Clay Minerals in Triassic Rocks of the Colorado Plateau

GEOLOGICAL SURVEY BULLETIN 1147-C

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

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CONTRIBUTIONS TO THE GEOLOGY OF URANIUM

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CLAY MINERALS IN TRIASSIC ROCKS OF THE COLORADO PLATEAU

By LEONARD G. SCHULTZ

ABSTRACT

Kaolinite, illite, montmorillonite, chlorite, palygorskite, and mixed-layer clay composed of different proportions of illite, montmorillonite, and chlorite were identified in samples from the Moenkopi formation and the overlying Chinle formation using X-ray-diffractometer methods.

Predominantly illitic sediments, inferred to have come from an eastern source, characterize the Moenkopi formation, and the upper part of the Chinle formation in the northern part of the Colorado Plateau. While the illitic sediments were being transported westward, some of the less resistant accessory components, such as chlorite, were destroyed and kaolinite was formed.

Montmorillonitic clays, inferred to have come from a southern source, characterize most of the rocks in the lower part of the Chinle formation and also are abundant components of the upper part of the Chinle in the southern part of the Colorado Plateau. They were derived mostly by alteration of volcanic debris. Part of the volcanic debris probably was altered before deposition, but rounded tuff particles, now composed of aggregates of swelling clay, must have altered after deposition. Latite tuff altered to highly montmorillonitic clays; rhyolite tuff altered to mixed-layer illite-montmorillonite clays. The altered rhyolite tuff is the less abundant of the two types and generally occurs stratigraphically below the altered latite tuff.

Clay assemblages in some rocks near the Chinle-Moenkopi contact are mostly the result of weathering. The effects of weathering are most pronounced in mottled soil zones formed on rocks at the surface during the Chinle-Moenkopi hiatus and in rocks laid down during the initial intermittent stage of Chinle deposition. Characteristic clays of the weathered rocks are kaolinite, particularly a poorly crystallized variety, and a type of mixed-layer illite-montmorillonite. In contrast to the mottled soil zones, clays in bleached zones just below the Chinle-Moenkopi contact are unaltered; the bleached zones apparently were caused by ground water circulating in the overlying Chinle sandstones.

Palygorskite is locally abundant near the middle of the Chinle formation. Its origin is undetermined.

No one clay or assemblage of clays is characteristically associated with uranium deposits in the Triassic rocks. Clays from some mines are predominantly kaolinitic; some are chloritic; some are illitic; and others are montmorillonitic, but in each deposit they are similar to the clays found in nearby barren rocks. Secondary kaolinite and chlorite occur both in mineralized and unmineralized

rocks and seem to represent recrystallization or slight modification of clays deposited with the sediments. The only observed postdeposition change which can be attributed to mineralizing solutions is adsorption of vanadium on some chlorite.

Uranium-vanadium mineralization in the Triassic rocks was closely related to the occurrence of altered rhyolite tuffs. These tuffs logically should have contained large amounts of uranium. As they were altered, in part, after deposition, uranium and other elements released during their alteration may have formed the ore deposits in favorable host rocks nearby.

INTRODUCTION

This investigation outlines the distribution of clay minerals in the Moenkopi formation of Early and Middle(?) Triassic age and the Chinle formation of Late Triassic age and their lateral equivalents throughout most of the Colorado Plateau. Quantitative analysis of the clays is intended to give evidence of source terranes, the conditions of deposition, and the extent of post-depositional alteration. Clay data are related as far as possible to studies of other features of these rocks, including stratigraphy, lithofacies, petrology, and sedimentary structures. As most samples for this study came from southeastern Utah, stratigraphic nomenclature used in this report (table 1) follows the nomenclature for that area. Much of the stratigraphic description is after Stewart and others (1959).

Special topics considered are the probable extent of volcanic origin of the Triassic rocks, the origin of certain mottled and bleached strata near the base of the Chinle formation, and the nature of clays found in uranium ores. Uranium deposits in the sandstones near the base of the Chinle formation are among the principal sources of uranium in the United States. Knowledge of clays in these deposits and in associated rocks should serve to limit speculation on the origin of the ore deposits.

About 1200 samples from 70 stratigraphic sections and from 19 localities where uranium mineralization occurred were analyzed. Their approximate locations are shown on plate 1; and their exact locations are listed in the table at the end of the report under "sample localities." The writer's own samples collected from 1954 to 1956 were augmented by samples furnished by J. H. Stewart, R. A. Cadigan, W. D. Keller, T. E. Mullens, and by 19 volcanic pebbles collected by William Thordarson from the seven localities shown on plate 1. Samples from the several formations were referred to sections previously measured by the U.S. Geological Survey. The samples were obtained by digging a foot or so into the outcrop to a point where the rock looked fresh. To check the suitability of such samples for this study, 10 samples were taken from 4 drill cores, and samples were also taken from nearby outcrops at equivalent strati-

TABLE 1.—*Triassic stratigraphy in southeastern Utah*

[Modified after Stewart and others, 1959]

Formation	Member	Thickness (feet)	Dominant lithology
Wingate sandstone		200–350	Pale-brown to orange crossbedded sandstone.
Chinle formation	Church Rock	0–350	Reddish-brown siltstone and silty sandstone.
	Owl Rock	0–450	Reddish siltstone with minor silty limestone beds.
	Petrified Forest	0–600	Varicolored swelling claystone.
	Moss Back	0–150	Buff fine- to medium-grained sandstone.
	Monitor Butte	0–250	Greenish-gray swelling claystone and clayey sandstone.
	Shinarump	0–200	Buff medium- to coarse-grained sandstone.
	Temple Mountain	0–30	Mottled red-gray-purple sandy siltstone (San Rafael Swell area only).
Moenkopi formation		0–900	Reddish-brown siltstone with some sandstone and limestone beds.

graphic positions. A very close similarity in the mineralogical composition of the core samples and of the fresh-looking surface samples indicates that weathering has not affected the surface rock appreciably. Samples for the study of clay minerals associated with uranium-bearing rock were collected from underground mines.

The writer wishes to acknowledge help received from many members of the Geological Survey, particularly J. H. Stewart, whose work on the Triassic stratigraphy of the Colorado Plateau served as an indispensable guide for the clay sampling. The writer is grateful to R. A. Cadigan, W. D. Keller, C. C. Hawley, and William Thordarson for the use of their thin sections of Triassic sediments. Capable and willing assistance of D. H. Phail and R. W. Wheeler facilitated the laboratory work. Mrs. H. A. N. Schultz also helped with the field, laboratory, and microscopic work. The report concerns work done by the U.S. Geological Survey on behalf of the Division of Raw Materials of the U.S. Atomic Energy Commission.

LABORATORY ANALYSIS

X-RAY DIFFRACTOMETER EXAMINATION

In this project, X-ray diffractometer traces were used for both the qualitative and quantitative analysis of the clay minerals in each sample. The X-ray diffractometer measures the angular diffraction of an X-ray beam by a mineral and records it as a trace on graph paper. Peak positions on the diffractometer trace characterize lattice spacings in the crystal structure and serve to identify the mineral.

For the clay minerals, spacings between structural zones parallel to the basal cleavage (001 reflections) are most useful for identification. The intensities of these basal reflections from these basal zones are greatly enhanced by sedimenting an oriented aggregate in which the clay flakes are parallel to a flat sample holder. Reflections from nonbasal zones of clay minerals are also useful and are seen best on diffractometer traces of finely ground material having no preferred orientation of the clay flakes. Unoriented powders are also most suitable for identification of nonclay minerals, such as quartz, carbonates, and feldspar. Chemical and heat treatments were essential for identification of individual clay minerals in the many-component clay mixtures common in the Triassic rocks. A brief nontechnical description of clay-mineral analysis by use of X-ray diffractometer techniques is given by Weaver (1958a, p. 262–271). More complete descriptions are given by Grim (1953, p. 84–105) and by Brindley (1951 and 1955).

Samples of Triassic rock were disaggregated either in a roller mill or in a mechanical mixer, depending upon the swelling properties of the sample. The < 2-micron fraction was separated by settling in water, and an oriented-aggregate slide was prepared for X-ray study. The coarse fraction of some samples was separated on a 325-mesh sieve and was saved for study of the nonclay minerals. An unoriented-powder slide was also prepared from the powder of the whole unfractionated sample. One X-ray diffractometer trace was made of the unoriented powder of the whole sample, and four traces were made of the oriented aggregate of the < 2-micron fraction, as follows: (1) After air drying, (2) after treatment with glycol, (3) after heating at 300°C for half an hour, and (4) after heating at 550°C for half an hour. For some samples, traces were also made of the unoriented powder of the < 2-micron fraction. Traces were run on an XRD–3 diffractometer using filtered copper radiation, at a scanning speed of 2 degrees per minute. When more detailed information was needed, scanning speeds of less than 2 degrees per minute or powder-camera techniques were used. Some samples were X-rayed both before and after immersion overnight in warm 6*N* hydrochloric acid to determine if they contained acid-soluble minerals, such as some kinds of chlorite.

Quantitative estimates of the relative amounts of each clay mineral in the samples were made by comparing the intensities of certain peaks of each clay mineral. The general method has been described previously (Schultz, 1960). The quantitative estimates of each clay mineral are probably accurate to within 10 percent of the graphed value.

X-ray analysis was also the principal method for identification of nonclay minerals, particularly the feldspar. Feldspar is present in amounts of only a few percent in most samples taken for this study, so that usually only the strongest peaks can be distinguished clearly. A peak at about 3.24 A was interpreted as potassium feldspar; a peak at about 3.18 A was interpreted as plagioclase feldspar. An estimate of which type of feldspar was dominant could be made for most samples. For samples containing a high proportion of feldspar, X-ray analyses could be used to supplement petrographic identification of different types of sanidine. According to Bowen and Tuttle (1950, p. 493), the $20\bar{1}$ spacing of alkali feldspar varies almost linearly, from 4.23 A for potassium feldspar to 4.04 A for albite, and serves to indicate the extent of solid solution between the two end members.

MICROSCOPIC EXAMINATION

Microscope work augmented the X-ray studies. Observation of fresh broken surfaces under the high power of the binocular microscope proved to be an effective means of identifying and estimating the amount of tuff particles. Thin sections of 75 samples showed some textural relations significant to the origin of the clay minerals; these will be discussed later in the report. Nineteen additional thin sections of volcanic pebbles were classified on the basis of their mineral content. Feldspar from several samples was concentrated by density separation of particles which did not pass through a 325-mesh sieve; the feldspar was then identified under a polarizing microscope with a universal stage and by X-ray diffraction. According to MacKenzie and Smith (1956, p. 406), sanidine can accommodate as much as 40 percent of the albite molecule in solid solution and the optic angle of the sanidine increases from less than 20° to more than 30° with increase in sodium content. Two types of sanidine are recognized in the Triassic rocks: (1) a low-sodium variety that has an optic angle of 20° or less and a $20\bar{1}$ spacing ranging from 4.20 to 4.22 A and (2) a high-sodium variety that has an optic angle of about 30° and contains between 25 and 40 percent of the albite molecule.

CHEMICAL AND BASE-EXCHANGE ANALYSIS

Chemical analyses shown in table 2 were made of six samples that represent six of the clay mineral types in the Triassic rocks. Base-exchange analyses made on a representative group of montmorillonitic and illitic samples are shown in table 3. These analyses are discussed under the section describing the clay minerals. Uranium-vanadium determinations obtained for critical samples will be discussed in connection with vanadiferous chlorite in the section on mineralization.

TABLE 2.—*Chemical analyses of Triassic clays*

[Rapid rock analyses, in percent, by P. L. D. Elmore, K. E. White, P. W. Scott, and S. D. Botts. X-ray traces for these six samples are shown on pl. 2]

	Illitic clay	Mixed-layer illite-montmorillonite	Mixed-layer montmorillonite	Montmorillonite	Chlorite	Palygorskite [1]
	Wi-10	LS-2	OR-6g	JH-10	453	PH-15
SiO_2 [2]	53.4	48.6	52.5	49.6	39.6	51.0
Al_2O_3	22.2	22.8	19.1	20.0	16.3	13.4
Fe_2O_3	4.7	[3] 7.4	4.7	5.2	3.5	4.2
FeO	.62	.30	.28	.16	6.9	.21
MgO	2.8	2.2	3.2	2.2	14.0	6.7
CaO	.32	.90	1.0	2.2	.85	4.4
Na_2O	.25	.24	1.2	.56	.78	.24
K_2O	6.9	5.5	4.2	.65	1.4	2.6
TiO_2	.70	.84	.52	.51	.71	.40
P_2O_5	.18	.26	.06	.38	.78	.06
MnO	.02	.00	.01	.04	.07	.03
H_2O	8.2	11.2	12.7	18.8	13.0	14.2
CO_2	.16	.41	.46	.12	.12	3.7
Total (rounded)	100	101	100	100	[4] 98	101

[1] Also contains 25 percent illite, 10 percent mixed-layer montmorillonite, and 8 percent carbonates.
[2] Includes a few percent quartz (see pl. 2).
[3] Includes a few percent hematite.
[4] Also contains 0.48 percent uranium and 1.02 percent V_2O_5 (not shown).

Wi-10. Loc. 69, taken 70 ft above base of Church Rock member; analysis 148256.
LS-20. Loc. 65, taken 35 ft above base of Chinle formation; analysis 148257.
OR-6g. Loc. 39, taken 200 ft above base of Petrified Forest member; analysis 148258.
JH-10. Loc. 11, taken 145 ft above base of Chinle formation; analysis 148259.
453. Loc. 27, collected by W. D. Keller; analysis 148261.
PH-15. Loc. 38, taken 30 ft above base of Owl Rock member; analysis 148260.

TABLE 3.—*Base-exchange analyses of Triassic clays*

[In milliequivalents per 100 grams. Analyses by Dorothy Carroll and H. C. Starkey]

Exchangeable cations	Illitic clay	Mixed-layer illite-montmorillonite	Mixed-layer montmorillonite	Montmorillonite						
	Wi-10	LS-2	OR-6g	JH-10	JH-17	P-10	CW-7r	OR-6.5	PH-9	JH-7
Ca	6.8	27.1	32.7	67.7	41.2	31.9	33.2	34.5	32.2	53.0
Mg	1.3	7.3	6.9	30.2	15.5	9.8	18.3	11.4	18.7	14.0
Na	1.8	5.4	31.0	26.0	49.0	83.0	94.0	93.0	75.0	25.0
K	0	0	7.0	4.0	4.0	8.0	7.0	8.0	8.0	6.0
H	6.6	0	-------	3.8	21.6	-------	-------	-------	-------	-------
Total cations	16.5	39.8	77.6	131.7	131.3	132.7	152.5	146.9	133.9	98.0
Base-exchange capacity [1]	41.0	58.3	97.1	111.6	112.9	136.6	131.9	109.0	132.9	111.5

[1] Determined by the ammonium chloride method.

Wi-10. Loc. 69, taken 70 ft above base of Church Rock member.
LS-2. Loc. 65, taken 35 ft above base of Chinle formation.
OR-6g. Loc. 39, taken 200 ft above base of Petrified Forest member.
JH-10. Loc. 11, taken 145 ft above base of Chinle formation.
JH-17. Loc. 11, taken 700 ft above base of Chinle formation.
P-10. Loc. 5, taken 345 ft above base of Petrified Forest member.
CW-7r. Loc. 37, taken 190 ft above base of Chinle formation
OR-6.5. Loc. 39, taken 215 ft above base of Petrified Forest member.
PH-9. Loc. 38, taken 170 ft above base of Monitor Butte member.
JH-7. Loc. 11, taken 10 ft above base of Chinle formation.

CLAY MINERALS DISTINGUISHED IN THE TRIASSIC ROCKS

The Triassic rocks of the Colorado Plateau commonly contain varieties of illite, kaolinite, chlorite, and mixed-layer combinations of illite and montmorillonite or of chlorite and montmorillonite. Palygorskite is also present in a few samples. Ten varieties of clay minerals recognized in this study are defined, and the criteria used to identify each are described. The mixed-layer combinations of illite and montmorillonite are given arbitrary limits appropriate to this study, and informal names are assigned to each restricted combination. X-ray diffraction traces of the different clay minerals are shown on plate 2, together with schematic illustrations of some of the clay-mineral structures and with structural formulas calculated according to the method of Ross and Hendricks (1945, p. 41–42) from some of the chemical analyses given in table 2.

Brief discussions of the possible geologic interpretations of the groups of clay minerals found in the Triassic rocks are also given below. As most clays are known to form under a variety of conditions, generalizations regarding the clay minerals as environmental indicators can be made only in the broadest terms, with the expectation that exceptions may be found. Much of the data for these generalizations is summarized by Grim (1953, p. 316–368; and 1958).

ILLITE-MONTMORILLONITE GROUP

The lattice structures of montmorillonite and illite are closely related. The common aluminous varieties have two sheets of tetrahedrally coordinated silica separated by a sheet of octahedrally coordinated alumina, pl. 2 *A* and *D*. The three structural sheets compose a micalike layer that is slightly less than 10 A thick. Much less common are structurally similar clays that contain 3 divalent magnesium or iron ions for every 2 trivalent aluminum ions in the octahedral layer of the common variety. The aluminous variety is called dioctahedral, and the magnesium or ferrous varieties are called trioctahedral. Dioctahedral clays have 060-spacings of 1.50–51 A; trioctahedral clays have 060 spacings of 1.53–1.57 A. The 060 spacings of about 1.50 A shown on plate 2*A–D* are typical of the illite and montmorillonite in the Triassic rocks and indicate that the minerals are dioctahedral and aluminous. The same dioctahedral aluminous character is indicated by the structural formulas.

The basic micalike layers of illite are separate by potassium ions that are not readily exchanged and which bind adjacent layers together so that water or other molecules will not penetrate between the layers. Thus, illite has a basal spacing of 10 A that is not changed

either by mild heat or by chemical treatment. Montmorillonite differs from illite in that its micalike layers are separated by cations—such as sodium, calcium, magnesium, or hydrogen—that are readily replaced (exchanged) by other cations. Water and other molecules readily penetrate between the layers, producing basal spacings of more than 10 A. At normal humidities, one or two water layers between the mica sheets, produce basal spacings of 12.5 A to 15 A; adsorption of ethylene glycol molecules invariably produces a spacing of 17 A; heat treatment drives volatile molecules from between the layers and produces a basal spacing of about 9.8 A that is very close to the 10-A spacing illite.

Illite and montmorillonite also may be interlayered with each other. Peaks for the basal spacings recorded on the X-ray patterns are generally broad and at positions intermediate between spacings expected from the individual components. A whole series of mixed-layer clays with different proportions of illite and montmorillonite are found in the Triassic rocks. A progressive change in the proportions of illite and montmorillonite in this group of mixed-layer clay minerals is also indicated by their base-exchange capacities (table 3).

Illite.—Illite is the predominant clay mineral in most of the Triassic rocks. The X-ray diffractometer trace of a nearly pure illite (pl. 2*A*) is distinguished by the persistence of the 10 A basal spacing through all treatments. Careful examination of the X-ray traces of glycol-treated illitic clays from the Triassic rocks almost always, however, reveals a slight bulge on the low-angle side of the 10–A peak; after heat treatment the bulge disappears with a corresponding slight increase in the height of the 10–A peak. This fact indicates the presence of some mixed-layer illite described in the following section.

In the Triassic rocks, the many-component mineral mixtures generally prevented distinction between the different mica polymorphs (Yoder and Eugster, 1954 and 1955). Only in favorable samples could the distinction be made, and this information will be discussed in the section on relations between clay minerals and uranium-vanadium mineralization.

Mixed-layer illite.—Mixed-layer clay composed of illite and montmorillonite in which the expandable montmorillonite layers comprise a third or less of the total layers is here called mixed-layer illite. It does not make up the major part of any sample studied but is commonly present in all samples that contain illite. This ubiquitous mixture of illite and mixed-layer illite is here called illitic clay.

Mixed-layer illite-montmorillonite.—Many Triassic samples contain a mixed-layer illite-montmorillonite clay in which the montmorillonite layers are estimated to constitute from a third to about a half

of the total; such clay is here designated mixed-layer illite-montmorillonite. After glycol treatment, its first basal reflection is at about 12–13 A (pl. 2*B*). After heat treatment the basal spacing decreases to about 10 A.

Mixed-layer montmorillonite.—Mixed-layer clay in which montmorillonite exceeds illite is abundant in many samples and is here designated mixed-layer montmorillonite. Glycol treatment causes a shift of the first basal reflection to a very broad peak (pl. 2*C*) that centers closer to the 17–A position of montmorillonite than the 10–A position of illite. After heat treatment the basal spacing decreases to 10 A.

Montmorillonite.—Montmorillonite is an important constituent in some Triassic rocks. Its X-ray diffractometer trace, after glycol treatment, shows a series of sharp basal reflections with the 001 at 17 A (pl. 2*D*); after heat treatment, its basal spacing is about 10 A. Base-exchange data (table 3) show that varieties high in both calcium and sodium are present.

In this report, a combination of montmorillonite and mixed-layer montmorillonite is called montmorillonitic clay.

Geologic interpretation.—Of the illite-montmorillonite group of clay minerals, illite is the most common in sedimentary rocks. It can form by leaching of many silicate minerals, such as mica or feldspar, in almost any environment which contains some potassium. Illite may be derived directly from bedrock or from mildly leached soils that formed on these rocks. It is also known to occur as a product of hydrothermal alteration and reportedly of diagenetic action in marine waters. Aluminous illite, which makes up by far the largest proportion of illite in sedimentary rocks, is relatively stable and, unless subjected to fairly intense leaching, may go through several sedimentary cycles unchanged.

Montmorillonite also can form from a variety of materials under diverse conditions. Presence of alkali and alkaline earths, particularly magnesium, favors its formation. Strong leaching generally destroys it or inhibits its formation. The best known occurrence of montmorillonite is in bentonite beds formed by alteration of tuffs. Most volcanic debris, particularly volcanic glass, is highly unstable under near-surface conditions, and its chemical composition commonly is such that it readily—almost spontaneously—alters to montmorillonite. Montmorillonite has been reported in mildly leached soils, particularly where drainage is poor. It also occurs as a product of hydrothermal alteration. Stability of montmorillonite in a potassium-rich marine environment depends somewhat upon the extent of atomic substitutions within its crystal lattice. According to Weaver (1958b), most volcanic-derived montmorillonite is not readily altered

in marine waters, but varieties in which large amounts of aluminum substitute for silicon in the tetrahedral layers ("degraded illite") may adsorb potassium ions and be converted to nonexpanding illite.

