present the relationships to bleached strata make it clear that the bleached rocks are altered equivalents of reddish rocks.

The Dakota Sandstone, being exceptionally carbonaceous, consists wholly of chemically reduced rocks, and in a general way could be inferred to belong to the carbon facies. The mineralogical and chemical characteristics of the formation, however, suggest that it is entirely of the altered facies.

DETAILED RELATIONSHIPS

In the Morrison Formation, in which lithologies are more complex than in formations such as the Wingate, Navajo, and Entrada Sandstones, facies distributions are complex in detail. Red-beds-facies sandstone and mudstone lie above and below the ore-bearing sandstone, as shown in a drill log of diamond-drill hole DV—112A (Shawe and others, 1959, fig. 3) and in a drill log of diamond-drill hole DV—115 (Bowers and Shawe, 1961, fig. 3). The red-beds-facies sandstone layers both above and below the laterally continuous ore-bearing sandstone in each drill hole are lenticular and not laterally connected with other widespread sandstone layers. Carbon-facies sandstone also makes up a lenticular layer above the ore-bearing sandstone as shown in a drill log of diamond-drill hole DV—96 (Shawe and others, 1959, fig. 4). Altered-facies sandstone makes up the ore-bearing sandstone penetrated by the three cited drill holes (Shawe and others, 1959, figs. 3 and 4; Bowers and Shawe, 1961, fig. 3). In these cases carbonaceous material (coalified and carbonized plant debris) is abundant throughout the ore-bearing sandstone, indicating that prior to alteration and mineralization the ore-bearing sand-stone consisted largely of the carbon facies. The ore-bearing sandstone in many places is light gray in its lower part (half to three-fourths of the unit) and reddish brown in its upper part (for example, see Shawe and others, 1968, pl. 12), in contrast to the common situation in many other sandstone units that are reddish brown in their lower parts and altered (light gray or buff) in their upper parts. Possibly shortly after deposition of the ore-bearing sandstone, oxidation above the water table took place to account for the absence of plant debris and abundance of hematite in the upper part of the unit.

Additional details of the relationships among red-beds, carbon, and altered facies in the lower part of the Brushy Basin Member and in the upper part (including the ore-bearing sandstone) of the Salt Wash Member are shown in a diagrammatic cross section through a line of 13 diamond-drill holes about 3 miles long extending northward across the west end of Disappointment Valley (pl. 1). From the distribution of facies shown on plate 1, it is apparent that the altered facies was superimposed on both red-beds- and carbon-facies rocks; the coincidence of altered facies with the thickest and most continuous part of the ore-bearing sandstone indicates that alteration took place where permeability was higher than in adjacent rocks and therefore alteration likely was caused by the passage of solutions after the development of the red-beds and the carbon facies.

Development of an altered selvage around a detrital slab of claystone in altered-facies ore-bearing sandstone of the Salt Wash Member in the Cougar
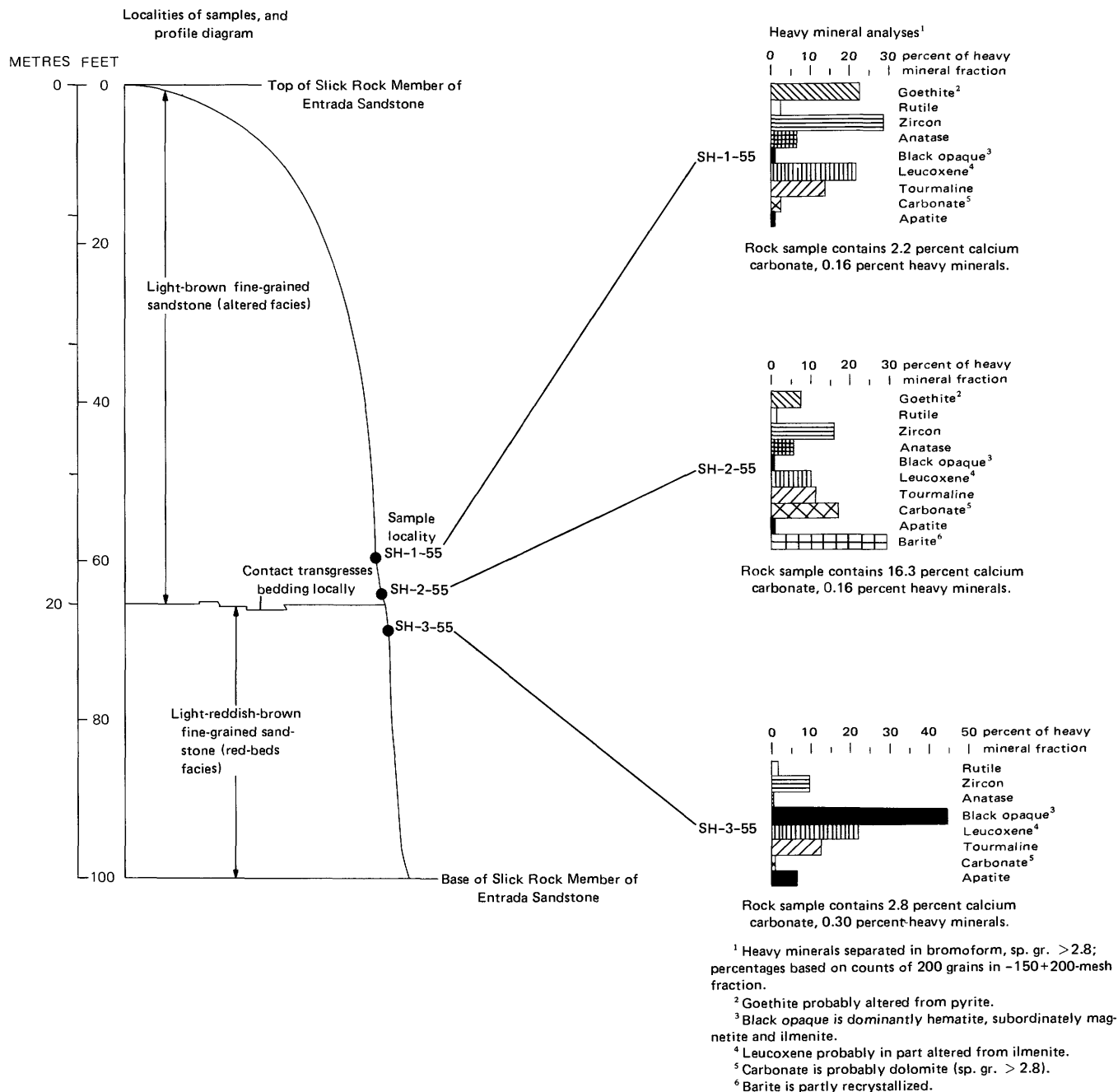
F IGURE 9.—Profile diagram of the Slick Rock Member of the Entrada Sandstone at Poverty Flat showing localities of three samples and relative abundances of heavy minerals in altered and red-beds facies of the member.

mine is shown in figure 11. Here the impermeable claystone slab inhibited alteration so that a zone of pink sandstone remained beneath the claystone slab, and a core of reddish-brown claystone remained within the slab, as surrounding sandstone was altered to white, and concentric selvages of claystone were altered to red and to green.

Contacts between altered-facies and red-beds-facies rocks are nowhere strictly along lithologic-stratigraphic boundaries. For example, where the silty

Dewey Bridge Member of the Entrada Sandstone overlies the sandy Navajo Sandstone in Summit Canyon, the contact between underlying altered-facies sandstone in the Navajo and overlying red-beds-facies sandstone in the Dewey Bridge is slightly irregular and does not coincide with the formational contact (fig. 12).

Within the ore-bearing sandstone of the Salt Wash Member at the Lower group of mines the boundary between altered-facies sandstone above and red-beds-

FIGURE 10.—Sectional diagram of light-brown (altered-facies) sandstone bounding fractures in reddish-brown (red-beds-facies) sandstone in the lower part of the Summerville Formation in Summit Canyon. Note how clay in bedding layer of sandstone has decreased permeability and inhibited alteration.

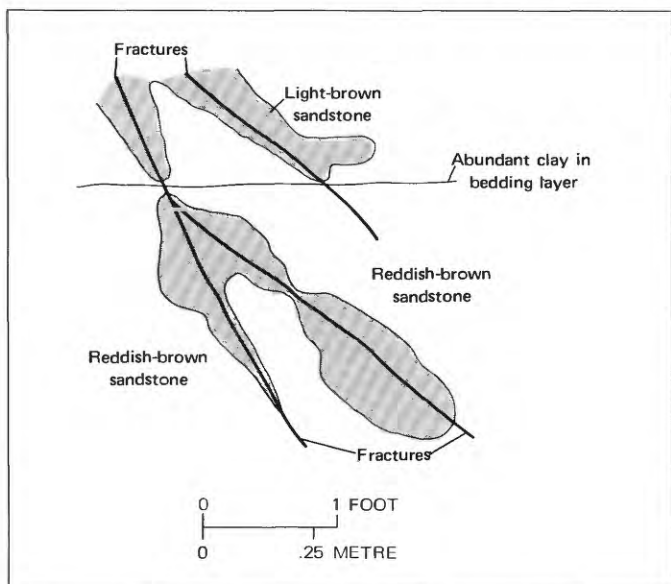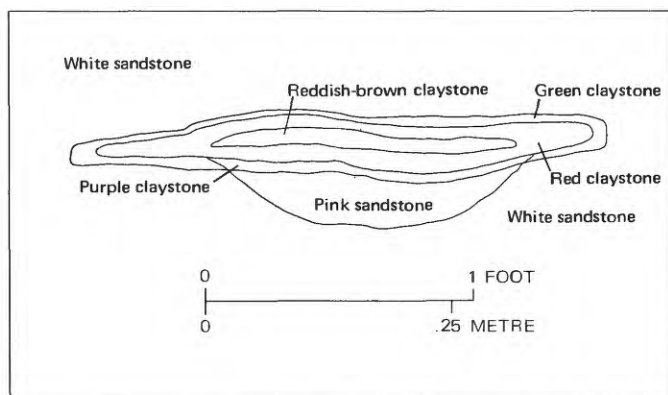FIGURE 11.—Detrital claystone slab in altered-facies ore-bearing sandstone of the Salt Wash Member in the Cougar mine, showing zone of sandstone beneath the slab where alteration was inhibited, and selvages of altered claystone around the slab.

facies sandstone below is irregular and intertonguing (fig. 13). A tongue of altered-facies sandstone extending into red-beds-facies sandstone terminates against a series of layers of hematite and limonite after pyrite concentric with the lobate tip of the altered-facies tongue, suggesting that the altered facies developed by encroachment of solutions along a permeable layer in red-beds-facies sandstone. Concentrations of secondary minerals shown in figure 13 near the contact between altered facies and the red-beds facies will be discussed in a later section.
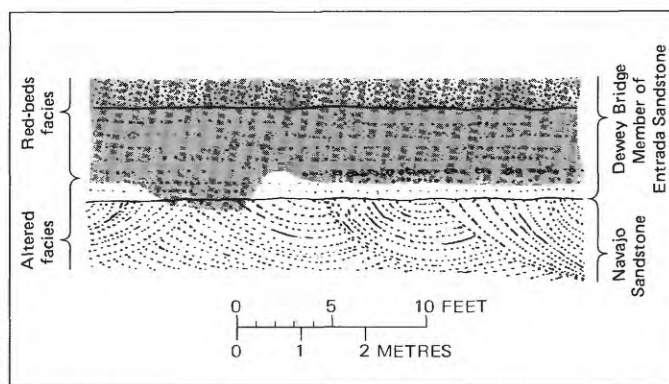
FIGURE 12.—Diagrammatic section at the Entrada Sandstone – Navajo Sandstone contact showing irregular boundary between altered facies and red-beds facies. Reddish-brown very fine grained silty sandstone of the Dewey Bridge Member lies conformably on fine-grained sandstone that contains pebbles and cobbles of black chert, gray chert, and reddish-brown to brown very fine grained quartzitic sandstone as much as 8 inches (20 cm) in diameter; this in turn overlies light-brown very fine grained crossbedded sandstone typical of the Navajo. Sec. 26, T. 44 N., R. 19 W., north side of Summit Canyon.
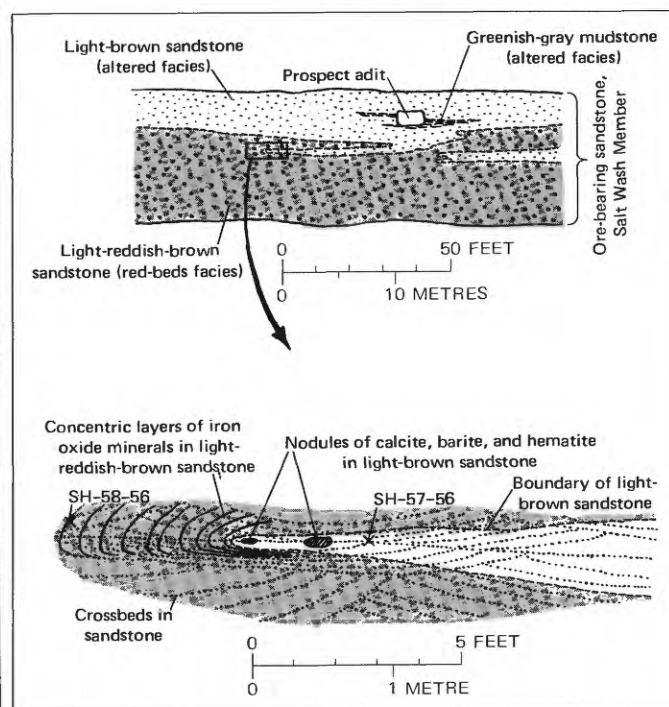
FIGURE 13.—Sketch of ore-bearing sandstone of the Salt Wash Member, and detail, showing intertonguing of altered-facies sandstone (sample SH – 57 – 56) and red-beds-facies sandstone (sample SH – 58 – 56). Mildred F claim, Lower group of mines, NW¼ NW¼ sec. 26, T. 44 N., R. 19 W.

Semiquantitative spectrographic analyses of a sample (SH – 57 – 56) from the tongue of altered-facies sandstone and of a sample (SH – 58 – 56) of red-beds-

facies sandstone collected 7 feet (2 m) laterally therefrom and nearly in the same bedding layer are given in table 16. Analyses of two samples (SH – 63 – 56A and C) collected across a similar alteration boundary in the ore-bearing sandstone of the Salt Wash Member west of the Lower group of claims, where a pod of dark-reddish-brown sandstone rimmed by limonite-stained sandstone is enclosed in light-brown sandstone, are also presented in table 16. Although most elements determined in the spectrographic analyses are equally abundant in samples of red-beds facies and of altered facies, a few are different in amount.

Small-scale irregularities in the boundary between altered-facies and red-beds-facies sandstone in the lower brown unit of the Brushy Basin Member are illustrated in figure 14. The vertical, downward penetration of altered-facies sandstone into red-beds-facies sandstone suggests a density contrast between connate water in the red-beds facies and solutions that caused the alteration, such that altering solutions "leaked" downward at the contact under the influence of gravity. In later pages this suggestion is rationalized with the occurrence of altered-facies rocks in the upper parts of deeper permeable formations. A gamma-ray log of diamond-drill hole DV – 125 from which the sample illustrated in figure 14 was collected shows that a 1-foot-thick zone near the middle of the altered sandstone layer is anomalously radioactive. Part of the radioactivity is attributable to potassium, but most of it is due to uranium daughter products indicating about 0.002 percent uranium in the sandstone. Abnormally high radioactivity in a layer of altered sandstone that is not carbonaceous suggests that the altering solutions introduced uranium.

