Clay Minerals in the Morrison Formation of the Colorado Plateau

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

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By W. D. KELLER

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CONTENTS

ILLUSTRATIONS

TABLES

CLAY MINERALS IN THE MORRISON FORMATION OF THE COLORADO PLATEAU

By W. D. KELLER

ABSTRACT

The clay minerals in the Morrison formation of Late Jurassic age on the Colorado Plateau were studied to determine whether they could be used as guides to uranium deposits, whether they were related to the genesis of the ore deposits, and what they might contribute to the understanding of the geologic history of the Morrison formation.

More than 500 samples of mudstone and sandstone were collected from 23 selected stratigraphic sections of the Morrison formation distributed eastward from central Utah, through southwestern Colorado, and into central New Mexico. The stratigraphic sections were chosen to include some from which uranium ore was produced, some that were nonproductive although within a mining district, and some from presumably barren areas which might serve as controls.

Within the Morrison formation, the Salt Wash sandstone member is characterized predominantly by the illite, or hydrous mica, group of clay minerals. A tongue that pinches out toward the east in the lower part of the Salt Wash member in Utah contains montmorillonite. Chloritic clay minerals and mixed-layer illite-chlorite are widely distributed in the rocks of the Salt Wash, particularly in the sandstones. Kaolinite has also been formed, probably secondarily, in the sandstones of the Salt Wash.

In northwestern New Mexico the Recapture shale member of the Morrison and the underlying Bluff sandstone of Late Jurassic age correlate and intertongue with the Salt Wash member. The Recapture member contains illite in the northwest corner of the State, an abundance of montmorillonite at Thoreau, N. Mex., and commonly mixed-layer clay minerals east of Thoreau. These clay-mineral changes are interpreted as facies variations resulting from different source rocks. The Bluff sandstone, although scanty in clay content, yields montmorillonite in its clay-size fraction.

The Brushy Basin shale member of the Morrison is characterized in the northwestern part of the Colorado Plateau by a predominance of montmorillonite, but illite, chlorite, and mixed-layer clay minerals increase relatively in amount and become prominent toward the south. Illite, chlorite, and mixed-layer clay minerals are prominent as well in the Westwater Canyon sandstone member of the Morrison, which intertongues with the Brushy Basin member in New Mexico. The similarity in clay-mineral composition of the two members leads to the interpretation that part of the mudstone of the Brushy Basin is a clay facies of the Westwater Canyon member. The clay fraction of the Jackpile sandstone, a local term for a sandstone near the top of the Brushy Basin member in the Laguna, N. Mex., mining district, is dominantly kaolinite (one speci-

men contained some dickite), but the associated mudstone is mainly illite-montmorillonite and illite-chlorite.

The concept of a terrigenous and fluvial origin for the Morrison formation is sustained by the clay minerals. In general, illite-rich clastic materials derived from terranes of sedimentary rocks were available throughout Morrison time, but during periods of prolific volcanic activity the amount of ash far exceeded the clay minerals derived from sedimentary rocks and the montmorillonite resulting from it has for the most part obscured the presence of clastics derived from sedimentary rocks. The illite in the Salt Wash member and in parts of the Brushy Basin member is presumed to have a sedimentary source. Mixed-layer clay minerals represent inheritances from a previous generation of clay minerals, or a transitional stage in alteration between the clay-mineral varieties which comprise the mixed layers. The montmorillonite in the Brushy Basin member is thought to have developed by the hydrolysis of volcanic ash. Shards, which at different localities have been well preserved by replacement, and numerous faintly preserved microscopic structures of ash in the mudstone attest to volcanic ash as its parent rock. Mainly on the basis of distribution of iron-oxide colors in the mudstone of the Brushy Basin, the hydrolysis and oxidation of the ash are interpreted to have occurred at the site of the present occurrence of the clay, and at a rate that kept pace with the infall of ash.

Although the mudstone of a thick zone in the Brushy Basin member at the head of Courthouse Wash in Utah is anomalously green, it contains neither significantly large concentrations of chromium, copper, nickel, or vanadium, nor higher concentrations of them than the closely associated variegated part of the mudstone; therefore its vivid green color cannot be attributed to those metals. Likewise, the blue mudstone on Blue and Lone Tree Mesas in Colorado does not contain above-average amounts of the above metals, and its anomalous blue color does not arise from them. The blue and green colors of these clays are postulated to be due to iron that coexists in two states of oxidation and whose chemical-bond resonance generates the appropriate color vibration. The green clay at Courthouse Wash is potassium-rich montmorillonite accompanied by some illite, and the blue clay on Blue and Lone Tree Mesas is mainly illite (rich in potassium as an essential element) and subordinate amounts of montmorillonite. A green zone near the top of the Brushy Basin member on Lone Tree Mesa owes its green color to glauconitic mica which is rich in potassium and ferric iron. Apparently potassium-rich clay minerals, such as illite, glauconitic mica (illite), and potassium-rich montmorillonite can most readily incorporate a ferrous-ferric silicate combination favorable for production of vivid green and blue colors. The unusually large amounts of potassium incorporated at these localities may have been derived from evaporites of Pennsylvanian age in the salt-cored anticlinal structures in nearby Salt, Paradox, and Sinbad Valleys, which were close to the surface during deposition of the Brushy Basin member.

A sequence of stages in the transformation of typical montmorillonite to illite and glauconitic mica may be arranged in the order: pink montmorillonite from Duma Point, Grand County, Utah; green potassium-rich montmorillonite-illite from Courthouse Wash; and blue illite-montmorillonite and green glauconitic mica from Lone Tree Mesa.

No individual clay mineral, clay-mineral assemblage, or absence of clay mineral, in terms of gross clay-mineral families, was uniquely diagnostic of the occurrence of uranium minerals, and none was a guide to such occurrences.

The possible role of trace-element substitution in clay-mineral crystals was not investigated, however.

The clay minerals, as such, in the Morrison formation do not provide direct evidence that is conclusive or restrictive in deducing the origin of the uranium minerals. Indirectly, however, the enormous volume of the montmorillonite in the Morrison formation bespeaks a deposit of parent volcanic ash of great size which likewise contained an enormous amount of uranium. During argillation of the ash, probably most, if not all, of its uranium content was mobilized and migrated to undetermined distances. It seems almost incredible, geologically, that such a large amount of uranium could be removed in entirety from the associated relatively insoluble rock and mineral residues of the geochemical reaction in which the uranium was released. It seems far more likely and plausible that a large part of the migrated uranium would be redeposited within the associated permeable rock, and upon concentration by repeated solution and accretion, would form ore deposits of uranium in the Morrison formation. Further concentration may have occurred where superimposed hydrothermal activity localized the movement of fluids.

INTRODUCTION

The Morrison formation of Late Jurassic age on the Colorado Plateau was for a long time the principal source of uranium and vanadium minerals in commercial quantities in the United States (Coffin, 1921); therefore the increased demand for uranium in the 1940's prompted an intensive search for additional uranium deposits in the Morrison formation. A comprehensive geologic investigation of the Morrison formation was begun by the U.S. Geological Survey on behalf of the Division of Raw Materials of the U.S. Atomic Energy Commission, and, because argillaceous rocks constitute a prominent part of the Morrison, this study of the clay minerals was made as a part of the general investigation. Earlier work on the clay minerals of the Morrison formation includes that by Weeks (1953) on the Colorado Plateau, by Tank (1956) in the Black Hills, and by Keller (1953b) at the new type section of the Morrison formation.

The objectives of this clay study were to determine whether clay minerals in the Morrison formation could be used as guides to ore, whether they played a significant part in the genesis of the ore deposits, and what information might be gleaned from them which would contribute to an understanding of the geologic history of the Morrison formation. The procedure followed in the study was to contrast the mineralogy of the clays and clay-bearing rocks found in close spatial association with ore minerals with that of the clay minerals present in the rocks of nonproductive stratigraphic sections in otherwise generally productive districts, and with that of clay minerals present in rocks of barren areas.

Samples were collected in the field during parts of the summers of 1955 and 1956 and were processed and studied at the laboratories

of the University of Missouri during the following winters. The writer wishes to acknowledge much help from many members of the U.S. Geological Survey and the Atomic Energy Commission.

STRATIGRAPHY AND LITHOLOGY

The description of the stratigraphy of the Morrison and related formations on the Colorado Plateau will be very brief in this report, because its only purpose is to provide a framework for individual stratigraphic sections from which clay minerals were collected. A concise informative discussion of Morrison stratigraphy on the Colorado Plateau has been presented in a report by Craig and others (1955).

Over most of the Colorado Plateau the Morrison formation is divided into two members, the Salt Wash sandstone member and the overlying Brushy Basin shale member. In northwestern New Mexico and northeastern Arizona these two interfinger with, and give way to, other members: the Recapture shale member, which intertongues with the Salt Wash; and the Westwater Canyon sandstone member, which intertongues with the Brushy Basin. In the Four Corners area, the Bluff sandstone locally tongues with and replaces a lower part of the Salt Wash member; farther south in New Mexico and Arizona the Cow Springs sandstone tongues with and locally replaces all the Recapture member of the Morrison. On a less extensive scale, the Jackpile sandstone is recognized as an informal unit in the upper part of the Brushy Basin member in the Laguna area west of Albuquerque, N. Mex.

SALT WASH SANDSTONE MEMBER

The Salt Wash member (Lupton, 1914, p. 127; Gilluly and Reeside, 1928, p. 82) is composed of units of sandstone interstratified with layers or "splits" of mudstone. The units of both the sandstone and mudstone are commonly wedges, lenses, stringers, and beds which change notably in thickness over short distances. No single bed extends far enough to be very useful as a widespread reference datum in the formation. The sandstone in the Salt Wash member is commonly grayish yellow, grayish to a very pale orange, and off white. It is fine to medium grained, although it commonly contains stringers of granules and pebbles. Cross-lamination is common. Most of the sandstone of the Salt Wash is moderately well cemented with carbonate minerals and silica, although it ranges from weakly cemented to strongly cemented and quartzitic. Clay minerals, which are interstitial to the sand grains, include both allogenic detritus and probably smaller amounts of white secondary clay in flakes and tiny clusters.

The mudstone units of the Salt Wash member range from thin discontinuous layers through tapering lenses to thick wedges, commonly referred to as mudstone splits. Most of the mudstones are silty to sandy and are composed of clay minerals and quartz, but in some places they are slightly calcareous or contain locally developed muddy limestones which may contain remains of algae or fresh-water ostracodes and mollusks. The mudstones vary in color, commonly from reddish brown to red, grayish red, and light greenish gray; locally they are buff. Many of the greenish-tinted areas, which may occur as spots, mottled areas, horizontal stringers (along bedding planes), and vertical stripes (along joints), are interpreted as having been bleached from previously red-pigmented rocks.

The thickness of the Salt Wash member on the Colorado Plateau ranges, according to Craig and others (1955), from about 200 feet to more than 600 feet. The member represents a large fan-shaped alluvial deposit of streams that diverged north and eastward from an apex in south-central Utah (Craig and others, 1955).

RECAPTURE SHALE MEMBER

The Recapture member (Gregory, 1938; Harshbarger, Repenning, and Jackson, 1951; Harshbarger, Repenning, and Irwin, 1957) forms the lower part of the Morrison formation over a part of northeastern Arizona and northwestern New Mexico. The Recapture member, like the Salt Wash member, is composed of interstratified sandstone and mudstone. The sandstone in the Recapture is fine to medium grained, tan to pinkish gray, and, because it is generally less well cemented than is the Salt Wash, weathers to less conspicuous ledges. The mudstone of the Recapture is generally some light shade of red to grayish red; it is commonly silty to slightly sandy. Craig and others (1955, p. 140) report that the Recapture attains a maximum thickness of 680 feet in northeastern Arizona. The member was formed as a large alluvial plain deposited by aggrading streams from a source south of Gallup, N. Mex. (Craig and others, 1955).

BRUSHY BASIN SHALE MEMBER

The Brushy Basin member (Gregory, 1938) of the Morrison formation is a conspicuously variegated usually nonfissile mudstone containing varying amounts of sandstone beds, conglomeratic sandstone lenses, chert pebbles, a few thin discontinuous limestone layers, and petrified (siliceous) wood and dinosaur bones. The greater part of the member is composed of impure bentonite which was derived from volcanic detritus. At least some, if not most, of the volcanic ash was altered in place, as shown by unworn shards that in a few localities are well preserved by replacement. Marker beds of wide extent have not been detected in the mudstone of the Brushy Basin. The Brushy Basin weathers commonly to steep bare clayey mudstone slopes that are conspicuous because of their prominent colors. Although the colors are variegated, red and purplish red to gray predominate in the north across Utah and Colorado, and grays modified with light green, bluish tints, and red and tan predominate in the southern occurrence of the member. Wetting of the bentonite clays containing the swelling-type montmorillonite clay minerals leaves a rough-textured so-called frothy or popcorn weathered surface. Craig and others (1955, p. 156) report that the Brushy Basin member is more than 600 feet thick at Vernal, Utah; it is as much as 450 feet in southwestern Colorado and thins to the south. The Brushy Basin is interpreted as consisting of sedimentary deposits formed in fluvial and lacustrine environments (Craig and others, 1955).

WESTWATER CANYON SANDSTONE MEMBER

The Westwater Canyon member (Gregory, 1938; Harshbarger, Repenning, and Irwin, 1957) of the Morrison formation occurs over a part of northeastern Arizona and northwestern New Mexico, and interfingers with the Brushy Basin toward the north. It is primarily a sandstone but contains a little interstratified mudstone. The sand is medium to coarse grained and is fairly well cemented, as shown by the steep high bluffs in which it occurs. The color of the sandstone of the Westwater Canyon tends more toward yellowish brown, modified by some red tints, than do the other sandstones of the Morrison formation. The Westwater Canyon member, which attains a measured thickness of 330 feet 30 miles north of Gallup, N. Mex., is interpreted as a continuation of Recapture deposition (Craig and others, 1955).

JACKPILE SANDSTONE OF LOCAL USAGE

A sandstone at the top of the Morrison formation cropping out in the vicinity of the Jackpile mine near Laguna, N. Mex., has been called informally the Jackpile sandstone. It is medium to coarse grained and gray to light brown.

METHODS OF STUDY

COLLECTION OF SAMPLES

The fieldwork for this project consisted chiefly of collecting representative clay-bearing samples from the Morrison formation. Geologic sampling for analytical purposes is always critically important, and it varies in complexity and difficulty with the kinds of rocks and analytical objectives involved. The procedure for sampling clays and clay-bearing rocks is complicated and made difficult by the fact that neither the identification of the clay minerals in bulk nor the visual resolution of individual clay particles is possible under field conditions, and therefore at the time of collection it cannot always be determined whether the sample taken actually contains clay minerals. Furthermore, the use of clay minerals in interpreting the history of sedimentation and ore deposition is a relatively new tool, whose worth has not been completely established by trial and proof.