Mixed-layer clays have been reported to be abundant in many sedimentary rocks (Weaver, 1958a, fig. 1). Some varieties of volcanic debris, as those found in the Tertiary rocks near Denver, Colo., (Schlocker and Van Horn, 1958) and in Ordovician bentonite (Weaver, 1953), may also alter to these clays. Probably the most characteristic occurrence of mixed-layer clays, however, is in moderately leached soils. When illite-bearing sedimentary rocks are weathered, many of the potassium ions are stripped from between the micalike layers, and the illite becomes partly expandable. Mixed-layer clays probably are affected by changes in environment in about the same way as their individual components.

KAOLINITE

Kaolinite is the most aluminous of the clay minerals. Single structural sheets of silica tetrahedra combine with single structural sheets of alumina octahedra to produce a kaolin layer about 7 A thick. (pl. 2*E*).

Well-crystallized kaolinite.—The well-crystallized variety of kaolinite (pl. 2*E*) is characterized by the complete series of sharp reflections it produces on its X-ray-diffractometer trace (Brindley, 1951, p. 41).

Poorly crystallized kaolinite.—All gradations were found between well-crystallized and poorly crystallized varieties of kaolinite. Poorly crystallized kaolinite (pl. 2*F*) is characterized by relatively broad basal peaks and by absence of certain nonbasal reflections. For this study, kaolinite is classified as poorly crystallized if its 7–A diffractometer peak is so broad that it gives an area-height ratio of greater than 1.3 (Schultz, 1960).

Geologic interpretation.—Formation of kaolinite is favored by an oxidizing acid environment. Intensely leached feldspathic rocks are cited most often as a source for kaolinite; however, under favorable conditions kaolinite can form from materials as diverse as feldspar, volcanic ash, and basalt or from almost any other rock which contains some alumina and silica. Kaolinite is common in highly leached soils of the lateritic type and in yellow and red podsols, such as those of the southeastern United States. It also forms by acid hydrothermal alteration. It has been characterized as typical of a freshwater environment with a good circulation of oxygenated water. Kaolinite seldom forms in marine or saline waters. Once formed, kaolinite is relatively stable and can survive a considerable change in environment.

CHLORITE

Chlorite is composed of 4 sheets that normally include 2 tetrahedral silica sheets and 2 octahedral brucite [$Mg(OH)_2$] sheets (pl. 2*G*). The 2 silica sheets and 1 brucite sheet combine to form a 10–A layer similar to trioctahedral mica. This micalike layer alternates with the second brucite sheet. The brucite sheet is about 4 A thick, so that the chlorite structure is repeated at intervals of about 14 A. Aluminum commonly substitutes for some of the silicon atoms, and both aluminum and iron substitute for some magnesium ions. The chlorite structure normally produces a series of basal X-ray diffractometer peaks at about 14 A, 7 A, 4.7 A, and 3.5 A, with an intensity ratio of about 1½, 3, 1, and 2, respectively. The peak positions do not shift appreciably after glycol or heat treatment, but after heat treatment at 550° C, the 14–A peak about doubles in size and higher order basal peaks practically disappear. The magnesian varieties of chlorite are soluble in strong acid solutions.

Part of the chlorite in the Triassic rocks is the common variety just described. This variety is most common as a minor component in the fine-grained sedimentary rocks. Other chlorite in the Triassic rocks, however, differs from the common variety in several ways, which all indicate that it is an unusually aluminous variety. Twenty samples of chlorite (including the three illustrated in pls. 2*G–I*) gave 060 reflections between 1.50 A and 1.51 A, indicating that they are of the dioctahedral aluminous variety instead of the common trioctahedral variety, which would give 060 reflections of 1.53–1.57 A. In many other samples in which the 060 reflection is obscured by reflections from other minerals, the large intensity of the third-order basal reflection of the chlorite (pls. 2*G–I*, 4.7–A position) indicates aluminous chlorite. Normally this third-order basal reflection is much smaller than the second-order reflection, but Brindley and Gillery (1956, p. 178) suggest that an intense third-order basal reflection would be expected from an aluminous chlorite, particularly if the aluminum were concentrated in the micalike layer rather than in the brucite sheet.

Chemical and solubility data also indicate that much of the chlorite in Triassic sediments is aluminous. The only chlorite chemically analyzed for this study (table 2, sample 453) contains alumina about equal in amount to magnesium plus ferrous oxide; this contrasts with typical magnesium chlorite in which alumina is only about half as abundant. Furthermore, the samples of Triassic chlorite determined to be aluminous from their X-ray patterns were all insoluble in warm 6*N* hydrochloric acid. However, subordinate amounts of chlorite present in some other samples were soluble and thus presumably

were magnesian. As the chemical character of the chlorite in many samples is in doubt, this property cannot be used as a primary basis for clay mineral classification in this study.

An expandable constituent, montmorillonite, is mixed layered with some of the chlorite in the Triassic sediments. Its presence or absence can almost always be determined, and in this study it serves to differentiate two types of chlorite: well-crystallized chlorite and mixed-layer chlorite. The unmodified term "chlorite" refers to both types undifferentiated.

Well-crystallized chlorite.—The positions of the basal reflections on the X-ray diffractometer traces of well-crystallized chlorite (pl. 2*G*) are not appreciably changed by treatment with either glycol or heat. Expandable layers are not present.

Mixed-layer chlorite.—Chlorite that is mixed layered with montmorillonite is here called mixed-layer chlorite. Presence of expandable montmorillonite layers caused the normal 14–A position of the first basal reflection to expand slightly with glycol treatment and to contract slightly with heat treatment (pls. 2*H–I*). The sample in plate 2*I* is composed of a regular alternation of chlorite and montmorillonite that produces a regular series of basal reflections midway between positions expected for chlorite and montmorillonite. This regular alternation also produces a basal reflection at a spacing between 24 A and 31 A, depending on the degree of hydration or gylcol in the sample; this spacing represents the sum of the basal spacings of chlorite and montmorillonite. All gradations were found between mixed-layer chlorite (pl. 2*I*) with equal amounts of regularly alternated chlorite and montmorillonite and well-crystallized chlorite (pl. 2*G*) with no montmorillonite, but in no sample was montmorillonite the dominant component. An X-ray trace of a mixed-layer chlorite in which about a quarter of the layers are expandable is shown on plate 2*H*.

Different types of chlorite occur together in many samples. For example, the sample in plate 2*I* contains a small amount of well-crystallized chlorite, in addition to the dominant mixed-layer chlorite, as indicated by the persistence of the 003 chlorite peak at 4.7 A after glycol and heat treatments.

Optical properties of the dioctahedral mixed-layer chlorite range from those characteristic of chlorite to those of montmorillonite. The birefringence is low (0.006–0.008), and the index of refraction is about equal to that of balsam (1.54). The mixed-layer chlorite generally is colorless except for the vanadiferous variety, which has a pale greenish-gray cast.

Geologic interpretation.—The magnesian chlorite common in most sedimentary rocks forms by mild leaching of ferromagnesian minerals such as biotite, is inherited from older rocks such as chlorite schists, or may form in marine waters. It is stable only in a magnesium-rich environment, and under conditions favoring strong leaching conditions it is among the first silicate minerals altered (Jackson and Sherman, 1953, p. 235–236). Aluminous varieties of chlorite, such as those found in the Triassic rocks should be more stable, however. Their resistance to leaching is probably about the same as that of aluminous illite or aluminous montmorillonite.

PALYGORSKITE

Palygorskite (attapulgite) is a magnesium-rich fibrous clay mineral structurally composed of silicate chains similar to those of amphibole. Aluminum may substitute for either magnesium or silicon. Although palygorskite is scarce in most sedimentary rocks, a few Triassic clays contain substantial amounts. Its diffractometer trace (pl. 2*J*) is characterized by a strong peak at 10.5 A which persists after treatment with ethylene glycol and after heating to 300°C, but which disappears after heating to 550°C. Solubility tests and the chemical analysis indicate that the palygorskite in the Triassic rocks is an insoluble aluminous variety. The true structural formula for the chemically analyzed palygorskite probably is more complex than that given on plate 2*J* because, in the process of correcting for other minerals in the sample, all the less abundant oxides were assigned to carbonates, illite, and mixed-layer montmorillonite.

Palygorskite is found in desert soils and in sediments that accumulated in desert basins where magnesium is abundant. Its structural similarity to the amphiboles suggests that some times it may form from these minerals. It has also been reported, along with montmorillonite and sepiolite to occur as an alteration product of volcanic material (Martin-Vivaldi and others, 1955). Apparently palygorskite may form in a magnesium-rich environment from different types of material, but the exact conditions favoring its formation rather than the formation of montmorillonite are not understood (Mumpton and Roy, 1956).

PRESENTATION OF DATA

CLAY MINERALS

Clay-mineral analyses are reported in the columnar sections on plate 3. The graphic presentation is intended to show both the stratigraphic and geographic distribution of clay minerals in the Triassic rocks of the Colorado Plateau. Most of the vertical columns shown on plate 3 represent the stratigraphic section at one sample locality.

A few of the vertical columns represent composite sections at two localities—the first locality number of a composite section is for Chinle rocks and the second locality number is for Moenkopi rocks. Each horizontal line within a column indicates the stratigraphic position of a sample; in places crowding of sampling points near the Chinle-Moenkopi contact required some distortion of scale. Different clay minerals are represented by various colors, and the proportion of each type of clay is indicated by the extent of the color on the horizontal line. Thus, if kaolinite constitutes 10 percent of the clay in a sample, the color for kaolinite extends over one-tenth of the width of the column. Mineralogical boundaries between samples are generally straight lines drawn between the adjacent samples, except at a few places where the boundaries are squared off to conform with abrupt lithologic changes.

The field classification of each sample is indicated on plate 3 by a symbol along the horizontal line representing the sample; for example, "st" indicates siltstone. The terms "sandstone," "siltstone," and "claystone" are used in their usual sense. "Mudstone" refers to a heterogeneous mixture of abundant sand- , silt- , and clay-sized particles. The name "tuff" is applied to claystone formed of rounded sand- or silt-sized aggregates of clay which, for reasons discussed later, are believed to be particles of altered tuff. Tuffaceous sandstone contains quartz grains as the major constituent and sand-sized particles of altered tuff particles as the minor component. Tuffaceous siltstone contains silt-sized particles of altered tuff, whose abundance is usually difficult to estimate because of the fine particle size.

The information from plate 3 is summarized in a more general and schematic form on plate 4, which illustrates the salient points of clay distribution throughout the Colorado Plateau.

Additional data concerning a variety of characteristics of the clay samples and clay minerals are given in tables 4–11.

FELDSPARS

Distribution of potassium and plagioclase feldspars in the Triassic rocks is summarized in table 4. The data are grouped primarily on a stratigraphic basis, but a secondary breakdown based on the associated clay-mineral assemblages illustrates relations between clay and feldspar types that are discussed later.

CARBONATES

Calcite and dolomite are common throughout the Moenkopi and the upper part of the Chinle formation. In table 5, clay-mineral composition of closely spaced pairs of carbonate-rich and carbonate-

poor samples is compared to determine if clay composition is related to carbonate content. Half of the pairs contain identical clay-mineral assemblages. Where the clay minerals are different, the differences are not consistently related to carbonate content, but commonly are related to grain size. As will be shown later, clay minerals, such as well-crystallized kaolinite, that tend to have a large particle size are concentrated in the coarser grained rocks. Thus, the sandy limestones from localities 58 and 68 contain more kaolinite than adjacent siltstones; the fine-grained limestones from localities 70 and 71 contain less kaolinite than the siltstone. It is concluded, therefore, that clay-mineral composition is not related to carbonate content in the Triassic rocks.

TABLE 4.—*Feldspar in samples of Triassic rocks*

[Figures are number of samples]

Stratigraphic unit and type of sample	Potassium feldspar > plagioclase	Potassium feldspar = plagioclase	Plagioclase > potassium feldspar	Feldspar present but type unknown	Feldspar absent	Total samples
Owl Rock and Church Rock members:						
Montmorillonitic	12	10	35	12	5	74
Kaolinitic	28	7	10	29	2	76
Chloritic	8	8	59	9	3	87
	[1] 48	25	104	50	10	237
Petrified Forest member:						
Upper part	6	4	22	10	4	46
Lower part	22	6	45	15	40	128
	28	10	67	25	44	174
Moss Back member:						
Kaolinitic	21	0	0	3	20	44
Chloritic	6	8	13	5	2	34
	27	8	13	8	22	78
Monitor Butte member:						
M—clay	3	1	13	2	17	36
M_m—clay	24	0	3	7	37	71
Kaolinitic	3	0	0	0	12	15
Illitic	5	0	0	0	2	7
Chloritic	1	0	0	0	1	2
	36	1	16	9	69	131
Shinarump member:						
Kaolinitic	30	0	0	1	31	62
Chloritic	1	0	4	0	2	7
	31	0	4	1	33	69
Mottled zone	0	0	0	0	53	53
Moenkopi formation:						
Kaolinitic	79	1	2	25	25	132
Chloritic	34	8	29	10	3	84
Montmorillonitic	8	1	2	4	3	18
	121	10	33	39	31	234

[1] Potassium feldspar is more abundant than plagioclase in 48 samples from the Owl Rock and Church Rock members; 12 of these samples contain montmorillonitic clays, 28 samples contain kaolinitic clays, and 8 samples contain chloritic clays.

TABLE 5.—*Carbonate content and clay minerals*

Explanation of symbols: K_g, well-crystallized kaolinite; $K_?$, kaolinite, crystallinity not determined; I, illite; I_m, mixed-layer illite; IM_m, mixed-layer illite-montmorillonite; M_m, mixed-layer montmorillonite; M, montmorillonite; Cl_g, well-crystallized chlorite; Cl_m, mixed-layer chlorite; >>, more than twice as much as; >, more abundant than; =, about equal to.

Locality		Member	Feet above base of stratigraphic unit	Lithology	Mineralogy
Name	No.				
Chinle formation					
Buckhorn Wash	72	Church Rock	46	Calcareous claystone	$I>>I_m$
			36	Claystone	$I>>I_m$
Moab Canyon	78	Church Rock(?)	10	Calcareous siltstone	$I>IM_m>>Cl_g$
			7	Claystone	$I>IM_m>>Cl_g$
Muley Twist	56	Owl Rock	158	Limestone	$I>>I_m$
			152	Siltstone	$I>>I_m$
Owl Rock	39	do	135	Limestone (nodule)	$IM_m>I>>M$
			135	Calcareous claystone	$IM_m>I>>M$
Jacob's Chair	51	do	77	Limestone	$I>>I_m$
			13	Calcareous siltstone	$I>I_m$
Bears Ears	49	do	426	do	[1] $I>>IM_m$
			311	Sandy limestone	$I>>IM_m=Cl_m$
Bridger Jack Mesa	33	do	243	do	[1] $I=M_m$
			238	Calcareous siltstone	$I>IM_m$
			45	do	$I>>I_m$
			41	Limestone	$I>>I_m$
Poncho House	38	do	365	do	$I>IM_m$
			362	Calcareous siltstone	$I>IM_m$
			3	Sandy limestone	[1] $M_m>M>I$
		Petrified Forest	[2]—10	Calcareous claystone	$M_m>>M=I$
Black Point	10	Owl Rock	286	Limestone	[3] $M=I>>Cl_g$
			268	Siltstone	$M_m>I>>Cl_g$
		Petrified Forest	710	Claystone	[3] $M_m>>M>I$
			700	Limestone	$M_m>>I$
Ghost Ranch	19	do	175	Siltstone	[3] $M_m>>I=M>Cl_g$
			140	Limestone conglomerate.	$M_m>>I>Cl_g$
			100	Claystone	$M_m>>I>M=Cl_g$
			30	Sandy limestone	[1] $M_m>I>Cl_g>Cl_m$
			25	Claystone	$M_m>>I>Cl$
Fort Wingate	17	do	228	Limestone nodule	$M>>M_m$
			224	Claystone	$M>>M_m$
South Draw	59	do	80	Calcareous claystone	[3] $M_m=I$
			46	Claystone	M_m
Clay Hills Divide	45	Monitor Butte	147	Limestone nodule	$M_m>>M$
			147	Claystone	$M_m>>M$
Lucky Strike mine	65	do	26	Limestone nodule	$I>IM_m>>K_g$
			26	Claystone	$I>IM_m>>K_?$
Moenkopi formation					
Straight Wash	71	Sinbad limestone	8	Limestone	[1] $I>>I_m$
			6	Siltstone	$I>>I_m>>K_g$
Temple Mountain	68	do	145	Sandy limestone	[1] $K_g>>I>I_m$
			40	Calcareous siltstone	$I>>I_m>K_g$
Block Mountain	70	do	142	Limestone	[1] $I>>I_m$
			78	Siltstone	$I>>I_m=K_g$
Muddy River	64	do	170	Limestone	$I>>I_m>K_g$
			80	Siltstone	$I>>I_m>K_g$
Range Canyon	74		39	do	$I>>I_m>K_g$
			29	Calcareous siltstone	$I>>I_m>K_g$
Chimney Rock	62	Sinbad limestone	90	Limestone	$I>>I_m=K_g$
			77	Siltstone	$I>>I_m=K_g$
Capitol Wash	60	do	115	Limestone	[1] $I>K_g>I_m$
			85	Siltstone	$I=K_g>I_m$
Horse Canyon	58		70	do	[1] $I>K_g>I_m$
		Sinbad limestone	45	Sandy limestone	$K_g>>I>I_m$
St. George	2	Shinarump	1010	Siltstone	$I>I_m=Cl_g$
			831	Limestone	$I>I_m=Cl_g>Cl_m$
		Virgin limestone	233	do	[3] $I=M_m>Cl_g$
		Lower red	151	Siltstone	$I>M_m=Cl_g$
Vermilion Cliffs	6		47	do	[1] $I=K_g>I_m$
			36	Sandy limestone	$I>>I_m>>K_g$
Fredonia	4	Virgin limestone	148	Claystone	[3] $I>I_m>Cl_g$
			145	Limestone	$I=I_m>>Cl_g$

[1] Differences apparently related to the sandiness of the rocks.
[2] Feet below top of the unit. [3] Differences not related to the sandiness of the rocks.

COLOR

Color of the Triassic rocks varies widely and may change abruptly within short distances. To determine if the clay composition is related to these color changes, closely spaced pairs of samples of different color were taken. Their clay-mineral composition is compared in table 6. For example, at the first locality listed, Buckhorn Wash (loc. 72), clay in the purple siltstone at 161 feet above the base of the Church Rock member differs from that in a nearby red siltstone from the same stratigraphic level only in that it contains a very small amount of chlorite. Most of the color pairs contain identical clays, and the small differences noted in a fifth of the pairs are not consistently related to color.

TABLE 6.—*Color and clay-mineral composition of samples*

Explanation of symbols: K_g, well-crystallized kaolinite; K_p, poorly crystallized kaolinite; $K_?$, kaolinite, crystallinity not determined; I, illite; I_m, mixed-layer illite; IM_m, mixed-layer illite-montmorillonite; M_m, mixed-layer montmorillonite; M, montmorillonite; Cl_g, well-crystallized chlorite; Cl_m, mixed-layer chlorite; >>, more than twice as much as; >, more abundant than; =, about equal to.

Locality		Member	Feet above base of stratigraphic unit[1]	Color and Lithology	Mineralogy
Name	No.				
Chinle formation					
Buckhorn Wash	72	Church Rock	161	Purple siltstone	[2] $I>>I_m>>Cl_g$
			161	Red siltstone	$I>>I_m$
Straight Wash	71	do	88	Green siltstone	$I>>I_m$
			88	Purple siltstone	$I>>I_m$
Bridger Jack Mesa	33	Owl Rock	45	do	$I>>I_m$
			45	Green siltstone	$I>>I_m$
Jacob's Chair	51	do	231	do	$I>I_m$
			231	Red siltstone	$I>I_m$
Bears Ears	49	do	60	Purple siltstone	$I=M_m$
			51	Red siltstone	$I=M_m$
Poncho House	38	do	264	Red claystone	[2] $I>IM_m$
			259	Purple siltstone	$I=M_m$
Paria	5	Petrified Forest	270	Purple claystone	$M_m>>I>K_?$
			255	Red claystone	$M_m>>I>K_?$
Owl Rock	39	do	300	Green claystone	$M_m>>I$
			300	Red claystone	$M_m>>I$
			208	Green claystone	M_m
			208	Purple claystone	M_m
Monitor Butte	44	do	374	Green claystone	$M_m>>I$
			374	Purple claystone	$M_m>>I$
Silver Falls Creek	55	do	242	Red claystone	$M_m>>I$
			215	Yellow claystone	$M_m>>I$
Spring Canyon	77	Moss Back	17	Red claystone	$I>I_m$
			15	Green claystone	$I>I_m$
Comb Wash	37	Monitor Butte	100	do	$M_m>>M$
			96	Purple claystone	$M_m>>M$
Red House	46	do	31	Red claystone	[2] $M_m>>I$
			23	Green claystone	[2] $M_m>M$
Milk Ranch Point	36	do	61	do	$M_m>>I$
			61	Purple claystone	$M_m>>I$
Buckhorn Wash	72	do	60	Red siltstone	[2] $K_p>>IM_m$
			60	Purple siltstone	[2] $K_p=IM_m$
			53	Green siltstone	$IM_m>K_g$
			53	Purple siltstone	$IM_m>K_g$
Chavez-Prewitt	18	Shinarump	3	Green sandstone	[2] $K_g>>Cl_m>I$
			3	Red sandstone	[2] $K_g>>Cl_m=I$
Muley Twist	56	Mottled zone at base.	9	Green siltstone	$K_g>>IM_m$
			9	Purple siltstone	$K_p>>IM_m$
Lucky Strike mine	65	do	0	Red siltstone	$I>IM_m>K_g$
			0	Purple siltstone	$I>IM_m>K_g$

See footnotes at end of table.