The three contact relations just illustrated indicate that solutions flowing in permeable zones encroached upon rocks of the red-beds facies and altered them.

Development of the altered facies along fractures further substantiates that alteration resulted from solution flow along permeable zones. On the northwest side of Summit Canyon in the Dolores zone of faults, the Navajo Sandstone is bleached along fractures and outward from fractures along permeable beds (fig. 15). Most of the Navajo Sandstone in Summit Canyon is bleached rock, and the preservation of red-beds facies locally near some fractures suggests that fracturing increased permeability sufficiently to permit most solution flow to occur close to fractures; elsewhere in Summit Canyon in unfractured Navajo Sandstone altering solutions spread evenly throughout the permeable formation. Semiquantitative spectrographic analyses of a pair of samples collected
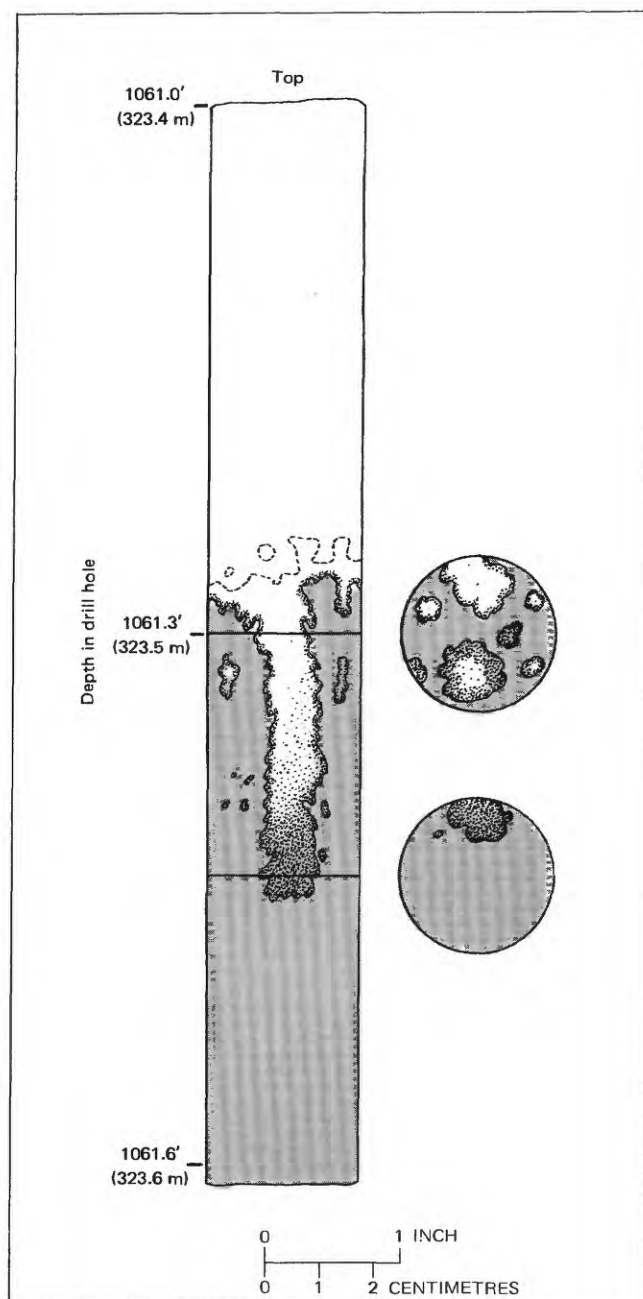
FIGURE 14.—Sketch of a segment of diamond-drill core from drill hole DV – 125, Disappointment Valley, showing irregular contact between altered-facies sandstone (white, above) and red-beds-facies sandstone (shaded, below). Altered facies shown is the lower part of a 4-foot (1-m) thick layer within a 46-foot-(14-m)-thick sandstone layer at top of the lower brown unit of the Brushy Basin Member; red-beds facies shown is at the base of the sandstone layer. Vertical fingers of altered sandstone bordered by hematite extend downward into red-beds-facies sandstone; density of stippling indicates abundance of hematite. Calcite is abundant below, sparse above, the irregular dashed line. Circles show cross sections of the drill core at the horizontal section lines. A detail of one of the small fingers of altered-facies sandstone in the upper cross section, which is in the plane of thin section DV – 125 – 1061.3(c), is shown in Shawe (1968, fig. 16).

TABLE 16.—*Semiquantitative spectrographic analyses, in weight percent, of six pairs of red-beds-facies and altered-facies sandstone collected at alteration contacts in Jurassic formations in the Slick Rock district*

[Analyses by Nancy M. Conklin. M, major; Tr, trace; 0, looked for but not found (below limit of detectability). Also looked for but not found: P, Au, Bi, Cd, Ce, Dy, Er, Eu, Gd, Ge, Hf, Hg, Ho, In, Ir, Li, Lu, Nd, Os, Pd, Pr, Pt, Rb, Re, Rh, Ru, Sb, Sm, Ta, Tb, Te, Th, Tl, Tm, U, W, Zn]

Sample No-----	Navajo Sandstone		Entrada Sandstone				Morrison Formation					
			Dewey Bridge Member		Slick Rock Member		Salt Wash Member					
	Red-beds facies	Altered facies	Red-beds facies	Altered facies	Red-beds facies	Altered facies	Red-beds facies	Altered facies	Red-beds facies	Altered facies	Red-beds facies	Altered facies
	1	2	3	4	5	6	7	8	9	10	11	12
Si-------	>10	>10	>10	>10	>10	>10	M	M	M	M	M	M
Al-------	3	3	3	3	3	3	1.5	1.5	1.5	1.5	3	3
Fe-------	.7	.3	1.5	1.5	.7	.3	.7	.7	.7	3	.7	.3
Mg-------	1.5	.3	1.5	1.5	1.5	1.5	.7	.7	.7	.3	.3	.3
Ca-------	3	.3	3	3	3	1.5	3	3	3	3	1.5	.7
Na-------	.15	.15	.3	.3	.15	.15	.3	.15	.07	.07	.15	.15
K--------	3	3	3	3	3	3	1.5	.7	0	0	1.5	1.5
Ti-------	.15	.3	.3	.3	.3	.3	.15	.15	.07	.07	.15	.15
Mn-------	.07	.007	.07	.07	.015	.015	.03	.03	.015	.03	.015	.015
Ag-------	0	0	0	0	0	0	0	0	0	0	0	0
As-------	0	0	0	0	0	0	0	0	0	0	0	0
B--------	.003	.007	.007	.007	.003	.007	.003	Tr	Tr	0	.003	.003
Ba-------	.03	.07	.03	.03	.03	.03	.015	.015	.015	.015	.03	.03
Be-------	0	0	.00015	.00015	0	0	0	0	0	0	0	0
Co-------	Tr	0	Tr	.0015	0	0	Tr	.0007	0	0	0	.00015
Cr-------	.003	.0015	.003	.003	.0015	.0015	.007	.0015	.0007	.0007	.0015	.0015
Cu-------	.0015	.0015	.0015	.0015	.0015	.0015	.003	.007	.0015	.0015	.0015	.0015
Ga-------	Tr	Tr	.0007	.0007	Tr	Tr	Tr	0	0	0	0	0
La-------	0	0	0	0	0	0	0	0	0	0	0	0
Mo-------	0	0	0	0	0	0	0	0	0	0	0	0
Nb-------	.0015	0	.0015	.0015	.0015	0	.0015	0	0	0	0	.0015
Ni-------	.0007	.0015	.003	.007	Tr	0	.0007	.0007	Tr	0	Tr	.0007
Pb-------	Tr	.0015	.0015	.0015	Tr	Tr	0	0	0	0	0	Tr
Sc-------	0	0	.0007	.0007	Tr	0	0	0	0	0	0	0
Sn-------	0	0	0	0	0	0	0	0	0	0	0	0
Sr-------	.007	.003	.007	.007	.003	.007	.007	.007	.003	.003	.003	.003
V--------	.003	.007	.003	.007	.015	.015	.015	.015	.007	.007	.003	.003
Y--------	.0015	.0015	.003	.003	.0015	.0015	Tr	.0015	0	0	Tr	.0015
Yb-------	.00015	.00015	.0003	.0003	.0003	.0003	Tr	.00015	0	0	Tr	.00015
Zr-------	.03	.03	.03	.03	.07	.03	.03	.015	.003	.007	.015	.015

SAMPLE DESCRIPTIONS

Sample No.	Field No. SH–	Description	Sample No.	Field No. SH–	Description	Sample No.	Field No. SH–	Description	Sample No.	Field No. SH–	Description
1-----	45-56	Light reddish brown.	4-----	56-56A	Light brown.	7-----	58-56	Light reddish brown.	10----	63-56C	Light brown.
2-----	47-56	Light brown.	5-----	43-56	Light reddish brown.	8-----	57-56	Light brown.	11----	33-56B	Light reddish brown.
3-----	56-56B	Reddish brown.	6-----	44-56	Light brown.	9-----	63-56A	Dark reddish brown.	12----	33-56A	Light brown.

on either side of an alteration boundary near fractures in the Navajo Sandstone in Summit Canyon are shown in table 15. Several elements have equal abundance in red-beds-facies sandstone (SH – 45 – 56) and in altered-facies sandstone (SH – 47 – 56), but iron, magnesium, calcium, manganese, cobalt(?), chromium, niobium, and strontium seem to have been leached from, and titanium, boron, barium, lead, and vanadium added to, altered-facies sandstone.

In places relatively impermeable rocks of the red-beds facies, where strongly fractured adjacent to permeable units, have been bleached and converted to the altered facies. Open fractures in the Dewey Bridge Member of the Entrada Sandstone immediately above Navajo Sandstone in Summit Canyon have allowed sufficient solution penetration of the Dewey Bridge to convert red-beds facies to altered facies (fig. 16). Semiquantitative spectrographic analyses of a pair of samples (SH – 56 – 56A and B) collected on either side of an alteration boundary near fractures in the Dewey Bridge Member in Summit Canyon are given in table 16. Almost all elements are identical in abundance in the two samples; only cobalt, nickel, and vanadium appear to have been added to altered-facies sandstone (SH – 56 – 56A). Data on a similar pair of samples (SH – 43 – 56 and SH – 44 – 56) collected from the Slick Rock Member of the Entrada Sandstone in Summit Canyon are also presented in table 16. Again, most elements show similar amounts in the two samples, but iron, calcium, niobium, nickel(?), scandium(?), and zirconium seem to have been removed from, and boron and strontium may have been added to, altered-facies sandstone (SH – 44 – 56).

The Dolores zone of faults and associated joints have exerted a pronounced control on the distribution of alteration in the Morrison Formation. Permeable though lenticular sandstone layers below the widespread ore-bearing sandstone of the Salt Wash Member have been altered prominently in a linear
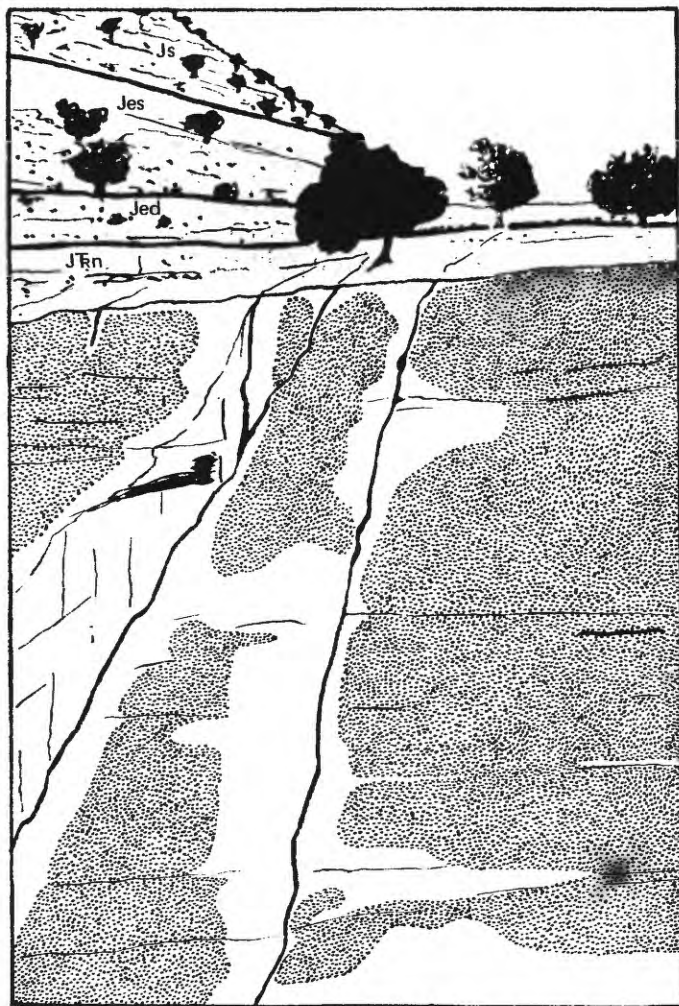
FIGURE 16.—Altered-facies rock along fractures in the Dewey Bridge Member of the Entrada Sandstone; altered-facies rock is very light brown and red-beds-facies rock is reddish brown. Sec. 35, T. 44 N., R. 19 W., Summit Canyon. Photograph by N. L. Archbold.

FIGURE 15.—Navajo Sandstone (Jrn) on the northwest side of Summit Canyon showing bleached rock along joints. White in the Navajo is buff sandstone of the altered facies; stippled is reddish-brown sandstone of the red-beds facies. Jed, Dewey Bridge Member of the Entrada Sandstone; Jes, Slick Rock Member of the Entrada Sandstone; Js, Summerville Formation. Drawn from a photograph.

zone that extends from the updip side of a west-north-westerly oriented fault extending through the center of sec. 27, T. 44 N., R. 19 W., southeastward 6 miles to the center of the E½, sec. 7, T. 43 N., R. 18 W., and in a second linear zone about one-half mile farther southwest that extends from the area south of the fault in sec. 27 in a broad zone 1 – 2 miles wide southeastward 12 miles to the Horseshoe Bend of the Dolores River. This second linear zone lies along and just updip from the major faults of the Dolores zone of faults (fig. 4; Shawe and others, 1968, pl. 7). In addition, joints in red-beds-facies sandstone are commonly bounded by altered-facies sandstone within 1 – 2 miles updip of the major faults of the Dolores

zone (fig. 4). An example is shown in figure 17. The effect of a strong set of joints on the distribution of altered-facies sandstone in the Salt Wash Member northeast of the Charles T. group of mines is illustrated in figure 18. Here joints are found in all the sandstone layers in the Salt Wash, superimposed one set above the other in successive layers, but not extending through intervening mudstone and siltstone layers. Apparently sandstone was fractured because of its relative brittleness whereas the argillaceous rocks were not fractured because of their relative plasticity. Altering solutions flowed preferentially along the joints in each sandstone layer and thus must have been introduced into the Salt Wash throughout its entire thickness, probably along a nearby fault zone.

Semiquantitative spectrographic analyses of a sample of altered-facies sandstone (SH – 33 – 56A) collected adjacent to a joint in sandstone of the Salt Wash Member and of a sample of red-beds-facies sandstone (SH – 33 – 56B) collected 3 inches laterally in the same bedding layer are shown in table 16. Most

FIGURE 17.—Fracture-controlled altered sandstone in the middle unit of the Salt Wash Member, northeast of the Charles T. Mines, sec. 10, T. 43 N., R. 19 W. Altered-facies rock is very light brown and red-beds-facies rock is light reddish brown.

elements determined in these spectrographic analyses are equally abundant in the samples of red-beds-facies and altered-facies sandstone, but a few have different values.