The stratigraphic position of sampled rocks and their association with ore-bearing zones had already been determined by previous geologic work at the sampling localities. The localities to be sampled were selected to give wide geologic coverage of the Morrison formation on the Colorado Plateau, to collect where an exposure of the formation was at a maximum, and to collect both from areas where rocks contain uranium ore minerals and from areas where they do not. Because so much field stratigraphic control was available, the clay-mineral data were grouped in terms of stratigraphic units, and therefore the relation of the clay minerals to the stratigraphy of the formation is presented as a byproduct of this study.

In sampling a section of the Morrison, the formation was divided first into whatever members were present and then into major lithologic units within each member. At a certain locality the Salt Wash member might consist, for example, of a silty mudstone at the base, then perhaps 50 or 100 feet of sandstone separated at irregular intervals by thin layers of mudstone (mudstone splits), followed upward by a thick dominantly mudstone zone, and then by more sandstone, and so on. A representative specimen from the basal mudstone and one or more specimens from the sandstones above, including at least one from the thin mudstone splits were collected; this routine then was repeated throughout the member. To collect from a mudstone, or other lithologic zone that was relatively thick (5 to 20 ft), one to three separate samples were taken: perhaps one near the base, one near the center, and one near the top, or, alternatively, at visible changes in lithology.

During the first part of the collecting schedule more specimens were taken of clay-rich mudstones than of sandstones because the project was concerned primarily with the clay minerals. As work progressed, however, it was decided that the sandstones also merited full consideration because it became apparent that a sandstone might contain as many as four genetically different types of clay minerals: (1) clay minerals dispersed as original fine-grained detritus in the sandstone; (2) galls and clay pebbles constituting conglomeratic(?) claystone fragments in the sandstone; (3) secondarily developed clay minerals (white) which had been deposited from solution or recrystallized; and (4) clay minerals secondarily developed as replacements and deposits from ore-bearing solutions, for example, vanadiferous clay minerals which filled the corroded margins of quartz grains, replaced quartz grains, and grew into pore spaces between them. Consequently, sandstone was sampled more liberally, relative to mudstone, in the latter part of the fieldwork than in the first part. Several of the localities first sampled were revisited to collect more sandstone specimens.

The procedure followed for sampling the members that are dominantly mudstone throughout (the Brushy Basin, for example) was to collect specimens for each of the zones characterized by marked differences in color, texture, resistance to weathering, and appearance of the weathered surface on the outcrop. As experience was gained in relating field appearances of mudstone to mineral identification in the laboratory, more and more reliance was placed on distinguishing clay-mineral zones by the differences in their weathered surfaces. The weathered surface of clay-containing rocks may be one of the best field guides to tentative identification of the clay minerals therein. For example, expanding clay minerals (montmorillonites) in a mudstone weather to the frothy, or popcorn surface (fig. 1), well known to field geologists working in the semiarid West. The dominance, but not the character, of this structure is decreased as the content of quartz, feldspar, or silica cement increases. Illites tend to weather to a relatively smoother (slicker) clay surface (fig. 2), which is crisscrossed by many tiny rather uniformly spaced shrinkage cracks and checks. Kaolinitic mudstones tend to weather to a surface that is commonly somewhat granular in appearance. These brief descriptions illustrate the value of weathered surfaces of argillaceous rocks as a rough field guide to identification of their clay minerals. A change in appearance of the weathered surface of a mudstone was found to be a good basis for collecting an additional sample.

Change in color of mudstone, on the other hand, probably does not reliably reflect change in clay-mineral composition, provided the change in color is among purple, red, brown, or tan—colors which originate from pigmented coatings of iron oxides. However, changes

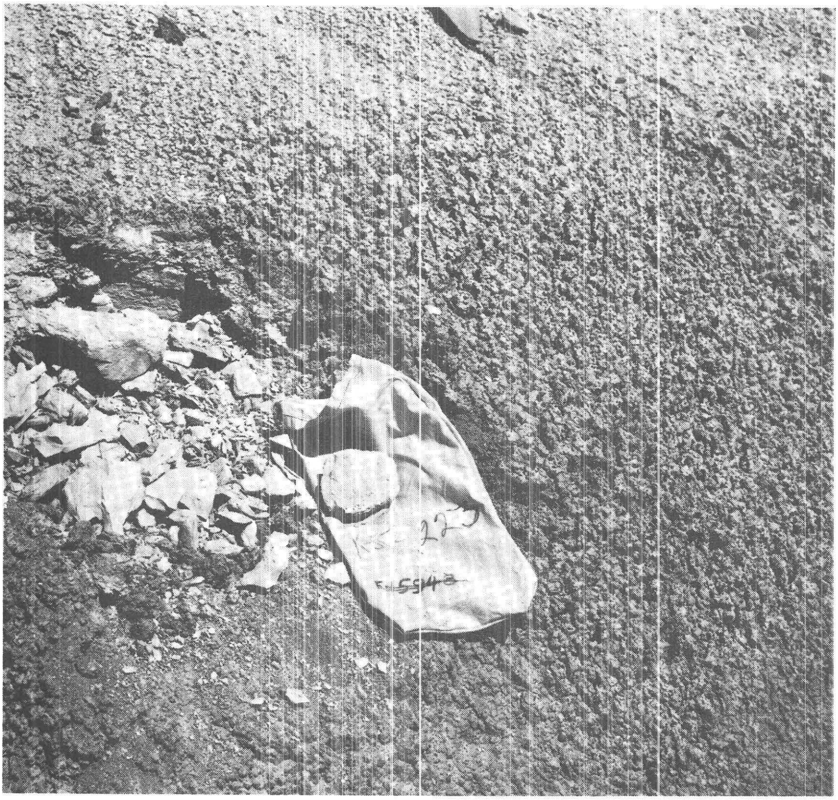

FIGURE 1.—So-called frothy, fluffy, or popcorn weathered surface of swelling montmorillonite clays in the Brushy Basin member. From the Duma Point section, No. 6 (64), Grand County, Utah.

in color involving blue or green may indicate a significant difference in clay-mineral composition.

LABORATORY PROCEDURE

The clay-sized fractions of mudstones and sandstones were studied in the laboratory by X-ray diffraction, differential thermal analysis, and thin section. Textural and mineral associations were determined from thin section, of which more than two hundred were examined. X-ray diffraction patterns were determined for bulk powders and for thin clay films—result of sedimentation of particles equivalent in settling velocities to spheres less than 2 microns in diameter—which will be referred to subsequently as 2-micron fractions. The suspensions used in fractionating by settling were made by grinding the mudstone (or sandstone), stirring in distilled water, and repeatedly decanting the clear water above the clay until soluble salts in the clay were largely removed and the clay remained in suspension. By repeated decanting of water the addition of a dispersing agent was usually avoided, but with a few specimens addition of a small amount of NH_4OH was necessary to aid dispersion. Clay minerals were usually concentrated in the suspension, but fine-grained quartz, feldspar, analcime, calcite, dolomite, gypsum, and uranium-vanadium minerals were recovered also in the 2-micron fractions.

The 2-micron fractions from some specimens were studied as dry powder mounted in random orientation in the X-ray specimen holder, but most specimens were X-rayed as oriented films (parallel orientation) on glass slides, or on porous porcelain plates using a technique slightly modified from that described by Kinter and Diamond (1956).

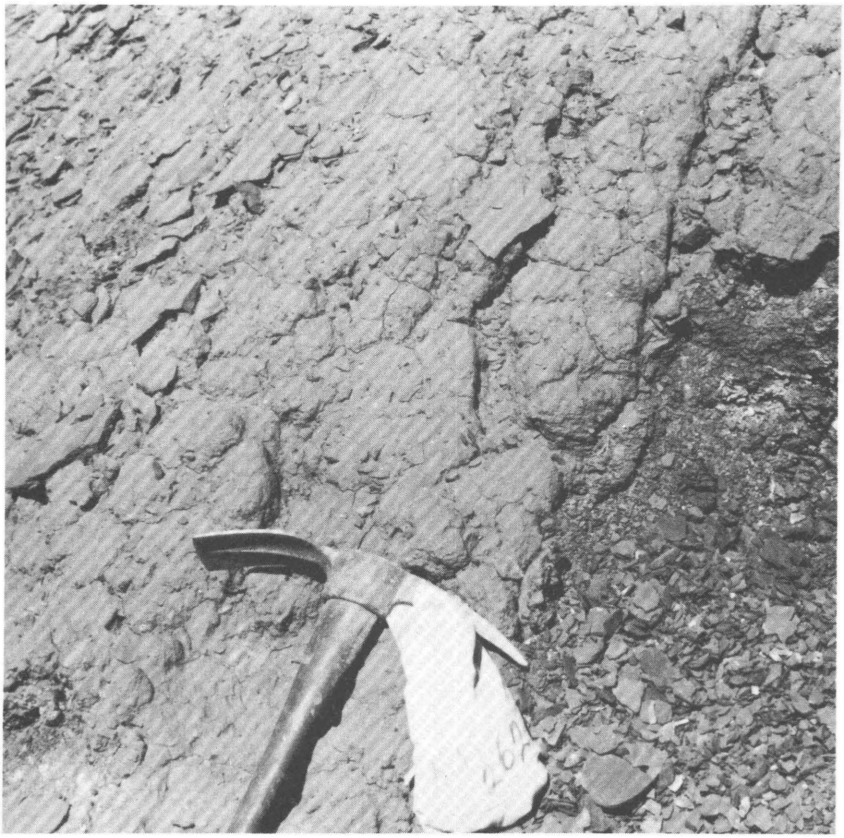

FIGURE 2.—"Slick" weathered surface of an illitic mudstone. This appearance is probably caused by a surficial coating of micaceous clay minerals oriented roughly parallel to the surface. From an exposure of mudstone (illitic) in the Moenkopi formation in Capitol Reef National Monument, Utah.

No one of the above-described methods seems to be universally best. Where nonplaty minerals, such as feldspar or analcime are important in the rock, the randomly oriented dry-powder mount gives good results. If identification of clay minerals alone is the objective, oriented-film mounts are most efficient. A clay film settled on a glass slide is prepared with a minimum of equipment and expense, is well oriented, convenient to store, and shows little or no diffraction interference from the glass base beneath it. On the other hand, if several clay-mineral species are present in one specimen, segregation of them may occur during settling from suspension owing to differences in their dispersibility in water and in particle sizes, and this may yield a different clay-mineral composition on the front than on the back of the film, as was shown by Schultz (1955).

Such separation is avoided, or at least minimized, by mounting the clay, using suction, on a porous porcelain tile; this tends to incorporate all the clay in suspension into the film, and thereby largely eliminates the tendency toward segregation during settling. Also, solutions containing ethylene glycol, or a chosen cation, are easily pulled through the clay film on the tile, and thus expanding clays, and any other clays whose physical properties are affected by the exchangeable cation absorbed, are conveniently studied when mounted on these porous plates. Disadvantages of the porcelain-plate mount are that some spurious diffraction lines from substances in the porcelain, such as quartz or cristobalite, may register through a thin clay film. This might be avoided by using a thick film or a fritted glass filter. Some clays achieve a less uniform state of parallel orientation if pulled by rapid suction onto porcelain than if they settle more slowly onto a glass base, whereas other clays are better oriented by suction than by settling. The reasons for these differences are not known.

All X-ray diffraction was done on a high-angle diffractometer unit using nickel-filtered copper K-alpha radiation and a scanning speed of 1° per minute. Clay specimens were heated in a wire-wound electric muffle whose temperature was controlled by a thermostatic unit.

Another method used to identify clay minerals is to measure their thermal stability under dynamic heating (differential thermal analysis). In this method a mineral sample being analyzed is placed adjacent to a thermally inert substance (calcined Al_2O_3) in a specimen holder which is heated in a furnace whose temperature is raised uniformly (10° to 12°C per minute). A pair of similar thermocouples is placed one in the sample and one in the inert material, and connected serieswise in electrical opposition to each other, and thence to a recording instrument. As long as the temperature of both samples rises uni-

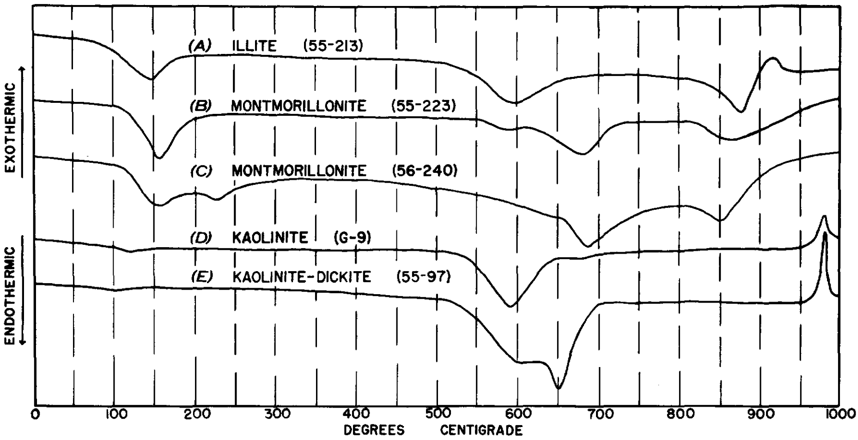

FIGURE 3.—Differential thermograms of clay minerals from the Morrison formation.

A. Illite (sample 55–213), exhibiting typical endothermic reactions at about 145°, 590°, and 880° C, and an exothermic reaction at 915° C. From a mudstone in the Salt Wash member at the Duma Point section, No. 6 (64), Grand County, Utah, near the type locality of the Salt Wash member.

B. Montmorillonite (sample 55–223) shows a single endothermic reaction at about 160°C characteristic of Na-montmorillonite, a slight endothermic reaction at about 590°C which is probably due to illite "impurity," montmorillonite endothermic dehydroxylation reaction at about 680° C, and diffused gradational endothermic-exothermic reaction from 840° to 950° C. From the Brushy Basin member, same locality as in *A*.

C. Montmorillonite (sample 56–240) exhibiting a double endothermic reaction (dehydration) at about 155° and 230°C which is characteristic of Mg- and Ca-montmorillonites, a slight endothermic "shoulder" at 640°C due probably to admixed illite, a dehydroxylation endothermic peak at 680°C and endothermic-exothermic reactions in the 825°–900°C range. From the undifferentiated upper part of the Morrison formation at Mesa Gigante section, No. 20, Valencia County, N. Mex.

D. Kaolinite (sample G–9) exhibiting typically the small endothermic loss of weakly held water at about 125°C, the endothermic dehydroxylation reaction at about 590°C, and the exothermic crystallization at about 980°C. From the Brushy Basin member, probably secondarily kaolinized by hydrothermal solutions, at the Los Ochos locality, No. 23, Saguache County, Colo.