TABLE 6.—*Color and clay-mineral composition of samples*—Continued

Explanation of symbols: K_g, well-crystallized kaolinite; K_p, poorly crystallized kaolinite; $K_?$, kaolinite, crystallinity not determined; I, illite; I_m, mixed-layer illite; IM_m, mixed-layer illite-montmorillonite; M_m, mixed-layer montmorillonite; M, montmorillonite; Cl_g, well-crystallized chlorite; Cl_m, mixed-layer chlorite; >>, more than twice as much as; >, more abundant than; =, about equal to.

Locality		Member	Feet above base of stratigraphic unit [1]	Color and Lithology	Mineralogy
Name	No.				
Chinle formation—Continued					
Spring Canyon	77	Mottled zone at base	8	Green claystone	$IM_m>>K_p>>I$
			8	Red claystone	$IM_m>>K_p>>I$
			2	Green mudstone	$IM_m>>I$
			2	Purple mudstone	$IM_m>>I$
			2	Red mudstone	$IM_m>>I$
Buckacre Point	73	do	2	Purple claystone	[2] $IM_m>K_p>>I$
			2	Green claystone	[2] $IM_m=K_p=I$
Bridger Jack Mesa	33	do	2	Purple claystone	[2] $M_m>>K_p>>I$
			2	Green claystone	[2] $M_m>>K_p$
Moenkopi formation					
Bridger Jack Mesa		Mottled zone at top	−½	Purple claystone	$I=IM_m=K_g$
			−½	Green claystone	$I=I_m=K_g$
			−9	Green claystone [3]	$I>IM_m>>Cl_g>>K_?$
			−9	Red claystone	$I>IM_m>>Cl_g>>K_?$
North Sixshooter Peak	32	Mottled zone at top	−1	Green claystone	$I=M_m>>K_p$
			−1	Red claystone	$I=M_m>>K_p$
Silver Falls Creek	55		51	Red siltstone	$I>>K_g>I_m$
			40	Yellow siltstone	$I>>K_g>I_m$
Muddy River	64		565	Green siltstone [3]	$I>>I_m>>Cl_g$
			565	Red siltstone	$I>I_m>>Cl_g$
Buckhorn Wash	72		−1	Green siltstone	$I>I_m$
			−15	Yellow siltstone	$I>I_m$
Temple Mountain	68		599	Green siltstone [3]	$I>I_m>>K_g$
			599	Red siltstone	$I>I_m>>K_g$
Range Canyon	74		8	do	$I>>I_m>K_g$
			7	Yellow siltstone	$I>>I_m>K_g$
Taylor Canyon	76		−5	Red siltstone	$I>I_m>>Cl_g$
			−30	Yellow siltstone	$I>I_m>>Cl_g$
Monitor Butte	44		217	Green siltstone [3]	$I>>I_m>>Cl_g$
			217	Red siltstone	$I>>I_m>>Cl_g$
Red House	46		−40	Green siltstone [3]	$I>>IM_m>>Cl_g$
			−40	Red siltstone	$I>>IM_m>>Cl_g$

[1] A minus sign (−) indicates sampling point is below top of unit.
[2] Pair with a notably different clay-mineral assemblage.
[3] Sample taken from greenish-gray spots in predominantly reddish-brown siltstone of the Moenkopi.

MOENKOPI FORMATION

DESCRIPTION

The Moenkopi formation extends throughout the western two-thirds of the Colorado Plateau, and unnamed strata of Permian and Triassic age, probably equivalent to part or all of the Moenkopi, extend into northwest Colorado. Correlation with the Moenkopi of rocks in west-central and central New Mexico (McKee, 1954) is uncertain, and therefore these rocks are here referred to as Moenkopi(?). In the western part of the Colorado Plateau the Moenkopi commonly overlies Permian strata unconformably. In most areas in the East, it conformably overlies Permian red beds that are litholog-

ically similar to the Moenkopi and are difficult to differentiate from it. The Hoskinnini member (pl. 3) is one such unit that recently has been reassigned from the Permian to the Triassic(?) system (Stewart, 1959). The Hoskinnini was sampled only in part for this study. The Moenkopi formation is separated from the overlying Chinle formation by a widespread unconformity. Thickness of the Moenkopi ranges from a knife edge at most places near the Colorado-Utah and the New Mexico-Arizona State lines to about 2,000 feet in southwestern Utah.

The major part of the Moenkopi formation is composed of reddish-brown siltstone that in some areas is interbedded with brown to buff crossbedded sandstone and in other areas with beds of carbonate and gypsum. Distribution of lithofacies is shown on figure 1. Sandstone ranges in abundance from about 50 percent of the total Moenkopi in the east to about 5 percent in the west. In a zone west of the dominantly sandy rocks, the formation is composed mostly of ripple-laminated siltstone, and still farther west it is composed mostly of structureless or horizontally laminated siltstone. In the westernmost zone, the red siltstone is interbedded with marine carbonate and gypsum beds of the Timpoweap, Virgin limestone, and the Shnabkaib members in southwestern Utah and adjacent Arizona and the Sinbad limestone member in southeastern Utah (pl. 4). A unit that McKee (1954) called the lower massive sandstone is also shown on plates 3 and 4, because it will be useful in the description and interpretation of the clay-mineral distribution.

Gradation of predominantly coarse-grained strata in the east into partly marine fine-grained strata in the west clearly indicates that most of the Moenkopi sediments came from the east. The crossbedded sandstones are fluviatile, and their crossbedding dips predominantly to the west. McKee (1954) interprets the abundance of ripple marks, salt casts, shrinkage cracks, and reptile tracks in much of the red siltstone of the Moenkopi as indicative of flood-plain or tidal-flat deposits. Periodically, sedimentation did not keep pace with the rate of sinking of the area of deposition, so that the sea in which the limestone units of the Moenkopi were deposited extended across the tidal flats far to the east of its usual position. The area of very sandy sedimentary rocks in central Arizona possibly indicates proximity to an additional source area of Moenkopi sediments.

CLAY-MINERAL DISTRIBUTION

Illite is the dominant clay mineral in most Moenkopi rocks. Two other principal types of Moenkopi illitic clay-mineral assemblages are distinguished: (1) a type with kaolinite as a minor component and (2) a type with chlorite as a minor component. In places, mixed-layer

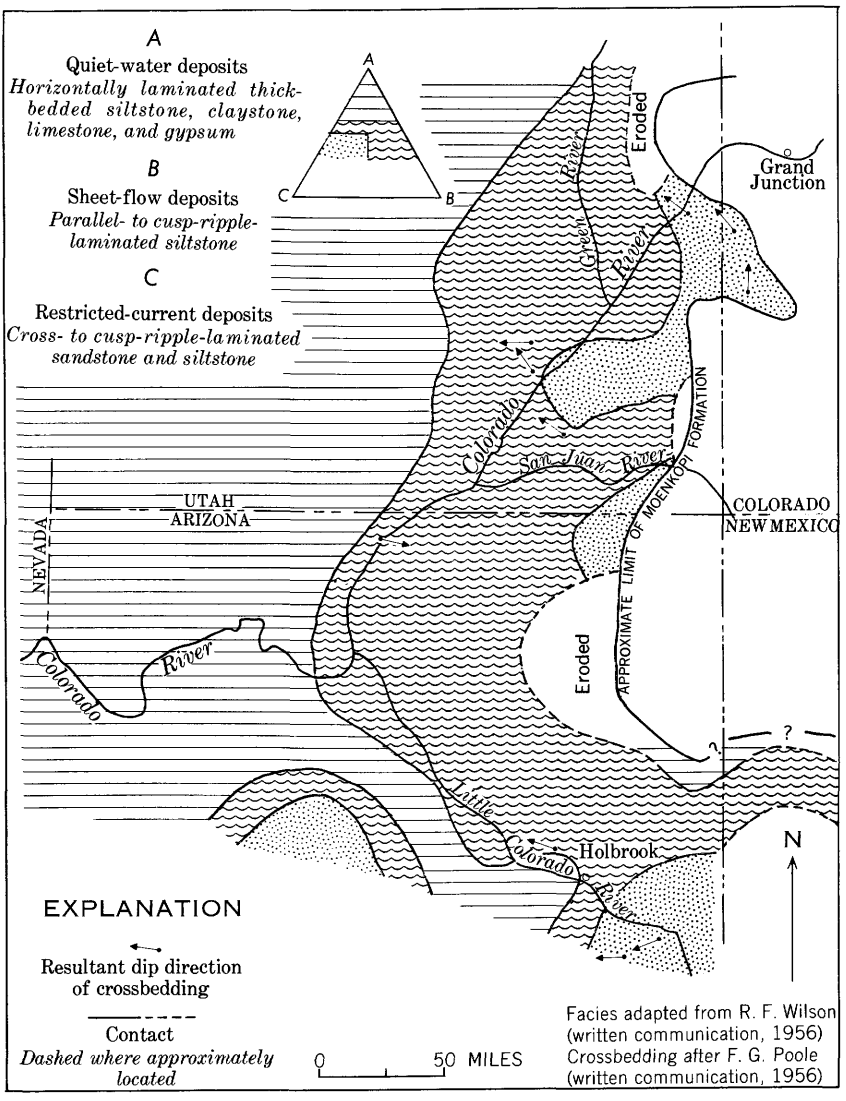

FIGURE 1.—Sedimentary facies and structures in the Moenkopi formation.

illite-montmorillonite rather than mixed-layer illite accompanies the illite and chlorite. In a few samples, a chlorite-illite assemblage also contains a fairly large amount of mixed-layer montmorillonite. This assemblage will be considered as a montmorillonitic variety of the chloritic type clays from the Moenkopi.

Distribution of the kaolinitic and chloritic clays of the Moenkopi formation is shown on plates 3 and 4 and is also summarized on figure

2. In the northern part of the Colorado Plateau, clays in the Moenkopi formation are chloritic in the east and kaolinitic in the west. Few samples contain both kaolinite and chlorite. This mutually exclusive distribution of kaolinite and chlorite may not be so perfect as shown on plate 3 because detection of small amounts of kaolinite in the presence of chlorite is difficult. However, the general change from chloritic to kaolinitic Moenkopi clays from east to west is unquestionable.

Over a wide area in eastern and north-central Arizona, kaolinitic Moenkopi clays occur in and below the "lower massive sandstone" bed.

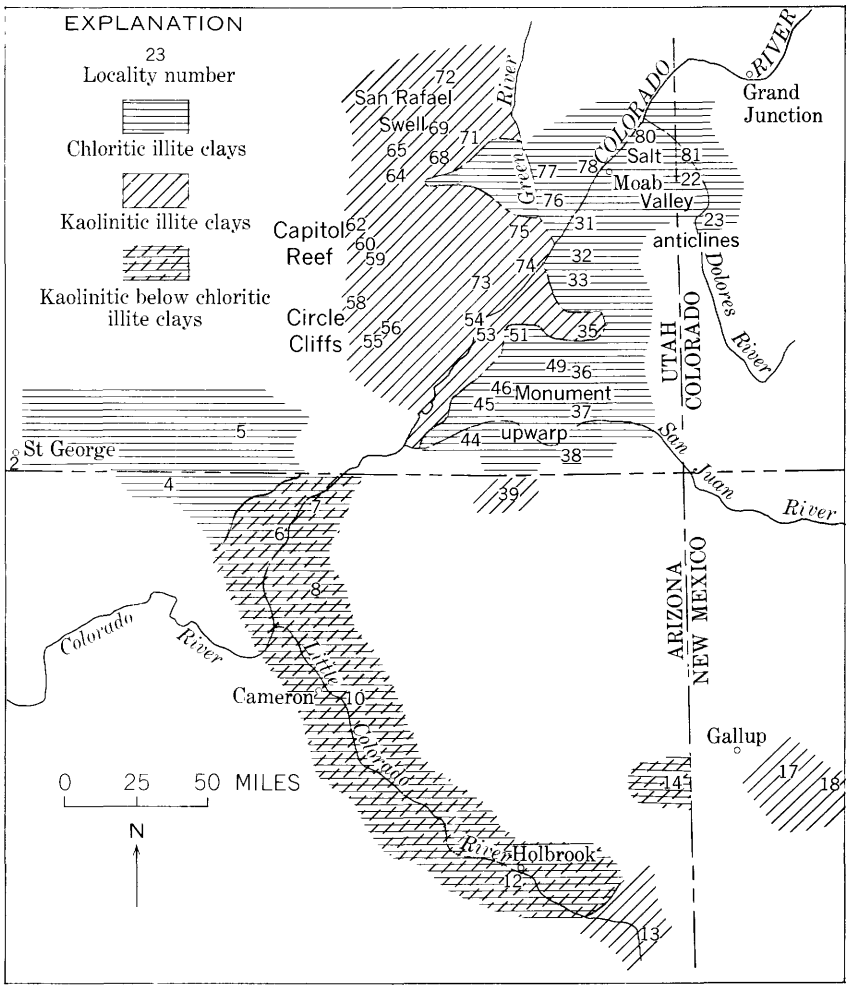

FIGURE 2.—Distribution of kaolinitic and chloritic clays in the Moenkopi formation.

Above this bed, the clays are chloritic, and at localities 2 and 4 the entire Moenkopi is chloritic.

The montmorillonitic variety of the chlorite-illite type clay occurs most extensively along Comb Ridge (locs. 37–38), but small patches of it were also found at widely scattered places.

Although kaolinite and chlorite are minor components in the siltstone and claystone that compose the bulk of the Moenkopi formation, they commonly are major components of the clay-mineral fraction in the coarse-grained rocks. This relation is illustrated at many localities (39, 45, and so forth) and is also applicable to the Chinle formation.

INTERPRETATION OF GEOGRAPHIC DISTRIBUTION OF CLAY MINERALS

Most rocks in the Moenkopi formation clearly came from an eastern source. The distribution of clay minerals must be interpreted in the light of this fact. The preponderance of illitic clay in almost all Moenkopi samples, regardless of whether the samples are from the terrestrial facies nearer to the source or from farther west, indicates that the bulk of the clay has been transported from the source area and deposited without very much alteration. However, in the northern part of the Colorado Plateau, occurrence of chloritic illite clay to the east and kaolinitic illite clay to the west probably suggests some alteration during transportation. Kaolinite in the marine Sinbad limestone member suggests that the kaolinite did not form at the site of deposition because an alkaline marine environment in which such a limestone is deposited is not favorable for formation of kaolinite. Furthermore, if chlorite survived transportation until it entered marine waters, it would likely still be preserved. Therefore, chlorite derived from the eastern source must have been destroyed some place to the east of the area where marine conditions prevailed. A comparison of the lithofacies map (fig. 1) with the clay-distribution map (fig. 2) shows that the change from chloritic to kaolinitic sediments takes place in an area of dominantly sheet-flow deposits. Perhaps the alteration on tidal flats was promoted by repeated wetting and drying. Plagioclase is common in the chloritic sediments; its general absence in the kaolinitic sediments in the Moenkopi (table 4) may be due to the same weathering that altered the chlorite. Plagioclase normally is more easily altered than potassium feldspar. The inferred area of alteration and probable transport directions of sediment are shown on figure 3.

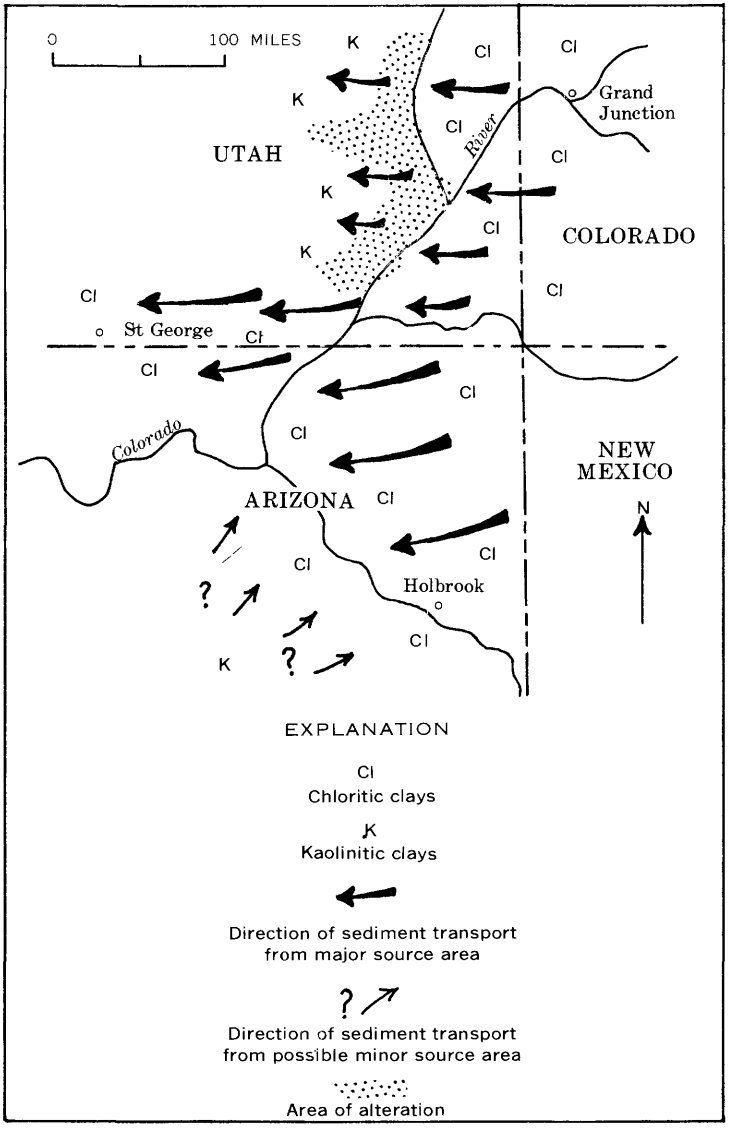

FIGURE 3.—Probable area where Moenkopi sediments were altered from chloritic to kaolinitic varieties.

Mineralogic evidence from Moenkopi strata in Arizona and southwest Utah suggests a history different from that of the northern area just discussed. The chloritic illite clays in most Moenkopi rocks throughout the southern part of the Colorado Plateau suggest that they were probably derived from the same general source area to the east as were the clays in the northern area but that they were trans-

ported more rapidly across the tidal flats and were deposited and then buried without appreciable alteration (fig. 3). The kaolinitic illite clays in and below the "lower massive sandstone" bed in northeastern Arizona (fig. 2) probably did not result from weathering of chloritic sediments derived from the east, because they occur on the eastern, or shoreward, side of the thick sequence of unaltered chloritic sediments at localities 2 and 4 (fig. 2). Abundant sandstone in central Arizona (fig. 1) suggests a probable southern source for Moenkopi strata in that area. Studies by McKee (1949; 1954, fig. 18) of sedimentary structures in the Moenkopi formation indicate that the shorelines and possibly also the directions of sediment transport in this area changed after deposition of the "lower massive sandstone" bed at about the time when kaolinitic sediments gave way to chloritic sediments. Thus, a minor southern source area may have supplied kaolinitic sediments to an area in eastern and north-central Arizona during the early part of Moenkopi time; later the area received chloritic sediments from the east.

The origin of the chloritic illite clays that contain some mixed-layer montmorillonite cannot be explained at this time. Because abundant volcanic-derived mixed-layer montmorillonite occurs in the Chinle formation, evidence of volcanic debris was sought in the Moenkopi rocks containing similar clays, but none was found. Furthermore, the montmorillonitic Moenkopi clays are most abundant in Comb Ridge, which is far from areas of known volcanism during Triassic time. Probably, like other chloritic illite clays in the Moenkopi, they came from an eastern source. The difference in these clays may be due to different conditions of weathering or deposition, but available information does not indicate what these conditions were.

INTERPRETATION OF ABUNDANCE OF KAOLINITE AND CHLORITE IN COARSE-GRAINED ROCKS

Kaolinite and chlorite commonly constitute a notably higher proportion of the clay minerals in the coarse-grained rocks than in the fine-grained rocks. By comparing the abundance of the different clay minerals in the <2-micron fraction with their abundance in the whole sample, an evaluation of their relative average particle size is possible. In this great majority of samples, kaolinite and well-crystallized chlorite are notably coarser grained than most of the other clay minerals. Kaolinite and chlorite therefore, should be more abundant in the coarser grained rocks, whereas other clay minerals should be more abundant, relative to kaolinite and chlorite, in the fine-grained rocks.

Mixed-layer chlorite is even more abundant in the coarse-grained rocks than kaolinite and well-crystallized chlorite. It occurs almost

exclusively in the coarser grained sedimentary rocks, and in a few samples it is the only clay mineral detected. Yet, grains of the mixed-layer chlorite seems to be no coarser than the average-sized grains of other clay minerals in the Triassic rocks and are probably finer. Of course, this particle-size observation is based on examination of disaggregated laboratory samples; and during the disaggregation some clay-mineral grains may have been broken into smaller particles. Such a disaggregation might be expected of mixed-layer chlorite because of its expandable montmorillonite layers. The photomicrographs on figure 4 show the upper of the two sandstone samples from the Moenkopi at Clay Hills Divide (loc. 45). Both fields show large grains that are composed of aggregates of tiny crystals of mixed-layer chlorite. As the larger aggregate grains break up during laboratory disaggregation, they probably could not have survived transportation under natural conditions, and must have altered to mixed-layer chlorite after they were deposited. The mixed-layer chlorites occur in rocks that are normally chloritic, and therefore probably resulted from slight alteration of coarse crystals of well-crystallized chlorite deposited with the sandstone. Mixed-layer chlorite occurs almost exclusively in sandstone, because the greater permeability of sandstone allows access of the altering agent, probably circulating ground water.

Another mode of occurrence of mixed-layer chlorite is also shown by the thin section on figure 4. Some of the mixed-layer chlorite crystals radiate into intergranular spaces. Chlorite of this radial texture is not likely to result from sedimentation and therefore must have formed after deposition. The size of such secondary crystals would not be controlled by sedimentary fractionation during deposition and therefore need not bear any particular relation to the particle size of the enclosing rock.

In summary, the mixed-layer chlorite in the Moenkopi and other triassic sedimentary rocks seems to be a secondary mineral formed by slight reconstitution or recrystallization of primary well-crystallized chlorite. The greater abundance of well-crystallized chlorite and kaolinite in coarser sediments is due to sedimentary fractionation during deposition of the sediments.