Differences in heavy mineral content of these two samples have been reported on previously by Bowers and Shawe (1961, p. 201, 211 – 213, and fig. 16). We pointed out that the principal difference between the heavy minerals in altered-facies (called altered) sandstone and red-beds-facies (called unaltered) sandstone is sparsity of black opaque minerals in the former and abundance in the latter. We also noted the similarity between the heavy-mineral content of altered rock near the joint and the average heavy mineral content of 74 samples of sandstone adjacent to mineralized layers in the Salt Wash Member. Finally, we indicated that by removing most of the black opaque minerals from the heavy fraction of red-beds-facies sandstone, the amounts and proportions of heavy minerals in altered-facies sandstone are matched. We concluded that alteration of rock adjacent to fractures was similar to that close to mineralized layers.

The detailed relationships among the red-beds-, carbon-, and altered-facies rocks in the Slick Rock district indicate that all three rock types were originally deposited within the same sedimentary environment and were mineralogically similar; carbon-facies rocks were unique only in the fact that abundant carbonized plant material was deposited with the mineral sediment.

With the detailed relationships among red-beds-, carbon-, and altered-facies rocks described, some general compositional comparisons among the three facies can now be made. Table 17 shows the relative abundances of minerals in heavy fractions of sandstone of the red-beds, carbon, and altered facies, as well as the calculated absolute amounts of heavy minerals in the total rock samples of the three facies. Significantly the absolute amounts of most heavy minerals remain constant in the three facies, with the exception that black opaque minerals decrease in amount from 0.20 to 0.10 to 0.003 percent, and pyrite increases in amount from 0.0015 to 0.003 to 0.011 percent, in red-beds, carbon, and altered facies, respectively. Also, barite and anatase are about twice as abundant in the carbon facies sandstones as in those of the other two facies. From these data it is concluded that as red-beds- and carbon-facies rocks evolved simultaneously from their original depositional condition, about half the original black opaque minerals—that in red-beds-facies sandstone survived—were dissolved into pore solutions and a small amount of pyrite was precipitated in carbon-facies sandstone. Apparently, barite and anatase, both authigenic minerals, were increased twofold by deposition from ground waters in the reducing environment of the carbon-facies rocks. Alteration may have concentrated barite and anatase in and near ore deposits, to reduce the average barite and anatase contents of altered-facies rocks elsewhere to values similar to those in red-beds-facies rocks, as discussed later. Altered-facies rocks that developed by solution attack on both red-beds- and carbon-facies rocks are notable for their almost complete loss of black opaque minerals and gain of significant pyrite. Notably the gain in pyrite content does not account for the loss of iron that resulted from destruction of black opaque minerals, and this discrepancy will be discussed in later pages.

A comparison of the chemical compositions of red-beds-, carbon-, and altered-facies rocks averaged from tables 7, 8, 10, 13, and 14 is presented in table 18. Probably not enough analyses of carbon-facies sandstone are available for a valid average chemical composition, and comparisons of the carbon facies average with the averages of the other facies will not be made. Average compositions of sandstones of the red-beds facies compared to those of the altered facies, and of siltstones, mudstones, and claystones of
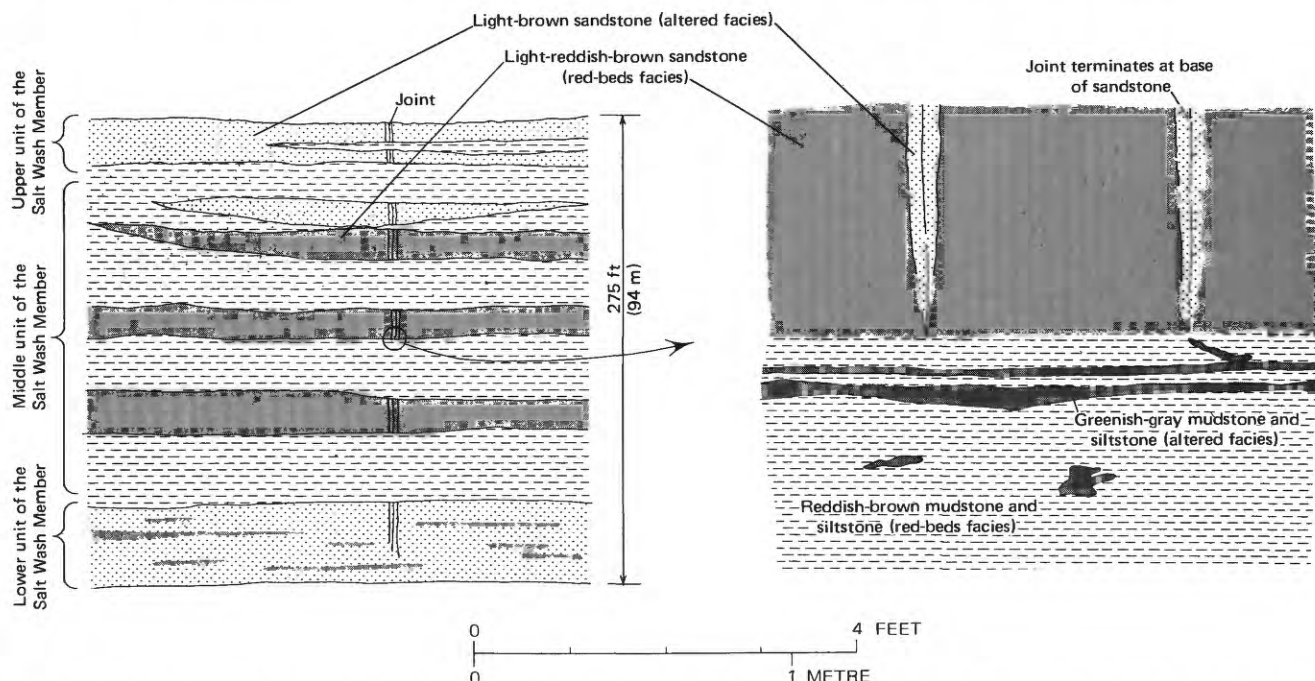
FIGURE 18.—Diagrammatic section of the Salt Wash Member, showing superimposed joint sets in sandstone layers, and detail showing altered-facies sandstone along joints that terminate at the base of a sandstone layer. Sec. 10, T. 43 N., R. 19 W., northeast of the Charles T. group of mines.

TABLE 17.—*Relative and absolute heavy-mineral contents of 129 samples of red-beds-facies sandstone, 73 samples of carbon-facies sandstone, and 95 samples of altered-facies sandstone*

[Number of samples in parentheses]

	Relative abundances of minerals in heavy fraction			Absolute amounts of heavy minerals in total rock		
	Red-beds facies (129)	Carbon facies (73)	Altered facies (95)	Red-beds facies (129)	Carbon facies (73)	Altered facies (95)
Black opaque minerals-----	61	35	2.5	0.20	0.10	0.003
Zircon--------------------	13	18	30	.043	.050	.036
Tourmaline---------------	4	5	8	.013	.014	.010
Apatite------------------	1.5	1.5	2	.005	.004	.002
Rutile-------------------	1	1	1	.003	.003	.002
Leucoxene----------------	6.5	8.5	14.5	.027	.024	.017
Barite-------------------	10	26	27	.033	.073	.032
Anatase------------------	1	2.5	3.5	.003	.007	.004
Pyrite-------------------	---	1	9.5	---	.003	.011
Others-------------------	2	1.5	2	.007	.004	.002
Heavy fraction in weight percent-----------------	0.33	0.28	0.12	0.33	0.28	0.12

the red-beds facies compared to those of the altered facies are similar for most elements. However, sodium, potassium, and chromium appear to be significantly less abundant, and lead significantly more abundant, in altered-facies sandstone than in red-beds-facies sandstone; manganese may be significantly less abundant, and copper, lead, nickel, and vanadium significantly more abundant, in altered-

facies siltstone, mudstone, and claystone than in red-beds-facies siltstone, mudstone, and claystone.

A summary of the differences in composition between red-beds-facies and altered-facies sandstones that were collected as pairs on either side of alteration contacts is presented in table 19. The differences are interpreted to represent either leaching of or addition to altered-facies sandstone as a result of alteration.

TABLE 18.—*Comparison of the average chemical compositions of rocks of the red-beds, carbon, and altered facies*

[Based on data in tables 7, 8, 10, 13, and 14. M, major. Number of samples in parentheses]

	Sandstones			Siltstones, mudstones, and claystones	
	Red-beds facies (21)	Carbon facies (4)	Altered facies (35)	Red-beds facies (7)	Altered facies (14)
Si-------	>10	M	M	M	M
Al-------	2	2	1.7	7	8
Fe-------	.9	2	.8	2	3
Mg-------	.7	.15	.8	.8	1
Ca-------	1.8	4	1.9	5	.5
Na-------	.4	1	.2	1	1
K--------	1.4	.6	1	3	2.4
Ti-------	.13	.11	.10	.3	.3
Mn-------	.03	.09	.02	.03	.01
Ag-------	0	<.00001	0	0	<.00001
As-------	<.01	0	<.01	<.01	<.01
B--------	.003	0	.003	.007	.01
Ba-------	.06	.10	.04	.04	.03
Be-------	<.00015	0	0	<.0001	.0001
Co-------	<.0008	<.001	<.001	.002	.002
Cr-------	.003	.002	.001	.009	.01
Cu-------	.002	.002	.002	.003	.005
Ga-------	<.001	<.001	<.001	.002	.003
La-------	0	0	0	<.01	<.01
Mo-------	0	0	0	0	0
Nb-------	<.0015	0	<.0015	0	0
Ni-------	.0009	.001	.001	.003	.005
Pb-------	<.0013	.001	.002	<.001	.002
Sc-------	<.0008	.001	<.001	.002	.003
Sn-------	0	<.01	0	0	0
Sr-------	.008	.05	.006	.03	.03
V--------	.004	.001	.004	.003	.01
Y--------	.0013	.001	.001	.003	.003
Yb-------	.00014	.0001	.0001	.0003	.0003
Zr-------	.018	.01	.02	.03	.02

From the table, it appears that commonly iron, calcium, and niobium, and less commonly magnesium and chromium, were leached from altered-facies sandstone during alteration. On the other hand, commonly cobalt, and more rarely lead(?), vanadium, yttrium, and ytterbium may have been added to altered-facies sandstone during alteration. Other elements such as sodium, potassium, titanium, manganese, boron(?), barium, copper, gallium, nickel(?), scandium(?), strontium, and zirconium either were leached or added only rarely, or were both leached and added in different pairs of samples. Niobium was added to one altered-facies sandstone sample although commonly leached from other samples, and cobalt(?) was leached from one altered-facies sandstone sample although commonly added to other samples.

Variations in the chemical compositions of calcite in the three facies of rocks in the Slick Rock district are an additional suggestion of the effects of alteration on the composition of the sedimentary rocks. In comparing the compositions of calcite separated from red-beds- and altered-facies rocks shown in table 3 (calcite from carbon-facies rocks is represented by only one sample and is not considered in this comparison), the contents of some elements are ignored, such as silicon, aluminum, sodium, potassium, titanium, boron, barium, and zirconium

that indicate mostly the presence of impurities such as quartz, clay minerals, feldspars, titanium oxides, tourmaline, barite, and zircon—components of the prealteration rock. Elements such as iron, magnesium, manganese, and strontium are believed to be mostly in the calcite structure. Some other elements, such as chromium, copper, vanadium, yttrium, and ytterbium, although perhaps not residing principally in the calcite structure, are believed to represent valid chemical differences between red-beds-facies and altered-facies rocks that were the result of alteration. On this basis it is seen that the averages of iron, chromium, copper, strontium, vanadium, yttrium, and ytterbium are greater in calcite of the altered facies than in calcite of the red-beds facies. Only manganese appears to be less abundant in calcite of the altered facies than in calcite of the red-beds facies.

Despite the fact that numerous chemical and radiometric measurements have been made to indicate the uranium content of mineralized rocks from the Slick Rock district, few have been made to indicate the uranium content of so-called unmineralized rocks. Analytical data are sparse, therefore, on the uranium content of red-beds-, carbon-, and altered-facies rocks. Nevertheless it is possible to estimate the uranium content of these rocks—using assumptions regarding the potassium and thorium contents of the rocks—by means of gamma-ray logs that were made of all diamond-drill holes drilled by the U.S. Geological Survey in the Slick Rock district. Such estimates made from the gamma-ray logs of drill holes shown on plate 1 as well as some other drill holes indicate significant differences between the uranium content of red-beds- and carbon-facies rocks and of altered-facies rocks.

Gamma-ray logs were recorded on strip charts as a continuous line indicating counts per minute; gamma radiation was a result of the presence of potassium, and daughter products of uranium and thorium, and the assumption is made that radioactive equilibrium pertained for uranium and thorium and their daughter products. Primary uranium deposits on the Colorado Plateau are generally nearly in radioactive equilibrium, and the uranium in the Mancos Shale is in equilibrium with daughter products (Pliler and Adams, 1962, p. 1119). For the purpose of the estimates made here, the amount of radioactivity due to potassium is based on the overall average potassium contents for the rock types sandstone and siltstone-mudstone-claystone in the Morrison Formation, Burro Canyon Formation, and Dakota Sandstone given in tables 5, 6, 8, 11, and 12. The average

TABLE 19.—*Summary of elements that appear to have been leached from or added to altered-facies sandstone as a result of alteration, based on semiquantitative spectrographic analyses of red-beds- and altered-facies pairs*

	Leached from altered facies	Added to altered facies
Navajo Sandstone---	Fe -- - Mg - Ca Mn Co Cr -- Nb -- -- Sr __	Ti -- B Ba -- -- -- -- Pb -- V - -- --
Dewey Bridge Member	-- -- - -- - -- -- -- -- -- -- -- -- --	-- -- - -- Co -- -- Ni -- -- V - -- --
Slick Rock Member--	Fe -- - -- - Ca -- -- -- -- Nb Ni Sc -- Zr	-- -- B -- -- -- -- -- -- Sr - - -- --
Salt Wash Member---	-- Na K -- B -- -- -- -- Cr Ga Nb -- -- -- Zr	-- -- - -- Co Cu -- -- -- -- -- Y Yb --
Salt Wash Member---	Fe -- - Mg B -- -- -- -- -- -- -- -- -- --	-- Mn - -- -- -- -- -- -- -- - -- -- Zr
Salt Wash Member---	Fe -- - -- - Ca -- -- -- -- -- -- -- -- --	-- -- - -- Co -- Nb Ni Pb -- - Y Yb --

potassium content of all such sandstone samples (45) is 0.7 percent and of all such siltstone-mudstone-clay-stone samples (17) is 2.8 percent. Potassium is assumed on the basis of the content of four samples (table 14), to average 1 percent in Mancos Shale. Thorium is ruled out as a significant contributor to the radioactivity of the rocks on the basis of the known low thorium-derived lead contents of lead minerals in Colorado Plateau sedimentary rocks (Cannon and others, 1958, p. 219). Counts per minute indicated on the gamma-ray strip charts were converted to eU_3O_8 (total gamma radioactivity) on the basis of a chart prepared by C. M. Bunker of the U.S. Geological Survey in July 1954. The amount of radioactivity due to the presence of potassium was determined by the formula 1.5 percent $K=0.0010$ percent eU_3O_8 (Bunker, oral commun., June 1962). As the conversion factor eU_3O_8 to eU is nearly unity, it is ignored here.