E. A kaolinite-dickite mixture (sample 55–97) showing the endothermic dehydroxylation reaction of dickite at 650°C (50° to 60° higher than that of kaolinite) in addition to the typical reactions of kaolinite. From the Jackpile sandstone at the Jackpile mine, No. 19, Valencia County, N. Mex.

formly during the heating of the sample holder no current flows through the thermocouple circuit, and the instrumental record is a relatively straight-line thermogram (fig. 3). If the analyzed sample breaks down endothermally, as when kaolinite dehydroxylates at 575° to 625°C, the temperature rise of the sample lags behind that of the inert material and a corresponding flow of current in the thermocouple circuit is registered as a trough in the thermogram. At other temperatures exothermic reactions may occur, as in the mineral transformation from dehydroxylated kaolinite to crystalline material at about 980°C, at which the temperature of the mineral exceeds temporarily that of the inert substance; this is indicated by the raised peak on the curve. The direction of the thermal reactions, their intensities, and the temperatures at which they occur are diagnostic criteria by which various minerals are identified.

IDENTIFICATION AND CLASSIFICATION OF CLAY MINERALS

The clay minerals were identified mainly from their X-ray powder diffractograms; but optical properties, differential thermal analysis, and a few chemical analyses were also used where available or appropriate. In general, minerals and mineral families may be distinguished by differences in physical properties, chemical composition, optical behavior, thermal stability, electrical properties, external morphology, and internal structure. Overlap in some properties is shown between the individual minerals in all families, and therefore arbitrary limits of mineral parameters may be required to separate the individuals. Where overlaps of some properties occur between minerals in which other properties differ, a perplexing situation arises as to which set of properties will be considered diagnostic of mineral identification and classification. Such a situation prevails within the clay-mineral family.

Physical properties, optical properties, and chemical composition may be notably similar or almost continuously gradational between clay minerals which can be readily distinguished by structural differences. On the other hand, certain clay minerals which are structurally similar, such as the group of expanding "montmorillonites," may be clearly dissimilar among themselves in chemical compositions, ionic substitution (diadochy), origin, and reaction to geologic solutions. For an example of the latter case, degraded or stripped illite expands structurally, as does montmorillonite derived from volcanic glass or other nonphyllosilicate-structure parent materials, but they react differently to geologic solutions. Thus, no single criterion now known for the differentiation and classification of clay minerals is wholly satisfactory.

Nevertheless, the most useful means of differentiating clay minerals at present is determination of their internal structure. The internal structure of clay minerals is measured by X-ray diffraction in terms of the regular periodic spacing of ions or ion groups in the minerals, referred to as interplanar, or *d*, spacings. These spacings are observed instrumentally by measuring the positions and inten-

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sities of so-called reflected (actually diffracted) X-rays from repetitive geometric ionic patterns in mineral specimens. The positions of the reflections are recorded by the X-ray apparatus as angular deviations, designated "two-theta", in degrees from the directions of the incident X-ray beam. The widths of the *d*-spacings are related inversely to the size of the angles two-theta by Bragg's equation,

$$n\lambda = 2d \sin \theta$$

where n refers to the order of reflection, and λ to the wavelength of the radiation used. When copper radiation is used, $d=0.77$ Angstroms times sin θ. Thus, a *d*-spacing of 7.2A is located 12.3° two-theta (diffractogram of a kaolin mineral); a 10A reflection (illite) at about 8.9° two-theta; and a 17A reflection (expanded montmorillonite) at about 5.2° two-theta. (See figs. 4–6). Diffractograms have not been retouched to avoid any possible alteration during reproduction of the original instrumental record.

In this study diffractograms were made of the entire (or bulk) sample of many mudstones from which nonclay minerals were identified. Oriented clay films were X-rayed in a room-dry condition, solvated in ethylene glycol, and heated, if necessary, to 550°C for 4 hours. Montmorillonite expands in the *c*-axis direction by the absorption of molecules of ethylene glycol between clay-crystal "sandwiches," whereas kaolinite, illite, and chlorite do not expand. Kaolinite and chlorite both yield 7A reflections, but upon heating to 550°C the structure of kaolinite is destroyed whereas that of well-crystallized chlorite remains. Some clays were saturated with potassium or magnesium ions, which may alter diagnostically their *c*-axis spacing, and thus aid in identifying them.

Differential thermal analysis (DTA) ordinarily yields less definitive information about clay minerals than does X-ray diffraction, and therefore it has been subordinated to X-ray methods of identification. DTA is probably most useful in studies of the kaolin group where it may be used to detect otherwise-confusing mixtures of kaolinite and dickite (fig. 3) and to confirm kaolinite in the presence of chlorite. DTA also indicates single-layer hydration of sodium-montmorillonite and two-layer hydration of calcium- and magnesium-montmorillonites, both of which occur in mudstone in the Brushy Basin member.

In this study, mineral identification was made primarily to assign the clay minerals to their major groups—kaolin, montmorillonite, illite, or hydrous mica, chlorite, and interstratified random mixtures of these groups—for the purpose of applying the data to geologic interpretations rather than to study for its own sake detailed mineralogy of individual specimens. Where a geologic problem required additional detailed work, as in the question of the origin of the potassium-rich anomalously blue-green clay in parts of the Brushy Basin, more than the structural identification of the clay minerals was done.

KAOLIN GROUP

Clay minerals of the kaolin group were identified by their characteristic 7A (001) interplanar spacing, supporting reflections at higher orders, and prism reflections (fig. 4). Although very well crystallized kaolinites have a (001) spacing of approximately 7.1 to 7.2A, the kaolin minerals in many sedimentary rocks, including those of the Morrison formation, show a slightly wider (001) spacing—as much as 7.3A. The wider spacing is generally interpreted as being due to a small amount of interlayer water between some of the platy clay-mineral crystals.

Well-crystallized kaolinites yield relatively sharp reflections (peaks on the diffractograms), but commonly rock-forming kaolins, as in fire-clay deposits and sedimentary-rock formations, show dull or certain omitted reflections from crystal units spaced along the *b*-crystal axis, owing to disordered stacking of crystal plates along the *b* axis. Such poorly crystallized kaolins were called fire-clay minerals by Brindley and Robinson (1947). Most samples from the Morrison that contain kaolin yield incompletely developed diffraction patterns which are interpreted as representing the fire-clay-mineral type of kaolin. Pos-

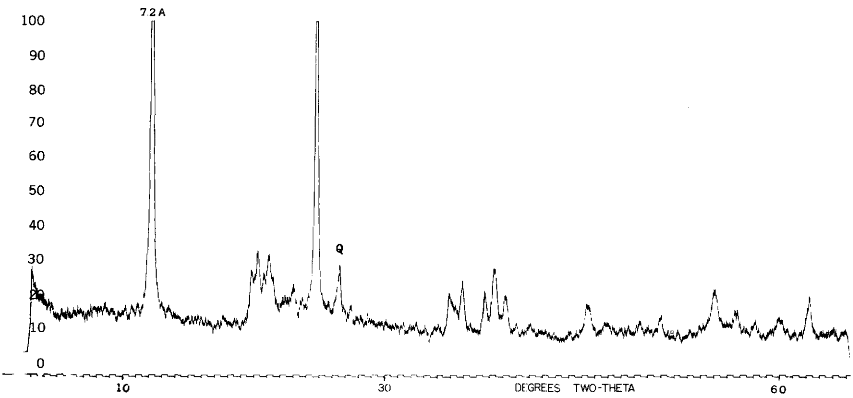

FIGURE 4.—X-ray powder diffractogram of kaolinite from the Jackpile sandstone; a bulk (not parallel-oriented) powder specimen 55–118. A characteristic interplanar, or *d*, spacing at 7.2A is determined by a peak at 12.3° two-theta, recorded along the base of the diffractogram. The peak (*Q*) is reflected from quartz in the sample. Nickel-filtered, copper radiation.

sibly, however, incompleteness and imperfections in some patterns are due to the overshadowing amounts of other minerals of clay size with the kaolin. Attempts to separate or concentrate the kaolin fraction of such samples to obtain the best possible and most definitive kaolin record would be so time consuming as to be impractical, and usually would be fruitless owing to the scant success achieved in separating natural mixtures of clay minerals.

Dickite, which was found mixed with kaolinite in the clay fraction of the Jackpile sandstone, is typically better crystallized than kaolinite. The peak of the dehydroxylation reaction of dickite is at about 650°C, about 50°C higher than the dehydroxylation peak of kaolinite (fig. 3). Poorly crystallized kaolinites lose hydroxyl at slightly lower temperatures than do better crystallized kaolinites.

Clay minerals in both the kaolin and chlorite groups yield a 7A interplanar spacing, but they can be distinguished by heating to 550°C for 4 hours (or overnight) and again X-raying the sample. Under this heat treatment, the 7A spacing of fire-clay mineral is completely destroyed, that of the well-crystallized kaolinite is almost, if not completely, destroyed, and that of chlorite in ancient sediments (where chlorite crystals apparently have had sufficient time to mature into well-organized structures) remains intact. Heating chlorite usually enhances the intensity of its 14A peak. The identification of all kaolin reported in this study was confirmed by heat treatment.

The kaolin group of minerals are commonly referred to as the 2-layer or 1:1-layer type clay minerals in contradistinction to the montmorillonite and illite types which are called 3-layer or 2:1-layer types. In the kaolin crystals each unit cell contains 1 layer of silica tetrahedra adjacent to and interconnected with 1 layer of alumina octahedra; hence the names 1:1 layer or 2 (sum of 1 and 1)-layer type. Montmorillonite and illite crystals are constructed of 2 layers of silica tetrahedra bound by 1 layer of alumina octahedra between them; hence the designations 2:1-layer or 3-layer clays.

MONTMORILLONITE GROUP

The montmorillonite group of clay minerals was identified by a (001) spacing of about 15A (depending upon the absorbed cation and degree of hydration), which expands to 17A when solvated with ethylene glycol (fig. 5) and collapses to about 10A when heated. Many of the montmorillonitic samples show deviation from idealized interplanar spacings owing to interlayer mixtures with illite and chlorite. The swelling clays in the Brushy Basin member of the Morrison formation are montmorillonite, which originated from the alteration of volcanic dust and not from degraded micas. Evidence for their volcanic origin is the numerous observations of relict or replacement structures of volcanic shards (fig. 11) and abundant unaltered feldspar and tiny books of dark mica in the siltstone. A diffractogram of montmorillonite from the Brushy Basin is shown in figure 5.

ILLITE, OR HYDROUS MICA, GROUP

The illite, or hydrous mica, group of clay minerals was identified by a (001) spacing of approximately 10A which does not expand upon solvation with ethylene glycol. Illites of most mudstones, and notably those of the Morrison formation, exhibit a (001) peaked arch (fig. 6) rather than a sharp 10A peak which characterizes well-crystallized muscovite mica. The peaked arch represents disordered and random interstratification of different micaceous minerals in the illite group. Mixtures of clastic muscovite flakes and associated illite, which occur sporadically in siltstones of the Salt Wash member, may be recognized by the presence of a sharp 10A peak rising abruptly above the arched base. Glauconitic mica, some of which was found on Blue and Lone Tree Mesas, was identified by strong (001) and (003) peaks and a weak (002) peak (fig. 12) in addition to characteristic optical properties, such as refractive indices, green color, and pleochroism.

CHLORITE GROUP

The chlorite group of clay minerals was identified by a (001) interplanar spacing at about 14A, and other spacings, generally well developed, at integral high orders. The chlorite structure (in chlorite of ancient sediments) is not destroyed by heating the specimen to 550°C for 4 hours, and the 14A peak is usually enhanced in intensity by heating (fig. 7*A*). Chlorite does not expand when solvated in ethylene glycol.

MIXED-LAYER CLAY MINERALS

Random mixed-layer clay minerals are common in the Morrison formation. Interlayer mixing may be of at least three types: (1) regular and integral; (2) random mixing, in which the composition and mixing are fairly uniform and homogeneous, characterized by diffractograms which show fairly sharp peaks located between the positions of peaks from ideally crystallized pure minerals; and (3) random mixing which is nonuniform, ranges between wide limits, and gives rise to broad peaks or plateaus in the diffractograms. Type 2 and especially type 3 are abundant in clays of the Morrison (fig. 7*B*). Moreover, a single clay specimen may consist of a physical mixture of two or more groups of clay minerals, each of which is random-mixed-layer in type; thus montmorillonite that contains interlayer, randomly mixed illite, may be commingled with illite

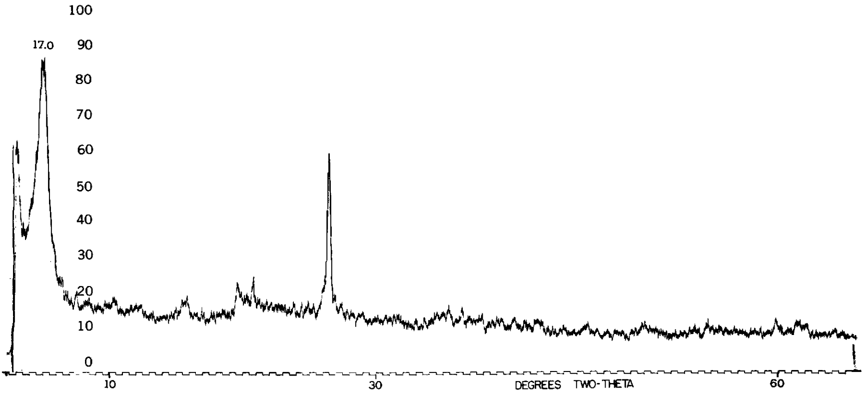

FIGURE 5.—X-ray powder diffractogram of typical montmorillonite from mudstone in the Brushy Basin member. Shows the characteristic (001) interplanar, or *d*, spacing at 17A, 5.2° two-theta, when the clay is solvated with ethylene glycol. Nickel-filtered, copper radiation.

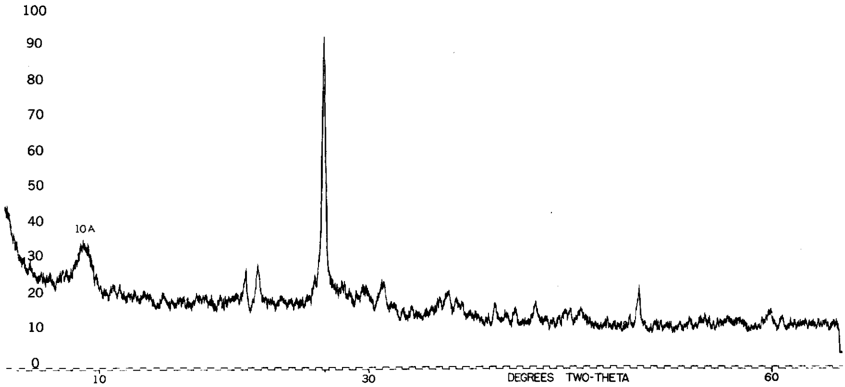

FIGURE 6.—X-ray powder diffractogram of typical illite, sample 56–4 (No. 3), in the Salt Wash member. The interplanar spacing at 10A, 8.9° two-theta, is recorded by a broad arched peak which is indicative of a variation in spacings and stacking above and below 10A, a typical condition of sedimentary illite. The clay specimen is an oriented film on tile. Nickel-filtered, copper radiation.

that contains randomly intermixed montmorillonite. The composition of mixed-layer clay minerals was estimated by observing the displacement of the (001) peaks in diffractograms of specimens that were room-dry, solvated in ethylene glycol, and then heated to 300° and 550°C.