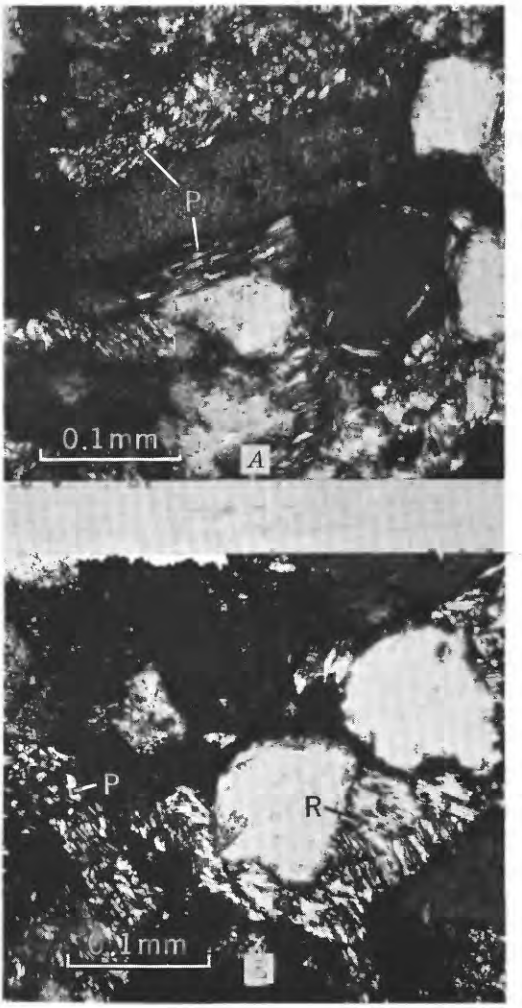

FIGURE 4.—Pseudomorphic (*p*) and radial (*r*) textures of mixed-layer chlorite in sandstone from the Moenkopi formation at Clay Hills Divide (loc. 45). Crossed nicols.

CHINLE FORMATION

The Chinle formation occurs throughout the Colorado Plateau. It is more than 1,000 feet thick in parts of Arizona and generally thins to the north. On the basis of lithologic differences it is separated into several members (table 1). These members characteristically do not have sharp contacts but grade both vertically and laterally into each other. The Chinle formation is entirely continental in origin (Stewart and others, 1959, p. 522).

TEMPLE MOUNTAIN MEMBER

The Temple Mountain member occurs at the base of the Chinle formation in parts of the San Rafael Swell area. Its thickness rarely exceeds 30 feet. It is composed mostly of mottled purple, red, and white siltstone, generally with a few scattered sand grains, but in places it may be composed of claystone, sandstone, or even clayey conglomeratic sandstone.

The most characteristic mineralogical features of the Temple Mountain member are: (1) abundance of kaolinite, commonly of the poorly crystallized variety, (2) abundance of mixed-layer illite-montmorillonite, and (3) absence of feldspar. These same features were noted for many other zones of mottled rocks occurring near the base of the Chinle formation beyond the San Rafael Swell area. The origin of the Temple Mountain member, and of these other mottled rocks will be discussed in a later section of this report. As will be shown, the mottled zones are former soils, and much of the kaolinite and mixed-layer illite-montmorillonite in these rocks result from soil-forming processes.

SHINARUMP MEMBER

DESCRIPTION

The Shinarump member, as redefined by Stewart (1957), extends over the southern part of the Colorado Plateau. Its distribution is shown on figure 5A. In Arizona and southwestern Utah it forms a fairly continuous unit, which is as much as 225 feet thick in Arizona but to the north it thins and is more lenticular. It unconformably overlies the Moenkopi formation and fills channels cut into the Moenkopi. It grades upward and, in places also laterally into the Monitor Butte member; in many places the fine-grained lateral equivalents are mottled.

The Shinarump member is typically a buff medium- to coarse-grained sandstone with minor lenses of conglomerate and siltstone or claystone. In many places the sandstone is crossbedded. The direction of dip of these crossbeds (fig. 5A) indicates transportation mainly from south to north.

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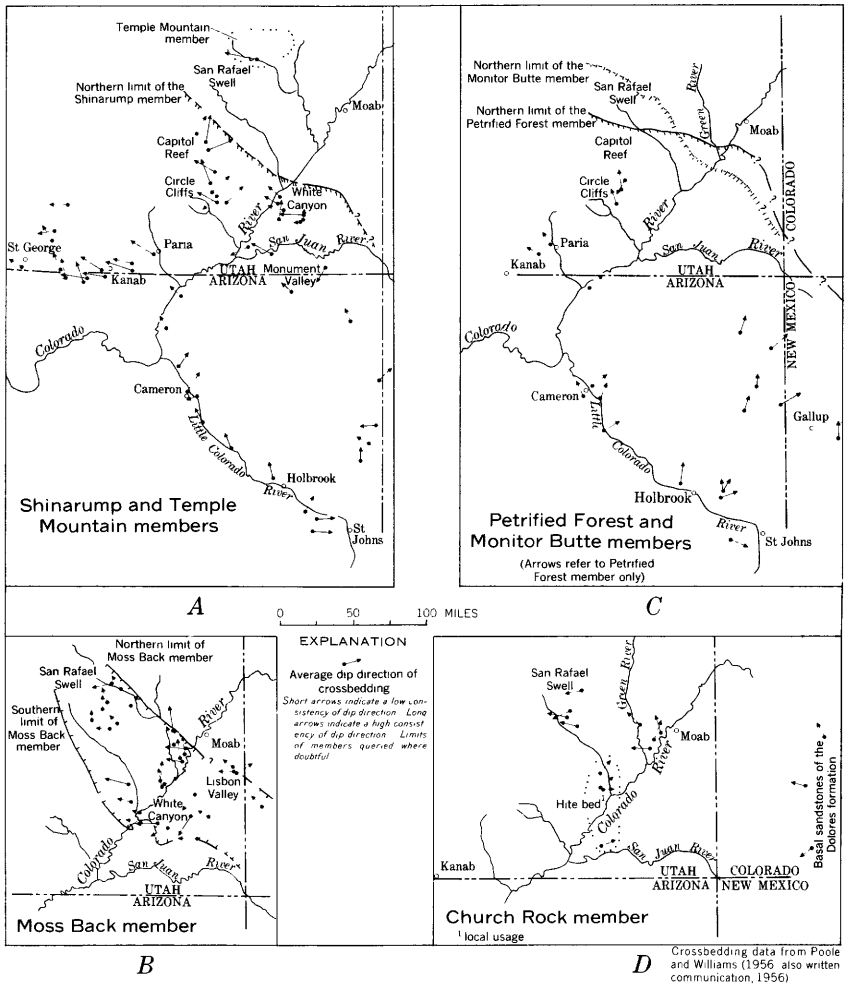

FIGURE 5.—Distribution of members and orientation of sedimentary structures in the Chinle formation.

Silicified volcanic pebbles occur sparsely in the Shinarump member in Arizona between Lees Ferry (loc. 7) and Grand Falls (near loc. 10). Seven of these pebbles from the Shinarump near Grand Falls and Cedar Ranch (pl. 1) were studied in thin section and by X-ray methods. All contained abundant quartz and orthoclase phenocrysts, but no plagioclase was identified either in the phenocrysts or in the groundmass. The pebbles are rhyolite.

Feldspar is present in detectable amounts in about half of the analyzed Shinarump samples (table 4). Potassium feldspar is generally much more abundant than plagioclase. Microline is the most common

feldspar. None of the potassium feldspar in the Shinarump has been specifically identified as sanidine.

CLAY-MINERAL DISTRIBUTION

The dominant and most characteristic clay mineral in the sandstone of the Shinarump member is well-crystallized kaolinite. Poorly crystallized kaolinite is common in fine-grained parts of the member. Illitic clays and mixed-layer illite-montmorillonitic are common as minor components. More montmorillonitic clays tend to take the place of the illitic clays in the southern part of the Colorado Plateau. Chlorites are scarce, but an aluminum-rich variety is found along the eastern fringe of the Shinarump member.

INTERPRETATION

The highly kaolinitic composition of most Shinarump clays suggests intense leaching, probably by the same weathering processes mentioned for the Temple Mountain member and other mottled rocks. Several features indicate that part of the weathering must have occurred prior to deposition. In highly kaolinitic samples in which the feldspars were studied optically, some of the feldspar grains appear absolutely fresh. As strong leaching would be necessary to form kaolinite from other minerals, it does not seem likely that all the kaolinite could form in place without some alteration of these feldspar grains. Furthermore, chloritic rocks of the Moenkopi occur immediately below kaolinite-bearing rocks of the Shinarump (locs. 38, 40, 44), and in a few places (locs. 40 and 43) chlorite-bearing Moenkopi pebbles occur in kaolinitic rocks of the Shinarump. Again, it seems unlikely that abundant kaolinite in the Shinarump sedimentary rocks would form in place without simultaneous alteration of chlorite in the Moenkopi rocks adjacent to and enclosed in the Shinarump rocks.

Some thick books of kaolinite found in the Shinarump (similar to those illustrated on fig. 11) could not have survived transportation in their present form and therefore must have formed in place. Such large kaolinite books, however, make up only a minor part of the kaolinite in these rocks. Textural relations of most kaolinite suggest transportation and deposition with other detrital minerals in the rock.

Occurrence of rhyolite pebbles in the Shinarump member indicates that the sediments were in part volcanic; these pebbles are in part altered to kaolinite. However, other volcanic material in the Shinarump is seldom recognized. Tuffaceous particles and sanidine were not recognized in Shinarump samples, even though they are abundant in the overlying rocks; montmorillonitic clay occurs in the Shinarump

only in the southernmost outcrops. Prevalence of microcline and of other monovolcanic minerals, such as muscovite, proves that nonvolcanic debris must have formed a considerable part of the sediments.

General thickening, greater continuity, and increase in average pebble size toward the south (Albee, 1957, p. 138), as well as crossbedding studies (fig. 5*A*) indicate that the main source of the bulk of the sediments of the Shinarump member lay to the south, probably in east-central Arizona. The sediments were deposited from meandering streams; the coarser sediments, including coarse-grained well-crystallized kaolinite flakes, were deposited mainly in the stream channels; the finer sediments, including poorly crystallized kaolinite, were deposited on the channel flanks. The sediments probably accumulated intermittently and were subjected to repeated cycles of weathering, erosion, and redeposition, so that the most of the alteration that produced their present kaolinitic composition occurred prior to their final deposition. Both volcanic and nonvolcanic debris were included, but the present highly altered state of the rocks makes an evaluation of their relative abundance impossible. Occurrrence of several thin chloritic lenses along the east edge of the area of deposition of the Shinarump (locs. 36–38) suggests that some materials came from the same eastern source that contributed to the chloritic sediments in the Moenkopi. Such a dual source of Shinarump sediments in southeastern Utah is supported by crossbedding studies (fig. 5*A*) and by the east-west trend of channels in the White Canyon area (Johnson and Thordarson, 1959); this trend contrasts with the general south to north direction of transport elsewhere.

MONITOR BUTTE MEMBER

DESCRIPTION

The Monitor Butte member is present throughout most of southeastern Utah and in adjacent parts of Monument Valley in Arizona. The northern limit of the Monitor Butte is shown on figure 5*C*. Farther south in Arizona, lithologically similar rocks that occur in the stratigraphic interval of the Monitor Butte (Stewart and others, 1959, p. 511–512) are shown on plates 3 and 4 as equivalent to the Monitor Butte. The Monitor Butte member averages about 100 feet thick. It overlies the Shinarump member conformably and also probably grades laterally into it. It commonly is overlain by channel-filling sandstone of the Moss Back member. Where the Moss Back is absent, the Monitor Butte is conformably overlain by the Petrified Forest member and can be difficult to distinguish from it.

The Monitor Butte member consists predominantly of greenish-gray claystones and clayey sandstones. Except in its lower part, most

claystones in the Monitor Butte are swelling varieties. Some sandy beds in the Monitor Butte are cross-stratified, but no information is available on their direction of dip.

CLAY-MINERAL DISTRIBUTION

Clays of the Monitor Butte member are composed of three principal clay-mineral assemblages: (1) a kaolinitic phase, (2) a mixed-layer illite-montmorillonite phase, and (3) a montmorillonitic phase. In the third phase, montmorillonite is most common in the coarser-grained rocks and mixed-layer montmorillonite is most common in the fine-grained rocks. Where the three principal mineral assemblages occur together, the kaolinitic phase generally is at the bottom and the montmorillonitic phase is at the top of the member (locs. 7, 35, 49, 51, 56). Small amounts of chlorite are present at a few places, mostly in the eastern areas of outcrop.

Feldspars associated with the three principal clay phases of the Monitor Butte differ considerably (table 4).

INTERPRETATION

The kaolinitic clays of the Monitor Butte are most common where the member grades downward into underlying highly kaolinitic rocks of the Shinarump member or into the Temple Mountain member or similiar rocks. They probably were derived by the same weathering processes as outlined for the underlying rocks. Absence of feldspars in the most kaolinitic Monitor Butte rocks (table 4) also suggests their highly altered condition.

The mixed-layer illite-montmorillonite clay phase of the Monitor Butte member commonly contains small amounts of illite and of both poorly crystallized and well-crystallized kaolinite. Close mineralogic similarity with parts of the underlying Temple Mountain member and other mottled zones of former soils near the base of the Chinle formation would indicate that the mixed-layer illite-montmorillonite clay phase of the Monitor Butte also is composed largely of weathered rocks. Weathering is indicated also by absence of feldspar in about half of the samples, although the weathering was not as intense as it was for the kaolinitic rocks. Presence of microcline and muscovite in some samples indicates that some of the parent materials were non-volcanic in origin.

Other features observed in the mixed-layer illite-montmorillonite clay phase indicate that some of the parent materials are of volcanic origin. The most widespread evidence of volcanic materials are particles that the writer interprets as altered tuff. These particles have rounded outlines and are composed of aggregates of clay flakes. As shown on figure 6, the rounded aggregates are commonly about as

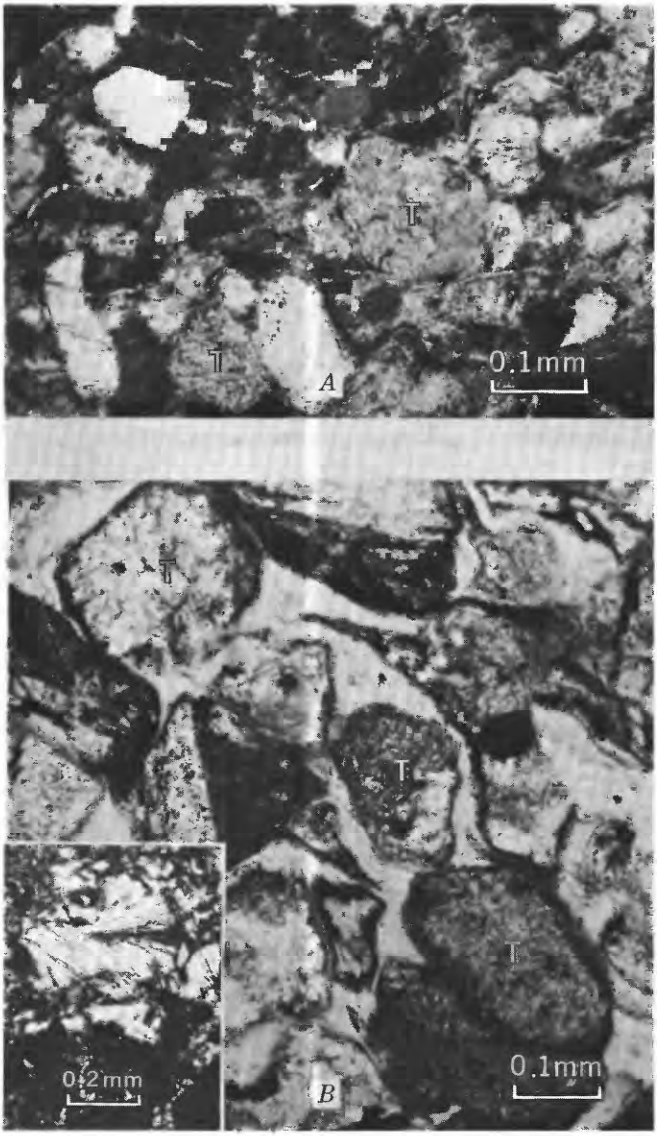

FIGURE 6.—Rounded altered tuff particles (*T*) in the Chinle formation. *A*, Monitor Butte member at Poncho House section (loc. 38); crossed nicols. *B*, Equivalent of the Monitor Butte member at Lees Ferry section (loc. 7); plain light. Inset shows kaolinite books; crossed nicols.

large or slightly larger than accompanying monocrystalline grains. When disaggregated in the laboratory, such rocks always yield much more clay-size material than is normally expected from rocks of this grain size. Tests made under the binocular microscope demonstrate that the aggregates are composed of swelling clay and that the clay expands and the aggregates disintegrate spontaneously when wetted with water. The rounded outlines of the aggregates indicate that the particles are water transported, but their spontaneous disintegration in water shows that they could not be water transported in their present form. They must have altered to swelling clay from more physically resistant material after deposition. Association of the rounded clay aggregates with small amounts of unaltered biotite, chlorite, and feldspar—all sensitive to alteration processes—indicates that the alteration must have been chemically very mild and that the original fragments were not fragments of rock such as chlorite-schist, sericite-schist, or shale. Fragments of volcanic glass are sensitive to just such mild chemical alteration; they commonly alter to swelling clays, and they appear to be the only geologically reasonable parent material for the clay aggregate. Finally, it should be noted that: (1) sanidine (low-sodium variety) is associated with the rounded clay aggregates in most areas and (2) similar rounded clay aggregates in the montmorillonitic clay phase of the Monitor Butte and in the Petrified Forest member are accompanied by additional evidence of volcanic origin—volcanic pebbles, euhedral biotite and plagioclase, and relict volcanic textures (Allen, 1930; Waters and Granger, 1953). Thus, the classification of the rounded clay aggregates as altered tuff particles rests on the peculiar inherent characteristics of the particles themselves, and is supported by their association with other volcanic material in the sediments. For this study, disintegration of rounded clay aggregate particles in water is considered as evidence sufficient to establish their volcanic origin; conversely, aggregates are not called altered tuff particles unless disintegration is observed.

Good examples of rounded particles of altered tuff have been found in several of the coarser beds in the Monitor Butte member and in its lateral equivalents in Arizona. The best examples in the mixed-layer illite-montmorillonite clay phase occur at localities 7 and 56. The tuff particles become progressively finer grained and more difficult to recognize northward. They are still easily recognized in the northern part of Capitol Reef (loc. 62) and in White Canyon, and fine-grained tuff particles composed of mixed-layer illite-montmorillonite can be recognized in the southern part of the San Rafael Swell and in Lisbon Valley.

An evaluation of the relative importance of the different parent materials of the mixed-layer illite-montmorillonite clay phase is difficult. The foregoing discussion indicates that mixed-layer illite-montmorillonite clays were derived from two entirely different types of material by different processes. These clays are mineralogically identical and cannot be distinguished from each other except by texture and other evidence found in the rocks. The other lines of evidence clearly suggest that some of the mixed layer illite-montmorillonite, particularly in the southern and western parts of the Colorado Plateau, is of volcanic origin. The mixed-layer illite-montmorillonite in other parts of the Monitor Butte member could have been derived from volcanic debris too fine grained to be recognized as such. However, the similarity of this clay to that of soils formed at the same time indicates it also could have been derived, in part, from weathered nonvolcanic rocks.

The montmorillonitic clay phase of the Monitor Butte is widespread wherever the member occurs, except in its northern outcrop areas. The coarser grained parts of this clay phase contain abundant rounded tuff particles that are associated with a high-sodium variety of sanidine and also with abundant plagioclase and biotite; some of the biotite and plagioclase are euhedral. These coarser grained tuffaceous rocks are composed largely of montmorillonite and are mainly of volcanic origin. Evidence is less certain for a volcanic origin of the parent material of the mixed-layer montmorillonite that composes most of the very fine grained claystones. Apparent absence of volcanic textures and of sanidine in the claystones may indicate only that they are very difficult to recognize in such fine-grained rocks. Probably the most convincing evidence for the volcanic origin of the claystones is their common interbedding and gradational relations with obviously tuffaceous coarser grained rocks and the general similarity between the montmorillonitic clays found in both types of rock. However, the difference between the mixed-layer montmorillonite common in the claystones and the unmixed montmorillonite common in the coarse-grained rocks is still to be explained. A slight tendency for clay flakes in the claystones to be oriented parallel to their bedding would indicate that they were deposited as clay flakes; in contrast, montmorillonite in the coarser tuffs was formed by alteration mainly after deposition. Therefore, a possible hypothesis to explain their mineralogical difference is that at one time the mixed-layer montmorillonite was montmorillonite altered from volcanic debris in the source area. During transportation of the montmorillonite, sufficient potassium ions were adsorbed and fixed in the exchange positions to render some of the clay layers nonexpansible. Similar adsorp-

tion did not affect the coarse tuffaceous rocks, because they altered after deposition.

Direct evidence of source areas for the parent sediments of the Monitor Butte is scant. The lower highly kaolinitic clay phase may have been locally derived and transported over relatively short distances. On the basis of the apparent increase southward in tuff particle size in the mixed-layer illite-montomorillonite clay phase, this volcanic debris likely came from the south. There is no evidence available for the direction of the source of the parent volcanic material of the montmorillonitic clay phase, but analogy with mineralogically identical rocks in the Petrified Forest member (discussed in a later section of this report) suggests that the montmorillonitic sediments of the Monitor Butte also came from the south. Small amounts of chlorite in the east suggest an additional source in that direction. Weathered materials that were exposed to erosion during Monitor Butte time on the eastern highlands also may have contributed significantly to the mixed-layer illite-montmorillonite clay phase.

MOSS BACK MEMBER

DESCRIPTION

The Moss Back member extends over a belt about 100 miles wide in southeastern Utah (fig. 5*B*). It averages about 60 feet in thickness but may be as much as 150 feet thick where it fills channels. It grades upward into finer grained rocks within the Chinle formation and is normally underlain by the generally finer grained rocks of the Monitor Butte member.

The Moss Back member is composed of fine- to medium-grained sandstone with subordinate lenses of siltstone and conglomerate. The sandstone is commonly crossbedded (fig. 5*B*); direction of dip of the crossbeds indicates transportation of sediments generally from the southeast.