Estimates of the uranium content of red-beds-facies, carbon-facies, and altered-facies rocks, made on the basis of an evaluation of hundreds of feet of drill core logs and gamma-ray strip charts, and using the assumptions stated above, are given in table 20. With the exception of Mancos Shale, all mudstone lithologies were estimated to contain no uranium inasmuch as the estimated potassium content accounted for more than the observed radioactivity. The estimated potassium content of these mudstones may be high and a small amount of uranium probably is present. The value of 0.0003 percent uranium in Mancos Shale is close to the value given by Pliler and Adams (1962, p. 1115), 0.00037 percent, which is an average of more than 135 samples from Colorado, Utah, Arizona, and New Mexico. As seen in table 20, the uranium content of sandstones of the red-beds and carbon facies is low (about 0.0001 percent) and that of sandstones of the altered facies (except in the Burro Canyon Formation) appreciably higher (0.0002 – 0.0005 percent). These values are not accurate but they probably indicate correctly the relative amounts of uranium present in sandstones of the three facies. Shoemaker, Miesch, Newman, and Riley (1959, p. 31) suggested that the average uranium content of

unmineralized sandstone of the Salt Wash member on the Colorado Plateau is about 0.0001 percent; this average probably includes samples of all three facies described in this report.

As is evident on plate 1, sandstones of the red-beds and carbon facies show uniformly low gamma radioactivity, mudstones of all facies show higher radioactivity commensurate with their higher potassium content, and sandstones of the altered facies (with the exception of those in the Burro Canyon Formation) show higher radioactivity commensurate with their higher uranium content.

Lyman C. Huff and Charles E. Thompson of the U.S. Geological Survey made a geochemical study in May 1954 to determine the uranium and vanadium content of about 100 samples of drill core of sandstone, siltstone, mudstone, and claystone, mostly in or adjacent to the ore-bearing sandstone of the Salt Wash Member. The samples were reddish brown and light gray to greenish gray; some of the light-gray to greenish-gray samples contained coalified or carbonized plant fragments. No data were available to distinguish altered-facies from carbon-facies rocks among the carbonaceous samples, and the grayish-colored rocks were all arbitrarily grouped as altered facies. The samples were analyzed for vanadium content by a method devised by F. N. Ward and A. P. Marranzino of the Survey consisting of digesting the samples in nine molar sulfuric acid and determining the vanadium as a green thiocyanate complex in an ether layer. The analysis is sufficiently sensitive to distinguish between samples containing 0.015 percent or more vanadium and those having distinctly less than 0.015 percent vanadium. The samples were analyzed for uranium content by a method used at that time by the U.S. Geological Survey, involving the digestion of samples in dilute nitric acid, chromatographic separation of uranium from other metals on a strip of filter paper dipped in an ethyl acetate solution, and determination of uranium as the brown uranium ferrocyanide simply by spraying this filter paper with a potassium ferrocyanide solution. The analysis is sufficiently sensitive to distinguish between samples

TABLE 20.—*Estimated average uranium content, in percent, of red-beds-facies, carbon facies, and altered-facies rocks in some Mesozoic formations in the Slick Rock district*

[Figures in parentheses are logged drill hole footages on which estimates of average uranium content are based. Leaders (---) indicate that rock type is absent]

	Red-beds facies		Carbon facies		Altered facies	
	Sandstone	Siltstone-mudstone-claystone	Sandstone	Siltstone-mudstone-claystone	Sandstone	Siltstone-mudstone-claystone
Mancos Shale-------	-----------	---------	-----------	---------	-----------	0.0003 (850)
Dakota Sandstone---	-----------	---------	-----------	---------	0.0002 (560)	0 (790)
Burro Canyon Formation--------	0.0001 (100)	0 (70)	-----------	---------	0 (620)	0 (140)
Morrison Formation, Brushy Basin Member-----------	.0002 (220)	0 (620)	0.0001 (50)	---------	.0005 (150)	0 (460)
Morrison Formation, Salt Wash Member-	.0001 (40)	0 (20)	.0001 (150)	---------	.0004 (100)	0 (5)

containing 0.0002 percent or more uranium and those having distinctly less than 0.0002 percent uranium. Results of the analyses are presented in table 21.

TABLE 21.—*Uranium and vanadium content, in weight percent, of red-beds-facies and carbon- and altered-facies undifferentiated, sandstone, siltstone, mudstone, and claystone in and near the ore-bearing sandstone of the Salt Wash Member*

[Analyses by C. E. Thompson]

Uranium and vanadium content	Red-beds facies light-reddish-brown and reddish-brown		Carbon and altered facies, undifferentiated, light-gray, gray, and greenish-gray	
	Number of sandstone and siltstone samples	Number of mudstone and claystone samples	Number of sandstone and siltstone samples	Number of mudstone and claystone samples
<0.0002 uranium-----	17	22	33	14
>0.0002 uranium-----	0	2	12	3
<0.015 vanadium-----	16	8	41	17
>0.015 vanadium-----	1	16	4	0

The table shows that most rocks of the red-beds facies contain less than 0.0002 percent uranium; most sandstones and siltstones of the facies contain less than 0.015 percent vanadium but most mudstones and claystones contain more than 0.015 percent vanadium. On the other hand, most rocks of the carbon and altered facies contain less than 0.0002 percent uranium but appreciably more of the total contain more than 0.0002 percent uranium than was true for red-beds facies; most rocks of the carbon and altered facies contain less than 0.015 percent vanadium. On the basis of these data, I believe that altering solutions introduced uranium into some of the light-gray, gray, and greenish-gray rocks when they were altered from the reddish rocks, and that the solutions leached vanadium from many of the reddish-brown mudstones and claystones at the time they were altered to grayish rocks.

CHEMICAL VARIATIONS AMONG LITHOLOGIC GROUPS AND STRATIGRAPHIC UNITS

Despite the remarkable similarities in chemical composition among lithologic types from different stratigraphic units, some chemical variations exist. Such differences have a bearing on interpretation of the cause of alteration in the sedimentary rocks, the source of the solutions that effected alteration, and the source of the elements involved in alteration.

For the purpose of comparison of some of the chemical data, major elements determined by semiquantitative spectrographic data were recalculated to oxides, primarily to afford a comparison of such components as CO_2 and SiO_2. CO_2 was estimated on the basis of the amount required to balance the calculated amounts of CaO and MgO, assumed to be present in calcite and dolomite. SiO_2 was determined simply by subtracting from 100 the total of other calculated oxides. In order to check the validity of using semiquantitative spectrographic data in this way, the average mineral compositions of groups of samples were calculated for comparison with average empirical compositions determined from modal analyses. Assumptions used to make the calculations were that all the iron is present in hematite, all the magnesium in dolomite, all the calcium in dolomite and calcite, all the sodium in albite and clay minerals, all the potassium in potassium feldspar and clay minerals, and all the excess aluminum in clay minerals; clay minerals were assumed to contain 10 percent K O and

2 percent Na_2O. In some instances it was required to calculate minor excess MgO in clay minerals. On these assumptions, mineral composition determined by calculations from the oxide values is close to that determined by modal analyses.

Average chemical compositions of groups of rocks from several Mesozoic formations determined by the calculations are shown in table 22. Variations in the major components shown in table 22, of course, reflect major mineralogic variations, as for example higher quartz content and lower clay content in the group of sandstones than in the group of siltstones; mudstones, and claystones. The clayey character of sandstones from the Dewey Bridge Member is reflected by commensurate variations in SiO_2 and Al_2O_3 content. Carbonate minerals (estimated from the sum of MgO, CaO, and estimated CO_2 contents) vary erratically throughout the formations; they tend to be more abundant in the group of clayey rocks, and carbonate minerals are highest in the Mancos Shale (estimated 28.6 percent). Variation in Na_2O content (0.1 – 0.8 percent in sandstones, 1.1 – 1.9 percent in siltstones, mudstones, and claystones) reflects variation in clay content; such is also true for K_2O (0 – 3.1 percent in sandstone; 1.2 – 3.6 percent in siltstone; mudstone; and claystones). However, K_2O content decreases in sandstones from the Navajo Sandstone upward to the Dakota Sandstone, reflecting the similar decrease in potassium feldspar content of these rocks from the Navajo upward to the Dakota. As emphasized earlier, major chemical variation related to rock type is as great within some formations as it is from formation to formation.

Perhaps more significant than the major oxide components in distinguishing the chemical differences among the formations and lithologic groups are the minor elements. Average minor element compositions of the same groups of rocks from several Mesozoic formations for which major oxide components were calculated are shown in table 23. A number of elements, as shown in table 23, tend to be more abundant in the group of clayey rocks (siltstones, mudstones, and claystones) than in the group of sandstones, suggesting their affinity with either clay minerals or carbonate minerals. Among these elements are boron, beryllium, cobalt, chromium, copper, gallium, nickel, scandium, strontium, vanadium, yttrium, and ytterbium.

Other elements show different patterns of distribution. Silver has an erratic distribution and may be highest (0.00001 percent) in the Dakota Sandstone. Arsenic too is erratically distributed: <0.3 percent in the Navajo Sandstone and 0.01 percent in sandstones of the Burro Canyon Formation and

Dakota Sandstone; other rock groups contain 0 – <0.01 percent arsenic. Barium is 0.03 – 0.04 percent in most rock groups but is higher in Navajo Sandstone (0.1 percent) and in the Brushy Basin Member (0.05 – 0.1 percent). Lanthanum was detected only in the Brushy Basin Member (<0.01 percent in both the group of sandstones and the group of clayey rocks), the Dakota Sandstone (0.01 percent in clayey rocks) and the Mancos Shale (0.01 percent). Molybdenum was detected only in sandstones of the Salt Wash Member (<0.0015 percent) and in Mancos Shale (<0.003 percent). Niobium was detected only in sandstones of the Navajo Sandstone, Entrada Sandstone, and Salt Wash Member (<0.0015 percent); all higher strata sampled contain no detectable niobium. Lead also is erratically distributed: none detected in sandstones of the Burro Canyon Formation which are altered-facies rocks that contain virtually no carbonaceous material; <0.0015 or <0.001 percent in sandstones of the Navajo Sandstone, Brushy Basin Member, and Dakota Sandstone, and clayey rocks of the Salt Wash Member and Burro Canyon Formation; 0.001 percent in sandstones of the Entrada Sandstone and clayey rocks of the Dakota Sandstone and Mancos Shale; and 0.002 percent in sandstones of the Salt Wash Member and clayey rocks of the Brushy Basin Member. Tin was detected only in sandstones of the Salt Wash Member. Zirconium is evenly distributed throughout the sampled section (0.02 – 0.03 percent), except in sandstones of the Brushy Basin Member and Burro Canyon Formation, where it is lower (0.01 percent).

The foregoing data provide a necessary background to permit assessing, in later pages, the significance of differences in composition, already described, of the various facies in different formations. Also the consistency of much of those data lend substantial assurance to the validity of the spectrographic data.

DISTRIBUTION AND CHARACTER OF CONCENTRATIONS OF CARBONATE AND IRON MINERALS

Carbonate and iron minerals have been leached, recrystallized, and reconcentrated as a result of the action of the altering solutions that caused the development of altered-facies rocks. The distribution and character of these minerals, therefore, provide additional information on the properties of the altering solutions and on the pathways of solution movement, and provide further clues to the origin of the uranium-vanadium deposits.

In addition to the small-scale differences in carbonate mineral distribution that resulted from alteration, such as the general increase in the size of

TABLE 22.—*Average chemical compositions, in weight percent, of major components of rocks from Mesozoic formations in the Slick Rock district*

[Determined by calculations of semiquantitative spectrographic data given in tables 7, 8, 10, 13, 14, and 15. (----), not determined. Number of samples in parentheses]

	Sandstones							Siltstones, mudstones, and claystones				
	Navajo Sandstone	Entrada Sandstone		Morrison Formation		Burro Canyon Formation	Dakota Sandstone	Morrison Formation		Burro Canyon Formation	Dakota Sandstone	Mancos Shale
		Dewey Bridge Member	Slick Rock Member	Salt Wash Member	Brushy Basin Member			Salt Wash Member	Brushy Basin Member			
	(3)	(5)	(9)	(26)	(12)	(3)	(3)	(5)	(8)	(5)	(1)	(4)
SiO_2---	85	76	86	85	85	93	90	58	68	64	68	49
Al_2O_3--	4.7	5.7	3.8	2.8	3.2	1.5	4.3	8.7	17.2	15.9	18.9	15.1
Fe_2O_3--	1.1	1.7	1	.9	1.7	1.4	3.3	2	4.3	4.3	4.3	4.3
MgO----	1	3.3	1.2	1.3	.8	.2	.3	1.2	1.7	1.3	1.7	1.7
CaO----	1.8	3.5	1.7	3.4	3.4	1.5	.3	12.6	1	4.2	.4	14.
Na_2O---	.2	.5	.4	.4	.8	.1	.3	1.3	1.9	1.1	1.3	1.3
K_2O----	3	3.1	2.2	1	.8	----	----	3.6	2.9	3.6	3.6	1.2
TiO_2---	.3	.4	.2	.2	.2	.03	.2	.4	.5	.5	.5	.5
MnO----	.04	.08	.01	.03	.06	.03	.01	.04	.03	.01	.004	.01
CO_2----	2.5	5.5	2.7	4.1	3.5	1.4	.5	11.3	1.6	4.7	.6	12.9

TABLE 23.—*Average chemical compositions, in weight percent, of minor components of rocks from Mesozoic formations in the Slick Rock district*

[Based on semiquantitative spectrographic data given in tables 7, 8, 10, 13, 14, and 15. Tr, trace. Number of samples in parentheses]

	Sandstones							Siltstones, mudstones, and claystones				
	Navajo Sandstone	Entrada Sandstone		Morrison Formation		Burro Canyon Formation	Dakota Sandstone	Morrison Formation		Burro Canyon Formation	Dakota Sandstone	Mancos Shale
		Dewey Bridge Member	Slick Rock Member	Salt Wash Member	Brushy Basin Member			Salt Wash Member	Brushy Basin Member			
	(3)	(5)	(9)	(26)	(12)	(3)	(3)	(5)	(8)	(5)	(1)	(4)
Ag----	0	0	<0.00001	0	<0.00001	<0.00001	0.00001	<0.00003	0	0	0.00001	<0.00001
As----	<.3	0	<.01	0	<.01	.01	.01	0	<.01	<.01	0	0
B-----	.003	.008	.003	.002	.002	.003	.003	.007	.006	.01	.01	.01
Ba----	.1	.03	.03	.03	.1	.03	.04	.03	.05	.03	.03	.03
Be----	0	<.00015	0	0	0	0	0	0	<.0001	.0001	.0001	.0001
Co----	<.001	.001	<.0007	<.0007	<.001	0	0	.001	.002	.001	.003	.003
Cr----	.002	.004	.002	.002	.002	.002	.002	.009	.008	.008	.03	.02
Cu----	.002	.002	.001	.002	.002	.002	.002	.008	.003	.002	.003	.003
Ga----	Tr	.0006	<.001	<.001	<.001	0	.001	.001	.003	.003	.003	.003
La----	0	0	0	0	<.01	0	0	0	<.01	0	.01	.01
Mo----	0	0	0	<.0015	0	0	0	0	0	0	0	<.003
Nb----	<.0015	<.0015	<.0015	<.0015	0	0	0	0	0	0	0	0
Ni----	.003	.003	<.001	.0005	<.001	.002	.002	.003	.003	.002	.01	.01
Pb----	<.0015	.001	.001	.002	<.001	0	<.001	<.001	.002	<.001	.001	.001
Sc----	0	.0008	0	<.0007	<.001	0	.001	.002	.003	.003	.003	.003
Sn----	0	0	0	<.01	0	0	0	0	0	0	0	0
Sr----	.004	.007	.005	.007	.02	.02	.005	.03	.03	.03	.03	.03
V-----	.004	.003	.005	.004	.004	.001	0	.004	.005	.008	.01	.01
Y-----	<.0015	.003	<.0013	.001	.001	.001	.001	.003	.003	.003	.01	.003
Yb----	<.00015	.0003	<.00018	.0001	.0001	.0001	.0001	.0002	.0003	.0003	.0003	.0003
Zr----	.02	.03	.02	.03	.01	.01	.03	.02	.03	.02	.03	.02

optically continuous patches of calcite in altered-facies sandstone compared to that in red-beds- and carbon-facies sandstone, some gross redistribution of calcite among lithologies and stratigraphic units appears to have occurred. For example, in the lower part of the Brushy Basin Member and in the upper part of the Salt Wash Member calcite-rich selvages are common and more enriched at or near the top or bottom of altered-facies sandstone layers whereas they are not as common and are less enriched at or near the top or bottom of red-beds-facies sandstone layers (Archbold, 1959, fig. 5). Additional examples that show this relationship are illustrated in plates 1 and 2. Also distribution of calcite appears to be more uniform in red-beds- than in altered-facies sandstone in the Salt Wash Member, and locally in altered-facies sandstone it has higher and lower concentrations than in red-beds-facies sandstone. Plates 1 and 2 also show this general relationship.