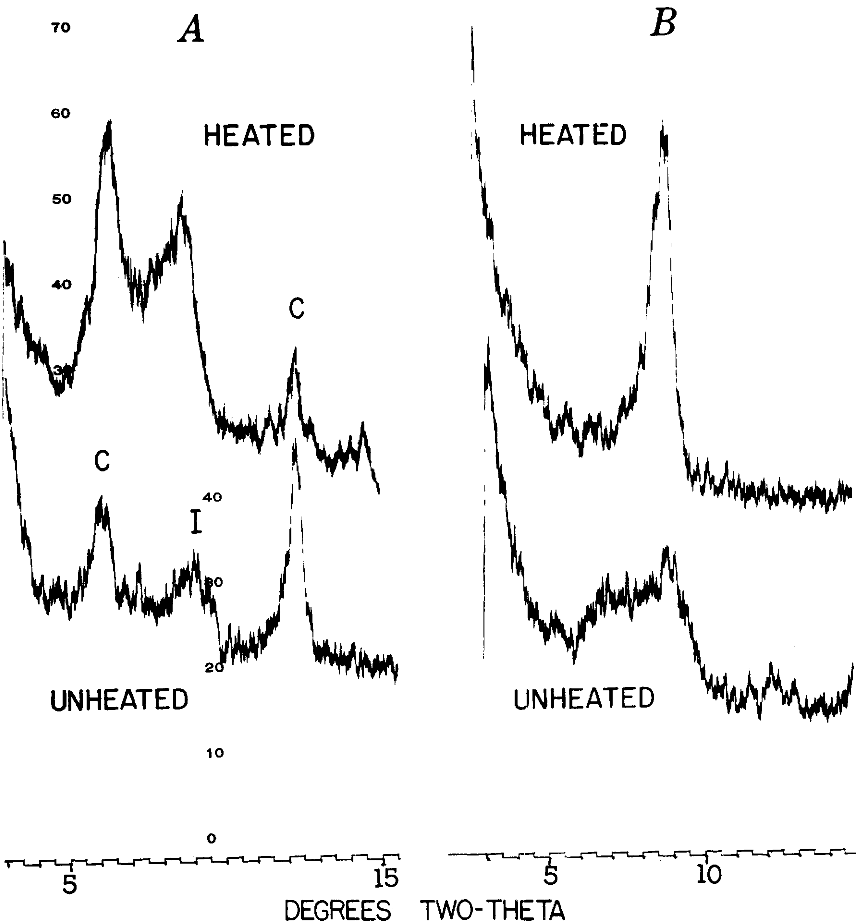

FIGURE 7.—X-ray powder diffractograms of specimens (*A*) containing illite (I) and chlorite (C); sample 56–152 (No. 11), from the Brushy Basin member, and (*B*) containing illite mixed with an expanding clay mineral, sample 56–140 (No. 11), from the Salt Wash member; they are clay films mounted on tile and solvated in ethylene glycol. Diffractograms were made before and after heating to 550°C for 4 hours. Note that the chlorite (001) peak has been enhanced by heating, and that the (002) peak at 7.1A (12.4° 2-theta) also persists after heating, whereas a peak of kaolinite would have disappeared. In (*B*) the expanded mixed layers are collapsed upon heating to 550°C for 4 hours; they are interpreted as representing montmorillonite—not degraded illite—because the clay comes from a zone which weathers to a frothy surface. Nickel-filtered, copper radiation. Degrees 2-theta are shown along base lines of diffractograms.

The di- or trioctahedral character, and the kinds of octahedrally coordinated cations of the clay minerals were inferred from the (060) spacing and relative intensities of integral (001) peaks.

The names of the mixed-layer clay minerals used in this report are arranged by hyphenating the names of the constituent minerals and placing the dominant constituent first; for example, illite-montmorillonite means that the clay mineral is predominantly illite but contains a subordinate amount of montmorillonite.

QUANTITATIVE ESTIMATION OF CLAY MINERALS IN THE MORRISON FORMATION

An ideally complete mineral analysis of a clay-bearing material includes both the qualitative identification and the quantitative estimation of the minerals present. The minerals in mudstones may be identified qualitatively by X-ray diffraction in amounts as low as perhaps 1 or 2 percent if an intense reflection is available, as from quartz or calcite, but a particular clay mineral probably cannot be detected confidently in amounts less than 5 percent. Satisfactory quantitative analyses of clays have been made under favorable conditions, using procedures described by Johns and others (1954), and Weaver (1958). Quantitative estimations are based on the comparison of appropriate diffraction peaks or lines in patterns of unknown samples with those of standard reference samples. Such comparisons are quantitative if the clay minerals involved are relatively clean and well defined, but the validity of the comparisons deteriorates significantly as particle sizes differ between constituent clay minerals in a mudstone. If the chemical composition of the clay minerals (for example, the iron content in montmorillonites and micaceous clay minerals) in mudstones is not constant, if the amount of amorphous (to X-ray) material changes from specimen to specimen, if the ratios of mixing vary between clays that show randomly mixed layering, and if the degree of weathering differs in naturally occurring samples, it may be deceptively misleading to express by a number (that is, quantitatively and implicitly rigorously) the clay-mineral ratio or content in terms of a standard reference.

Early in this study it was observed that the diffraction-pattern intensities of materials collected from weathered mudstones in the Brushy Basin member differed sufficiently from those of their unweathered counterparts taken only a few inches back of the weathered surface that the precision of the mineral analyses was no better than semiquantitative. In some pairs the weathered material yielded the stronger reflections, whereas in others the unweathered counterparts exhibited the stronger ones. As much as a fourfold difference between the weathered and unweathered materials was observed, although the laboratory processing of them was as closely similar as was routinely possible.

Diffractograms of weathered and unweathered montmorillonitic mudstone (sample 55–223) from the Brushy Basin member, as shown in figure 8 are typical of such differences. The weathered material

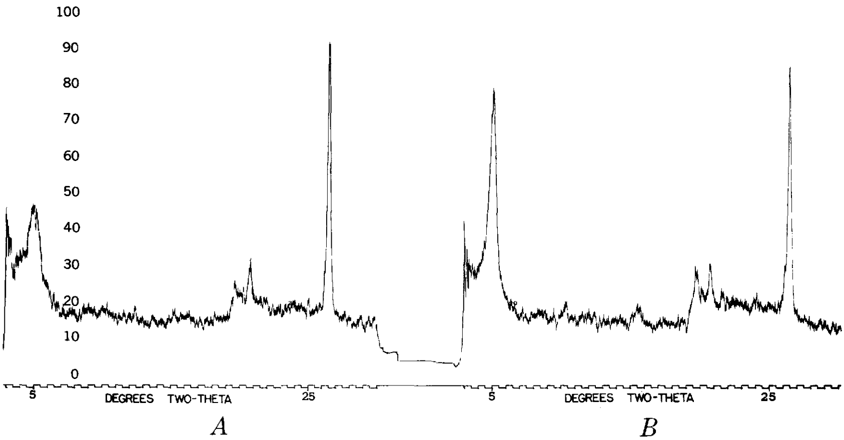

Figure 8.—X-ray powder diffractograms of montmorillonitic mudstone of the Brushy Basin member of the Morrison formation (sample 55–223), from a weathered outcrop (*A*) and unweathered material (*B*). The unweathered material was collected a few inches behind and at the same elevation as the weathered material. Note difference in patterns of the (001) interplanar spacings, although the two specimens were processed identically in the laboratory; both are bulk samples solvated in ethylene glycol. From the Duma Point section, No. 6 (64), Grand County, Utah. Nickel-filtered, copper radiation.

is from a frothy surface on Duma Point near Crescent Junction, Grand County, Utah, and the unweathered material was taken laterally inward a few inches, at the nearest place where firm mudstone was found (fig. 1).

The basic cause for the difference between the X-ray measurements of weathered and unweathered samples of the Brushy Basin is interpreted as being geologic, and thus is a variable which cannot be controlled or modified in the laboratory to obtain precise analyses. The variability arises from the fact that mudstone of the Brushy Basin is basically an alteration product of volcanic ash in which the alteration is nonuniform and has generally not gone to completion—primarily because the argillation has occurred in the first cycle of deposition and hydrolysis of the ash. In contrast to redeposited ($N+1$ cycles) shales and other argillaceous rocks whose clay minerals have uniformly tended toward equilibrium with surrounding conditions, the clays in the Brushy Basin are still readily susceptible to differential modification by weathering of the outcrop. For example, between the weathered and unweathered counterparts, lithologic modifications may occur which include (1) finer clay particles dispersed on the weathered surface than in the unslaked mudstone; (2) clay minerals more highly hydrated on the weathered surface; (3) surface clay more highly oxidized than that in the interior; (4) exchangeable cation population changed owing to leaching at the surface; (5) less opaline silica, silica gel, and fine particles of cherty silica present in the surface clay than in the lump clay; and (6) a different ratio of unaltered ash to clay at the surface than that in the interior. Apart from the immediate effects of surface leaching, slaking, and weathering, the degree of argillation of the ash may vary laterally. Thus, field collections cannot be made of mudstones which have all been weathered to the same degree; and it would be misleading and geologically unrealistic to report apparently precise quantitative results on the clay minerals in these mudstones.

Therefore, instead of expressing the analyses in terms of percents, the amounts of minerals present will be described as "dominant," "strong," "moderate," "small," "slight," and "trace," or occasionally as approximate fractional amounts such as "equal parts," or "about 2 to 1." The term "dominant" means that a given mineral constitutes essentially all the clay detected by the X-ray of a specimen; "strong" means a mineral comprises about three-fourths of the clay in the specimen; "moderate" indicates about half of the clay; "small" and "slight" refer to about ¼ and ⅛, respectively, of the clay; and a "trace" means that the relative amount is barely recognizable on the diffractogram.

Although a more exact estimation of the clay-mineral content of each specimen would be preferable, it probably would not alter significantly the final geologic conclusions and inferences that have been drawn from the data. The lithology of the fluvial Morrison formation is so highly variable that no widespread lithologic or stratigraphic marker exists, and two sections only a few hundred yards apart may differ so much in detail that specific correlation between them is impossible. Thus, semiquantitative clay-mineral analyses are compatible with the geologic characteristics of the Morrison formation.

DISTRIBUTION OF THE CLAY MINERALS

The distribution of the clay minerals identified from the Morrison formation in this study is described in terms of the stratigraphic sections from which the samples were collected. Their distribution is summarized below; the original and detailed data giving the location of individual samples, brief descriptions of them, and their clay mineralogy are given on pages 63–85. The distribution of the clay minerals in the stratigraphic sections is also shown graphically on plate 1. The 23 stratigraphic sections will be described in two sequences. The first sequence begins with the southwesternmost locality examined, on Pine Creek near Escalante, Utah, thence north to Emery County, Utah, and eastward across the Utah-Colorado line; the sequence continues south along the State line to north-central New Mexico and terminates near Laguna, Valencia County, N. Mex. The second and shorter sequence is made up of three sections in west-central Colorado; near Glenwood Springs, Sapinero, and Gunnison. Nearly all these section were selected from a large number of localities at which stratigraphic studies were made in connection with the Geological Survey's study of the Morrison formation. The number following the locality name is the number assigned in this study; the second number (in parentheses) was used in the original stratigraphic study (Craig, 1959).

PINE CREEK SECTION

No. 1 (159); Garfield County, Utah; sec. 13, T. 34 S., R. 2 E; unmineralized

The Morrison formation is relatively thin in the Pine Creek section, having a total thickness of 231 feet (Salt Wash member, 168 ft; Brushy Basin member 63 ft), about one-fourth the thickness in other sections examined. The lowest unit of the Salt Wash contained illite and mixed-layer chlorite-illite. The top zone of the Salt Wash member yield mixed-layer montmorillonite-chlorite and a small amount of illite. The contact between the Salt Wash and Brushy Basin members is not clearly defined here, and it is entirely possible that the upper unit of the Salt Wash is transitional to the Brushy Basin.

Three samples collected from the Brushy Basin member yielded montmorillonite.

HANKSVILLE SECTION

No. 2 (88); Wayne County, Utah; along Utah Highway 24, sec. 18, T. 28 S., R. 11 E., and sec. 13, T. 28 S., R. 10 E; unmineralized

The Salt Wash member is characterized by illite in all samples except one taken at approximately the center of the member (unit 6, 135–140 ft above the base) in which montmorillonite is dominant. The similar presence of montmorillonite in the lower part of the Salt Wash member in the Little Cedar Mountain-Buckhorn Flat and

San Rafael River Bridge sections, supports the interpretation that volcanic detritus was deposited during part of early Salt Wash time.

Four specimens of mudstone of the Brushy Basin yielded montmorillonite.

LITTLE CEDAR MOUNTAIN—BUCKHORN FLAT SECTION

No. 3 (24); Emery County, Utah; secs. 34 and 35, T. 18 S., R. 9 E., and secs. 2 and 3, T. 19 S., R. 9 E.; unmineralized

The claystone in the lower 21 feet of the Salt Wash was sampled in three specimens, and all contained illite. At 35 feet above the base, montmorillonite (slightly mixed-layer) is present, and siltstones and mudstones alternating in illite and montmorillonite content continue upward to 90 feet above the base. Alternations of these clay minerals in beds or lenses is visible in the field by the alternating frothy expanded weathered surface of montmorillonitic mudstone and the smoother unexpanded or slicker surface of the illitic mudstone. The considerable amount of montmorillonitic clay in the Salt Wash member here is noteworthy. The upper 34 feet of Salt Wash (above the zone containing montmorillonite) is characterized by illite-chlorite.

The base of the Brushy Basin member is a clayey sandstone; the clay mineral consists of montmorillonite that contains some intermixed illite. In the lower 65 feet of the Brushy Basin member, mixed-layer montmorillonite predominates, but some illite is also present. The upper 245 feet of the Brushy Basin member, as represented by 8 samples, contains predominantly montmorillonite, some of which is slightly mixed/layered. The mudstone weathers to a series of benches or steps in which the clay mineral is dominantly montmorillonite. The flat parts, or treads of the steps, are characterized by strongly swelling clay that weathers to a frothy surface. The vertical faces, or risers of the steps, owe their superior resistance to weathering to either quartz silt or possibly chalcedonic cement, which seems to be more abundant in the risers than in the easily eroded treads of the steps. Cements of iron oxide or carbonate minerals probably also aid in holding up a vertical face, but silica was observed more often than other cements in thin sections of mudstones from the vertical parts of steps and benches.

SAN RAFAEL RIVER BRIDGE SECTION

No. 4 (178); Emery County, Utah; sec. 27, T. 22 S., R. 14 E., mineralized

The Salt Wash member at this locality characteristically contains illite in its clay-mineral fraction, but in addition to the illite, mixed-layer montmorillonite was observed in two samples, 20 feet and 54 feet above the base, and in a third sample about 157 feet above the base. This is the easternmost locality in which montmorillonite was observed in the Salt Wash member, and is probably near the thin edge of a montmorillonite-bearing lens that thickens toward the west.