Pebbles in the Moss Back member differ from those in the Shinarump in one important respect. Some conglomeratic lenses in the Moss Back member contain abundant pebbles of red siltstone typical of the Moenkopi and Permian red beds. As the red siltstone pebbles probably were not transported far and as the Moenkopi and older red beds were covered by Shinarump and Monitor Butte sediments in nearby areas to the west and south (pl. 4), some of the Moss Back sediments must have come from the north or east. A northeast source is also indicated by an increase in maximum pebble size in that direction (William Thordarson, written communication, 1958).

CLAY-MINERAL DISTRIBUTION

The characteristic clay mineral in most samples of the Moss Back, as in most samples of the Shinarump, is well-crystallized kaolinite. However, samples of the Moss Back generally contain less kaolinite and more chlorite and illitic clay than those of the Shinarump. As in the Shinarump member, chlorite in the Moss Back occurs almost exclusively in the eastern outcrop area (locs. 29, 30, 31, 32, 36, 49).

INTERPRETATION

The general similarity of the clay-mineral assemblages in the Moss Back and Shinarump members indicates that the kaolinitic clays of the Moss Back member, like those in the Shinarump, are largely the products of weathering. The lower kaolinite content and generally higher feldspar content (table 4), particularly of plagioclase, suggest that the Moss Back sediments were less intensely leached than those of the Shinarump. The greater prominence of chloritic clay in the Moss Back member indicates that an eastern source was a more important contributor to these sediments than to those of the Shinarump. The kaolinitic Moss Back strata found in the San Rafael Swell and White Canyon areas may be either alteration products of chloritic sediments which came from the east or of materials derived from an entirely different source. Moss Back rocks are not generally tuffaceous. Scarcity of tuff particles in the Moss Back may be due to alteration of such particles beyond recognition. However, if some Moss Back sediments did contain volcanic debris from the south, it is difficult to visualize what sedimentary conditions might cause the generally fine-grained bentonitic sediments of the Monitor Butte and Petrified Forest members to grade northward into the generally coarse-grained nonvolcanic sediments of the Moss Back. Thus a southern source seems unlikely. Previously mentioned crossbedding, increase in maximum pebble size to the east, and abundance of red siltstone pebbles also suggest the major eastern source area inferred from the clay distribution.

PETRIFIED FOREST MEMBER

DESCRIPTION

The Petrified Forest member extends over the southern part of the Colorado Plateau (fig. 5*C*). From a maximum thickness of more than 1000 feet in parts of Arizona it thins to the north. It grades both downward and laterally into lower members of the Chinle and grades upward and laterally into the Owl Rock member.

The Petrified Forest member is composed predominantly of varicolored swelling claystone, which is red, green, gray, pale-purple, and pink. Although sandy beds are generally not common, several prom-

inent crossbedded sandstones in which the direction of the dip of the crossbeds has been studied (fig. 5*C*), occur in parts of the formation. The most prominent of these, the Sonsela sandstone bed, is differentiated on plates 3 and 4.

In places the Sonsela sandstone bed contains partly altered volcanic pebbles. Eleven of these pebbles collected by William Thordarson from near Lukachukai, Sonsela Butte, Nazlini, the Petrified Forest, and Mesa Redonda (pl. 1) have been studied in thin section and by X-ray diffraction. Quartz and plagioclase phenocrysts are common, but potassium feldspar is scare. A few of the plagioclase crystals were identified as oligoclase. The pebbles appear to have been either quartz latite or dacite, and they are clearly of a more basic composition than the rhyolite pebbles from the Shinarump member.

CLAY-MINERAL DISTRIBUTION

The great majority of rocks in the Petrified Forest member are highly montmorillonitic. As in the montmorillonitic phase of the Monitor Butte, the claystones commonly contain mixed-layer montmorillonite and the coarser grained rocks commonly contain abundant montmorillonite. Principal variations from this clay composition are chloritic rocks, mainly to the east, and palygorskite-bearing zone that occurs locally in the upper part of the Petrified Forest member (locs. 10, 11, 16, 37, 39, 44, 62). Similar palygorskite-bearing rocks in the lower part of the Owl Rock member (locs. 10 and 38) will be considered with those in the Petrified Forest member.

INTERPRETATION

Most of the Petrified Forest member closely resembles the montmorillonitic clay phase of the Monitor Butte mineralogically and lithologically. Both contain abundant rounded altered tuff grains, high-sodium sanidine, and euhedral biotite and plagioclase phenocrysts; however, the Petrified Forest also contains volcanic pebbles and fragments with relict volcanic textures (Allen, 1930; Waters and Granger, 1953). A volcanic origin for most of the sediments of the Petrified Forest seems obvious. The rounded outlines of most of the tuff particles suggest that the volcanic debris was transported by water rather than by air. Crossbedding studies (fig. 5*C*), the occurrence of volcanic pebbles only in the south, and a general thickening of the member southward all indicate that the principal volcanic source area lay to the south. As in the Monitor Butte, the tuff particles altered after deposition, but the mixed-layer montmorillonite in the finer grained beds may have altered from volcanic debris in the source area.

Another highly montmorillonitic unit makes up part of the Chinle formation at the Vernal section (loc. 93), well north of the limit of

deposition of the Petrified Forest member. This unit has been interpreted by Keller (1953) as a southward extension of altered volcanic debris from the main body of the Popo Agie member of the Chugwater formation in Wyoming. Thus the southern source area, though the principal one, was not the only source of volcanic debris in the Chinle formation.

A comparison of the clays in the Petrified Forest and Monitor Butte members shows that two types of clay of volcanic origin occur in the lower part of the Chinle formation: a highly montmorillonitic clay, which is common in most of the Petrified Forest member and the upper part of the Monitor Butte member, and a mixed-layer illite-montmorillonite clay, which occurs in other parts of the Monitor Butte member. Alteration to these two types of clay from different types of volcanic material is indicated by four factors: (1) differences in the chemical composition of the clays, the montmorillonitic clay containing less potassium; (2) differences in overall feldspar content (table 4), the montmorillonitic clay having a much higher ratio of plagioclase to potassium feldspar; (3) differences in sanidine, a high-sodium variety occurring with the montmorillonitic clay and a low-sodium variety occurring with the mixed-layer illite-montmorillonite clay, and (4) differences in volcanic pebbles, latitic pebbles occurring locally with the montmorillonitic clay and rhyolitic pebbles occurring lower in the Chinle formation closer to the mixed-layer illite-montmorillonite clay. All four factors indicate that mixed-layer illite-montmorillonite clay altered from a potassium-rich rhyolite tuff, whereas the montmorillonitic clay altered from a potassum-poor latitic tuff. The rhyolitic tuff generally is older than the latitic tuff, but to some extent they probably overlap in age.

Small amounts of nonvolcanic debris in the sediments of the Petrified Forest member are indicated by nonvolcanic minerals, such as microcline, muscovite, illite, and chlorite. As in other Triassic units, the chlorite occurs mainly in the east. A particularly good example illustrating the nonvolcanic eastern origin of chlorite is the Sonsela sandstone bed (pl. 3). In Arizona the Sonsela is very montmorillonitic; it contains abundant rounded tuff particles and locally altered volcanic pebbles. In New Mexico, where only chlorite was found in the Sonsela samples, no tuff or volcanic pebbles have been recognized. Thus, montmorillonite and chlorite apparently represent different parent materials derived from different source areas.

The palygorskite zone in the upper part of the Petrified Forest and in adjacent parts of the Owl Rock member is overlain and underlain by highly montmorillonitic rocks. Both the palygorskite-bearing rocks and the adjacent montmorillonitic rocks contain similar amounts

of calcite, dolomite, feldspars, and other nonclay minerals. A thin section of a rock from the palygorskite zone at Poncho House (loc. 38) shows seemingly perlitic cracks and rounded tuff particles (fig. 7), but these clay aggregates do not swell and disintegrate in water and therefore they have not been labeled as tuffs or tuffaceous rocks. Palygorskite (attapulgite) is reported to be particularly prevalent in many sediments that have accumulated in alkaline desert lakes (Grim, 1953, p. 356); palygorskite in such rocks presumably is a diagenetic mineral. The palygorskite in the Chinle formation could have a similar origin. The problem in the Chinle formation is why some of the volcanics are altered to montmorillonitic clays, whereas other presumably similar volcanic debris is altered to palygorskite, even though available evidence indicates that both types of rock were deposited in the same alkaline-lake environment. One possible hypothesis is that the palygorskite represents glassy material altered in an alkaline lake, whereas the mixed-layer montmorillonite dominant in the associated montmorillonitic rocks came from glass material altered before deposition in the alkaline lake. An implication of this hypothesis is that the nonmixed-layered montmorillonite in the tuffs, which previously has been shown to have altered in place, must have altered in a less alkaline environment than the palygorskite.

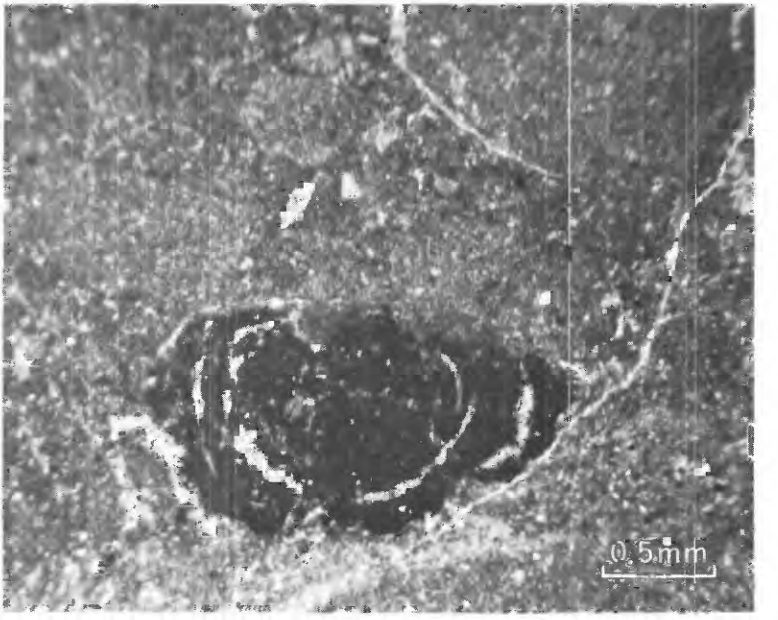

FIGURE 7.—Particle with seemingly perlitic cracks in a palygorskite-bearing siltstone from the Poncho House section (loc. 38). Plain light.

OWL ROCK AND CHURCH ROCK MEMBERS

Clay-mineral assemblages of the Owl Rock and Church Rock members are so similar that they are described and interpreted together.

DESCRIPTION OF OWL ROCK MEMBER

The Owl Rock member of the Chinle formation extends over most of the southern part of the Colorado Plateau. From a maximum thickness of about 450 feet in southeastern Utah, it grades northward and eastward into the red siltstones of the Church Rock member, and thins southward and intertongues with the upper part of the Petrified Forest member.

The Owl Rock member is composed predominantly of pale-red, purple, and brown calcareous siltstones and claystones. The distinguishing feature of the Owl Rock is the occurrence of minor light-colored silty limestone beds, most of which are several feet thick. The Owl Rock characteristically weathers to steep smooth slopes, which alternate with limestone ledges, and contrasts markedly with the frothy-appearing weathered outcrops of the underlying Petrified Forest member.

No sedimentary structure studies are available for the Owl Rock member to indicate directions to its source areas. Its sedimentary rocks are flood-plain and lacustrine types.

DESCRIPTION OF CHURCH ROCK MEMBER

The Church Rock member occurs throughout most of southeastern Utah and adjacent parts of the Monument upwarp in Arizona. In this report, lithologically similar units that are probable stratigraphic equivalents in Colorado and other parts of Arizona are described with the Church Rock member. These equivalents include most of the Chinle formation in west-central and northwestern Colorado, the Dolores formation in southwestern Colorado, and the Rock Point member of the Wingate formation of Arizona (Stewart and others, 1959, p. 519). The Church Rock member and its equivalents make up the bulk of the Chinle formation in most of the northern and eastern parts of the Colorado Plateau. They generally thin westward from a maximum thickness of 850 feet in southwestern Colorado. The Church Rock overlies and grades laterally into the Owl Rock member and is overlain by and, in places, intertongues with the massive cross-bedded eolian sandstone of the Wingate formation.

The Church Rock member and its equivalents are composed predominantly of brown to reddish-brown siltstone and sandy siltstone. Locally some sandstone beds are cross-stratified (fig. 5*D*). The rocks of the member are mainly fluviatile or flood-plain deposits; in parts

of northeastern Arizona (Harshbarger and others, 1957, fig. 18), they are lagoonal in origin.

CLAY-MINERAL DISTRIBUTION

Illitic clays are dominant in the northern part of the Colorado Plateau in both the Owl Rock and Church Rock members. Many of these illitic rocks contain a few percent of chlorite, generally to the east, or a few percent of kaolinite, generally to the west. The illitic rocks grade and intertongue southward into rocks containing a predominantly montmorillonitic clay-mineral assemblage with moderate amounts of illite and chlorite. Distribution of these clays is summarized on figure 8.

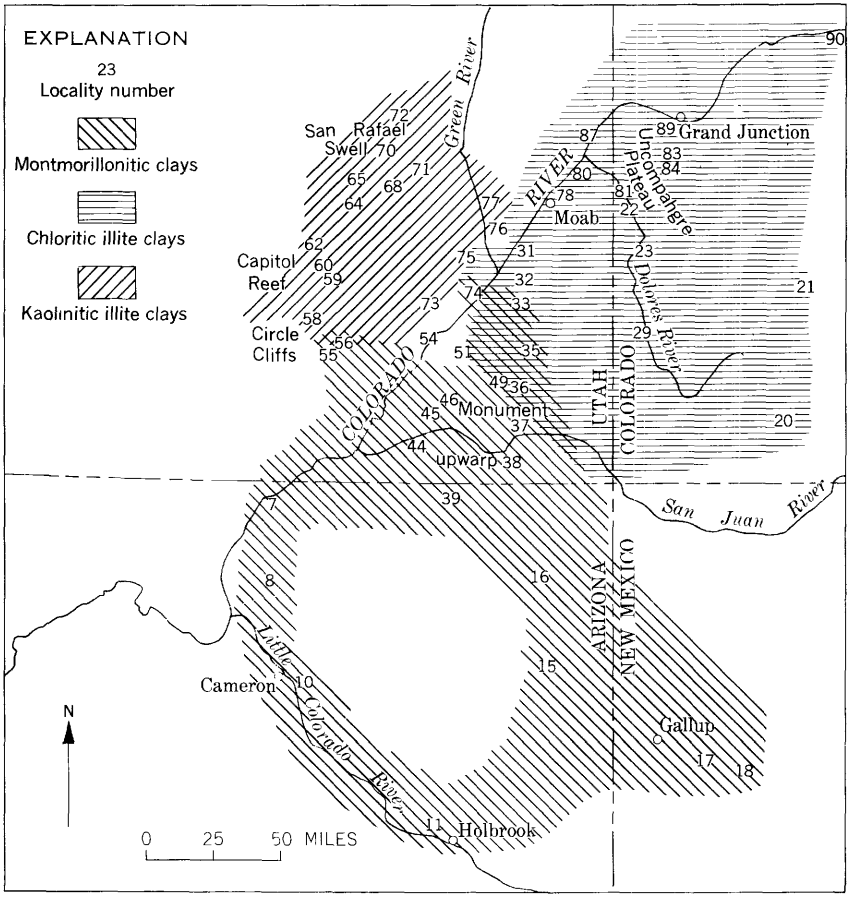

FIGURE 8.—Distribution of clays in the Owl Rock and Church Rock members of the Chinle formation.

INTERPRETATION

The montmorillonitic composition of the Owl Rock and Church Rock members in the southern part of the Colorado Plateau closely resembles that of the Petrified Forest member. Differences noted in their weathering characteristics appear to result from less cementation of the Petrified Forest by carbonates and also from less dilution by nonswelling minerals. The similarity of their clay composition indicates that all these montmorillonitic rocks probably had a similar mode of origin, and the Petrified Forest member has been shown to be derived largely from volcanic debris from a southern source. The geographic distribution of the montmorillonitic rocks in the Owl Rock and Church Rock members also suggests a southern source. The principal difference, indicated by their mineral composition, is that the Owl Rock and Church Rock contain more nonvolcanic minerals, such as microcline, muscovite, chlorite, and illite.

The illitic sediments of the Owl Rock and Church Rock members in the northern part of the Colorado Plateau were probably derived from a different source than the montmorillonitic equivalents to the South. This is suggested because they have none of the mineralogic or textural criteria for volcanic material, and by the fact that neither volcanic material nor montmorillonitic clay normally alters to illite under most continental conditions. Furthermore, if illite did alter from volcanic debris, it most likely would do so from potassium-rich varieties. Volcanic debris coming from the southern source during the later part of Chinle time was of latitic in composition and, hence, did not contain unusually large amounts of potassium.

Evidence for direction of the source of the illitic sediments of the Owl Rock and Church Rock members that can be deduced from the clays depends on distribution of the accessory clay minerals—chlorite to the east and kaolinite to the west. Under most terrestrial conditions, formation of kaolinite and weathering of chlorite is much more likely than is the reverse process. Feldspar distribution (table 4) indicates that some plagioclase was weathered with chlorite, but the more resistant potassium feldspars remained largely unaltered. Thus, chloritic illite sediments must have been transported westward from an eastern source, and parts of the sediments were weathered along the way. This interpretation is exactly the same as that for similar clays, similarly distributed in the Moenkopi formation, but the interpretation for the Moenkopi is more fully substantiated by clearcut east-west facies changes (fig. 1).

An eastern source for illitic sediments in the Owl Rock and Church Rock is in general agreement with thickening of these sediments to the east and with the small amount of crossbedding evidence available

(fig. 5*D*). Though the crossbedding evidence is too scant for a detailed interpretation, the contrast between the general westward trend and the northeastward trend in the Hite bed of local usage seems noteworthy. All the crossbedding studies, except those of the "Hite bed," were made in areas of illitic rocks; the studies of the Hite bed were made in areas on the north fringe of the montmorillonitic rocks.

In summary, sediments in the Owl Rock and Church Rock members came from two principal sources. A predominantly illitic sediment with minor amounts of chlorite came from the east. Simultaneously, volcanic-derived montmorillonitic sediments came from the south. The montmorillonitic sediments are, in part, mixed with the illitic sediments; they may also be mixed with nonvolcanic material derived from the southern source after the main period of volcanic activity. Eroding streams cutting down through the volcanic cover could have provided the nonvolcanic material.

MOTTLED AND BLEACHED ROCKS

MOTTLED ROCKS

DESCRIPTION

In this report the mottled rocks include rocks of Moenkopi, Chinle, and Precambrian age. They are grouped together for convenience of discussion and because their distinctive mottled coloration has probably resulted from similar processes at about the same time. These rocks are all (1) mottled purple, white, red, and—in places—brown, and (2) localized at or near the base of the Chinle formation. Thickness of the mottled rocks rarely exceeds 20 feet. Their distribution, though widespread, is very sporadic. They occur most commonly where the thick basal sandstones of the Chinle are absent. Most typically the mottled rocks are siltstone, in some places with a few scattered coarse sand grains or pebbles; but in a few places they are claystone, sandstone, and even clayey conglomeratic sandstone. The mottled rocks have been given a formal name only in the San Rafael Swell area where they are called the Temple Mountain member of the Chinle formation.

Within the Chinle formation, the mottled rocks have different stratigraphic relations with several members of the formation (fig. 9). They may occur below or within the Shinarump member, particularly where the unit is thin. The mottled rocks, however, are most common in areas where the Shinarump member is absent. In such places they may occur at the base of any of several other members that happen to be at the base of the Chinle formation. They commonly grade upward through an interval of several inches into unmottled rocks.

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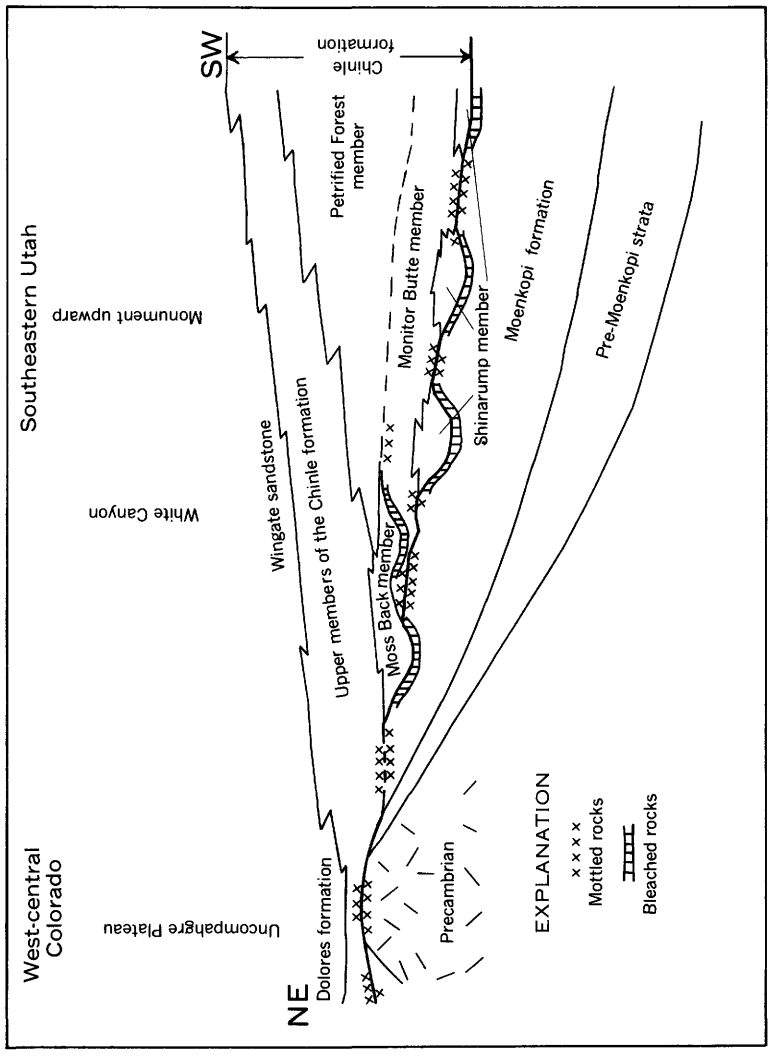

FIGURE 9.—Generalized sketch showing the occurrence of mottled rocks.