Both the small-scale distribution of calcite (as blebs and clots) and the large-scale distribution of calcite (in enriched layers) indicate redistribution of calcite as a result of alteration that formed the altered-facies rocks, but the average abundances of calcite in the various facies generally are not greatly different.

Despite the higher indicated calcite content of red-beds-facies mudstone compared to that of altered-facies mudstone in the Morrison Formation (table 2),

the two types may have nearly equal calcite contents. This conclusion is based on the fact that fine-grained calcite nodules (essentially, limestone nodules) are more abundant in altered-facies argillaceous rocks than in red-beds-facies equivalents, and that they may represent segregations of calcite formed during alteration and therefore are not included in the analyses given in table 2. In the Cougar mine, Lower group of mines, greenish-gray mudstone at the base of the ore-bearing sandstone locally contains numerous slablike nodules of gray limestone (or fine-grained calcite) 1 – 3 inches wide, about a foot in vertical dimension, and several feet long, spaced a few inches to a few feet apart, occurring as two conjugate sets oriented nearly N. 75° W. and N. 45° E. The orientations of these sets of nodules in mudstone are nearly parallel to dominant joints in sandstone in the vacinity (Shawe, 1970, fig. 5), and perhaps formed at the same time and as a result of the development of the Dolores zone of faults.

Near the Dolores River just south of Disappointment Creek, (fig. 4) the lower part of the basal conglomeratic sandstone layer of the Burro Canyon contains segregations of calcite that on flat surfaces weather as pedestals 0.5 – 1 inch high. Elsewhere in altered-facies rocks of the Burro Canyon Formation calcite is commonly concentrated along bedding planes.

Carbonate minerals were deposited in concentrations in and adjacent to faults and joints in many places in the Slick Rock district. Faults that offset the Entrada Sandstone in Summit Canyon commonly are bounded by large concentrations of carbonate minerals that impregnate sandstone and make it resistant to erosion so that spires stand locally along the faults (fig. 19).

In the Dolores zone of faults close to the top of the crossbedded unit of the Slick Rock Member, where the rocks have been bleached by altering solutions and are light brown because of near-surface weathering of pyrite, carbonate has accumulated at the junctures of polygonal joints. Such accumulations weather out as vertical rods that rise above a specific horizontal bed at the corners of the joint polygons (fig. 20, A and B). Apparently the carbonate in rods was localized because of preferential flow of solutions where several joints intersect, and obviously was deposited after lithification and jointing of the rock. The rods occur in a zone between two faults about 300 feet apart, but no closer than about 50 feet to either fault. Iron-stained carbonate is abundant along the planes of both faults in many places. Carbonate in the rods and adjacent altered sandstone is calcite, and that along the faults is dolomite, according to differential thermal analyses

FIGURE 19.—Carbonate-cemented rock along a fault that offsets the Entrada Sandstone. Contact between altered-facies sandstone of the Slick Rock Member above and red-beds-facies sandstone of the Dewey Bridge Member below is shown approximately by the dashed line; altered-facies rock bounds shears and fractures in the Dewey Bridge Member in and near the fault. (Chemical alteration changes here are discussed under "Detailed Relationships.") Trees are about 6 feet tall. Sec. 2, T. 43 N., R. 19 W., Summit Canyon. Photograph by N. L. Archbold.

corroborated by dilute hydrochloric acid tests made by N. L. Archbold at the University of Michigan (written commun., May 1960).

Carbonate minerals in places have been concentrated adjacent to joints in sandstone of the Salt Wash Member of the Morrison Formation where the sandstone consists of the altered facies (fig. 21). Numerous joints lined with calcite were mapped by W. B. Rogers of the Survey and these are dominantly in or close to altered-facies sandstone near the Dolores zone of faults (fig. 4).

FIGURE 20.—Altered-facies sandstone containing vertical calcite-cemented sandstone rods localized at joint intersections in the upper part of the crossbedded unit of the Slick Rock Member of the Entrada Sandstone. A, Relationship of rods to bedding layer and vertical joints. B, Relationship of rods to the corners of joint polygons. SW¼ sec. 1, T. 43 N., R. 19 W., Bush Canyon. Photographs by N. L. Archbold.
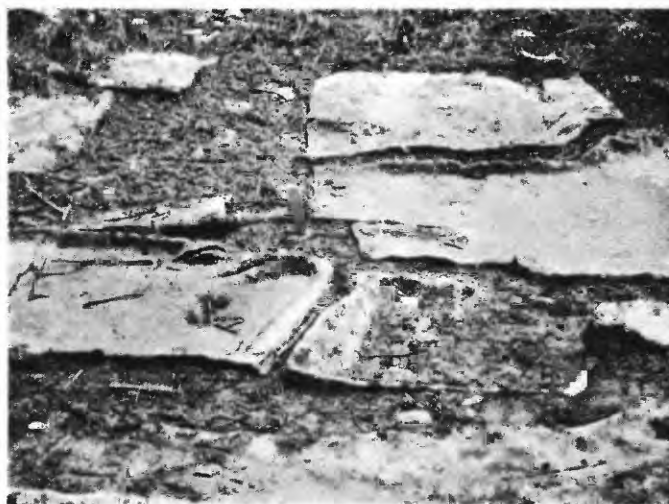
FIGURE 21.—Ridges along joints in weathered light-brown sandstone of the upper unit of the Salt Wash Member; abundant carbonate cement accounts for resistance of the ridges to weathering. Sec. 13, T. 43 N., R. 19 W. Photograph by N. L. Archbold.

In sec. 34, T. 44 N., R. 18 W., about 1,800 feet east of the Dolores River on the south side of Nicholas Wash, a silicified grayish-green siltstone layer 3 feet thick in the upper part of the Burro Canyon Formation (described as a "marker bed" by Shawe and others, 1968, p. A77) contains a thin calcite vein. A fracture bounded by calcite-cemented breccia 2–6 inches thick strikes east and dips 10° N.; as beds strike northwest and dip 5° NE here, the calcite vein transgresses bedding about 1 foot downward in every 15 feet horizontally, to the base of the silicified layer, and thence follows the base of the bed another 30 feet as a ½-inch layer of calcite. Calcite and pyrite specks are scattered throughout the silicified siltstone layer. Probably compression during folding of the strata accounted for formation of the low-dipping brecciated

fracture, and calcite may have been deposited in the fracture while the rocks were still deeply buried.

South of the Tailholt mine and in places elsewhere in open faults and fractures that have controlled alteration, calcite occurs as dogtooth spar crystals ranging in width from 1 mm to 1 cm.

No spectrographic data were obtained on the composition of carbonates from faults or joints. Calcite (sample SH–53–56) collected from a fault where it cuts the Summerville Formation just below the "marker bed" on the southeast side of Summit Canyon (sec. 2, T. 43 N., R. 19 W.) contained, by chemical analysis in the U.S. Geological Survey's Washington laboratories, 0.001 percent lead and 0.001 percent uranium. Another calcite sample (SH–96–56) collected from a fault where it cuts the Salt Wash Member south of the Tailholt mine contained, by similar analysis, 0.002 percent lead and 0.009 percent uranium. (Data from T. W. Stern, U.S. Geol. Survey, written commun., July 1963.)

Concentrations of iron minerals are common in altered-facies rocks, particularly at boundaries with red-beds-facies rocks. These have been observed only in outcrops and in near-surface mine workings, and the rocks of course are weathered. An example in the ore-bearing sandstone of the Salt Wash Member west of the Cougar mine has already been described in the section "Detailed Relationships." There, a large irregular pod of dark-reddish-brown sandstone about 30 feet thick and 100 feet long is visible in a rim exposure of altered-facies ore-bearing sandstone. The pod is generally surrounded by intense limonite stain

which in places shows concentric layers that cut sharply across bedding. Nearby, between the Chico claim and the Alice claim, reddish-brown sandstone forms a pod 15 feet long that is surrounded by conspicuous alternating concentric layers of dark-reddish-brown hematite-stained sandstone and of limonite-stained sandstone. Limonite in the sandstone likely is oxidized from pyrite as a result of weathering. Concentric layers of iron minerals (mostly hematite) bounding a tongue of altered-facies ore-bearing sandstone at the Mildred F claim have previously been described ("Detailed Relationships" and fig. 13). West of the Tailholt mine light-brown sandstone of the ore-bearing unit of the Salt Wash Member contains numerous limonitic "shells" or concretionlike forms 0.5 – 1 foot in diameter.

Altered-facies sandstone in the middle part of the Salt Wash Member just south of the Doss group of claims contains concentrations of iron and probably manganese oxides in purplish-brown curved layers similar to form to "rolls" of uranium-vanadium ore. (See for example, Shawe, 1956a.)

Calcite and barite have been concentrated along with hematite in nodules close to the boundary between altered-facies and red-beds-facies sandstone, as in the tongue of altered sandstone at the Mildred F claim illustrated in figure 13.

In places the concentrations of iron minerals are nearly black such as to suggest that manganese oxides may be present, or even dominant over iron minerals. Dark concretionlike forms were observed where light-reddish-brown sandstone is partly altered to light-brown sandstone in the middle part of the Salt Wash Member on the north side of Cougar Canyon north of the Lower group of mines.

Distribution of such iron-mineral concentrations in the Morrison Formation is shown in figure 4. These deposits of iron minerals lie mainly along the northeast edge of the Dolores zone of faults, in a zone generally transitional between red-beds-facies and altered-facies rocks.

East of the Dolores River and just south of Disappointment Creek two prominent conglomeratic sandstone ledges form the lower part of the Burro Canyon Formation. Small calcite pedestals (previously described on p. D36) remain on weathered surfaces of the lower of these sandstone layers. Near the top of the upper sandstone ledge very abundant limonite stain marks a conspicuous layer. Within this conspicuous layer occur numerous hematite-rimmed nodules ½ – 2 inches in diameter, some irregular in form and many spherical. Within the dense hematite-cemented rims of these nodules is soft, friable limonitic sandstone. Quartz sand grains in the cores of

the nodules, and within hematite cement, are well rounded; outside of the nodules, quartz sand grains have quartz overgrowths.

On the northeast side of Disappointment Valley northwest of Gypsum Gap, a large pod of dark-brown limonitic material several tens of feet long and a few feet thick occurs in sandstone of the Burro Canyon Formation. In places in sandstone of the Burro Canyon Formation limonite (pseudomorphous after pyrite) forms concentric curved layers similar in form to rolls of uranium-vanadium ore. One such example was observed just south of Glade Point on the east rim of the Dolores River canyon near the base of the Burro Canyon (fig. 22). Here the concentric layers of limonite are indented at layers of lower permeability, such as the conglomerate layers with abundant matrix clay shown in the lower half of figure 22, in much the same fashion as uranium-vanadium ore rolls have been modified in form by claystone layers of low permeability.

Manganese oxide minerals may also be concentrated with iron minerals in the Burro Canyon Formation. In sec. 34, T. 44 N., R. 18 W., about 1,200 feet east of the Dolores River on the north side of Nicholas Wash, dark-brown concentrations of iron and manganese(?) oxide minerals are irregularly distributed near the base of the 15-foot-thick upper sandstone layer of the Burro Canyon (fig. 23). Thin-section studies of light-brown altered-facies sandstone near the mottled concentrations of dark minerals show both solution effects and quartz overgrowths on detrital quartz grains, and abundant (about 20 percent) calcite cement in large optically continuous patches. Calcite cement appears to have protected quartz grains from solution and overgrowth effects, so the calcite may be an early feature in the rock. Polysynthetically twinned calcite suggests deformation (due to folding?) following calcite deposition. Sandstone in which dark minerals are concentrated, in thin section shows abundant quartz overgrowths on detrital quartz grains, some limonite (probably altered from pyrite), and about 10 percent calcite cement in large optically continuous patches. Calcite has completely replaced some detrital grains (plagioclase?) and has abundant polysynthetic twins. Intimate association of calcite and dark minerals may indicate simultaneous crystallization. This alteration probably occurred when the rocks were deeply buried prior to folding.

Iron oxide minerals are abundant along fractures, and iron oxide mineral stains are numerous in sandstone near fractures, within the altered zones that bound faults. Limonite pseudomorphs after cubic pyrite, commonly as slablike veinlets a millimetre to a

FIGURE 22.—Concentric limonitic layers (arrows) with roll-like form in crossbedded light-buff sandstone and conglomerate of the Burro Canyon Formation. Found at rim of the Dolores River canyon just south of Glade Point.
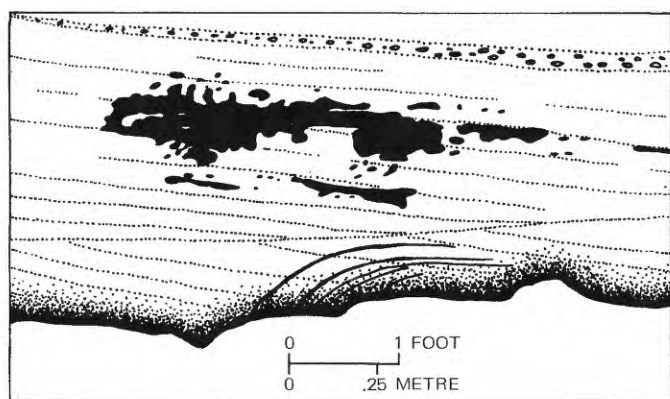

FIGURE 23.—Dark-brown concentrations of iron oxide and manganese(?) oxide minerals (black) near the base of the light-buff upper sandstone layer of the Burro Canyon Formation. Sec. 34, T. 44 N., R. 18 W., about 1,200 feet east of the Dolores River on the north side of Nicholas Wash. Dotted lines are bedding layers in sandstone; curved lines at base of sandstone (lower center) are "diffusion" layers of iron and manganese(?) oxide minerals; conglomerate lens at top. Grayish-green mudstone containing abundant limonite stains underlies sandstone.

few centimetres thick, occur in faults or joints in the Navajo and Entrada Sandstones in Summit Canyon; in sandstones of the Salt Wash Member west and south of the Tailholt mine, near the Cougar mine, and elsewhere; and in the Dakota Sandstone in the eastern part of Disappointment Valley, secs. 17 and 21, T. 43 N., R. 16 W., at the Glade graben, and in other places. At the Glade graben numerous vertical fractures parallel to the main faults are filled with limonite after cubic pyrite, as well as botryoidal layers of dark mineral, probably a mixture of iron and manganese

oxides. Iron oxide minerals impregnate sandstone on layers adjacent to the fractures in the manner of "wonder stone."