The Brushy Basin member at the San Rafael River Bridge section is characterized in clay mineral content by the preponderance of montmorillonite which dominates the X-ray diffractograms.

SMITH CABIN SECTION

No. 5 (near 186); Emery County, Utah; sec. 33, T. 20 S., R. 14 E.; unmineralized (not shown on pl. 1)

The Smith Cabin section was visited in the hope that some relatively fresh volcanic ash might be found in prominent white resistant beds that are exposed in the lower third of the Brushy Basin member. Unfortunately even the beds that appeared freshest in the hand specimen, and those containing well-preserved flakes of biotite and a shard fragment in thin section are highly silicified, and no ash could be found which had not been extensively altered. Both the massive and fissile varieties of the claystones yielded montmorillonite diffraction patterns. A slight reflection at the kaolinite position was obtained from a shaly specimen.

DUMA POINT SECTION

No. 6 (64); Grand County, Utah; sec. 19, T. 23 S., R. 18 E.; unmineralized

At the Duma Point section, the Salt Wash member of the Morrison formation, near its type locality, contains dominantly illite in its mudstone portion, but the clay fraction from the sandstone may contain chlorite with the illite. The chlorite may have originated by the addition to illite of magnesium introduced by percolating water.

X-ray analysis of the clay-sized fraction from the top thick sandstone unit yielded only quartz reflections.

Although some illite is present in the lower 50 feet of the Brushy Basin member, montmorillonite characterizes the member in general and is the dominant mineral constituent in most of the X-ray diffractograms. Most of the Brushy Basin member here exhibits frothy weathered surfaces and is commonly exposed in a series of benches or steps, where treads show the most expansion and frothiness. The steep to vertical risers of the steps apparently owe their greater resistance to weathering to a larger content of quartz silt and secondary silica cement. This reason for the steplike slopes in mudstone of the Brushy Basin seems to apply as a generalization throughout its extent.

The variegated color of the Brushy Basin here ranges from gray to reddish, including many intervening pastel shades of red diluted with gray. The typical montmorillonite, the variegated colors, and the general development of the Brushy Basin at the Duma Point locality may be considered representative of bentonitic Brushy Basin on the northern part of the Colorado Plateau. Photomicrographs of a thin section of this mudstone are shown in figure 9. The gross clay mineralogy of both the Salt Wash and Brushy Basin members is much the same at the unmineralized Duma Point locality as at the San Rafael River Bridge section which is classed as mineralized.

COURTHOUSE WASH SECTION

No. 7(43) ; Grand County, Utah; sec. 24, T. 24 S., R. 20 E.; unmineralized

A section of the Brushy Basin member near the head of Courthouse Wash was selected for study because a thick zone of anomalously bluish-green to vivid-green mudstone here contrasts strikingly with the shades of red common in the Brushy Basin elsewhere. The lower 135 feet of the member is composed of typically light-colored variegated gray to red mudstone and siltstone. Above this lower part are the prominent green zone, about 150 feet thick, composed of mudstone and minor amounts of siltstone and fine sandstone; and a 40- to 50-foot zone of mottled red and green mudstone that overlies the green zone.

The lower, reddish part of this section contains montmorillonite as the chief clay mineral, but a minor amount of illite, associated with mixed-layer montmorillonite-illite, occurs near the base. Likewise, the green zone and the mottled portion overlying it also contain montmorillonite as the chief clay mineral, but illite commonly makes up about $\frac{1}{10}$ to $\frac{1}{4}$ of the clay. Thus, the variegated reddish mudstones differ little from the green mudstones in gross clay mineralogy as indicated by X-ray diffraction. The green mudstone is relatively rich in potassium—it contains even more than can be assigned to exchangeable cations—and therefore some illite (the potassium-bearing clay), although not greatly within the threshold of detection by X-ray, may be present, interlayered in the green mudstone. The green clay does not have a ferric oxide coating (as is present on the red clay) and, therefore, the ferric iron in the green clay must be present within the silicate structure. The green color does not arise from a high content of copper, chromium, nickel, or vanadium in the clay, and the green clay does not contain more of these metals than does associated red clay. The green color is interpreted to arise from a favorable ferrous-ferric ratio of iron in a potassium-rich clay mineral, and the green clay is probably an example of a transition between montmorillonite and illite end members of that 3-layer clay

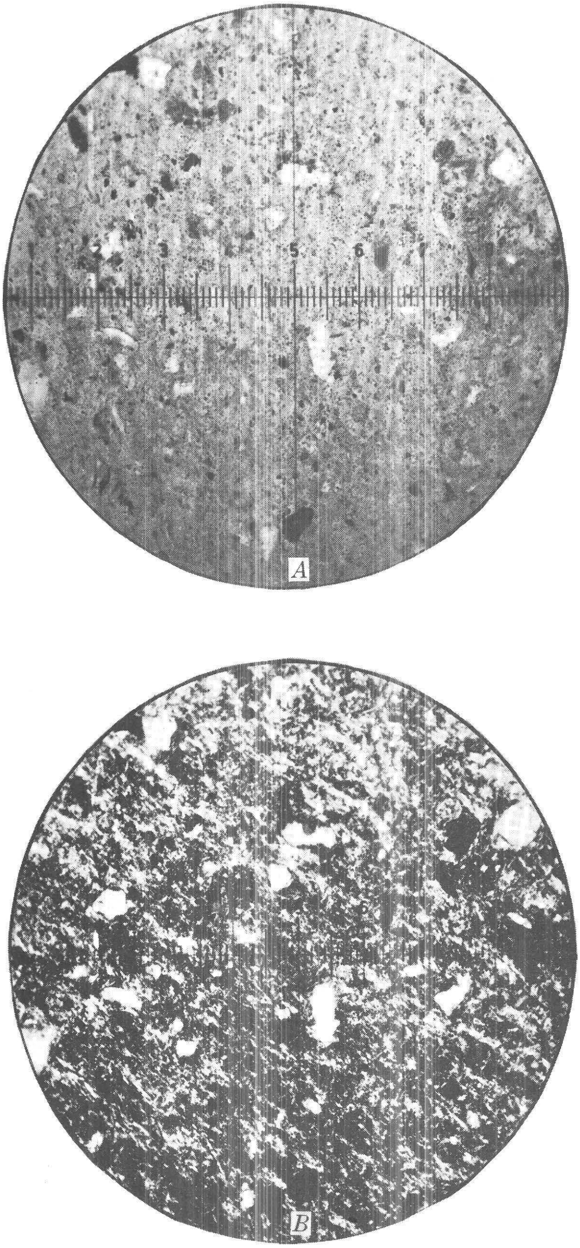

FIGURE 9.—Photomicrographs of typical montmorillonitic mudstone in the Brushy Basin member. *A*, plane-polarized light. *B*, crossed nicols. Magnification: 10 small divisions equal 0.12 mm. Shredlike shapes of highly birefringent montmorillonite cut across the altered matrix of volcanic ash. Silt-sized grains of quartz and feldspar are also present. Sample 55–223, Duma Point section, No. 6 (64), Grand County, Utah.

group. Details of this clay mineralogy will be elaborated in a following section of this report.

YELLOW CAT SECTION

No. 8(231); Grand County, Utah; near common corner of T. 22 S., R. 21 E., T. 23 S., R. 22 E; mineralized

The clay minerals in the Salt Wash member are chiefly mixed-layer types: mixed-layer chlorite, mixed-layer illite, and a relatively small amount of mixed-layer montmorillonite near the top. The Brushy Basin member also contains a noteworthy amount of mixed-layer clays. In the lower part of the member occur mixed-layer montmorillonite, chlorite, and illite. In the middle part purer montmorillonite is present. The upper part contains mixed-layer montmorillonite, some chlorite, and a relatively small amount of kaolinite.

Thus, almost the entire Morrison section at Yellow Cat, a mineralized section, is characterized by random mixed-layer types. Mixing in the clay minerals may have developed by ions that are characteristic of the random-layer clays being carried by solutions which moved through the rocks. Perhaps these solutions were mineralizing, or if not, perhaps they followed channels which were also accessible to the movement of mineralizing solutions, either hypogene or supergene.

LONE TREE MESA SECTION

No. 9 (117); Montrose County, Colo.; secs. 2 and 3, T. 48N., R. 18W.; generally mineralized area

The Morrison section in the Lone Tree Mesa and Blue Mesa region is of special interest because it is one of the thickest Morrison sections (about 750 ft. thick) on the Colorado Plateau, the Brushy Basin member is anomalously blue, and a 15-foot siltstone unit near the top of the Brushy Basin member is colored a typical glauconite green by glauconitic mica (Keller, 1958).

The clay minerals in the Salt Wash member are dominated by typical illite, as is commonly characteristic of that member. Thus, the clay minerals of the Salt Wash member here show no departure from their usual composition, although an anomalous clay mineralogy will be described for the Brushy Basin member.

The clay minerals in the Brushy Basin member can be rather closely identified by their color. The blue clay is composed chiefly of illite, its mixed-layer derivatives, and lesser amounts of closely intermingled montmorillonite and slight amounts of chlorite. The red and variegated clays are composed chiefly of montmorillonite and lesser amounts of illite and mixed-layer derivatives. These differences in mineralogy, as determined physically by X-ray diffraction, are confirmed by the chemical composition of two analyzed clays. Analcime also was found in several samples from the blue mudstone in the upper half of the Brushy Basin member, and identified in thin section and by X-ray diffraction (fig. 10).

The blue color does not arise from an anomalously high content of copper, chromium, nickel, or vanadium in the clay, nor are these metals in greater abundance in the blue clay than in the associated red clay. The blue color of the illite and the green color of the glauconitic mica are interpreted to originate from iron in two states of oxidation in the silicate structure of illitic minerals, as was previously suggested for the anomalous blue-green color in the clay at Courthouse Wash (section No. 7). The clay mineralogy relative to these colors is discussed in detail in a following section of this report.

DOLORES GROUP SECTION

No. 10 (56); Montrose County, Colo., secs. 19, 20, 23, and 30, T. 48N., R. 17W.; mineralized

The mudstone part, including the mudstone splits, of the Salt Wash member at this locality contains predominantly illite. The clay fractions from the sandstones of this member, however, contain kaolinite or chlorite as well as illite, and the kaolinite and chlorite may be more abundant than illite in the samples. The kaolinite and chlorite probably represent secondarily developed clay minerals that originated from the action of solutions moving through the sandstones. The mudstones, being less permeable than the sandstones, contain only the illite (with respect to clay minerals) originally present in them. No independent evidence was found to indicate whether or not the clay-modifying solutions were mineralizing in character. That such solutions did not necessarily carry uranium and vanadium is shown by (1) the greater abundance of chlorite in sandstones than in adjacent shales in nonmineralized localities, as at the Duma Point section, No. 6 (64), and (2) the enrichment of kaolinite in sandstone relative to adjacent shale in occurrences far removed in space and time from the Colorado Plateau: rocks of Pennsylvanian age in Illinois (Glass and others, 1956; Potter and Glass, 1958). Therefore, kaolinite and chlorite in sandstone merely confirm the fact that chemically active solutions, regardless of whether or not they were mineralizing in character, moved through the sandstones; these minerals are only permissive, but not diagnostic, indicators of ore.

The Brushy Basin member at the Dolores group section contains chiefly montmorillonite in its lower part, but mixed-layer illite increases in relative amount to become a major clay-mineral constituent near the top. The mixed-layer illite in the upper part may

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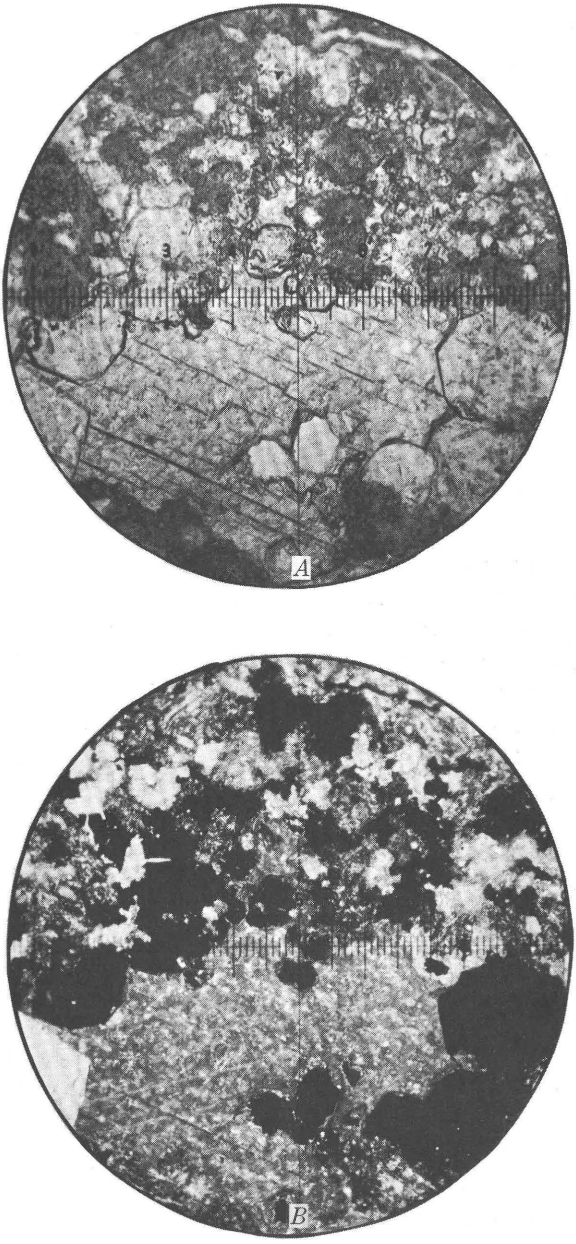

FIGURE 10.—Photomicrographs of analcime and carbonate in mudstone in the Brushy Basin member. *A,* plane-polarized light. *B,* crossed nicols. Magnification : 10 small divisions equal 0.12 mm. The analcime is dark between nicols. Silt-sized grains of quartz and feldspar are present in the clay. Sample 55–174, Lone Tree Mesa section, No. 9 (117), Montrose County, Colo.

represent a gradational facies of the illite that is so well developed about 5 to 10 miles to the north on Lone Tree Mesa.

SKEIN MESA SECTION

No. 11 (182), Bull Canyon district; Montrose County, Colo.; secs. 16 and 17, T. 46N., R. 19W.; unmineralized

The Skein Mesa section occurs in an unmineralized part of the otherwise generally mineralized Bull Canyon district and affords an opportunity to compare the clays of this unmineralized part with those of the mineralized section of Bachelor Draw, about 5 miles distant, but also in the Bull Canyon district. In the Salt Wash member at Skein Mesa, 4 samples contained illite and 2 samples contained chlorite. The same clay minerals were identified at the mineralized Bachelor Draw section.