In many localities, particularly where a basal sandstone is absent in the Chinle, mottling extends from the basal part of the Chinle formation into the upper several feet of the Moenkopi formation. In such places the contact between mottled Moenkopi and mottled Chinle rocks may be obscure, but insofar as possible it is placed at the lowest point within the mottled zone where scattered coarse sand grains or pebbles are found. The mottled Moenkopi rocks commonly have the uniformly fine grained texture typical of the rest of the Moenkopi formation. The mottled coloration grades downward into unmottled reddish-brown sediments typical of the Moenkopi formation.

The mottled zone may also extend from the Chinle formation downward into rocks older than Triassic in areas where the Chinle rests on older rocks. At Nazlini (loc. 15) it extends down into the De Chelly sandstone of Permian age, and it probably extends into other older sedimentary units. On the Uncompahgre Plateau the Chinle formation commonly rests on the Precambrian basement. In many such places the top 5 to 20 feet of the crystalline rock immediately below the base of the Chinle is decomposed and may have a mottled coloration similar to that of the mottled Triassic rocks. Alteration within this zone of crystalline rocks grades from intense at the top to slight near the base; in the lower part of the altered zone the texture of the underlying fresh crystalline rock is still evident. In this report, these altered crystalline rocks are considered together with the mottled Triassic strata, because many of them have the two diagnostic features of the mottled rocks—mottled coloration and proximity to the basal Chinle contact.

Although most mottled rocks of Triassic age occur near the mid-Triassic unconformity (Moenkopi-Chinle contact, fig. 9), some are known to occur in the Chinle formation well above the horizon of the unconformity (locs. 13, 39.) These mottled rocks are not included with the mottled rocks discussed in this report, because they do not occur near the base of the Chinle formation. These rocks, however, indicate that the conditions which produced mottled rocks, although most prevalent during the mid-Triassic hiatus, recurred locally at intervals during Chinle time.

No feldspar was found in any of the 53 analyzed samples of mottled Triassic rocks.

MOENKOPI FORMATION

Rocks from the mottled zone at the top of the Moenkopi formation from 11 localities were analyzed. The relation of the clay-mineral assemblages of these mottled rocks to those of the underlying rocks is shown on plate 3 and summarized in table 7. The mineralogy of

samples from near the Chinle-Moenkopi contact at three of these same localities is illustrated at an expanded scale on figure 10.

Mineralogic relations of mottled rocks at the Dirty Devel No. 4 mine (loc. 66), the Bears Ears (loc. 49), and Milk Ranch Point (loc. 36) are illustrated on figure 10 in more detail than could be shown on plate 3. In the right-hand column, for the Dirty Devil No. 4 mine, the lowest sample is from the typical red Moenkopi rock, and the next

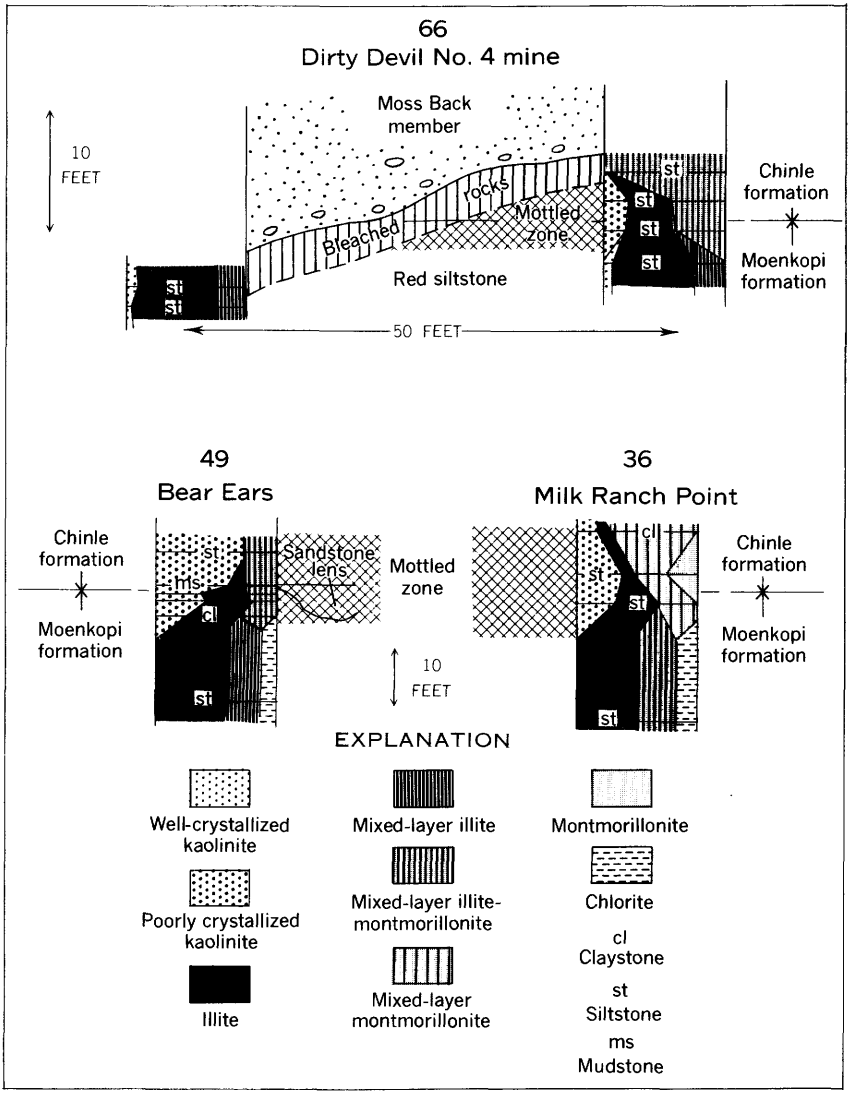

FIGURE 10.—Clays in mottled and bleached rocks.

sample above is from the mottled zone in the Moenkopi. The top two samples are from the Chinle formation. The lower of these two Chinle samples is mottled, and the upper is bleached greenish-gray claystone. As shown on figure 10 and in table 7, the red Moenkopi sample contains, in decreasing order of abundance, illite, mixed-layer illite, and well-crystallized kaolinite; the mottled Moenkopi sample (fig. 10) contains about equal amounts of illite and mixed-layer illite-montmorillonite and a small amount of poorly crystallized kaolinite. The mixed-layer illite-montmorillonite in the mottled sample is more abundant and more montmorillonitic than the mixed-layer illite of the red Moenkopi strata, and the kaolinite in the mottled sample is more poorly crystallized and slightly more abundant than in the red Moenkopi rocks. At the Bears Ears and Milk Ranch Point localities (fig. 10) the mottled zone overlies chloritic Moenkopi rocks. The mottled Moenkopi samples, however, contain no chlorite, but they do contain a little poorly crystallized kaolinite and a mixed-layer clay which is more montmorillonitic and relative to the illite, is more abundant than in the underlying red Moenkopi rocks.

TABLE 7.—*Clay minerals in mottled Moenkopi rocks*

Explanation of symbols: K_g, well-crystallized kaolinite; K_p, poorly crystallized kaolinite; $K_?$, kaolinite, crystallinity not determined; I, illite; I_m, mixed-layer illite; IM_m, mixed-layer illite-montmorillonite; M_m, mixed-layer montmorillonite; Cl_g, well crystallized chlorite; >>, more than twice as much as; >, more abundant than; =, about equal to; <, less abundant than.

Locality		Mineralogy	
Name	No.	Mottled rocks	Underlying unmottled red rocks
Dirty Devil No. 4 mine	66	$I=IM_m>K_p$	$I>I_m>>K_g$
South Draw	59	$I<IM_m=K_p$ [1]	$I>I_m>>K_?$
Bears Ears	49	$I=IM_m=K_p$	$I>>I_m>>Cl_g$
Richardson Amphitheater	80	$I=IM_m>>K_p$	$I>>I_m>>Cl_g$
Paradox Valley	23	$I>IM_m$	$I>I_m>>Cl_g$
North Sixshooter Peak	32	$I>M_m>>K_p$ [2] $I>IM_m>>Cl_g$ [3]	$I>I_m>>Cl_g$
Clay Hills Divide	45	$I=M_m=K_p$	$I=IM_m>>Cl_g$
Milk Ranch Point	36	$I=M_m=K_p$	$I>IM_m>>Cl_g$
Red House	46	$I>IM_m=K_p$	$I>IM_m>>Cl_g$
Black Point	10	$K_p>>M_m$ [1]	$I>M_m>Cl_g$
Bridger Jack Mesa	33	$I=IM_m=K_g$ [2] $I>IM_m>>Cl_g>>K_?$ [3]	$I>I_m>>Cl_g$

[1] Sample may be from the Shinarump member.
[2] Upper of two samples from mottled zone.
[3] Lower of two samples from mottled zone.

Clay-mineral data for the other samples of the mottled Moenkopi are also shown on plate 3 and are summarized in table 7. In general, clays in the mottled Moenkopi rocks differ from those in the underlying red strata in the following respects: (1) Mixed-layer clay is more montmorillonitic and slightly more abundant in the mottled zone; (2) the mottled Moenkopi rocks characteristically contain small amounts of poorly crystallized kaolinite in contrast to the well-crystallized kaolinite found in some of the underlying rocks; (3) chlorite

does not generally occur in the mottled zone of the Moenkopi even where it is common in the underlying Moenkopi strata; the only two samples of mottled Moenkopi in which chlorite was found (locs. 32 and 33) came from the bottom of the mottled zone; (4) the amount of illite in the mottled zone is less than in the underlying red part of the Moenkopi. These differences between the mottled part of the Moenkopi and the underlying red strata commonly involve less than half of the clay components, so that, even though differences are pronounced and consistent, the clay composition of the mottled Moenkopi rocks is in many respects related to that of the underlying strata.

CHINLE FORMATION

Samples from a mottled zone at the base of the Chinle formation were taken at 37 of the stratigraphic sections and mineralized localities. Clay-mineral data for these mottled Chinle samples are summarized in table 8. The clay mineralogy of the individual mottled Chinle samples shows considerably more variation than is found in the mottled Moenkopi samples. In table 8 the mottled zones are separated into six groups, according to the characteristic clay mineral of the assemblage.

Mixed-layer illite-montmorillonite is the most common clay in the mottled samples in the Chinle. It is the dominant clay at 12 of the 37 localities of mottled Chinle (table 8, groups C and E) and is present at another 14 of the localities. Mixed-layer montmorillonite is dominant at only 5 localities but occurs at 2 other localities of the mottled Chinle, and montmorillonite occurs at only 2 localities. Illite, a common minor component, is generally less abundant than in the mottled Moenkopi samples.

Kaolinite is generally more abundant in the mottled Chinle than in the mottled Moenkopi. As in samples of the mottled Moenkopi, the poorly crystallized variety is the most common type of kaolinite in samples of the mottled Chinle; it is dominant at 12 localities (table 8, groups *A* and *D*) and occurs at another 7 of the 37 localities of mottled Chinle. However, well-crystallized kaolinite was also found at 10 localities of mottled Chinle and is therefore more common than in the mottled Moenkopi. The well-crystallized kaolinite in the mottled Chinle is most common in the sandy rocks, particularly in the southern part of the Colorado Plateau. The highly kaolinitic mottled zones in the Chinle comonly occur where a fairly pronounced lithologic break separates the Chinle from the underlying Moenkopi. Where the contact is gradational, as at the Dirty Devil No. 4 mine (fig. 10), mineral assemblages are more similar to clays in the underlying Moenkopi.

TABLE 8.—*Clay minerals in mottled Chinle rocks*

Explanation of Symbols: K_g, well-crystallied kaolinite; K_p, poorly crystallized kaolinite; I, illite; IM_m, mixed-layer illite-montmorillonite; M_m, mixed-layer montmorillonite; M, montmorillonite; Cl_g, well-crystallized chlorite; Cl_m, mixed-layer chlorite; >>, more than twice as much as; >, more abundant than; = about equal to; <, less abundant than.

Locality		Mineralogy	Inferred equivalent of mottled rocks
Name	No.		
A. Abundant poorly crystallized kaolinite			
Rockville	3	$K_p>>IM_m>I$	Shinarump member of Chinle formation.
Cottonwood Creek	35	$K_p>>IM_m$	Do.
Bears Ears	49	$K_p>>IM_m$	Do.
Hideout mine	50	$K_p>>IM_m=I$	Do.
Jacob's Chair	51	$K_p>>IM_m=I$	Shinarump or Monitor Butte member of Chinle formation.
Muley Twist	56	$K_p>>IM_m$	Shinarump member of Chinle formation.
Horse Canyon	58	$K_p>IM_m=I$	Do.
Temple Mountain	68	K_p	Shinarump(?) member of Chinle formation.
Cane Wash	69	$K_p>>IM_m>I$	Monitor Butte member of Chinle formation.
Range Canyon	74	$K_p>>IM_m=I$	Do.
Vernal	93	$K_p>>M_m$	
B. Abundant well-crystallized kaolinite			
St. Johns	13	$K_g>IM_m>I$	Shinarump member of Chinle formation.
Nazlini	15	K_g	Do.
Fort Wingate	17	K_g	Do.
Moab Canyon	78	$K_g>>IM_m$	Shinarump or Monitor Butte member of Chinle formation.
Muddy River	64	$K_g>IM_m>I$	Monitor Butte member of Chinle formation.
C. Abundant mixed-layer illite-montmorillonite			
Paradox Valley	23	$IM_m>>K_g$	Monitor Butte member of Chinle formation.
Hite	54	$IM_m>>K_p>I$	Do.
Lucky Strike mine	65	$I>IM_m>K_g$	Do.
Dirty Devil No. 4 mine	66	$IM_m>I>K_p$	Do.
Buckacre Point	73	$IM_m>K_p>I$	Do.
Spring Canyon	77	$IM_m>>K_p>I$	Do.
Richardson Amphitheater	80	IM_m	Upper part of Chinle formation.
Westwater Canyon	87	$IM_m=I$	Do.
D. Abundant mixed-layer montmorillonite			
Paria	5	$M_m>K_p>I$	Shinarump member of Chinle formation.
Dolores Canyon	22	$M_m>>M$	Upper part of Chinle formation.
Bridger Jack Mesa	33	$M_m>>K_p$	Monitor Butte member of Chinle formation.
Milk Ranch Point	36	$M_m>K_p=I$	Shinarump(?) member of Chinle formation.
Clay Hills Divide	45	[1] $M_m>>M$ [2] $K_p>M$	Do.
E. Chlorite present			
The Palisade	81	$IM_m>>Cl_m=Cl_g$	Upper part of Chinle formation.
Whitewater	84	$IM_m=I>>Cl_m=Cl_g$	Do.
South Canyon Creek	90	$IM_m>I>Cl_m=Cl_g$	Do.
State Bridge	91	[1] $IM_m>Cl_m>Cl_g$ [2] $IM_m<Cl_m$	Do.
Meeker	92	[1] Cl_m [2] $IM_m>>Cl_m=Cl_g$	Do.
F. Chlorite and kaolinite both present			
Comb Wash	37	$K_g=Cl_m>M_m>I$	Shinarump (?) member of Chinle formation.
Red House	46	$K_g>>Cl_m>IM_m$	Do.
Chavez-Prewitt	18	$K_g>>Cl_m$	Shinarump member of Chinle formation.

[1] Upper of two samples from mottled zone.
[2] Lower of two samples from mottled zone.

Still another variety of clay assemblage was found in the mottled zone in the Chinle in northwestern Colorado (table 8, group *E*). Here chlorite, mostly of the mixed-layer acid-insoluble dioctahedral variety, is particularly common in the very sandy mottled rocks of the Chinle. However, mixed-layer illite-montmorillonite is dominant in the finer grained mottled rocks of this area.

In three samples of mottled Chinle (table 8, group *F*) well-crystallized kaolinite and an aluminous variety of chloritic clay were found. All are in mottled sandstone.

As previously mentioned, the mottled Chinle rocks do not represent a single stratigraphic unit because the mottling occurs in rocks ranging in age from that of the lowest Chinle member to upper Chinle time (fig. 9). It is not always clear with which units of the Chinle the mottled Chinle rocks belong. However, in table 8 the member of the Chinle which is apparently most closely related to the mottled zone is given. The mottled rocks associated with the Shinarump member are most commonly kaolinitic; those most closely associated with the Monitor Butte member commonly contain abundant mixed-layer illite-montmorillonite; these associated with the upper members of the Chinle are commonly chloritic.

ALTERED PRECAMBRIAN CRYSTALLINE ROCKS

Groups of samples from the zone of altered Precambrian crystalline rocks just below the Chinle formation were taken at eight localities. About half the altered samples are mottled. At several of these localities, samples were taken from more than one altered zone. The mineralogy of the altered zones and the type of crystalline rock underlying each altered zone is shown on plate 3 and summarized in table 9. These samples commonly contain abundant mixed-layer illite-montmorillonite accompanied by a small amount of poorly crystallized kaolinite, a little illite, and rarely chlorite. Mixed-layer illite-montmorillonite is dominant above rocks as diverse in composition as granite, monzonite, diorite, gneiss, schist, and amphibolite.

INTERPRETATION

Differences observed between the mottled rocks and the underlying rocks typical of the Moenkopi are ones that would be expected if the original rock had been exposed to weathering before it was covered by Chinle sediments. Moderate weathering of various types could be expected to destroy chlorite. Kaolinite might form by weathering of the feldspar and perhaps also by weathering of some of the clay minerals. The mixed-layer clays are very common weathering products which might form from the clays—particularly the illitic clays—

TABLE 9.—*Clay minerals in altered Precambrian crystalline rocks on the Uncompahgre Plateau*

Explanation of symbols: K_p, poorly crystallized kaolinite: $K_?$, kaolinite, crystallinity not determined; I, illite; IM_m, mixed-layer illite-montmorillonite; M_m, mixed-layer montmorillonite; M, montmorillonite; Cl_g, well-crystallized chlorite; Cl_m, mixed-layer chlorite; >>, more than twice as much as; >, more abundant than; =, about equal to.

Locality		Clays	Underlying crystalline rocks
Name	No.		
Indian Creek	82	$IM_m>>K_p=I$ $M>M_m>K_p=I$	Quartz monzonite. Do.
Taylor Ranch	83	$IM_m>>I>Cl_g$	Biotite-muscovite-quartz monzonite.
Whitewater	84	$IM_m=I>>Cl_m=Cl_g$ $IM_m=I>>Cl_m$	Biotite-microcline-plagioclase gneiss. Muscovite-biotite granite.
Coach Creek	85	$IM_m>>I$ IM_m	Biotite - actinolite - plagioclase - quartz greenstone. Chlorite-plagioclase-quartz schist.
Dry Gulch	86	$IM_m>>I$ IM_m $IM_m>>I$	Biotite granite. Chlorite-quartz-plagioclase schist. Biotite-quartz-plagioclase gneiss.
Westwater Canyon	87	IM_m $IM_m>>I=Cl_g$	Biotite-plagioclase-quartz schist. Chloritic amphibolite.
Fruita	88	$IM_m>>I=K_?$	Biotite quartz diorite.
The Serpents Trail	89	$IM_m>>K_p$	Biotite diorite.

in the original sediments. Absence of feldspar is also a likely result of weathering. Hematite in the original sediments might be redistributed to form the patchy, mottled coloration. The purple color in parts of these mottled rocks seems to be caused by recrystallization of hematite into relatively large particles. Part of the iron oxides also might have been leached downward and deposited below the mottled zone. Several samples taken just below the mottled zone had colors which were deeper red than normal for the Moenkopi formation, and the X-ray traces suggest that they contained larger-than-average amounts of hematite.

The mineralogy of the mottled rocks in the Chinle, like that of the mottled Moenkopi rocks, could have resulted from weathering. The highly kaolinitic mottled rocks in the Chinle indicate more intense weathering than that which took place in the mottled Moenkopi and in other mottled rocks in the Chinle. The chlorite in the mottled rocks of the Chinle seems to be aluminous; this indicates a degree of leaching similar to that which formed the abundant mixed-layer illite-montmorillonite clays of the mottled zones. The aluminous nature of the chlorite also can explain why the chlorite was not destroyed by leaching at the land surface, whereas some of the magnesian chlorite in the Moenkopi formation and other Triassic rocks was destroyed by mild surface leaching.

Variation in the mineralogy of the mottled rocks of the Chinle might be caused by a number of factors. Climate probably is an important one. The climate during early Chinle time was apparently warm and humid (Daugherty, 1941), but, as indicated by a progressive increase in chemically precipitated carbonates in the higher rocks of the Chinle,

the climate became progressivly more arid in later Chinle time. Thus, the most intensely leached kaolinitic mottled rocks in the Chinle, which are mainly associated with the Shinarump member, formed during a period of maximum rainfall. The less intensely leached mottled rocks associated with the Monitor Butte and the upper limits in the Chinle formed as the rainfall decreased.

Another factor that could cause variation in the mineralogy of the mottled rocks of the Chinle is reworking of the sediments and, subsequently, contamination with unweathered material of different types during each cycle of reworking. Thus, the relatively uniform mineralogy of the mottled beds in the Moenkopi developed during one cycle of weathering of strata of the Moenkopi that did not vary much in original composition. Basal rocks of the Chinle, however, may have gone through several such cycles, and during each cycle have been contaminated with diverse types of rocks eroded from the surrounding uplands or locally dredged from the underlying fresh and weathered sediments of the Moenkopi. Altered volcanic debris may explain the unusually high montmorillonite content of some mottled rocks in the Chinle, such as those at North Sixshooter Peak (loc. 32), Bridger Jack Mesa (loc. 33), Milk Ranch Point (loc. 36) and Dolores Canyon (loc. 22). At North Sixshooter Peak and Bridger Jack Mesa the mottled beds in the Chinle are at about the same stratigraphic position as the tuffaceous rocks in the Monitor Butte member in adjacent localities. Concentration of aluminous chlorite in the mottled rocks in northwestern Colorado may reflect a local source unique to that area. Because of the many variables that might have affected the mottled Chinle rocks, the differences observed in their mineralogy are not surprising.

In the mottled Precambrian crystalline rocks, the abundance of mixed-layer illite-montmorillonite clay, the gradation through a saprolitelike zone into unaltered crystalline rocks below, and the uniformity of composition of the alteration products regardless of the parent material suggest that the mottling of the rocks results from moderate and uniform soil-forming processes. The moderate intensity of weathering is generally commensurate with that of other mottled rocks formed relatively late in Chinle time.