Locally, such as south of the Moon group of mines, fractured red-beds-facies sandstone of the Salt Wash Member is bounded by Liesegang ringlike layers (fig. 24). The layers contain alternately hematite and limonite (probably altered from pyrite) and are similar to layers that bound isolated pods of iron-mineral concentrations in altered-facies sandstone. Here it is apparent that the layers formed by diffusion of altering solutions outward from the fractures.

In some places, where alteration has been more intense along fractures than is shown in figure 24, concentrations of dark-colored iron and manganese(?) oxide minerals have accumulated (fig. 25). Note the

FIGURE 24.—Alternating hematite and limonite layers adjacent to fractures in red-beds-facies sandstone of the Salt Wash Member south of the Moon group of mines.

local concentric layers of dark minerals shown in the lower photograph, figure 25.

Some joints in altered-facies sandstone, having become filled with iron minerals (probably originally pyrite but oxidized to limonite in the outcrops where observed), apparently served to impede the flow of altering solutions so that "diffusion" layers of iron minerals in sandstone adjacent to the joints are controlled by the positions of the joints. An example south of the Cougar mine is illustrated in figure 26.

The chemical compositions of samples of two concentrations of iron minerals are given in table 24. One of the samples (SH – 49 – 56) was collected from limonite-rich material along a fault plane in the Entrada Sandstone and one (sample SH – 52 – 56) was

FIGURE 25.—Concentrations of purplish-brown iron and manganese(?) oxide minerals (dark) near fractures that are bordered by intensely altered sandstone (light) of the ore-bearing sandstone of the Salt Wash Member. Johnstown No. 1 claim, NE¼ sec. 32, T. 44 N., R. 19 W., Stevens Canyon.

TABLE 24.—*Semiquantitative spectrographic analyses, in weight percent, of two samples of sandstone from iron-rich deposits in the Slick Rock Member of the Entrada Sandstone and the Salt Wash Member of the Morrison Formation*

[Analyses by Nancy M. Conklin. M, major; Tr, trace; 0, looked for but not found (below limit of detectability). Also looked for but not found: P, Ag, As, Au, B, Be, Bi, Cd, Ce, Co, Dy, Er, Eu, Ga, Gd, Ge, Hf, Hg, Ho, In, Ir, La, Li, Lu, Mo, Nb, Nd, Os, Pb, Pd, Pr, Pt, Rb, Re, Rh, Ru, Sb, Sc, Sm, Sn, Ta, Tb, Te, Th, Tl, Tm, U, W, Zn]

Sample No---	Slick Rock Member 1	Salt Wash Member 2	Sample No---	Slick Rock Member 1	Salt Wash Member 2
Si----------	>10	M	Ba----------	0.03	0.03
Al----------	1.5	1.5	Cr----------	.0015	.0015
Fe----------	3	7	Cu----------	.0015	.0015
Mg----------	.15	.15	Ni----------	0	Tr
Ca----------	.15	.15	Sr----------	.0015	.0015
Na----------	.07	.07	V-----------	.03	.03
K-----------	1.5	0	Y-----------	Tr	Tr.
Ti----------	.03	.07	Yb----------	<.001	<.001
Mn----------	.007	.007	Zr----------	.007	.007

SAMPLE DESCRIPTIONS

Sample No.	Field No.	Description
1-----	SH-49-56--	Brown sandstone adjacent to fault, sec. 34, T. 44 N., R. 19 W., north side of Stevens Canyon.
2-----	SH-52-56--	Dark-brown sandstone, SW 1/4 sec. 1, T. 43 N., R. 19 W., northwest rim of Bush Canyon.

collected from a layer enriched in iron oxide minerals in a lens of altered-facies sandstone surrounded by red-beds-facies sandstone in the middle part of the Salt Wash Member. Some elements in these samples are present in amounts similar to those in altered-facies rocks of the Slick Rock and Salt Wash Members (table 13), although magnesium, calcium, sodium, potassium, manganese, and strontium appear to be somewhat less, and iron and vanadium are significantly more, in these samples than in altered-facies rocks.

Samples of limonite-rich material collected along fractures in altered-facies sandstone were analyzed in the U.S. Geological Survey's Denver laboratory for equivalent uranium. Sample SH – 49 – 56, taken at the east-trending fault that cuts the Slick Rock Member in NE¼ sec. 34, T. 44N., R. 19 W., on the point between Stevens and Tailholt Canyons where the fault is irregularly bounded by altered facies sandstone in the lower reddish-brown part of the Slick Rock, contains 0.006 percent equivalent uranium of which about 0.001 percent is attributable to potassium (table 24). Sample SH – 48 – 56, collected at a fracture trending N. 72° W. in the upper part of the Navajo Sandstone on the north side of Stevens Canyon where fractures in reddish-brown sandstone are bordered by 1 – 6 feet of light-brown sandstone of the altered facies, contains 0.003 percent equivalent uranium. Thorium content is assumed to be negligible, and the bulk of the radioactivity of the samples is inferred to be due to daughter products of uranium.

Some concentrations of iron minerals appear to have resulted from weathering near the surface, but the relations of such concentrations in their geologic setting are different from those of previously described iron-mineral concentrations. An example is illustrated in figure 27. The illustration shows a fracture in a layer of sandstone, at the base of the Dakota Sandstone on the northwest side of Narraguinnep Canyon, filled with Holocene soil and bounded by limonitic "diffusion" layers. The limonitic layers extend into the underlying mudstone which is not fractured, and transgress the contact between altered-facies and red-beds-facies mudstone. The association with a fracture at the surface containing debris from weathering, and the lack of relation to an alteration contact inferred to have formed when the rocks were deeply buried, indicate this iron-mineral concentration to be a surficial phenomenon. None of the other previously described iron-mineral concentrations show such relations and none are inferred to
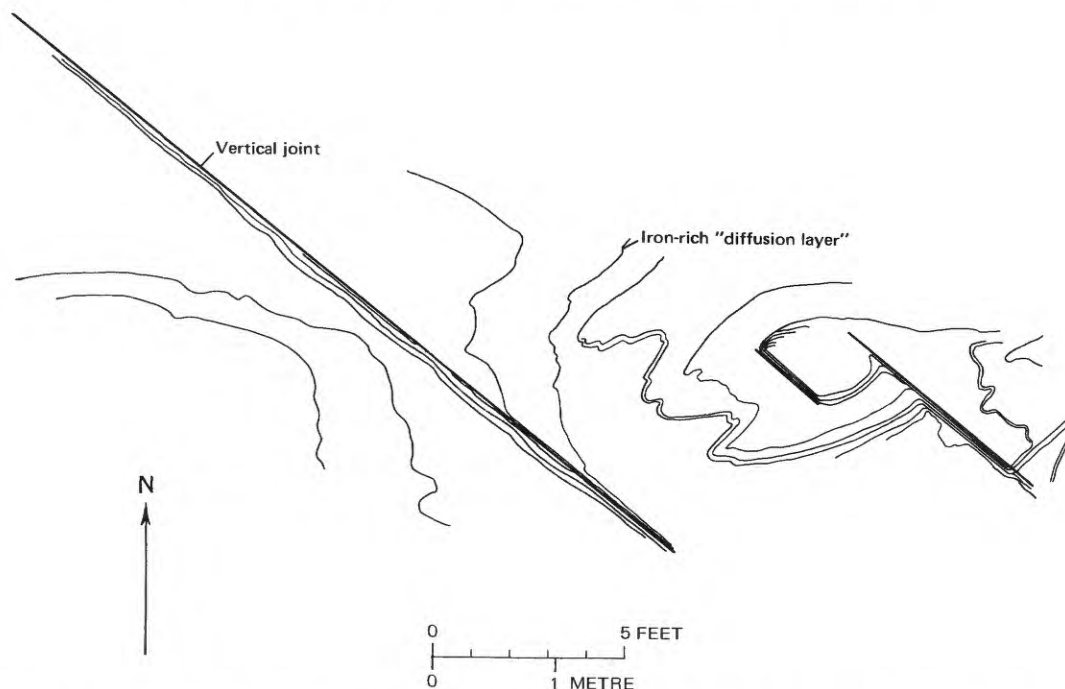
FIGURE 26.—Limonite-filled vertical joints and iron-oxide-rich "diffusion" layers in adjacent altered-facies sandstone in the middle part of the Salt Wash Member, SE 1/4 sec. 23, T. 44 N., R. 19 W., south of the Cougar mine in canyon bottom. Sandstone bedding is approximately in the plane of the sketch.
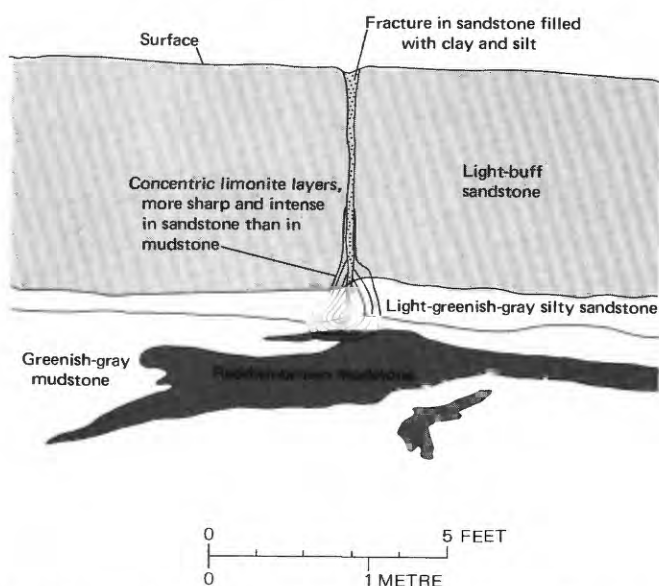

FIGURE 27.—Sketch of iron-oxide-mineral concentrations as "diffusion" layers related to a soil-filled fracture in sandstone at the base of the Dakota Sandstone on the northwest side of Narraguinnep Canyon. Note how limonite layers transgress contact between altered-facies (light-greenish-gray) mudstone and red-beds-facies (reddish-brown) mudstone.

have formed as a result of near-surface weathering, even though weathering has converted primary iron minerals (such as pyrite) in them to limonite.

AGE OF ALTERATION

I have concluded (Shawe, 1970, p. C17) from an analysis of structural relations that alteration of sedimentary rocks in the Slick Rock district occurred probably during early to middle Tertiary time. Faults and joints in the Dolores and Glade zones of faults and on the southwest side of the collapsed Gypsum Valley salt anticline are younger than strata of Late Cretaceous age and these fractures controlled movement of solutions that epigenetically altered the rocks. The fractures were likely formed during the early Tertiary before major uplift of the Colorado Plateau. Younger fractures that postdate alteration (they are not bounded by altered rocks, and some offset mineralized rocks) were probably formed during the late Tertiary and Quaternary.

Several features indicate that deposition of minerals identified with the development of the altered facies took place when the sediments were deeply buried. Maximum burial of the rocks occurred during early Tertiary time when perhaps 10,000 feet of strata of the Mesaverde, Wasatch, and Green River Formations, or equivalent formations—now eroded from the Slick Rock district—were deposited. "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" (Shawe, 1968, p. B33–B34). Also, calcite in altered-facies rocks is commonly polysynthetically twinned, and in places sheared subparallel to bedding, indicating that the rocks were deformed following crystallization of calcite, most likely when deeply buried. Much of the calcite in altered-facies rocks thus appears to have been deposited during or following deep burial but before major folding of the rocks was completed. In altered-facies rocks, simultaneous solution of silica and redeposition as overgrowths, where interpenetrating stylolites in quartz grains are normal to bedding, attest to alteration under high pressure of deep burial.

Calcite in altered-facies sandstones characteristically encloses euhedral crystals of other authigenic minerals such as anatase, pyrite, and marcasite (Shawe, 1968, figs. 18, 40), and calcite in altered facies mudstones and associated rocks commonly is closely associated with barite, analcite, albite, and chalcedony such as to suggest contemporaneous deposition (fig. 6; Shawe, 1968, figs. 27, 28, 29, 33), indicating that these minerals likely developed simultaneously at the time of the alteration that accounted for redistribution of calcite. Thus much of the development of authigenic minerals that characterize the altered facies, being associated with calcite recrystallization, appears to have occurred during the early Tertiary episode of deep burial of the sedimentary rocks.

SUMMARY, DISCUSSION, AND CONCLUSIONS

Three facies of sedimentary rocks in the Slick Rock district can be distinguished on the basis of both mineralogical and chemical differences. Red-beds-facies rocks are characterized by a high content of detrital black opaque minerals and almost no pyrite, carbon-facies rocks contain a moderate amount of black opaque minerals and minor pyrite, and altered-facies rocks contain only sparse black opaque minerals but appreciable pyrite. Black opaque minerals in red-beds-facies rocks contain, in addition to major iron and titanium, a significant amount of chromium and vanadium. Carbon-facies rocks, though not adequately characterized chemically, do not show any significant chemical differences from red-beds-facies rocks. Altered-facies rocks, however, contain notably higher amounts of lead and uranium than do red-beds-facies rocks. In addition, analyses of pairs of red-beds- and altered-facies rocks, collected in the same rock layer across an alteration contact, show that iron, calcium, chromium, and niobium commonly have been leached from altered-facies rocks, and cobalt, nickel, lead(?),

vanadium, yttrium, and ytterbium may have been added to altered-facies rocks.

Distribution of vanadium in altered-facies rocks appears to be somewhat complex, and will be described in detail. In sandstones it is low (0–0.001 percent) in the Dakota Sandstone and Burro Canyon Formation, higher (0.004–0.005 percent) in the Brushy Basin Member, Salt Wash Member, Dewey Bridge Member, and Navajo Sandstone, and highest (0.007 percent) in the Slick Rock Member. Vanadium in clayey rocks is low (0.002 percent) in the Salt Wash Member and high (0.01 percent) in the Brushy Basin Member, Burro Canyon Formation, Dakota Sandstone, and Mancos Shale.

Altered-facies rocks contain concentrations of minerals—other than the uranium-vanadium ore deposits—that occur near the boundaries between altered-facies and red-beds-facies rocks, and that are enriched in iron and vanadium. Fractures that have controlled alteration of the red-beds to the altered facies contain carbonate and iron minerals that carry significantly higher amounts of uranium, vanadium, chromium, copper, and some other elements than are present in surrounding rocks.

Alteration effects that reflect introduction of elements such as uranium, vanadium, and lead—elements that characterize the uranium-vanadium ore deposits—and the universal association of the altered facies with ore deposits, clearly relate the phenomenon of sedimentary rock alteration to the formation of the ore deposits.

The differences in composition among the three facies of rocks just summarized, and other compositional differences discussed earlier in this report, suggest that removal of elements from, redistribution of elements within, or addition of elements to altered-facies rocks has revealed not only the paths of altering solution movement but also the likely sources of some of the elements.

Red-beds-facies rocks developed by diagenetic processes in a near-surface, oxygenated environment. Shortly after deposition, probably where sediments still lay above the water table but were alternately wet and dry from periodic influxes of meteoric water, detrital black opaque minerals and other iron-bearing minerals such as amphiboles and pyroxenes were oxidized and iron was reprecipitated nearby as hematite. The hematite formed a wash, as coatings on other detrital grains, or dustlike material dispersed throughout the rocks, imparting reddish colors to the rocks. Deep burial of the sediments and the indigenous pore-filling ground waters that permeated the red-beds facies had no effect on the oxidized

character of the rocks, nor altered the fundamentally reddish colors. Nor did weathering, following uplift and erosion, have any apparent effect upon the color or oxidized condition of the red-beds facies.