The Brushy Basin member contains mixed-layer illite-chlorite and illite-montmorillonite, except for a montmorillonite-rich zone 300 to 350 feet above the base.

BACHELOR DRAW SECTION

No. 12, Bull Canyon district; Montrose County, Colo.; SW corner sec. 1, T. 45 N., R. 8 W.; mineralized

The clay-sized fractions of the samples from the Salt Wash member at Bachelor Draw yielded quartz, illite, and, in the ore-producing sandstone unit, mixed-layer chlorite. Although chlorite occurs in the ore-producing sandstone here and might be considered significant as a guide to ore, the presence of chlorite in two barren sandstones in the Skein Mesa section vitiates chlorite as a diagnostic indicator of ore.

The samples from the Brushy Basin member yield illite and chlorite in the lower half of the member, then mixed-layer montmorillonite-illite at about 155 feet above the base, and illite and chlorite in the upper part. It is noteworthy that the predominance of montmorillonite in the Brushy Basin on the northern part of the Colorado Plateau gives way to chlorite and illite in this region farther south. The change is interpreted as being a regional facies trend.

DRY CREEK ANTICLINE SECTION

No. 13 (61), Bull Canyon district; Montrose County, Colo.; secs. 19 and 20, T. 45 N., R. 16 W.; unmineralized

The Dry Creek anticline section, although in the generally mineralized Bull Canyon district, is not mineralized here and may be contrasted in clay mineralogy with the section at Bachelor Draw. The clay minerals in the Salt Wash member are illite in the mudstone, and illite and mixed-layer illite and chlorite in the clay-sized fractions of the sandstone.

The Brushy Basin member contains montmorillonite, commonly with some illite and mixed-layer clay minerals, in the lower four-fifths of the member. The clay minerals in the upper fifth are chiefly illite, a subordinate amount of chlorite, and a relatively small amount of kaolinite.

SLICK ROCK SECTION

No. 14 (184); San Miguel County, Colo.; secs. 28 and 33, T. 44 N., R. 18 W., mineralized

The Salt Wash member contains dominantly illite in its clay-sized fraction. However, the upper thick sandstone zone, which is the ore-producing rock in most of the Slick Rock mining district, contains illite and chlorite in about equal amounts. Independent evidence is lacking as to whether the chlorite is an original constituent of the ore-bearing sandstone or whether it was secondarily emplaced. Judging from the common occurrence of chlorite in Morrison rocks at other localities, its value as an indicator of ore minerals is probably not significant in the upper sandstones of the Salt Wash at Slick Rock.

In the lower 100 feet of the Brushy Basin member the clay mineral is chiefly illite, accompanied by a small amount of chlorite. In the upper 300 feet the clay minerals are chiefly montmorillonite, mixed-layer montmorillonite, and illite.

LOWER McELMO CANYON SECTION

No. 15 (124); Montezuma County, Colo.; sec. 30 T. 46 N., R. 18 W.; unmineralized

The previously described Morrison sections were divided into the Salt Wash and Brushy Basin members, but in the section at Lower McElmo Canyon and several of those following it, the Recapture shale and Westwater Canyon sandstone members are also present.

The clay minerals in the Salt Wash samples are illite chiefly, but mixed-layer illite-chlorite is present in the member's lowest and highest units.

The Recapture member yielded illite, a small amount of kaolinite, and montmorillonite(?) near the center of the member.

Clay minerals in the Westwater Canyon member include illite and chlorite in the lower part and well-defined montmorillonite near the top.

The clay minerals in the Brushy Basin member are chiefly mixed-layer derivatives of montmorillonite and chlorite, but two samples also contain some kaolinite.

OAK CREEK SECTION

No. 16 (151); San Juan County, N. Mex.; secs. 12 and 13, T. 29 N., R. 21 W.; mineralized

The mineralized Oak Creek section includes the same members as does the unmineralized section at Lower McElmo Canyon about 50 miles north. At Oak Creek illite is present near the base of the Salt Wash member, chlorite is sparsely present with illite in the center, and mixed-layer illite-chlorite occurs near the top. Likewise, the samples from the Recapture member show illite in the lower part, and chlorite and illite in approximately equal quantities in the upper part.

The clay-sized fraction from the sandstone of the Westwater Canyon member contains illite and chlorite, except at the top of the member where montmorillonite is the clay mineral. The Brushy Basin member is here characterized by montmorillonite.

Analcime was identified in the lower part of the central zone of the Brushy Basin. Shards replaced by carbonate are well preserved in a calcareous mudstone layer near the top of the section (fig. 11*A*).

THOREAU SECTION

No. 17 (207) ; McKinley County, N. Mex.; sec. 13, T. 14 N., R. 13 W.; unmineralized

In the prominent cliffs north of Thoreau, N. Mex., the lowest part of the Morrison formation is represented by the Bluff sandstone of Late Jurassic age. The Bluff sandstone here is nearly white, relatively clean, and almost devoid of clay minerals, but very scanty amounts of montmorillonite, and a minor amount of kaolinite in most samples, were detected in the clay-sized fraction of the sandstone.

The Recapture member yielded montmorillonite in every sample; the montmorillonite was accompanied by kaolinite in the lower half of the exposed part of the member, and by a relatively small amount of illite and kaolinite in the top unit.

The Westwater Canyon member is commonly porous, friable, and ranges in color from gray to some shade of tan, red, or brown. White sand- and silt-sized grains range in amounts from sparse to perhaps several percent of the sandstone. Apparently some of these white grains are kaolinite, but others are montmorillonite. They are interpreted as being secondary in origin, probably alteration products of volcanic material or detrital feldspar, although some seem to be deposited between and on the grains from solution. The clay-sized fractions of samples taken across this member yielded montmorillonite, chlorite, and kaolinite, but no illite.

In five samples collected from the Brushy Basin member montmorillonite accompanied by illite was found in the lower half, and kaolinite occurred in the upper half.

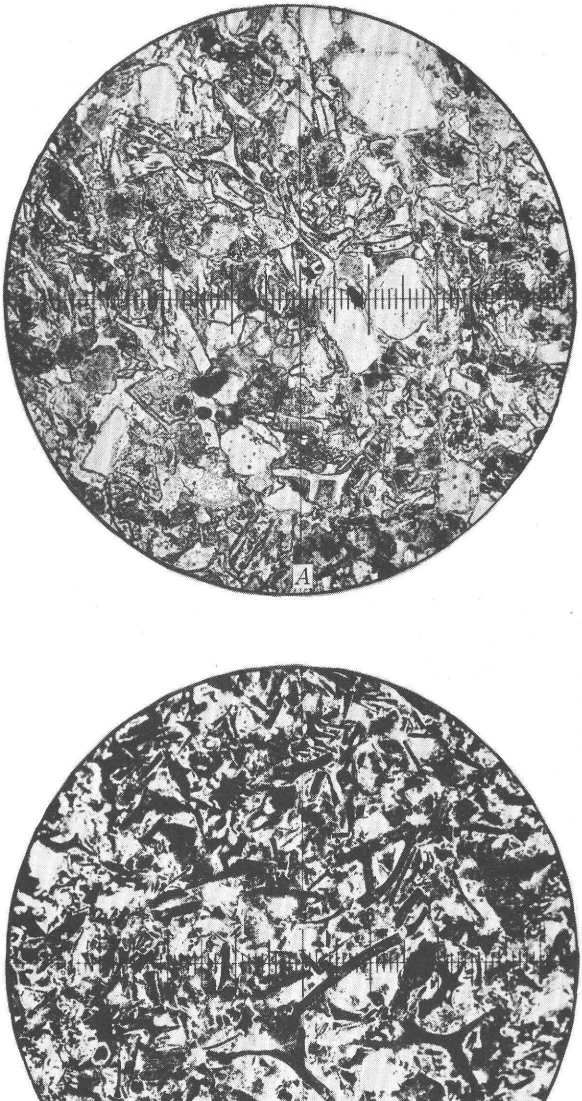

FIGURE 11.—Photomicrographs of shards in the Brushy Basin member: replaced (*A*) by carbonate and (*B*) by red iron oxide. Magnification: 10 small divisions equal 0.12 mm.

A, Sample 55–71, Oak Creek section, No. 16 (151).

B, Sample 56–177, Klondike region, supplemental to Dry Creek anticline section No. 13 (61), described on page 75.

HAYSTACK BUTTE SECTION

No. 18 (92); McKinley County, N. Mex.; secs. 7 and 18, T. 13 N., R. 10 W.; unmineralized section in a mineralized region

The clay-sized fraction of the Bluff sandstone contains montmorillonite which is commonly accompanied by a minor amount of kaolinite.

The Recapture member contains chlorite and illite in its lower half; the prominent sandstones near the top yield scarcely enough clay minerals in their clay-sized fractions to be identified; and the top mudstone zone contains illite.

The uppermost 237 feet of the Morrison formation here is divided (R. E. Thaden, oral communication, 1957) into a lower tongue of the Westwater Canyon member, 120 feet thick, and in rising sequence: a lower mudstone tongue of the Brushy Basin, 12 feet thick; the upper sandstone tongue of the Westwater Canyon, 42 feet thick; and at the top, the upper mudstone tongue of the Brushy Basin, 74 feet thick. The lower tongue of the Westwater Canyon member contains montmorillonite and kaolinite in about equal proportions; the upper zone also contains chlorite. The lower tongue of the Brushy Basin contains montmorillonite. The upper tongue of the Westwater Canyon contains mixed-layer chlorite-montmorillonite. The upper mudstone tongue of the Brushy Basin member yields montmorillonite and mixed-layer chlorite-montmorillonite.

LAGUNA SECTION

No. 19 (103); Valencia County, N. Mex.; NW¼ sec. 28, T. 10 N., R. 5 W., and at the Jackpile Mine; mineralized

At the Laguna section the Recapture member contains mixed-layer montmorillonite derivatives.

The clay fraction from the sandstone of the Westwater Canyon member yielded montmorillonite and kaolinite, whereas claystones that occur as pods and lenses (splits) in the member are composed of montmorillonite and mixed-layer montmorillonite with illite and chlorite. Here again, as in the Dolores group section, is evidence that kaolinite may occur in relatively permeable sandstones associated with relatively impermeable mudstones whose clay-mineral constituents are three-layer clay minerals and chlorite.

The Brushy Basin member contains montmorillonite throughout, except for the top 10 feet in which illite was found.

The Jackpile sandstone of local usage in the Laguna section yields mixed-layer illite and chlorite and a small amount of kaolinite in its clay-sized fraction. Illite in small proportion is present in a silty facies of the sandstone.

At the Jackpile mine, the Jackpile sandstone contains in its clay-sized fraction two clay-mineral assemblages: kaolinite and dickite, which are presumably intermixed, in some parts (represented by one sample) of the sandstone; and mixed-layer illite-montmorillonite and illite-chlorite in other parts. Mudstone layers within the Jackpile sandstone contain montmorillonite, illite, and mixed-layer chlorites.

Dickite, identified by differential thermal analysis, was found apparently mixed with kaolinite in only one specimen of the Jackpile sandstone. Dickite, in general, commonly crystallizes in well-formed hexagonal flakes, or at least in more nearly euhedral shapes than does kaolinite; but such morphological differences could not be detected within this clay fraction under the microscope. In older geologic literature dickite has been tentatively assigned to a hydrothermal genesis, but in more recent years many occurrences of dickite have been found in sedimentary rocks entirely removed from hydrothermal associations. For example, dickite and kaolinite are formed in cavities within chert at or near the unconformity between rocks of Mississippian and Pennsylvanian ages in central Missouri, hundreds of miles from any known surface indication of hydrothermal action. Presumably this dickite, which occurs in small but euhedral hexagonal flakes, owes its origin to the action of waters associated with the position of the unconformity. Likewise, although the dickite in the Jackpile sandstone might be hydrothermal in origin, it is equally possible that it originated by way of circulating ground water no warmer than the rocks into which that water migrated.

The hope that one or more diagnostic clay minerals might be an indicator of uranium is dimmed by the occurrence of virtually the entire assemblage of clay minerals—dickite, kaolinite, montmorillonite, illite, and mixed-layer chlorite—in the ore-bearing sandstone and mudstones of the Jackpile.

MESA GIGANTE SECTION

No. 20; Valencia County, N. Mex.; sec. 34, T. 11 N., R. 3 W., Canyoncito Navajo Indian Reservation; unmineralized

The upper 122 feet of the Bluff sandstone, which is characterized by planar crossbedding, is exposed in this section at Mesa Gigante. The clay-sized fraction of the sandstone is scanty, but montmorillonite occurs near both the top and the base of the section, and kaolinite and mixed-layer chlorite-illite are present in about equal amounts in a sample from near the center.

Undifferentiated Morrison formation about 270 feet thick overlies the Bluff sandstone and, in turn, is overlain by the Dakota sandstone of Cretaceous age. All 11 samples from the Morrison rocks yielded mainly montmorillonite, although minor amounts of illite, kaolinite, and mixed-layer chlorite are distributed sporadically among them.

Even the lower part of the Dakota sandstone, which contains coaly or at least carbonaceous clay, also yields montmorillonite and kaolinite.

SOUTH CANYON SECTION

No. 21 (188); Garfield County, Colo.; sec. 2, T. 6 S., R. 90 W.; unmineralized (not shown on pl. 1)

The northeasternmost section sampled (sampled only in part) in this study is located in South Canyon, Garfield County, Colo. The Salt Wash and Brushy Basin members, which are readily defined and separable over most of the Colorado Plateau, are not clearly delimited in South Canyon. L. C. Craig collected four specimens here: one definitely from the Salt Wash member, two that are equivalent to the Salt Wash in stratigraphic position, and one that is definitely from the Brushy Basin. The clay in the first three samples was identified as illite, and that from the Brushy Basin member as mixed-layer illite-chlorite. Craig reported (oral communication, 1958) that no swelling clays were observed in the field exposures of the entire section.

SAPINERO SECTION

No. 22 (179); Gunnison County, Colo.; sec. 23, T. 49 N., R. 4 W.; unmineralized

The Salt Wash member contains illite, mixed-layer illite, and a small amount, relative to the illite, of chlorite. The clay-mineral content here is similar, qualitatively, to that at other unmineralized and mineralized localities.

The Brushy Basin member at Sapinero is mostly greenish gray to tan, differing from the common red, purple, and bluish-gray colors it displays in western Colorado and Utah. The clay minerals in the Brushy Basin at Sapinero are dominantly montmorillonite and minor amounts of kaolinite. This kaolinite is more prominently developed here than at any other Brushy Basin section studied. Kaolinite is typically an indicator of intensive leaching, which may occur in a mudstone most readily during weathering or by hydrothermal action.