Evidence other than mineralogy also strongly suggests weathering as the mode of origin of the mottled rocks. Most important is the fact that the mottled rocks occur where a soil zone would be expected to occur. The mid-Triassic unconformity separating the Chinle from the Moenkopi and other underlying rocks is a widespread unconformity—one of the most widespread in the Paleozoic and Mesozoic rocks of the Colorado Plateau. Rocks at the surface during the long mid-

Triassic hiatus must have been weathered to some extent. Once Chinle deposition began, the soil zone should have been eroded in places by channel-cutting streams but most likely would be preserved in interstream areas. As would be expected, the mottled Moenkopi rocks are most common where thick channel-filling basal sandstones of the Chinle are absent. Apparently the first sediments of the Chinle were deposited slowly and intermittently from meandering streams, so that the weathering processes that formed the mottled Moenkopi rocks also greatly affected the basal sediments of the Chinle. Weathering probably affected the surficial rocks during most of Chinle and Moenkopi time to some extent, as indicated by the apparent weathering of chlorite and feldspar in many of the rocks, but its mark is left most strongly on those rocks which were exposed at the surface just before and just after Chinle deposition began.

Finally, the mottled coloration of the rocks themselves indicates soil formation. The sediments could not have been deposited to form such an irregular pattern of color. The formation of this pattern after burial is also unlikely, because the distribution of mottling would then be controlled by the altering agent, whose access would be a function of permeability. The mottled zones, however, are not particularly permeable, and they tend to occur away from, rather than adjacent to, permeable channel sandstones. Permeability would not be a factor if connate waters were the altering agent; but if this were so, the mottled coloration should be more prevalent throughout all the rocks rather than confined to certain rocks near the Chinle-Moenkopi contact. If mottling did not occur after burial of the sediments, it must have occurred before under atmospheric conditions; such atmospheric alteration is soil formation.

Mottled paleosoils are also present beyond the Colorado Plateau. Pisolitic mottling occurs in parts of a lateritic paleosoil formed on Jurassic metamorphic rocks just below the Ione formation of Eocene age, near Ione, Calif. (Allen, 1929) and in altered syenite in the Arkansas bauxite region that is unconformably overlain by Tertiary sedimentary rocks. Mottling occurs in Quaternary soils in southeastern Maryland (Nikiforoff, 1955, p. 55) and in other parts of the southeastern United States. In southwestern South Dakota, a mottled soil zone called the Interior formation by Ward (1922) is extensively formed on Cretaceous rocks and is overlain by Oligocene strata. Other examples probably could be cited, but the writer has seen all those just mentioned. The mottled coloration in all these areas is similar to that described in this report.

All evidence considered, the soil hypothesis seems the most geologically reasonable mode of formation of the mottled rocks near the Chinle-Moenkopi contact on the Colorado Plateau.

BLEACHED ROCKS IN THE MOENKOPI

DESCRIPTION

A bleached zone of rocks is present in places at the top of the Moenkopi formation. Although the bleached and mottled Moenkopi rocks occur in a stratigraphically similar position near the Chinle-Moenkopi contact (fig. 9), they are distinct from each other, both in appearance and in mode of occurrence. The bleached zones are uniformly pale greenish or yellowish gray and commonly have a sharp, sinuous contact with the underlying red Moenkopi beds. Bleached Moenkopi rocks occur below thick basal sandstone of the Chinle formation in a zone as much as several feet thick which parallels the lower contact of the sandstone. The bleached zone cuts across bedding in the Moenkopi where channel-filling sandstones of the Chinle truncate the bedding of the Moenkopi rocks. In contrast, the mottled Moenkopi rocks generally occur where thick basal sandstones of the Chinle are absent, and they commonly grade down into the normal red Moenkopi strata.

CLAY AND OTHER MINERALS

Mineralogic relations between bleached and mottled Moenkopi rocks are well illustrated by samples from the Dirty Devil No. 4 mine (fig. 10, loc. 66). Here, within a distance of 50 feet, a channel sandstone in the Moss Back cuts down through underlying Chinle strata into the Moenkopi formation. The clay minerals in the bleached zone at the top of the Moenkopi are almost identical with those in the underlying red siltstone; whereas, as previously indicated, clay minerals in the mottled Moenkopi are different from those in the underlying red siltstone. The mineralogy of samples of bleached Moenkopi rocks and of underlying red Moenkopi rocks from this locality and 12 other localities is shown in the upper part of table 10. Two samples of each rock type were taken at two of the localities. The mineralogy of the samples of the bleached Moenkopi rocks and of the underlying red Moenkopi rocks is very similar. Where the underlying red part of the Moenkopi contains a kaolinitic assemblage, the clay minerals in the bleached zone are similar; kaolinite in both the bleached-rock and red-rock samples is of the well-crystallized variety. Red Moenkopi rocks with a chloritic-clay assemblage are overlain by chloritic bleached rocks (locs. 40, 44); and, similarly, the montmorillonitic bleached rocks of the Moenkopi (loc. 38) overlie montmorillonitic red strata of the Moenkopi. Feldspar is equally abundant in the red rocks and the bleached rocks. The only consistent difference found between bleached zones and red zones is that in the bleached zones hematite is absent and carbonates are generally less common.

TABLE 10.—*Mineralogy of bleached rocks*

Mineralogy: K_g, well-crystallized kaolinite; I, illite; I_m, mixed-layer illite; IM_m, mixed-layer illite-montmorillonite; M_m, mixed-layer montmorillonite; M, montmorillonite; Cl_g, well-crystallized chlorite Cl_m, mixed-layer chlorite; >>, more than twice as much as; >, more abundant than; =, about equal to.
Dominant feldspar: K, potassium feldspar; P, plagioclase; S, present, type not determined.
Carbonates: C, calcite; D, dolomite.

Locality		Bleached Moenkopi			Underlying red Moenkopi		
Name	No.	Mineralogy	Dominant feldspar	Carbonates	Mineralogy	Dominant feldspar	Carbonates
Cottonwood Creek	35	$I > I_m >> K_g$			$I > I_m >> K_g = Cl_g$		DC
Owl Rock	39	$I > I_m >> K_g$	K		$I > I_m >> K_g$	K	
Deer Flat		$I > I_m > K_g$	S		$I >> I_m > K_g$	S	
		$I >> I_m > K_g$	S	D	$I >> I_m > K_g$	S	D
Hideout mine	50	[1] $I >> I_m > K_g$	K				
Dirty Devil No. 4 mine	66	[2] $I >> I_m >> K_g$			$I >> I_m >> K_g$		
Capitol Wash	60	$I > I_m >> K_g$	K		$I > I_m >> K_g$		D
Oyler mine	61	$I > IM_m >> K_g$	K	D	$I > IM_m >> K_g$	K	D
Rainy Day mine	57	[3] $I >> I_m >> K_g$			$I >> I_m >> K_g$		D
	57	[4] $I >> I_m >> K_g$	K	D	$I >> I_m >> K_g$		D
Block Mountain	70	$I >> I_m > K_g$	S		$I >> I_m >> K_g$	K	D
Millard Canyon	75	$I >> I_m >> K_g$	K		$I >> I_m >> K_g$		D
Monument No. 1 mine	40	$I >> I_m >> Cl_g$	S		$I > I_m >> Cl_g$	K	
Monitor Butte	44	$I > I_m > Cl_m$	P		$I > I_m > Cl_g$	P	D
Poncho House	38	$I = M_m > M = Cl_g$			$I = M_m >> Cl_g$	K	DC
		Bleached Moenkopi pebbles in base of Chinle formation			Underlying red Moenkopi		
Monument No. 1 mine	40	$I > I_m$	S		$I > I_m >> Cl_g$	K	
Whirlwind mine	43	$I > Cl_g > I_m$	P		[5] $I > I_m > Cl_g$	P	D
		Bleached Chinle			Underlying red Chinle		
North Sixshooter Peak	32	[6] $M_m >> K_g > M > I.$			$M_m >> K_g > M > I.$		

[1] Compare sample of bleached Moenkopi rocks at Hideout mine with sample of underlying red Moenkopi rocks from nearby Deer Flat locality.
[2] See figure 10.
[3] Upper of two samples from bleached zone.
[4] Lower of two samples from bleached zone.
[5] From red Moenkopi at nearby Monitor Butte section (loc. 44).
[6] Below sandstone in Moss Back member.

Also shown on table 10 are mineralogic relations between two greenish-gray bleached Moenkopi pebbles taken from the basal conglomerate of the Chinle and paired samples taken from the underlying red Moenkopi and the relation between a pair of bleached-rock and red-rock samples taken just below the Moss Back member of the Chinle formation. Like samples from the bleaced Moenkopi, samples from the bleached Chinle are mineralogically very similar to the underlying red rocks.

INTERPRETATION

The little-altered condition of bleached Moenkopi rocks indicates that they have been affected by a different, much less intense process than the weathering that produced the mottled Moenkopi rocks. The occurrence of the bleached rocks in a zone below thick channel sandstones shows that they must have formed after the channels were cut

and filled. They probably resulted from reduction and leaching of iron by ground waters circulating in the adjacent permeable sandstone.

RELATIONS BETWEEN CLAY MINERALS AND URANIUM-VANADIUM MINERALIZATION

The uranium-vanadium deposits in the Triassic rocks of the Colorado Plateau are commonly localized in thick channel-filling sandstone, particularly where the sandstone contains abundant carbonaceous material and where the normally high permeability of the sandstone is limited by mudstone partings and abundant fine-grained interstitial debris. The origin of such sandstone-type deposits has been discussed by McKelvey, Everhart, and Garrels (1955). The two leading theories are that: (1) the uranium in the ore deposits was introduced by hypogene solutions and (2) the uranium was concentrated into ore deposits by lateral secretion of elements deposited with the enclosing sediments. Clay-mineral data in this report bear on the mineralization process in two ways: (1) possible alteration of the host rock by the mineralizing solutions and (2) the possible relation between alteration of volcanic debris and uranium mineralization.

GENERAL DISTRIBUTION OF CLAYS

Mineralogy of clays in samples taken from uranium-vanadium mines is shown on plate 3. Samples that are highly mineralized are indicated by an *m* to the right of the column, those that are slightly mineralized are indicated by *sm*. A summary of the comparative mineralogy of the clays in mineralized and in nearby nonmineralized host rocks is given in table 11. Some of the comparisons in table 11 are between mineralized and nonmineralized rocks at the same locality; some of the comparisons are between mineralized and nonmineralized rocks from nearby but separate localities. Samples with about the same grain size are compared—for example, mineralized sandstone with nonmineralized sandstone, mineralized siltstone with nonmineralized siltstone, and mineralized claystone with nonmineralized claystone.

Although clays differ considerably from one mineralized region to the next, clays in mineralized rocks within a region differ little from those in nearby equivalent barren rocks. Regardless of whether the mineralized rocks are highly kaolinitic—as in the Shinarump in Red Canyon and White Canyon, moderately kaolinitic—as in the Moss Back in the San Rafael Swell, illitic—as in the Moenkopi in the Circle Cliffs and Capitol Reef, montmorillonitic—as in the Petrified Forest

TABLE 11.—*Clays in mineralized and nearby unmineralized rocks*

Explanation of symbols: K_g, well-crystallized kaolinite; K_p, poorly crystallized kaolinite; I, illite; I_m, mixed-layer illite; IM_m, mixed-layer illite-montmorillonite; M_m, mixed-layer montmorillonite; M, montmorillonite; Cl_g, well-crystallized chlorite; Cl_m, mixed-layer chlorite; >>, more than twice as much as; >, more abundant than; =, about equal to; <, less abundant than.

Locality		Mineralized rocks	Nonmineralized rocks
Name	Nos.[1]		
Cameron	*9*, 10	$M>>M_m>>K_g$	$M>>M_m>>K_g$
Lisbon Valley	*27*	$I=IM_m>Cl_g$	$I=IM_m>Cl_g$ or Cl_m
	26, 24	$IM_m=Cl_g>Cl_m$	$I=IM_m=Cl_g$
	25	$I<M_m>>Cl_g$	$I<M_m>>Cl_g$
Dolores River	*28*, 29	$I>IM_m>Cl_g$	$I>IM_m>Cl_g$
Monument No. 2 mine	*42*	$I=IM_m>K_g$	$I=IM_m>K_g$
Monument No. 1 mine	*40*	$I>IM_m=K_g$	$I<IM_m<K_g$
Red Canyon	*47*, *48*	$K_p>IM_m$	$K_p>IM_m>I$
White Canyon	*50*, 51, *52*, 53	$K_p>IM_m=I$	$K_p>IM_m=I$
Circle Cliffs	*57*, 56	$I>>I_m>K_g$	$I>>I_m>K_g$
Capitol Reef	60, *61*, 62	$I>I_m>K_g$	$I>I_m>K_g$
San Rafael Swell	*63*, 64	$I=IM_m>K_g$	$I=IM_m>K_g$
	66, 65	$IM_m>I>K_g$	$IM_m>I>K_p$
	67, 68	$I>I_m=K_g$	$I>I_m=K_g$

[1] Italicized numbers indicate mineralized localities.

at the Huskon No. 1 mine (loc. 9), or chloritic—as in Lisbon Valley, clays in nearby barren rocks are everywhere similar. The only fairly consistent difference noted by the writer between some mineralized rocks and equivalent country rocks is that chlorite in mineralized sandy rocks commonly is less mixed layered and contains small amounts of vanadium; this chlorite is discussed more fully later.

CLAY PEBBLES, BLEACHED ZONES, AND FELDSPAR

Moenkopi pebbles taken at three localities (40, 43, and 48) from mineralized sandstone of the Shinarump member contain clays which are similar to those of the underlying red Moenkopi rocks rather than to those of the enclosing sandstone. Bleached Moenkopi zones below both barren and mineralized sandstone of the Chinle contain clays which are also similar to those in the unbleached red Moenkopi rocks. For example, at the Monument No. 1 mine (loc. 40), clay in the mineralized sandstone of the Shinarump is very kaolinitic, whereas the pebble of the bleached Moenkopi taken near the base of the sandstone contains no kaolinite but is illitic like the underlying Moenkopi rocks. Also, the clay in the bleached zone is identical with that of the sample from the unbleached red Moenkopi. It seems impossible that mineralizing solutions could affect clays in the host sandstone without noticeably altering clays in adjacent Moenkopi beds or enclosed pebbles. Feldspar in both barren and mineralized rock is about the same in kind and abundance.

SECONDARY CLAY MINERALS

Most clay minerals in the nine thin sections of mineralized samples studied by the writer occur as disorganized interstitial masses that show no evidence of post-deposition alteration other than replacement by ore minerals. However, some of the kaolinite and chlorite have textures of secondary origin. Books of kaolinite were observed in minor amounts in thin sections from three mineralized localities (50, 52, and on Temple Mountain near loc. 68); one of these thin sections is illustrated on figure 11*A*. Radial growths of chlorite similar to those in figure 4 were seen in one thin section from the Mi Vida mine (loc. 27). However, as similar occurrences of secondary kaolinite and chlorite were observed in unmineralized rocks (figs. 4, 6*B* and 11*B*), they cannot be attributed specifically to mineralizing solutions. Similarity between these secondary clays and the primary clays in the same rocks indicates that the formation of secondary clay minerals involved recrystallization of clay minerals already present rather than the formation of entirely new types of clay minerals.

Alteration of fine-grained 1Md mica polymorphs (illite) to 2M mica under the influence of hydrothermal mineralizing solutions has been reported by Kelley and Kerr (1957) at Temple Mountain in the San Rafael Swell. However, both 1Md and 2M polymorphs are also common in clay-size fractions of samples collected by the writer in the San Rafael Swell from barren equivalents of the mineralized rocks at Temple Mountain. Therefore, like the recrystallized kaolinite and chlorite, the 2M mica may not be related to mineralizing solutions.

VANADIFEROUS CHLORITE

Chlorite in mineralized sandy rocks commonly differs slightly from chlorite in equivalent mineralized rocks. In and near the mineralized areas the chlorite generally is mixed layered with few expandable layers, whether the individual sample is from a mineralized rock or not. For example, the highly chloritic sandstone from the Mi Vida mine (loc. 27) is the most mixed-layered sample of all the chlorite from the mineralized localities studied by the writer. (See sample 453, table 2 and pl. 2*H* for chemical analysis and X-ray-diffractometer traces.) About a quarter of the layers in this chlorite are expandable. Most other chlorite from mineralized areas is not mixed layered at all. This has been noted also by John C. Hathaway (oral communication, 1959) in the many samples he has analyzed from the Colorado Plateau. The scant occurrence of mixed-layer chlorite in mineralized areas contrasts greatly with the very common occurrence of mixed-layer chlorite in sandy samples, which are far removed from mines, in many of which half of the layers are expandable.

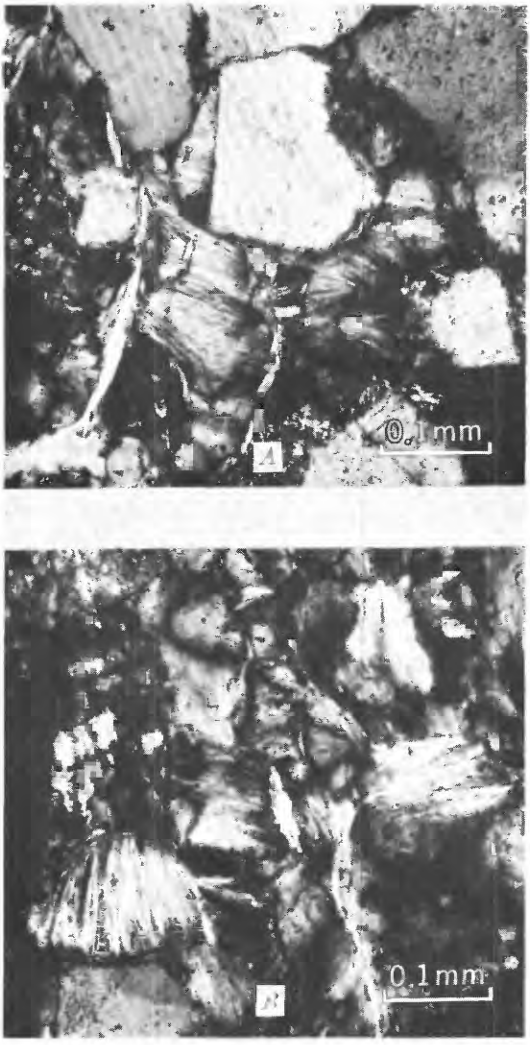

FIGURE 11.—Kaolinite books in the Moss Back member of the Chinle formation on Temple Mountain near locality 68. Crossed nicols. *A*, Mineralized sandstone. *B*, Unmineralized sandstone.

An explanation for the small amount of mixed-layering in chlorite in samples taken near mines is suggested by the concurrent presence of small amounts of vanadium. Clay-size fractions of three highly chloritic samples contained 1 to 2 percent V_2O_5. Organic material commonly present in ore deposits should reduce vanadium ions to the trivalent state and should insure a good supply of hydroxyl ions. The trivalent vanadium ion, with a radius of 0.66 A, is almost exactly the same size as the magnesium ion, which has a radius of 0.65 A and which

normally is a principal component of the brucite layers in chlorite. Chlorite in barren sandstones commonly contains some expandable montmorillonite layers. When such mixed-layered chlorite came in contact with mineralizing solutions, the trivalent vanadium ions could easily have been absorbed in the exchange positions of the montmorillonite layers in the mixed-layer chlorite; when coordinated by hydroxyl ions, the vanadium would form a brucitelike layer of vanadium hydroxide. The process would not involve much structural change. As shown schematically on figure 12, the main structural difference between montmorillonite and chlorite is that in chlorite the mica sheets

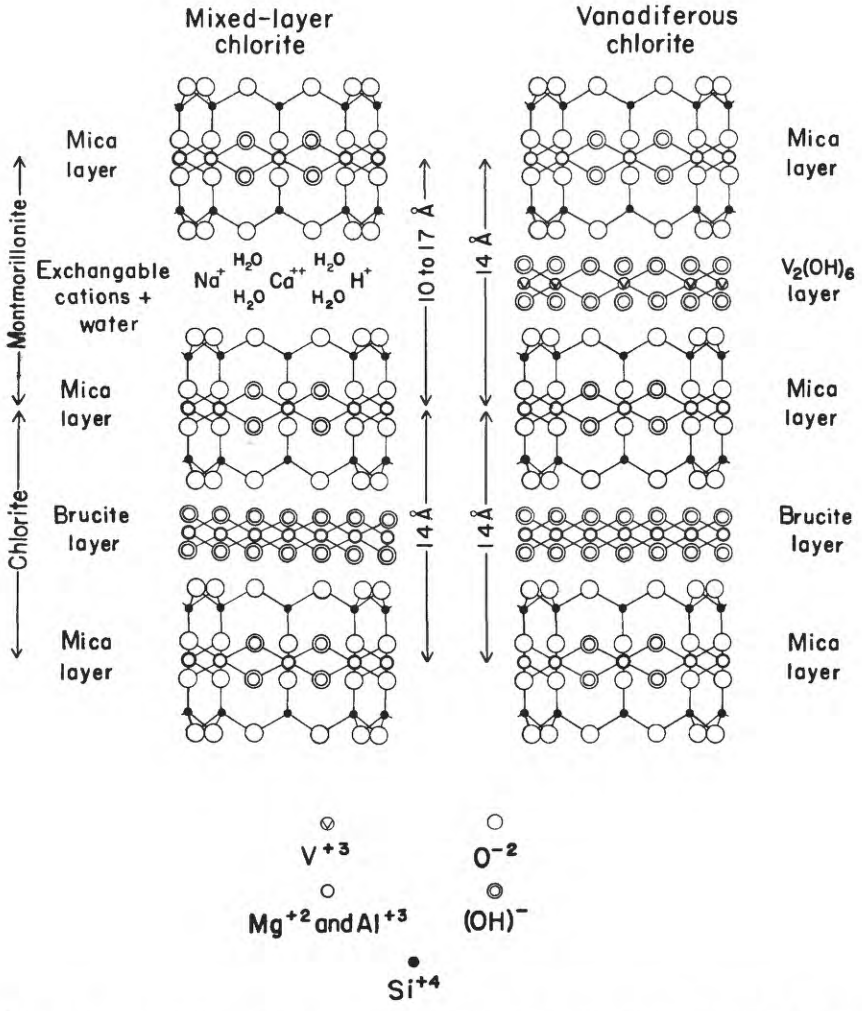

FIGURE 12.—Structural differences between mixed-layer chlorite and vanadiferous chlorite.

are separated by brucite layers, whereas in montmorillonite the mica sheets are separated by exchangeable cations and water. Formation of a vanadium hydroxide sheet in the layer occupied by the exchangeable cations would convert the mixed-layer chlorite back to the original completely nonexpandable state in which all the layers have a constant 14 A spacing.