Carbon-facies rocks also developed by diagenetic processes in a near-surface environment but, unlike red-beds-facies rocks, in an environment characterized by abundant carbonized plant debris which induced reducing conditions in the sediments. The carbon facies probably developed below the water table, where humic acid-charged ground waters dissolved some of the detrital black opaque minerals. Iron thus liberated was reprecipitated nearby partly in minor amounts of pyrite and partly in carbonate minerals. The rocks that formed in the carbon-facies environment are light gray and greenish gray; inherent mineral colors are not masked by iron oxide coatings. In the ore-bearing sandstone of the Salt Wash Member carbon-bearing rocks dominate the lower part and red-beds rocks the upper part. This common relation is a logical consequence of carbon-facies diagenesis below a water table and red-beds-facies diagenesis above a water table where oxygen was sufficient to oxidize any original carbonaceous plant material. Deep burial of the sediments alone was not sufficient to modify the carbon-facies environment; following uplift and erosion, however, near-surface weathering resulted in oxidation of pyrite to limonite so that the rocks took on buff and light-brown colors.

Altered-facies rocks, which on geologic evidence clearly have formed through epigenetic alteration of both red-beds-facies and carbon-facies rocks, apparently developed when the rocks were deeply buried. Alteration caused destruction of most detrital black opaque minerals, precipitation of substantial pyrite, and recrystallization of carbonate minerals that took up much of the iron liberated from solution of black opaque minerals. Other chemical changes already indicated were also a result of epigenetic alteration. The rocks are light gray and greenish gray; as were carbon-facies rocks they were weathered in the near-surface environment, with oxidation of pyrite to limonite, so that the rocks are now buff and light brown.

The relative proportions of the three facies of rocks, and the relationships among them, impose some constraints and requirements on any attempt to provide a rational explanation of the epigenetic alteration of red-beds- and carbon-facies rocks. Such an explanation is of significance because of the clear connection between epigenetic alteration and deposition of the uranium-vanadium ore bodies.

Throughout the Colorado Plateau the red-beds facies comprises thousands of cubic miles of rocks, the carbon facies some tens of cubic miles of rocks, and the altered facies several hundreds of cubic miles of rocks. The spatial disposition of the three facies in the Slick Rock district is illustrated by a diagrammatic section (fig. 28). At least four fundamental questions are posed by the spatial relations of the three facies, by their volume differences, and by their mineralogical and chemical differences. First, what was the source of the large volume of altering solutions that caused widescale chemical reduction of erstwhile oxidized red beds which themselves obviously were not capable of producing reducing solutions? Second, what rationale will satisfactorily explain the similar mineralogical changes that occurred both in red beds that became reduced and in carbonaceous strata close to the sites where uranium-vanadium deposits formed? Third, could solutions, while altering the rocks they traversed and depositing small amounts of uranium and other metals, have deposited these metals in significant amounts (as ore deposits) in favorable environments associated with carbonaceous strata within the red-beds sequence? And fourth, what were the sources of the uranium and other metals carried by the altering solutions, and deposited from them in carbonaceous strata?

I propose that the relationships already described suggest that chemically reducing saline pore waters were expelled from carbonaceous clayey strata (the unconsolidated mud of the Mancos Shale) above the red-beds section during compaction accompanying deep burial and that part of these solutions traversed downward into the red beds causing reducing alteration therein. (See fig. 28.) Mancos Shale pore water, as discussed below, likely carried significant amounts of uranium, vanadium, and other elements, which were then deposited in large concentrations locally in the red-beds section in strongly reducing humic acid environments associated with coalified or carbonized plant debris.

The unconsolidated mud of the Mancos Shale is a likely source of a large volume of chemically reducing water that accounted for the alteration that occurred in underlying red-beds-facies rocks. The Mancos was being compacted, and was expelling pore fluids, during deep burial that occurred in early Tertiary time, appropriate to the inferred time of development of alteration in red-beds strata. Reduced rocks in the Hermosa Formation underlying the red-beds section on the Colorado Plateau, though of sufficient volume to have yielded a large amount of reducing solutions capable of altering red beds, are an improbable source
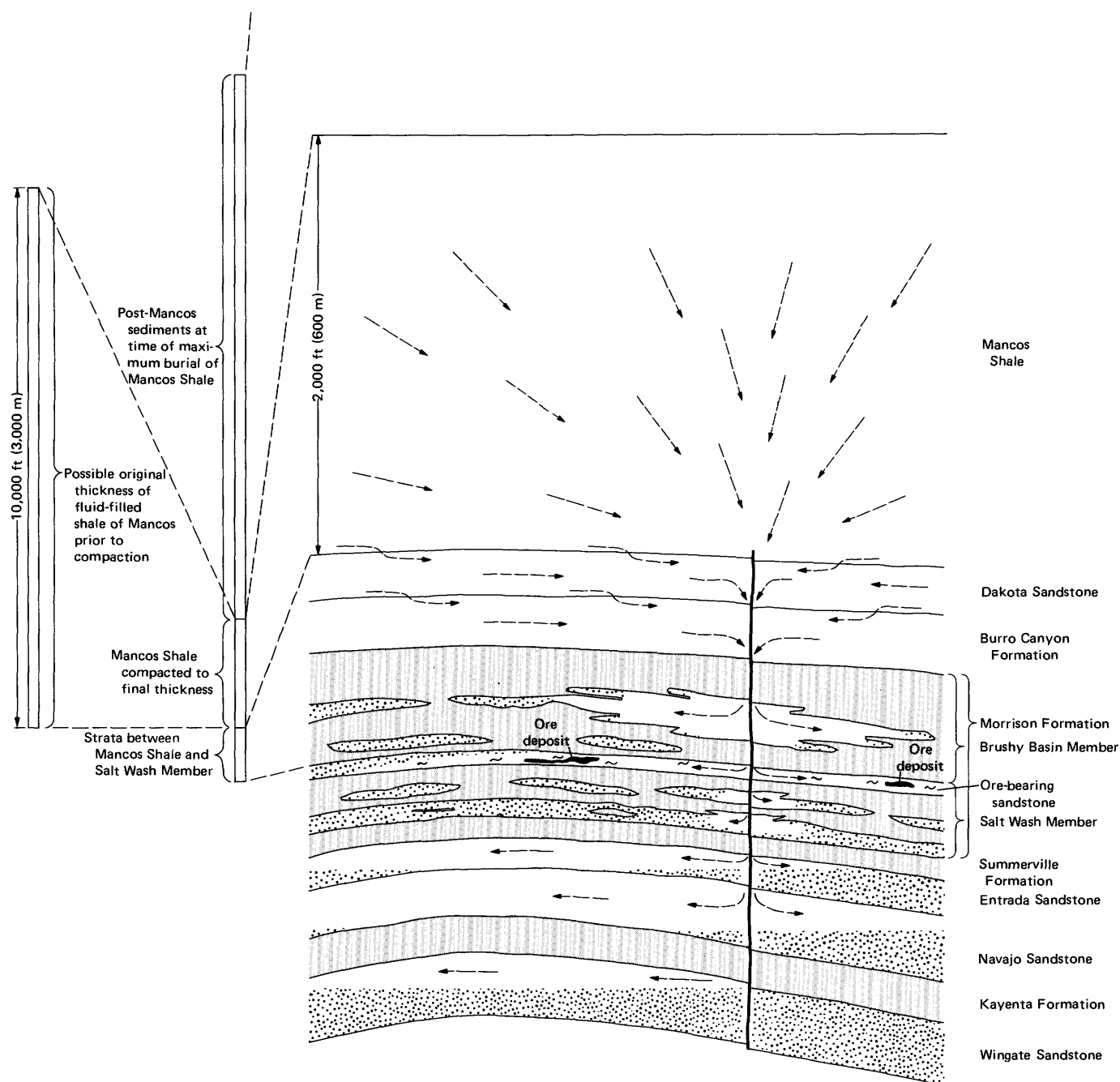
FIGURE 28.—Diagram showing distribution of altered-facies rocks (white), carbon-facies sandstone (∿), red-beds-facies permeable rocks (stippled), and red-beds-facies impermeable rocks (shaded) in the stratigraphic sequence Wingate Sandstone to Mancos Shale. Dakota Sandstone and Mancos Shale contain abundant carbonaceous material but are considered altered-facies rocks on the basis of mineralogical and chemical composition. Vertical line is a fault. Dashed arrows suggest flow of pore water as a result of expulsion upon compaction of the Mancos Shale with burial. Alteration of altered-facies rocks below the Mancos Shale is inferred to have resulted from action of pore water expelled from the Mancos.

because most of the pore water in the Hermosa likely was expelled by compaction before much of the red-beds sequence was deposited. Perhaps such waters may have been involved in alteration and ore deposition in the lower part of the red beds (Cutler and Chinle Formations) but this possibility is not evaluated further here.

The Mancos Shale belongs to the group of thick marine organic muds (black shales) generally thought of as deposited in geosynclinal areas; other marine

organic muds, characteristically much thinner and containing a higher percentage of carbonaceous material, are believed to have been deposited in epicontinental seas. Perhaps a further distinction between the groups of organic muds might be relatively rapid deposition of thick organic muds and relatively slow deposition of thin organic muds. Marine organic muds deposited on the stable continental areas generally contain more than 0.0020 percent uranium, whereas most marine organic muds deposited in geosynclines characteristically contain much less than 0.0020 percent uranium, more nearly what noncarbonaceous marine muds (shales) contain: 0.0001 to 0.0004 percent uranium (Swanson, 1961, p. 67, 70). The Mancos Shale contains an average of 0.00037 percent uranium according to Pliler and Adams (1962, p. 1115), probably a typical amount for carbonate-rich marine organic muds deposited in geosynclinal areas.

Uranium in the original mud of black shales was accumulated largely by adsorption from seawater onto organic material that was deposited with the mud, and partly precipitated by hydrogen sulfide at the sea bottom (Swanson, 1961, p. 86–95). Because of the character of the Mancos Shale and similar geosynclinal marine black shales, their uranium content seems anomalously low, being no higher than that of noncarbonaceous marine shales. The low uranium content of the Mancos may have resulted from abnormally low uranium content of seawater, rapid accumulation of sediment such that much less uranium was adsorbed by organic material than in organic muds that accumulated more slowly over a longer period of time, or by loss of uranium after deposition of the mud. According to Swanson (1961, p. 85) unusually low uranium content of seawater has never been likely. Relatively rapid accumulation of sediment in the Mancos may have been a factor, although probably the Mancos was deposited through a long interval of the Late Cretaceous in the order of 20 million years. Possibly uranium was lost from the Mancos when pore water was driven out during compaction.

Perhaps it should be emphasized that the Mancos Shale contains less vanadium (0.01 percent) than the partly equivalent Pierre Shale and similar rocks described by Tourtelot (1962, fig. 13) in which vanadium averages 0.018 percent, and considerably less than many other marine black shale formations (Davidson and Lakin, 1961, table 267.1; 1962, p. C74) which contain 0.02–0.7 percent vanadium. This unaccountably low vanadium content may indicate loss of vanadium during diagenesis and compaction.

Bentonitic volcanic ash layers are abundant in the Mancos Shale (Shawe and others, 1968, p. A88). 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 with the diagenetic development of pyrite. Hydrogen sulfide was abundant in the organic-rich sediments accumulating at the bottom of the Mancos sea, if it was a typical sapropelic marine environment as seems likely, and in addition sulfur may have been especially abundant in the volcanic ash (for example, Fenner, 1933, p. 86–87, 92–95).

Trapped seawater that was buried in the mud of the Mancos Shale undoubtedly had a low Eh because of the high content of organic material (about 3 percent) in the sediment, and as evidenced by the abundance of diagenetic pyrite. Chemical reduction resulting from hydrogen sulfide generated in carbon-rich sediments is characteristic of stagnant sea bottoms. The water also was carbonated, evidenced by the high original calcite content of the mud, it contained abundant chlorine (as all seawater does), and it was alkaline. The pore water, because of its carbonate ion content, likely contained available uranium as soluble uranyl dicarbonate and tricarbonate complexes, based on the suggestions of McKelvey, Everhart, and Garrels (1955, p. 469–470) and Hostetler and Garrels (1962, p. 143–144), and in addition it possibly contained uranium associated with soluble organic complexes such as humic acids derived from detrital organic material (Szalay, 1958). Vanadium, to be expected in an organic mud (black shale) environment, also formed soluble complex ions in the presence of abundant carbonate where pH was slightly alkaline, judged from the work of Hostetler and Garrels (1962, p. 149–152).

Original clay and silt deposited in the Mancos Shale became compacted to about a third to a tenth of its original water-saturated volume by the time it was buried to a depth of about 10,000 feet in early Tertiary time. Trask (1931), Hedberg (1926), Athy (1930), Jones (1944), and other authors indicate such amount of compaction of fine-grained clayey sediment with deep burial. Pore water, amounting in volume to perhaps well over 100,000 cubic miles throughout the Colorado Plateau, driven from the compacting mud, moved largely upward into younger sediments, judged from the evidence of Yoder (1955, p. 506) and Hedberg (1926, p. 1047). But much water, perhaps several thousand cubic miles, must have moved into lower more porous strata because of local conditions of rock structure (Hedberg, 1926, p. 1047), because of relatively high water density, and because of abnormally high fluid pressures. Expulson of water likely occurred throughout the deposition of the

Mancos in the Late Cretaceous and during deposition of younger sediments in the early Tertiary, and therefore it occurred during a period of many millions of years and from close to the surface to nearly maximum depths of burial. Hedberg (1936) described the various mechanisms of water expulsion during compaction, including early expulsion of free water accompanying rearrangement of clay particles (75 – 90 percent porosity), later expulsion of water adsorbed on clay particles (35 – 75 percent porosity), and final expulsion of water as a result of mechanical deformation and recrystallization of clay (0 – 35 percent porosity). S. W. Lohman (oral commun., 1973) pointed out the likely very high content of soluble components in water of late expulsion.

Faulting occurred in many places on the Colorado Plateau, including the Slick Rock district, during the Late Cretaceous and early Tertiary when the Mancos was being deeply buried by younger strata, and thus numerous avenues to allow water movement into underlying porous strata were available. If Mancos muds were too plastic to sustain fractures during compaction, underlying sandy strata undoubtedly were indurated sufficiently to fracture and drain away expelled pore water (fig. 28). The gash fracture in Mancos Shale referred to previously in the section "Altered-Facies Rocks," to which calcite and pyrite appear to have migrated solely because of pressure differential, suggests that carbonate and iron sulfide-bearing solutions tended to flow into fractured rocks where pressure differential was favorable. Because faulting was episodic, most downward expulsion of water from the Mancos must have been episodic also, and because downard expulsion probably depended mostly on high pore pressure, most downward movement of pore water probably occurred when the sediments were deeply buried, perhaps 5,000 – 10,000 feet. These requirements also suggest that most downward movement of water was during the early Tertiary rather than in the Late Cretaceous.

Trapped water in terrestrial rocks below the Mancos was probably relatively fresh, consisting originally of meteoric ground water, whereas Mancos pore water was saline and of higher density. With free circulation into underlying strata provided by faults, heavier saline water from the Mancos tended to move downward and displace lighter water. A discussion by Rubey and Hubbert (1959, p. 167 – 185) indicates that a newly deposited thick sequence of argillaceous geosynclinal sediments develops unusually high fluid pressures resulting from compaction, especially in sands within it or at its base. It seems highly likely therefore that the Dakota Sandstone at the base of the

Mancos Shale and the dominantly sandy underlying Burro Canyon Formation contained pore water which was squeezed from the Mancos and was under abnormally high fluid pressures. Development of faults at the time of high fluid pressures when the Mancos was deeply buried allowed "bleeding off" of pore water farther down into the red beds where permeable strata maintained lower fluid pressures (fig. 28).