LOS OCHOS MINE AREA

No. 23; Saguache County, Colo.; T. 47 N., R. 2 E.; mineralized, probably by hypogene solutions

A diamond-drill core from the mineralized rock in the Los Ochos mine area, Saguache County, Colo., was made available for sampling through the courtesy of the Gunnison Mining Co. This mineralized locality is about 30 miles (airline) southeast of the unmineralized

Sapinero section, No. 22. The core was started in the uppermost part of the Morrison formation at 47 feet and continued in Brushy Basin rocks to 242 feet, thence into sandstone, tentatively referred to the Salt Wash member, to a depth of 261 feet (L. C. Craig, oral communication, 1956), and bottomed in schist of Precambrian age at 266 feet. The exact angular relation between the direction of the drill core, which was inclined 60° to the horizontal, and bedding of the rocks is not known. If the beds were horizontal, the stratigraphic positions will be less than the drill-core footage by a multiplier factor of 0.866. Production of uranium ore, most of which is unoxidized black material, possibly uraninite, is reported from the Brushy Basin and Salt Wash members along a fracture or fault zone.

Sixteen samples of the Brushy Basin were analyzed. They yielded clay minerals in which kaolinite, commonly accompanied by some illite, was most prevalent down to about 200 feet in the hole, but between 200 and 242 feet illite probably mixed with, or possibly converted to, sericite predominated. The presence of kaolinite in dominating proportion in mudstones of the Brushy Basin at Los Ochos is in marked contrast to the predominant montmorillonite or mixed-layer illite that regularly comprises the Brushy Basin rocks elsewhere. The writer interprets this occurrence of kaolinite as being due to the leaching action of solutions, apparently sulfide-bearing and acidic in chemical character, which removed the univalent and bivalent metal cations and perhaps some silica from preexisting clays and left hydrogen and possibly enriched alumina in place in combination with silica to form the kaolinite. This chemical environment, whether hydrothermal or phreatic, produces the kaolin group among the clay minerals (Keller, 1956; 1957, p. 61–75; 1958).

No independent evidence is apparent to the writer for the proposition that ions of uranium (or vanadium) in the mineralizing solutions exerted a unique action, or physically recognizable change, in the gross mineral alteration of the clays. This does not say that uranium or vanadium ions did not enter the clay structure, as in the formation of vanadiferous micas or chlorites, but if they did, their detection must be based on chemical properties rather than their mineralogical (structural) effects on the clays. Kaolinite, but not dickite, is the kaolin mineral developed at Los Ochos by the alteration that is presumably hydrothermal. If dickite is dependably diagnostic of hydrothermal alteration, dickite would be expected to occur here.

Three samples were collected from the part of the core (depth, 242–261 feet) tentatively referred to the Salt Wash. Only one of these yielded a clay-mineral fraction: it was illite and minor amounts of chlorite.

SUMMARY

Although a wide variety of clay minerals occurs in both the Salt Wash and Brushy Basin members of the Morrison formation, the clays of the Salt Wash are dominated by illite and its mixed-layer derivatives, and the clays of the Brushy Basin member are mainly montmorillonite, derived from volcanic rock, and its mixed-layer derivatives. The distribution of such montmorillonite represents the distribution and argillation of volcanic ash to form a large clay-rich mudstone unit.

ARGILLATION OF THE BRUSHY BASIN SHALE MEMBER

Apart from the physical occurrence and distribution of the montmorillonite and its mixed-layer derivatives in the Brushy Basin member, the origin from volcanic ash of the montmorillonitic material, which comprises most of the member, and the ancillary products of the alteration process, are also of interest because of the vast amount of material involved. The argillation of the volcanic ash was a chemical and mineral reaction associated with a rock body of tremendous size—one that could have been derived from a source of batholithic dimensions (Ross, 1955). Even the amounts of the trace or minor constituents of the ash involved in the alteration become significantly large when they are measured in terms of quantities applicable to industry and technology. Consider, for example, 1 square mile of volcanic ash 350 feet thick (a conservative thickness for most of the Brushy Basin member), which has a probable bulk specific gravity of 1.0 (Lovering, 1957). This prism of ash would weigh about 300 million tons, and if only 1 ppm (part per million) of it were shifted in composition or position, the change would involve 300 tons per square mile, an amount that would be highly significant if the material were a valuable ore mineral. Thousands of square miles of clay about 350 feet thick in the Brushy Basin were argillized, and many minor constituents of the ash were more abundant than 1 ppm; so the magnitude of the chemical changes in both major and minor constituents during argillation is exceedingly great.

It would be desirable to know the stoichiometric relations betwen the participants, products, and the mobile and immobile materials of the argillation reaction, but such information is not available. No unaltered ash in the Brushy Basin could be found which might have been analyzed and compared in composition with that of an argillized equivalent. Even the geologic literature is almost without analyses of ash-clay pairs from which details of their chemical alteration may be learned; but one pair, an analysis of a slightly altered ash from the Puerco Valley, Ariz., and its bentonitic counterpart, is reported by Nutting (1943). This pair will be used to illustrate quantitatively the probable nature of the changes that occurred in the argillation of the Brushy Basin member, the chemical changes being calculated in terms of assumed immobile aluminum during the reaction. Actually, aluminum probably does not remain completely static during argillation, but such an assumption provides a convenient base line for reckoning, and for further adjustment in calculations if desired.

Nutting's analyses are recalculated on a water-free basis (table 1). The combined water, 6.60 percent, in his "partly altered tuff," is abnormally high for fresh tuff, and this figure has been reduced in the calculations to 4.75 percent, a mean value found by Kiersch and Keller (1955) for the loss on ignition of several samples of fresh tuff. Columns 1 and 2 of table 1 are recalculated analyses of tuff and bentonite, respectively. In column 3 the constituents from column 1 were increased proportionately by the factor used to raise 13.94 units of Al_2O_3 to 18.45 units (thus holding constant the Al_2O_3 in the ash and bentonite). Column 4 shows the gain or loss in oxides that occurred when the tuff was converted to bentonite. In column 5 the gain or loss of each oxide is expressed as a percentage of the fresh tuff.

TABLE 1.—*Recalculated analyses of tuff and bentonite from Puerco Valley, Ariz.*

	1	2	3	4	5
SiO_2	69. 87	60. 13	92. 47	−32. 34	−24. 26
Al_2O_3	13. 94	18. 45	18. 45	. 00	----------
Fe_2O_3	2. 77	3. 98	3. 67	+. 21	+. 16
MgO	2. 20	5. 32	2. 91	+2. 41	+1. 81
CaO	1. 83	2. 42	2. 42	. 00	----------
Na_2O	1. 25	. 27	1. 65	−1. 38	−1. 04
K_2O	3. 50	. 18	4. 63	−4. 45	−3. 34
H_2O^+	4. 75	8. 40	6. 29	+2. 11	+1. 58
TiO_2	. 34	. 48	. 45	+. 03	+. 02
	100. 45	99. 63			

1. Tuff. Recalculated from analysis by Nutting (1943).
2. Bentonite. Recalculated, free of mechanical water, from Nutting's analysis.
3. Calculated ratio of analysis 1 when Al_2O_3 is raised to 18.45; similar to content in analysis 2.
4. Gain (+) or loss (−) between columns 2 and 3 during argillation, holding Al_2O_3 constant.
5. Gain (+) or loss (−) during argillation, as a percentage of the fresh tuff.

If it is assumed now that argillation of the Brushy Basin member occurred by the same general reaction as that by which the Puerco Valley tuff was altered, it would follow that about 25 percent of the tuff in the Brushy Basin was converted to mobile silica, which thereupon could either be carried completely away from the system or redeposited as secondary silica in the residual clay. Accurate determination of the amount of secondary silica now in the mudstone is practically impossible, owing to the uncertainty of separating or even precisely distinguishing secondary from primary silica, and the difficulty of measuring quantitatively that which can be seen. Cherty microcrystalline quartz, fine fibers of chalcedony, and probably opal are so intimately dispersed with clay grains that the silica grains cannot be measured precisely with confidence in thin section. Although the quartz and chalcedony may be estimated by use of X-ray diffraction, that method does not distinguish secondary mineral grains and does not yield an analytical measure of opal. However, despite the lack of precise methods of determining the amount of secondary silica in the clay, a subjective estimate of the silica observed in thin section, and the amount of agate, silicified wood, bones, and sedimentary beds seen in the field is about 10 to 15 percent of the mudstone of the Brushy Basin; that is, about half of its mobilized silica was redeposited. Although the estimate is not precise, perhaps it is at least of the right order of magnitude.

Table 1 shows that sodium and potassium in the ash are largely lost. Possibly they stabilized the dissolved silica as dilute solutions of natural water glass. Calcium may have been dissolved and redeposited as calcite. Magnesium is apparently added during the formation of montmorillonite, but its source, whether it was added from outside the system or whether the amount remained constant during argillation and was proportionately enriched by the loss of other elements, is problematical. The source of apparently additional magnesium in certain other deposits of montmorillonite has likewise not always been known. Some water is gained (hydration) during hydrolysis of the tuff. Elemental iron probably remains virtually constant in amount, but it is oxidized in large part to the hematitic form.

Even less is known about the minor or trace elements in the tuff, or their behavior during argillation, than about the major elements. However, uranium would no doubt be released during the hydrolysis of such volcanic ash, and uranium might go into solution as complexed carbonate ions, like $(UO_2\ (CO_3)_3)^{-4}$, which Gruner (1956, p. 498) reports "are quite soluble in the presence of alkali ions like Na^+." Sodium was dissolved and lost during argillation of the tuff in Puerco Valley as shown in table 1. Thus, sodium would be available as a mobilizing agent as Gruner suggests. Uranium that was mobilized during argillation of ash in the Brushy Basin member might be carried ouside the ash deposit, or at least part of it might be redeposited, as was silica, in the Brushy Basin or in the sandstones of the Salt Wash member below. Waters and Granger (1953, p. 22), who suggested that volcanic debris might be a source of uranium on the Colorado Plateau, believed that the uranium would be absorbed by the bentonite, and "that simple leaching of ash and precipitation of the leached uranium and vanadium by organic matter is inadequate to explain the genesis of the sandstone-type ores of the Colorado Plateaus." Gruner (1956), however, proposed that uranium was mobilized and redeposited in several cycles, to which he gave the name "multiple migration-accretion hypothesis"; such a series of processes may discharge the inadequacy of a simple process considered by Waters and Granger.

The redissolution and reprecipitation of uranium, as in Gruner's hypothesis, demands an alternation in, or a variety of, environments within the parent or host rocks. A terrigenous environment (and rocks) can be characterized by wide fluctuations in temperature, pH, Eh, concentration of dissolved ions due to alternate evaporation and rainfall, and upward, downward, and lateral movement of ground water through organic-rich and organic-poor rocks. Thus, a maximum of opportunity was available in the Morrison rocks for repeated dissolution and precipitation by ground water of the products of hydrolytic and other reactions, such as calcium, magnesium, iron, and uranium ions. Geologists accept without question the irregular stepwise migration and reprecipitation of mineral compounds of calcium, magnesium, and iron, which are clearly visible and common in nonmarine rocks—why not likewise those of the less abundant uranium? The writer feels that Gruner's hypothesis for the origin of the type of uranium ores found on the Colorado Plateau is in better accord with the field and laboratory evidence than any other hypothesis proposed.

The concentration of uranium in the unaltered ash of the Brushy Basin member cannot be determined because fresh ash is unavailable, but its probable order of magnitude can be estimated from data on other volcanic ash. Osmond (1954) found the uranium content of 14 samples of volcanic ash (felsic) from Kansas to range from 6.0 to 8.22 ppm. and to average 6.9 ppm. McKelvey and others (1955) quote an oral communication from Denson that the uranium content of the White River formation (volcanic ash) of Oligocene age is remarkably uniform throughout and ranges from 10 to 20 ppm. Rankama and Sahama (1950) quote Senftle and Keevil (1947) that granitic rocks contain about 4 g of uranium per ton, or 4 ppm. Perhaps 7 to 10 ppm is a reasonable estimate of the uranium content of felsic to intermediate-silica types of volcanic ash and of the unaltered ash in the Brushy Basin member.

If this uranium was mobilized during argillation of the ash, what part of it was lost and what part redeposited? No analytical data on uranium content of ash-clay counterparts are known to the writer to answer the foregoing question. Osmond (1954), in reference to Cretaceous material, summarized the change in uranium content from average felsite to bentonite as a gain of 100 percent, and the change from a "hypothetical Cretaceous ash to Cretaceous bentonite" as a loss of 50 percent. These estimates differ so radically that they offer little help on the problem. But, lacking appropriate data, in a hypothetical calculation one might assume that half of the uranium (total uranium in the ash taken as 8 ppm) was lost, and half of it was redeposited. If half of the redeposited uranium (2 ppm) was concentrated as an ore deposit by the mechanism of Gruner's hypothesis, a figure of 600 tons (see p. 39) of elemental uranium, as ore per square mile of Brushy Basin member 350 feet thick, is obtained—far more than enough to account for the uranium being mined on the Colorado Plateau. Although these figures are primarily arithmetical gymnastics, they do demonstrate by an order of magnitude that it would be geologically difficult for a nonmarine formation as large as the Morrison (including the Brushy Basin) not to contain some deposits of uranium. In other words, it seems to be less difficult to explain how the deposits would be formed within the Morrison than to explain plausibly how the Morrison formation, rich as it is in parent volcanic ash and uranium-precipitating organic matter, could escape harboring deposits of uranium which was necessarily mobilized during argillation of the volcanic ash.

Another question concerning the argillation of the Brushy Basin member is that of the time or stage in the geologic history of the member when the major alteration of ash to clay took place. Closely interwoven with the time is the question of how the ash was deposited; did the ash fall as fresh ash directly from eruption to the place where it now occurs as clay, or did the ash fall elsewhere and undergo partial to virtually complete argillation prior, or en route, to deposition at its present location? If the ash fell at its present location, did argillation occur above the water table or below it; or did argillation take place by action of circulating artesian water long after burial? What part of the Brushy Basin member is eolian, fluvial, or lacustrine in origin?

Evidence that bears on these questions is not completely restrictive; nevertheless it leads to a fairly coherent interpretation of the geologic history of deposition and argillation. The presence of many shard structures fully preserved to the extent of razor-sharp edges suggests that much of the ash fell in place, or that it was not transported far enough to abrade the sharp edges. This interpretation may be subject to some qualification because ash that falls into water may be rapidly floated a long distance without destruction. The massive structure (lack of sharp bedding) suggests eolian deposition and little shifting after deposition for much of the Brushy Basin member, as has been postulated for the deposition of eolian loess which is also without sharp bedding. However, thin sections of some of the mudstones show a crude parallel arrangement of platy shard structure presumably parallel to the surface of deposition, such as is developed by the washing and winnowing actions of water and wind. Moreover, between massive zones in the Brushy Basin member, beds of sandstones and siltstones may occur that do contain sharp bedding and cross lamination, and that are plausibly interpreted as fluvial in origin (Craig and others, 1955). Thus, from these alternating structures, it seems likely that ash was falling over much of the Colorado Plateau during the deposition of the Brushy Basin member, and that braided and heavily laden streams simultaneously, in competition with eolian ash falls for preservation of their channels, were shifting the volcanic detritus on a rapidly aggrading surface. Furthermore, here and there were ephemeral-lake basins in which algal limestones were deposited.