A possible alternative hypothesis for the small amount of mixed-layering of chlorite in mineralized areas is that the chlorite was never mixed layered. Two previously developed generalizations are: (1) mixed-layer chlorite seems to have formed from well-crystallized chlorite by the leaching action of circulating ground waters, a process controlled by permeability; and (2) mineralization commonly was localized in "dirty" sandstone of lesser permeability. This lesser permeability may have reduced the leaching action of ground waters so that the mixed-layer chlorite never formed. This explanation, however, does not account for all the observed facts. It does not explain presence of vanadium in the chlorite. Also, some "clean" highly permeable sandstones occur in mineralized areas; like the "dirty" sandstones, these "clean" sandstones contain chlorite with scant mixed layering. Finally, in some thin sections vanadiferous chlorite has been observed with a radial texture similar to that previously described (fig. 4) for mixed-layer chlorite in unmineralized rocks; thus, some vanadiferous chlorite may have undergone a similar mixed-layer stage. For these reasons, the writer prefers the vanadium-adsorption hypothesis described in the preceding paragraph.

If vanadium was adsorbed on the montmorillonite layers of mixed-layer chlorite, it may also have been adsorbed on the montmorillonite layers of other clay minerals. The writer found no specific evidence of such adsorption in his samples, but logically it would be expected to occur, and it has been reported in other rocks. Waters and Granger (1953, p. 12–14) interpreted vanadium hydromica as having formed by adsorption of vandadium on volcanic-derived montmorillonite. J. C. Hathaway (oral communication, 1959) reported that all the vanadiferous clay from the Colorado Plateau studied by him is either mixed-layer illite-montmorillonite, chlorite, or mixtures of the two; therefore, vanadium probably is also present in clay minerals other than chlorite in the Triassic rocks.

RELATION OF ALTERED VOLCANIC DEBRIS TO MINERALIZATION

According to the lateral-secretion theory of the origin of the uranium-vanadium deposits of the Colorado Plateau, the uranium and possibly the vanadium and other elements were introduced into the

sediments during deposition; these elements were later redistributed to form the ore deposits, probably about 60 million years ago (Stieff and Stern, 1952). The generally unaltered condition of most of the Triassic rocks would indicate that if the ore-forming elements were derived from the enclosing rocks, the process probably was one that could occur readily, such as devitrification or other alteration of volcanic debris rather than leaching from more stable components. As volcanic debris alters largely to clay minerals, the clay studies bear particularly on this theory of genesis of the ore deposits.

A direct genetic relation between the alteration of volcanic debris in the Chinle formation and uranium mineralization would require the following:

1. There should be some relation between the distribution of volcanic debris and mineralized areas.
2. The volcanic debris must have been deposited before it was completely altered. Had it altered prior to or during deposition, any uranium escaping from the volcanic material would have been washed away or deposited long before the formation of the uranium deposits, which average only about half the age of the Triassic host rocks.
3. During post-deposition alteration of the volcanic debris, some uranium and vanadium must have been liberated. Thus, in their original unaltered state the tuffaceous sediments must have contained more uranium and vanadium than at present.

The sandstones of the Shinarump and Moss Back members are the host rocks of most large uranium deposits in the Triassic rocks. Although much of the lower part of the Chinle formation contains abundant altered volcanic particles, the only evidence observed by the writer that the Shinarump and Moss Back sediments contained volcanic debris is the presence of some altered volcanic pebbles in the Shinarump member in Arizona, some montmorillonitic clay in the Shinarump member in the southern part of the Colorado Plateau, and some tuff particles in the sandstone of the Moss Back(?) in Lisbon Valley and possibly also at Temple Mountain. Even if considerable parts of the parent rocks were volcanic, the probable widespread and intense weathering of the lowermost Chinle sandy sediments most likely would have altered the volcanic debris before burial and long before the uranium deposits in the Triassic rocks were formed.

On the other hand, some of the volcanic debris in the Monitor Butte and the Petrified Forest members was not altered prior to deposition. The rounded tuff particles, which are widespread in these two members, could not have been altered before deposition because they would have disintegrated during transportation.

Two types of volcanic debris—a geographically and stratigraphically widespread sodium-rich latitic type and a more restricted potassium-rich rhyolitic type—have been differentiated in the Chinle formation. Uranium mineralization is most closely related to the rhyolitic type. Altered rhyolite tuff now forms part or all of the mixed-layer illite-montmorillonite overlying the widely mineralized Shinarump in the White Canyon area; it is the only type of altered volcanic debris recognized in the southern half of the San Rafael Swell; it closely overlies mineralized Moenkopi rocks in the Circle Cliffs and Capitol Reef; it is also present in Lisbon Valley, but here it is mixed and intertongues with chlorite-illite-bearing rocks from the east and perhaps also with altered latitic volcanic debris. The only mineralized locality sampled for this study at which altered rhyolitic debris does not occur nearby or cannot be reasonably inferred to occur is the Huskon No. 1 mine (loc. 9) where the amount of mineralization is relatively minor.

As no unaltered volcanic materials from the Triassic rocks are available for study, the uranium and vanadium content of the original volcanic debris can be inferred only from analogy with similar materials. Uranium is a pronouncedly lithophilic element. According to Rankama and Sahama (1950, p. 634), granitic rocks average about 4 parts per million (ppm) uranium; more basic igneous rocks generally contain smaller amounts. Although vanadium is generally most abundant in basic igneous rocks, it still is several times more abundant than uranium in granitic rocks, so the problem at hand concerns mostly the mechanism for concentration of uranium. Igneous rocks with above-average amounts of uranium would be expected to be present in uranium-rich provinces like the Colorado Plateau. This expected trend is reflected in unaltered Tertiary rhyolites of the San Juan Mountains studied by Larsen and others (1956); although these rhyolites vary considerably in uranium content, most contain more than 4 ppm and some average 9 ppm. Furthermore, the low sodium content of sanidine associated with the rhyolitic volcanic tuff in the Chinle indicates that the parent magma must have been highly differentiated; such a magma should contain above-average amounts of uranium. It is this rhyolitic tuff which seems most closely related to uranium mineralization. The average uranium content of 27 samples of altered rhyolite tuff collected by the writer is 3.8 ppm (W. L. Newman, written communication, 1956). Therefore, the altered rhyolite tuff now present in the Chinle formation probably contains less uranium than it did in its original unaltered form.

Data on the uranium content of sediments in which the volcanic materials have not been completely altered lend support to the theory

of volcanic origin of the uranium deposits in the Triassic rocks. Observations by Denson and Gill (1956, p. 413, and oral communication, 1957) indicate that uranium in lignite beds in western North and South Dakota came from altering volcanic ash. The tilted lignite-bearing rocks of Eocene and Paleocene age are overlain unconformably by tuffaceous rocks of Oligocene and Miocene age. The unaltered tuffs commonly contain 30 to a few hundred parts per million uranium, but the devitrified tuffs contain only a few parts per million. Uranium, apparently freed during devitrification of the overlying tuffs, is now concentrated in the lignite beds. Other uranium concentrations in tuffaceous rocks are found in northwestern Colorado in the Browns Park formation of Miocene(?) age. According to C. P. Bromley (oral communication, 1957), altered tuff in the Browns Park is not abnormally radioactive, but where unaltered, it commonly has two to three times the normal background count. Also, in some Tertiary tuff beds in western Montana, Becraft (1958, p. 163) noted that the unaltered tuffs contained from 0.002 to 0.009 percent uranium, whereas bentonite formed by alteration of similar tuff beds contains no detectable uranium. Analogy with these younger rocks indicates that the original unaltered volcanic debris of the Chinle formation also may have contained more uranium than the present alteration products, and therefore some of the uranium may have escaped during the alteration.

The suggestion that uranium in the Triassic rocks of the Colorado Plateau was derived from altered volcanic debris is supported by permissive evidence only. Observations mentioned in the preceding paragraphs indicate but do not prove that volcanic debris was the source of the uranium. The only direct information likely to prove or disprove the hypothesis that the uranium is volcanic derived is the relative amounts of uranium in both altered and unaltered parts of the tuffaceous Triassic rocks, but unaltered volcanic debris has not yet been found.

CONCLUSIONS

Sediments in the Chinle and Moenkopi formations apparently came from two main source areas. An eastern source supplied most of the illitic sediments that make up the bulk of the Moenkopi formation and much of the upper part of the Chinle formation, particularly in the northern part of the Colorado Plateau. Chlorite is a minor component in these illitic sediments close to their source, but in many areas farther west chlorite is practically absent and kaolinite is the accessory component of the illitic clay. Apparently part of the chlorite was destroyed during transportation westward and small amounts of kaolinite were formed. A southern source supplied

volcanic debris, whose alteration products predominate in most of the other Chinle rocks. The volcanic debris apparently consisted mainly of latitic tuff, but included some rhyolitic tuff produced in the early stages of volcanic activity. The latite tuffs altered to montmorillonitic clays; the rhyolite tuffs altered to mixed-layer illite-montmorillonite. Chloritic and illitic sediments from the eastern source form minor tongues into the main body of the montmorillonitic sediments.

The clay-mineral assemblage in the mottled zone and in other rocks near the Chinle-Moenkopi contact has apparently been affected strongly by weathering. The weathering occurred during the mid-Triassic hiatus and also during the repeated cycles of intermittent deposition and channeling which characterized initial Chinle sedimentation. The hiatus continued longer in the eastern part of the Colorado Plateau than in the western part. Kaolinite is dominant in the earlier weathering products, which are now found in the sandstone of the Shinarump and the equivalent mottled rocks. Mixed-layer illite-montmorillonite and, locally, some aluminous chlorite are common in the mottled soils formed during the later part of the mid-Triassic hiatus. Some of these mixed-layer clays probably were eroded and may have been incorporated in the Shinarump and Monitor Butte sediments, which were concurrently being deposited farther to the west.

Clay-mineral assemblages in mineralized Triassic rocks are very similar to those in nearby barren rocks. Minor amounts of secondary clay minerals that were found in the Triassic sediments occur both in mineralized and barren rocks. Formation of vanadiferous chlorite by adsorption and fixation of vanadium ions on mixed-layer chlorite grains is the only observed change in the clays that can be attributed exclusively to the mineralizing solutions.

The clay minerals in the Triassic sediments suggest that the uranium in the Triassic rocks may have come from volcanic materials in the lower Chinle sediments. Distribution of altered rhyolite tuff is more closely related to the occurrence of uranium deposits than is the distribution of the more abundant altered latite tuff. The tuff particles were, in part, altered after deposition, possibly in Late Cretaceous or early Tertiary time when the uranium deposits are known to have formed.

SAMPLE LOCALITIES

Sample localities of clay minerals in Triassic rocks of the Colorado Plateau are given in the following table. Locality numbers are plotted on plate 1.

Locality	Name	Location
1	Leeds	Lat 37°12′ N., long 113°21′ W.
2	St. George	Lat 37°02′ N., long 113°40′ W., to lat 37°04′ N., long 113°40′ W.
3	Rockville	Sec. 36, T. 41 S., R. 11 W., Salt Lake meridian.
4	Fredonia [1]	Sec. 23 (unsurveyed), T. 41 N., R. 2 W., Gila and Salt River meridian.
5	Paria	Sec. 14, T. 41 S., R. 2 W., Salt Lake meridian.
6	Vermilion Cliffs [2]	Lat 36°43′ N., long 111°48′ W.
7	Lees Ferry [3]	Lat 36°51′ N., long 111°36′ W.
8	The Gap [4]	Lat 36°19′ N., long 111°28′ W.
9	Huskon No. 1 mine	Lat 35°52′ N., long 111°21′ W.
10	Black Point [5]	Lat 35°38′ N., long 111°11′ W., to lat 35°44′ N., long 111°22′ W.
11	Joseph City [6]	Sec. 5, T. 18 N., R. 19 E., to sec. 33, T. 21 N., R. 19 E., Gila and Salt River meridian.
12	Holbrook [7]	Sec. 18, T. 17 N., R. 21 E., Gila and Salt River meridian.
13	St. Johns	Lat 34°46′ N., long 109°11′ W., to lat 34°26′ N., long 109°22′ W.
14	Oak Springs [8]	Lat 35°27′ N., long 109°08′ W.
15	Nazlini	Lat 35°53′ N., long 109°25′ W., to lat 35°50′ N., long 109°32′
16	Round Rock [9]	Lat 36°26′ N., long 109°27′ W., to lat 36°29′ N., long 109°33′ W., lat 36°31′ N., long 109°33′ W., and lat 36°39′ N., long 109°38′ W.
17	Fort Wingate	Lat 35°28′ N., long 108°34′ W., to lat 35°29′ N., long 108°37′ W.
18	Chavez-Prewitt	Sec. 36, T. 13 N., R 12 W. to sec. 19, T. 14 N., R. 12 W. New Mexico principal meridian.
19	Ghost Ranch [10]	Sec. 2, T. 24 N., R. 4 E., New Mexico principal meridian.
20	Durango	Sec. 3, T. 35 N., R. 9 W., New Mexico principal meridian.
21	Ouray	Sec. 35, T. 45 N., R. 8 W., New Mexico principal meridian.
22	Dolores Canyon [11]	NE¼ sec. 8, T. 49 N., R. 18 W., New Mexico principal meridian.
23	Paradox Valley	N½ sec. 10, T. 47 N., R. 18 W., New Mexico principal meridian.
24	Outcrop near La Sal mine	Sec. 34, T. 29½ S., R. 24 E., Salt Lake meridian.
25	La Sal mine	
26	San Juan shaft	Sec. 27, T. 29½ S., R. 24 E., Salt Lake meridian.
27	Mi Vida mine [12]	Sec. 11, T. 30 S., R. 24 E., Salt Lake meridian.
28	Bullsnake mine	½ mile southwest of locality 29.
29	Egnar [13]	SE¼ sec. 1, T. 42 N., R. 18 W., New Mexico principal meridian.
30	Little Valley	Secs. 29 and 31, T. 30 S., R. 25 E., Salt Lake meridian.
31	Lockhart Canyon	Secs. 23 and 24, T. 28 S., R. 20 E., Salt Lake meridian.
32	North Sixshooter Peak	Secs. 30 and 31, T. 30 S., R. 21 E., Salt Lake meridian.

See footnotes at end of table.

Locality	Name	Location
33	Bridger Jack Mesa	Sec. 25 (unsurveyed), T. 32 S., R. 20 E., Salt Lake meridian.
34	The Notch mine [11]	Sec. 7, T. 35 S., R. 20 E., Salt Lake meridian.
35	Cottonwood Creek	Secs. 33, 34, and 35, T. 34 S., R. 20 E., Salt Lake meridian.
36	Milk Ranch Point	Sec. 35 (unsurveyed), T. 36 S., R. 20 E., Salt Lake meridian.
37	Comb Wash	Secs. 13 and 24, T. 40 S., R. 20 E., and secs. 18 and 19, T. 40 S., R. 21 E., Salt Lake meridian.
38	Poncho House	Lat 37°08′ N., long 109°45′ W., to lat 37°07′ N., long 109°45′ W.
39	Owl Rock	Lat 36°50′ N., long. 110°16′ W., to lat 36°52′ N., long 110°14′ W.
40	Monument No. 1 mine	Lat 36°57′ N., long 110°14′ W.
41	(No samples taken)	
42	Monument No. 2 mine [12]	Lat 36°56′ N., long 109°53′ W.
43	Whirlwind mine	Lat 37°15′ N., long 110°26′ W.
44	Monitor Butte	Lat 37°14′ N., long 110°26′ W.
45	Clay Hills Divide	Secs. 1 and 12, T. 39 S., R. 14 E., and sec. 7, T. 39 S., R. 15 E., Salt Lake meridian.
46	Red House	Lat 37°28′ N., long 110°13′ W.
47	Posey mine	Lat 37°32.5′ N., long 110°17′ W.
48	Blue Lizard mine	Lat 37°34′ N., long 110°18′ W.
49	Bears Ears	Sec. 30 (unsurveyed), T. 36 S., R. 19 E., sec. 3, T. 37 S., R. 18 E., and sec. 34, T. 36 S., R. 18 E., Salt Lake meridian.
50	Hideout mine	Sec. 27, T. 36 S., R. 17 E., Salt Lake meridian.
51	Jacob's Chair	Lat 37°44′ N., long 110°12′ W., to lat 37°43′ N., long 110°13′ W.
52	Happy Jack mine	Lat 37°45′ N., long 110°18′ W.
53	Blue Notch	Lat 37°46′ N., long 110°19′ W.
54	Hite	Secs. 1 and 12 (unsurveyed), T. 35 S., R. 13 E., Salt Lake meridian.
55	Silver Falls Creek	Secs. 25 and 26, T. 35 S., R. 7 E., and secs. 30 and 31, T. 35 S., R. 8 E., Salt Lake meridian.
56	Muley Twist	Lat 37°49′ N., long 111°01′ W., to lat 37°50′ N., long 111°02′ W.
57	Rainy Day mine	Lat 37°51′ N., long 111°02′ W.
58	Horse Canyon	Secs. 10 and 13, T. 33 S., R. 6 E., Salt Lake meridian.
59	South Draw	Sec. 7, T. 31 S., R. 7 E., Salt Lake meridian.
60	Capitol Wash [14]	Sec. 13, T. 30 S., R. 6 E., and sec. 7, T. 30 S., R. 7 E., Salt Lake meridian.
61	Oyler mine	SE¼ sec. 26, T. 29 S., R. 6 E., Salt Lake meridian.
62	Chimney Rock	Secs. 5, 7, and E½ sec. 6, T. 29 S., R. 6 E., Salt Lake meridian.
63	Delta mine [12]	Lat 38°34′ N., long 110°57′ W.
64	Muddy River	Lat 38°34′ N., long 110°58′ W.
65	Lucky Strike mine	Sec. 6 (unsurveyed) T. 24 S., R. 9 E., Salt Lake meridian.
66	Dirty Devil No. 4 mine	SW¼ sec. 26 (unsurveyed), T. 24 S., R. 8 E., Salt Lake meridian.

See footnotes at end of table.

Locality	Name	Location
67	Camp Bird No. 7 mine	West face of North Temple Mountain.
68	Temple Mountain	Lat 38°41.5′ N., long 110°41′ W.
69	Cane Wash	Secs. 23 and 24, T. 22 S., R. 10 E., Salt Lake meridian.
70	Block Mountain	Secs. 19, 29, and 30 (unsurveyed), T. 23 S., R. 11 E., Salt Lake meridian.
71	Straight Wash	Secs. 28, and 29, T. 23 S., R. 13 E., Salt Lake meridian.
72	Buckhorn Wash	Southeast corner of sec. 3 and sec. 10 (unsurveyed), T. 20 S., R. 11 E., Salt Lake meridian.
73	Buckacre Point	Lat. 38°06′ N., long 110°24′ W.
74	Range Canyon	Lat. 38°08′ N., long 110°06′ W.
75	Millard Canyon	Lat. 38°18′ N., long 110°08′ W.
76	Taylor Canyon	Lat. 38°29′ N., long 109°58′ W.
77	Spring Canyon	Lat. 38°38′ N., long 109°59.5′ W.
78	Moab Canyon	NW¼ sec. 19, T. 25 S., R. 21 E., Salt Lake meridian.
79	Shinarump No. 1 mine	SE¼ sec. 28 (unsurveyed), T. 24 S., R. 20 E., Salt Lake meridian.
80	Richardson Amphitheater	Sec. 25 (unsurveyed), T. 23 S., R. 23 E., Salt Lake meridian.
81	The Palisade	NE¼ sec. 16, T. 51 N., R. 19 W., New Mexico principal meridian.
82	Indian Creek	Secs. 32 and 33, T. 51 N., R. 17 W., New Mexico principal meridian.
83	Taylor Ranch	Lat 38°47′ N., long 108°35′ W.
84	Whitewater	Lat 38° 51′ N., long 108°32′ W.
85	Coach Creek	Lat 38°57′ N., long 109°01′ W.
86	Dry Gulch	S½ sec. 27, T. 21 S., R. 25 E., Salt Lake meridian.
87	Westwater Canyon [11]	SW¼ sec. 19, T. 21 S., R. 25 E., Salt Lake meridian.
88	Fruita	Sec. 32, T. 1 N., R. 2 W., Ute meridian.
89	The Serpents Trail	Sec. 31, T. 1 S., R. 1 W., Ute meridian.
90	South Canyon Creek	NW¼ sec. 2, T. 6 S., R. 90 W., New Mexico principal meridian.
91	State Bridge	Sec. 23, T. 2 S., R. 83 W., 6th principal meridian.
92	Meeker	Secs. 11, 13, 14 and 24, T. 1 S., R. 93 W., 6th principal meridian.
93	Vernal	Sec. 32, T. 2 S., R. 22 E., and sec. 5, T. 3 S., R. 22 E., Salt Lake meridian.

[1] From E. D. McKee (1954, p. 115-117).
[2] From E. D. McKee (1954, p. 112-114).
[3] Chinle formation measured by J. P. Akers and M. E. Cooley; Moenkopi formation from E. D. McKee (1954, p. 109-110).
[4] Measured by A. A. Wanek and J. G. Stephens (1953).
[5] Moenkopi from E. D. McKee (1954, p. 94-95).
[6] Surface section of Chinle adapted from water well measured by P. R. Stephens and C. A. Repenning.
[7] Measured by M. E. Cooley and J. P. Akers.
[8] Measured by J. P. Akers.
[9] Measured by C. A. Repenning.
[10] From E. H. Colbert (1950).
[11] Measured by L. G. Schultz.
[12] Samples collected by W. D. Keller.
[13] Composite of sections measured by G. C. Simmons and C. N. Holmes
[14] Chinle measured by L. G. Schultz.

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