Compaction of bedding around some pyrite crystals shows the early development of part of the diagenetic pyrite, and indicates that pore fluids were being squeezed out of the Mancos during the period of diagenesis. Displacement out of the Mancos, during diagenesis and compaction, of some elements that were in solution in the pore waters seems assured, and indicates that some metals were transported into adjacent permeable and relatively noncompressible units such as the sandstones in the Mesaverde Formation, the Dakota Sandstone, and older formations.

Although reducing solutions were present within the red-beds section, for example in reduced zones containing carbonaceous material in the ore-bearing sandstone of the Salt Wash Member, the volume of solutions available from such zones manifestly was far too little to account for the widespread alteration evident in the red beds above and below the ore-bearing sandstone. Further, alteration related solely to the carbon facies in the Salt Wash Member destroyed only about half the detrital black opaque minerals present, and hence could not have been responsible for the almost total destruction of black opaque minerals in altered-facies rocks. On the other hand, the nearly total lack of detrital black opaque minerals in rocks of the Mancos Shale, where they should have been present in significant amounts because the source areas of the Mancos were similar to those of black opaque mineral-bearing older formations, indicates that Mancos pore solutions were effective in causing nearly total destruction of black opaque minerals. Table 6 shows that rocks of the Mancos Shale contain heavy minerals similar in kind and proportion, except for abundant authigenic pyrite and sparse black opaque minerals, to rocks of the underlying red beds.

A reconstruction of events based on the foregoing data and inferences can now be presented. As pore fluids became trapped in the Mancos following deposition of sediment in Late Cretaceous time, they began immediately to react with black opaque mineral detritus, with magnetite deposited with the abundant ash fall material and possibly with volcanic glass and other iron-bearing material, to form pyrite. Any constituents of the original iron minerals that were not appreciably accepted in the pyrite structure, or

immediately redeposited in other minerals, were destined to be carried out of the Mancos as compaction progressed. Pore water in the Mancos Shale, mildly alkaline (pH about 8 – 10?) and of negative Eh (0 to -0.4), contained chlorine and hydrogen sulfide and associated sulfur-bearing ions, and it carried uranium as a complex carbonate ion, $[(U^{+6}O_2) (CO_3)_3]^{-4}$, suggested by Hostetler and Garrels (1962, p. 143 – 144), and vanadium as a vanadite ion, $V_4 O_9^{-2}$ suggested by Evans (1959, p. 92), or as $HV_2 O_5^-$ suggested by Hostetler and Garrels (1962, p. 149). Hydrogen sulfide may not have been an important component following deep burial and cessation of biologic activity. The pore water was in part squeezed into underlying strata during compaction of the Mancos in the Late Cretaceous and early Tertiary. Removal of uranium by expulsion of pore water could account for the low uranium content of carbonate-bearing black shales noted by McKelvey, Everhart, and Garrels (1955, p. 515). Faulting that occurred on the Colorado Plateau, including the Slick Rock district, in the Late Cretaceous and early Tertiary facilitated movement of the Mancos pore water into underlying beds. The pore water, because of its low Eh, reduced invaded red beds, causing removal of hematite coatings on sand grains, destruction of detrital black opaque minerals, and growth of iron sulfide minerals. Minute amounts of uranium and lead (probably significantly uranogenic) were deposited perhaps as the result of increasing acidity caused by reaction of solution with the oxidized rocks. However, Hostetler and Garrels (1962, p. 144) pointed out: "As P_{CO_2} increases in the system stronger and stronger reducing agents are required to remove uranium from solution as uraninite." Also, H. W. Lakin (written commun., June 1973) indicated that the tighter the complex, for example uranium tricarbonate, the more effective the removal of the components of the complex from solution when the proper chemical environment is encountered.

Mudstone in the Dakota Sandstone, judged from its physical and chemical similarity to that in the Mancos, responded to compaction in the same way as that in the Mancos, driving out pore water of similar composition. Sandstone in the Dakota was strongly altered during diagenesis, being saturated by strongly reducing solutions generated internally, as well as by similar solutions moving through it from the overlying compacting Mancos Shale, so that black opaque minerals were almost completely destroyed. Iron from the dissolved black opaque minerals was immediately reprecipitated as sulfides by the sulfur in the pore fluid, adding to the pyrite already formed during the period of diagenesis in the Dakota. Vanadium

liberated from the black opaque minerals and possibly from other minerals such as clays was taken up in solution and carried out of the sandstone. Retention of uranium in carbonaceous strata in the Dakota Sandstone just below the Mancos Shale was inhibited because of the constant renewal of carbonate ions by large volumes of pore water seeping downward; that is, the Dakota was "overwhelmed" by the Mancos environment. In fact the carbonate content may have been high enough to assure neutralization of acids formed from the decay of organic material and permit deposition of appreciable calcite in the sandstone and a small amount in the coal. Perhaps the condition of high carbonate ion concentration can explain the anomalous scarcity of uranium deposits in the Dakota Sandstone throughout the Colorado Plateau, despite the formation's physical and chemical similarity to other ore-bearing units. Uranium deposits are found in the Dakota Sandstone on the Colorado Plateau apparently where permeable units were isolated within impermeable strata (for example, Gabelman, 1956); through-going fluid movement which elsewhere effectively flushed uranium out of the rocks was inhibited in such places. Inasmuch as the humic derivatives of carbonaceous material are probably the principal agents of uranium concentration in rocks like the Dakota (Szalay, 1958), their retention in the rock would be required before appreciable uranium could accumulate there. Also, as Szalay (1958, p. 186) pointed out, unless humic material exists in an acid environment (pH 3 – 6) its uranium-fixing properties are not effective; surrounded by alkaline pore water from the Mancos the carbonaceous shale and coal probably had little propensity to accumulate uranium.

The estimated uranium content of coal in the Dakota Sandstone (0.001 percent) is more than the uranium content of coal of Palezoic age in the eastern United States, and less than the uranium content of lignitic coal of Tertiary age in the Western United States. According to Vine (1962, p. 124), several hundred high-grade coals of Palezoic age in the Eastern United States have a mean uranium content of 0.0001 percent or less, and according to N. M. Denson (Denson and others, 1959, p. 1), many hundreds of samples of lignitic coals of Tertiary age in the western United States range from about 0.005 to 0.02 percent uranium. On the basis of these figures, the uranium content of coals appears to decrease with an increase in age and rank, suggesting the possibility of loss of uranium with depth of burial or metamorphism. In consideration of the data, it seems plausible that the coal in the Dakota Sandstone has lost a considerable amount of uranium that accumulated with or shortly after its formation; at one time its uranium content

may have been comparable to that in the Tertiary coals studied by Denson and others. Such a possible loss of uranium is compatible with an environment, saturated by pore waters expelled from mud of the Mancos, that did not favor deposition of uranium.

Practically all of the rocks of the Burro Canyon Formation were altered by solutions moving into them from the Dakota and Mancos. In effect, the alteration of the Burro Canyon resulted from seepage of strongly reducing solutions from the immediately overlying formations—a sort of leached selvage against carbon-rich rocks (fig. 28). Solutions immediately began to attack the iron oxide minerals present, removing hematite coatings on detrital grains and dustlike hematite in matrix material, and dissolving detrital grains composed of hematite, magnetite, and ilmenite. Some iron immediately was reprecipitated as pyrite or marcasite, acquiring sulfur from the altering solutions. Much iron, however, was carried in solution for a distance and was deposited as sulfide in local concentrations within the sandstone, still acquiring the necessary sulfur from the altering solutions. As the solutions remained reducing and carbonated in the sandstone they did not drop any uranium or vanadium, and in fact may have picked up a small amount of these elements from the sandstone. Movement of the solutions through mudstone in the Burro Canyon Formation was considerably more retarded than in sandstone so that the invading water more nearly equilibrated to the chemical condition of the host material. Possibly no uranium was leached from the mudstone, and a small amount of vanadium may have been precipitated because of the increased acidity acquired by the introduced solutions. Iron oxides were reduced and sulfides formed, again acquiring sulfur from the altering fluids. Uranogenic lead, which had accumulated for a long time in Mancos pore fluids, was precipitated in small amounts along with iron in the newly formed sulfides.

Altering solutions driven out of the Mancos and part of the Dakota moved down from the Burro Canyon through the nearly impervious and already well-compacted mudstones of the Brushy Basin and into the Salt Wash only through fault zones where numerous fractures provided the necessary permeability. Alteration occured in all rocks bordering the fault zones, as well as in permeable units where solutions moved laterally outward from the zone. The middle green unit of the Brushy Basin Member, being more permeable than overlying and underlying units of the member, thus became bleached—reduced as a result of epigenetic alteration—at this time, most extensively in an area centered on the Dolores zone of faults.

The effect of altering solutions moving through the Brushy Basin Member was similar to that in the Burro Canyon, but there were some differences, perhaps because the strength of the solutions had been weakened by reaction with the rocks lying between the Morrison Formation and the Mancos Shale. Thus the sandstone in the Brushy Basin lost little if any of its vanadium, and the mudstone, as it did in the Burro Canyon, acquired some vanadium. But now, both sandstone and mudstone in the Brushy Basin took up a small amount of uranium, and along with it uranogenic lead, precipitated with iron sulfides formed as a result of the reduction of iron oxides.

Before altering solutions from the Mancos Shale had reached the Salt Wash Member, the ore-bearing sandstone had already been diagenetically altered over wide areas by the action of contained carbonaceous material. Black opaque minerals had been partly destroyed, and probably some vanadium and chromium liberated into the solutions which remained as stagnant pore waters in the sandstone layers. Mudstone also was diagenetically altered during this stage, and vanadium taken into solution. The stagnant waters close to accumulations of organic carbonaceous material contained a high proportion of humic acids. Because of the relatively low carbonate content of the Salt Wash Member, and particularly the ore-bearing sandstone, the stagnant waters never became appreciably carbonated close to organic material, in the face of the generation of abundant organic acids, even though solutions could have become mildly carbonated farther away from carbonized plant debris where the sedimentary rocks nevertheless still were reduced.

When pore water expelled from Mancos organic mud entered the Salt Wash Member, alteration occured in permeable units adjacent to the Dolores zone of faults. The effect on red-beds strata was similar to the effect on such rocks in the Brushy Basin Member. Iron, vanadium, and chromium may have been taken into solution because of destruction of black opaque minerals. Small amounts of uranium and uranogenic lead were deposited wherever the leaching solutions flowed, possibly because of a tendency for the solutions to be less alkaline. Iron was locally leached from red-beds rocks and reconcentrated mostly near the edges of zones of alteration—particularly in the vicinity of the Dolores zone of faults—in pods or concentric layers of iron minerals. Appreciable vanadium derived from destroyed black opaque minerals and the introduced solutions, was deposited in these mineral concentrations. The most extensive unit in the member, the ore-bearing sandstone, became widely altered at this time. Where the reduc-

ing solutions from the Mancos encountered local pockets of original carbonaceous material in the ore-bearing sandstone, rocks were further reduced, and remaining black opaque minerals mostly were destroyed; the solutions likely became acidified because of the presence of sulfur ion species residual from hydrogen sulfide, and humic acids derived during earlier degradation of organic (plant) debris and not yet flushed from the strata. Under these conditions the uranium-bearing complex carbonate ions and vanadite ions broke down and uraninite and montroseite were precipitated in abundance, as indicated by Hostetler and Garrels (1962, p. 142–147, 149–152), and perhaps some form of organic material was deposited. The temperature of transport and deposition of uranium probably did not exceed about 120°C; Hostetler and Garrels (1962) pointed out that uranium-bearing complex carbonate ions could not remain in solution above that temperature. Formation of the ore deposits will be discussed in more detail in the final chapter of this Professional Paper series.

Possibly, reducing solutions from the Mancos circulated into lower horizons, bleaching all rocks along fracture zones that permitted deep flow, and spreading laterally into permeable units such as the Slick Rock Member of the Entrada Sandstone, the Navajo Sandstone, the Wingate Sandstone, and possibly even older rocks. If Mancos pore waters were responsible for alteration of the Slick Rock Member of the Entrada and the Navajo and Wingate Sandstones they were less dense than ground water in those formations, as the alteration occurred in their upper parts (fig. 28). The Entrada, Navajo, and Wingate may have been saturated by relatively dense brines from underlying or laterally equivalent marine strata. Solutions that circulated into sedimentary rocks underlying the Morrison Formation retained some reducing capacity, and probably carried some uranium, vanadium, and uranogenically enriched(?) lead. Small amounts of these elements were precipitated in the rocks and destruction of black opaque minerals occurred, but there were no large amounts of organic material to cause extensive precipitation of uranium and vanadium as occurred in the Salt Wash Member. Conceivably alteration and deposition of uranium and vanadium minerals below the Wingate Sandstone, in the Moss Back Member of the Chinle Formation, had resulted earlier from the introduction of solutions from some other source besides the Mancos Shale, such as the underlying Hermosa Formation, but the data presented here are inadequate to evaluate this possibility.

A few general remarks can be made that are pertinent to all epigenetic alteration that took place in the sequence of red-beds rocks below the Mancos Shale discussed here. The highly variable content of carbonate (mostly calcite) in altered-facies rocks suggests ready redistribution of calcite as a result of alteration. Carbonate minerals such as dolomite and iron-enriched calcite were preferentially deposited in fractures.

The altering solutions may have contained considerable chlorine which would have enabled barite to dissolve, for barite characteristically was reconstituted throughout altered-facies rocks by the solutions. A "brine" of marine origin is indicated, substantiating pore water from the organic mud of the Mancos as the agent of alteration. Here the reader may recall the high chlorine content, potassium/sodium ratio similar to that of oil field brines, and fluorine/chlorine ratio similar to that of thermal waters, of springs issuing from the Morrison Formation in the Slick Rock district (Shawe and others, 1968, p. A8). As we pointed out, the springs probably are not mixtures of oil-field brines and thermal waters, but may contain components that earlier were deposited in the rocks by such solutions.

The characteristic development of albite, analcite, and barite in rocks of the altered facies indicates that altering solutions were saline. Saline solutions have been proposed as the reason for growth of barite and sodium-bearing minerals including albite and analcite in the Green River Formation in Utah (Milton, 1957, p. 143). Davidson (1965, p. 946), quoting Bogdanov (1962), noted the extensive albitization of copper-bearing red-bed arenites of Udokansk in eastern Siberia as a result of saline metamorphism.

Association of chalcedonic silica with other authigenic minerals such as albite, analcite, calcite, and barite indicates that alteration took place at a low temperature.

On the basis of fluid inclusion studies on calcite and barite from the Mancos Shale these minerals crystallized at a temperature of 120°–125°C. If the temperature was a result of a normal geothermal gradient for continental crust beneath a shallow sea where thick marine sediments accumulate, probably about 30°C per kilometre of depth, the depth of burial of these minerals at the time of crystallization was about 3+ km (10,000 ft). This depth of burial was also inferred on the basis of present porosity of the Mancos Shale (Shawe, 1968, p. B30) and the presumed thickness of lower Tertiary sediments deposited in the region prior to middle Tertiary uplift and erosion of the Colorado Plateau.

Even though the Mancos Shale is classified here as belonging to the altered facies, it is evident that the alteration that affected the Mancos was a diagenetic

process. It was a more intense phenomenon however than the diagenetic process that affected carbon-facies rocks in underlying strata. And, of course, with expulsion of pore fluids out of the organic mud of the Mancos and into underlying beds, the alteration resulting from these introduced solutions constituted an epigenetic process.

Perhaps the most significant aspect of the alteration of sedimentary rocks in the Slick Rock district, based on the evidence from gamma-ray logs, is that uranium was *introduced into* the Morrison Formation during alteration and hence could not have been *acquired from* those rocks during alteration. This fact alone is the strongest evidence for derivation of uranium from an extraneous source, such as the unconsolidated organic mud of the Mancos Shale.

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