The typical mudstone in the Brushy Basin is red to gray, but dominated commonly by some color produced by iron oxide in various stages of hydration (hematite, goethite, and "limonite"). These colors occur in zones and bands that intergrade, bifurcate, and fade in and out, commonly without sharp borders. The colors are observed not only on outcrops of the member but in drill cores taken from both the Brushy Basin and Salt Wash members far from the present exposures. The iron-oxide colors bespeak oxidation of the ash by waters of high redox potential that were charged with oxygen gas dissolved from the atmosphere, such as occurs in vadose waters today. Fluctuation of the ground-water table and an accompanying fluctuation in redox potential as it moves across the color boundaries might diffuse the colors into gradational borders. Argillation and oxidation in the Brushy Basin member are believed to have occurred simultaneously, for two reasons: (1) the combination of oxygen dissolved in the ground water with iron that had been bonded to silicate groups in the volcanic glass would abstract the iron from within the silicate glass structure, thereby wrecking the silicate structure and increasing its susceptibility to hydrolysis; and (2) the oxygen- and CO_2-rich descending meteoric water was fresh, unmineralized, and most effective for dissolving and moving products of hydrolysis.

Therefore, mobilization of silica, alkali metals, uranium carbonate complexes and other ions is interpreted to have occurred to a major extent during the deposition of the Brushy Basin member and to a depth commensurate with that of the fluctuating ground-water table. Permeability of the ash and clay would still have been high enough to permit adequate circulation of incoming and outgoing water. The argillation and oxidation stage is probably the first step in the multiple migration and accretion hypothesis of Gruner (1956). The argillation process as interpreted above differs from that envisaged by Waters and Granger (1953, p. 21) who "assumed that the rocks were buried deeply during devitrification." The writer, however, concurs with Waters and Granger that circulating connate and artesian waters later redistributed still farther the redissolved products of argillation. Such subsequent redistribution is equivalent to Gruner's multiple migration and, if continued into Eocene time, would meet the age requirements for deposition of the uranium ores as determined by Stieff and others (1953).

Furthermore, in local areas where hydrothermal activity has been superimposed upon regional geologic processes and the movement of fluids has been intensified or localized, ore minerals may possibly have been correspondingly concentrated in the hydrothermally active area. In other words, the formation of a uranium ore deposit on the Colorado Plateau is interpreted as having been primarily a function of concentration, rather than the extent of the source, and concentration may occur because of localized avenues of fluid movement and suitable chemical environment. These conditions may have been achieved wherever geologic structures, the transmissivity of sedimentary beds, or the mobilizing effects of hydrothermal activity were favorable.

CLAY MINERALS IN RELATION TO COLORS OF THE MORRISON FORMATION

The highly variegated colors exhibited by the clay-rich rocks of the Morrison formation place that formation among the most colorful of all sedimentary rocks in the geologic column. It is appropriate to inquire, therefore, into possible relations between the color of the mudstones and the clay minerals composing them. This inquiry is only exploratory and is not by any means exhaustive of the relations between color and sedimentary petrology.

The Brushy Basin member especially, in both its argillaceous and silicified (and agatized) materials, exhibits almost all colors, ranging from white through gray to black, from yellowish tan to red, brown, and purple, and from green to greenish blue and blue. In addition to the occurrence of single colors over large areas, spots, blotches, irregular bands, and ameboid shapes of gray, grayish green, and green occur along divisional openings and at isolated internal locations within the red beds in both the Salt Wash and Brushy Basin members. The colors in these rocks are partly exotic and partly inherent.

GENERAL CONSIDERATIONS OF COLOR

Whiteness in clay minerals arises from countless reflections from many tiny faces; it is analogous to the whiteness seen on the frosted face of clear glass or from powdered sugar or salt which in large lumps are clear to transparent. Pure kaolinite and magnesium-rich montmorillonite are white; they, along with possibly fine-grained silica and carbonate minerals, are the source of whiteness in the Morrison formation. Montmorillonite of other compositions than the magnesium variety and also illite and chlorite may or may not be white. Grayness in clay minerals arises from a mixture of white clay with a black pigment, which may be finely divided carbon, manganese oxide, or sulfides (commonly iron sulfide). Probably most of the dark-gray to black pigment in the Morrison rocks is carbon because practically all Morrison rocks tested for organic matter by Gruner (oral communication, 1955) contained detectible amounts of it.

Yellow, tan, red, brown, purple (including that of the purple-white rocks), and their intermediate hues in Morrison rocks arise principally from iron oxides which are hydrated to a greater or lesser degree. These colors are exotic and commonly may be removed by digestion of the rock in warm dilute acids.

Green, bluish-green, and blue hues are believed to arise from iron silicates (ferrous-ferric in oxidation states) and are inherent colors. Their origin is discussed in greater detail in the section "Green and blue clays at the Courthouse Wash and Blue Mesa areas."

In the Salt Wash member the tan, red, and brown sandstones and mudstones are colored by iron oxide films that coat the coarser grains and permeate the clay minerals. Ease of removal by solvents or by ultrasonic vibration demonstrates the surficial character of the pigmenting minerals. These iron oxide pigments in the Salt Wash member are believed by the writer to have been present generally in place on the grains when the rock was consolidated.

In the Brushy Basin member, the time at which the red and other colors due to iron oxide were formed may vary from place to place in the formation. The color films on certain quartz-rich sandstones presumably were deposited on the quartz grains as in those of the Salt Wash, prior to their consolidation. However, the pigment of the mudstones, whose clay minerals originated by the hydrolysis of glassy volcanic detritus, probably was developed after deposition, during hydrolysis of the ash. As already discussed in the section on argillation of ash in the Brushy Basin, most of the hydrolysis and oxidation probably occurred while the Brushy Basin sediment lay near the surface of the ground, or in the vadose-water zone shortly after burial, because at these times sufficient oxygen was available to oxidize the iron during the hydrolysis reaction. This mechanism explains the development of the red color that within short distances fades in and out as colored zones, tongues, and lenses in the clay-rich part of the member. Red colors are well developed west of Grand Junction, Colo. On the other hand, the blue color at Lone Tree and Blue Mesas and the green color at the head of Courthouse Wash probably represent effects of a late or post-depositional stage of alteration.

Innumerable spots and locally small-scale mottling of green to gray color occur in the red part of the Morrison formation (and probably in most other sedimentary red beds). These nonred areas within red beds have been interpreted as locales that lack ferric oxide, and thus exhibit the inherently gray-green color of certain three-layer clay minerals in the rocks, which elsewhere is masked by red iron oxide. The spots are interpreted to have been secondarily bleached of iron oxide by either: (1) transfer of ferric oxide from the coating possibly by means of sulfate waters to a position of intracrystal ferric silicate within the clay minerals (Gruner and others, 1953); or (2) reduction of ferric oxide by sulfide ions and solutions, dissolution by carbonic acid, and removal of the iron as the bicarbonate (Keller, 1929). Shawe (1956) attributed the red color of the sedimentary rocks of the Colorado Plateau to the oxidation of magnetite, ilmenite, and other heavy detrital minerals, whereas green color he found characterized pyrite-bearing rocks. He attributed the green color to loss of iron-bearing minerals, formation of anatase, and recrystallization of barite. Miller and Folk (1955) found detrital magnetite or ilmenite commonly abundant in mottled-red sedimentary rocks (not necessarily the Morrison formation) but absent or sparse in gray, green, or white sedimentary rocks. Langenheim (1955), on the other hand, found in his thin sections that "magnetite in the non-red rocks was equally as prominent as that in red rocks."

COLOR OF MUDSTONES IN RELATION TO CLAY MINERALOGY

A high ratio of green or greenish-gray to red color in the mudstone within or below the ore-bearing sandstone of the Salt Wash member has been used as a guide to favorable ground in prospecting for carnotite deposits (Weir, 1952). This observation led to inquiry whether certain clay-mineral families could be correlated with particular colors of rocks, and whether differences existed between the clay minerals in red and green mudstones in productive and in barren sedimentary rocks. Results of a study made on about 400 samples of mudstone and clayey sandstone from 6 uranium-producing formations, including the Morrison formation, on the Colorado Plateau are the subject of a previous report (Keller, 1959).

Clay minerals assignable to all of the common clay-mineral groups may be constituents of both red and green mudstone without restriction to color. Moreover in the Morrison, stratigraphic counterparts of red and green mudstone collected only a few inches apart show no significant difference in gross clay mineralogy. Furthermore, no difference was detected in the gross clay mineralogy of red-green counterparts, either in planes where the green color was developed along mineralized faults which transected the red beds a long time after lithification, or in isolated spots within thick relatively impermeable mudstones, whose color change may have occurred during diagenesis. Mudstones may be ore-bearing or barren without necessary difference in their clay-mineral components or colors. Schultz (oral communication, 1958) came to similar conclusions from his study of clay minerals in Triassic ore-bearing and barren mudstones and sandstones on the Colorado Plateau.

The fact that both red and green mudstones contain the same clay minerals is not relevant to Weir's correlation between green color and favorable ground. It simply points out that the correlation pertains not to the clay minerals, but rather to the ferric oxide coating, or lack of it, on the clay minerals.

GREEN AND BLUE CLAYS AT THE COURTHOUSE WASH AND BLUE MESA AREAS

Previous mention has been made of anomalously green to bluish-green (5*G* 5/2; 10*G* 4/2)[1] clays in the Brushy Basin member at the head of Courthouse Wash, sec. 24, T. 24 S., R. 20 E., Grand County, Utah, and blue (5*BG* 7/2; 5*BG* 7/6) clays and green (10*GY* 4/4; 10*G* 4/2; 5*G* 3/2) glauconitic mica in the area of Blue and Lone Tree Mesa in secs. 2 and 3, T. 48 N., R. 18 W., Montrose County, Colo. These clays are of special interest for several reasons: (1) the speculative possibility that they might have economic value because certain copper urano-vanadates (Weeks and Thompson, 1954) are green, and green chromium-bearing clay minerals (volkonskoite) have been reported by McConnell (1954) from near Thompsons, Utah (18 miles north of the Courthouse Wash locality), and at Temple Mountain (Kerr and Hamilton, 1958); (2) they may be steps in a mineralogic sequence from ash-derived montmorillonite to glauconitic mica; and (3) the bearing they have on the general problem of the source of color in sedimentary rocks.

To determine if copper, chromium, nickel, or vanadium were present in economically important or significantly large quantities in the blue-green rocks, semiquantitative spectrographic analyses were made of green samples from Courthouse Wash (table 2) and of blue samples from Lone Tree Mesa (table 3). To determine further if a differentially large content of these four (or other) metals was the cause of the blue and green colors, analyses were made also of red, gray, or normal greenish-gray rocks associated with, or stratigraphic counterparts of, the blue and green rocks (tables 2, 3).

[1] Color designations according to the Rock-Color Chart distributed by the Geological Society of America (Goddard and others, 1948).

TABLE 2.—*Semiquantitative spectrographic analyses of mudstone samples from the Brushy Basin member of the Morrison formation, Courthouse Wash section, No. 7 (43)*

Symbols: M, major constituent (> 10 percent); R, red; G, green, the common light green; RG, mottled red and green; Gc, vivid green; Gr, gray; G-Gr, greenish gray
[Analyst Nancy M. Conklin, U.S. Geological Survey. Nearest percent in the series 7, 3, 1.5, 0.7, 0.3, 0.15 . . .]

Element	56–38	56–39	56–40	56–41	56–43	56–44	56–45	56–46	56–47	56–48
Si	M	M	M	M	M	M	M	M	M	M
Al	M	3	M	M	M	M	M	M	M	M
Fe	3	.3	3	1.5	3	1.5	1.5	1.5	3	1.5
Mg	3	1.5	3	3	3	1.5	3	3	3	3
Ca	3	M	3	.7	.7	3	3	.7	.3	.3
Na	1.5	1.5	1.5	1.5	1.5	3	3	1.5	1.5	1.5
K	7	3	3	3	7	3	3	3	3	3
Ti	.3	.15	.3	.3	.3	.15	.3	.3	.3	.3
Mn	.015	.15	.03	.015	.015	.03	.015	.03	.015	.015
B	.003	Trace	.003	.003	.003	.003	.003	.003	.003	.003
Ba	.015	.015	.015	.07	.15	.03	.03	.07	.07	.015
Be	.00015	0	.00015	.00015	.00015	Trace	.00015	.00015	.00015	.0003
Co	.0007	0	.0007	.0007	.0007	Trace	.0007	Trace	.0007	.0015
Cr	.007	.0015	.003	.0015	.003	.003	.0015	.0015	.007	.0015
Cu	.003	.0015	.003	.0015	.003	.0015	.003	.0015	.0015	.0015
Ga	.0015	Trace	.0015	.0015	.0015	.0007	.0007	.0003	.0015	.0007
La	.007	0	.007	0	.003	.003	.007	.003	.007	.003
Nb	.0015	0	.0015	.0015	.0015	.0015	.0015	.0015	.0015	.0015
Ni	.0015	.0003	.0007	.0007	.0007	.0007	.0007	.0007	.0007	.0007
Pb	0	0	0	0	0	0	0	0	0	0
Sc	.0015	.0015	.0015	.0015	.0015	.0015	Trace	.0015	.0007	Trace
Sr	.03	.07	.03	.03	.03	.03	.03	.03	.03	.007
V	.015	.0015	.007	.007	.007	.003	.007	.007	.003	.003
Y	.003	.0015	.003	.003	.003	.003	.007	.003	.003	.0015
Yb	.0003	.00015	.0007	.0003	.0003	.0003	.0007	.0003	.0003	.00015
Zr	.03	.007	.03	.015	.015	.03	.03	.03	.03	.03
Color	RG	Gr	RG	G-Gr	RG	[1] Gc	[1] Gc	[1] Gc	[1] Gc	[1] Gc

[1] At Courthouse Wash.

TABLE 3.—*Semiquantitative spectrographic analyses of mudstone samples from the Morrison formation, Lone Tree Mesa section, No. 9 (117)*

Symbols: M, major constituent (>10 percent); R, red; G, gray green; RG, mottled red and green; B, blue; BG, blue green
[Analyst: Nancy M. Conklin, U.S. Geological Survey. Nearest percent in the series 7, 3, 1.5, 0.7, 0.3, 0.15 . . .]

Element	56-104	56-102	56-101	56-100	56-98	56-97	56-96	56-93
Si	M	M	M	M	M	M	M	M
Al	7.0	1.5	1.5	3.0	1.5	3.0	1.5	3.0
Fe	1.5	1.5	1.5	3.0	1.5	3.0	1.5	3.0
Mg	1.5	3	3	1.5	1.5	1.5	1.5	1.5
Ca	.3	.7	.7	3.0	.3	.3	.15	.07
Na	.7	3.0	3.0	1.5	3.0	.7	.7	.3
K	3.0	3.0	3.0	7.0	3.0	7.0	M	M
Ti	.15	.15	.3	.3	.15	.3	.3	.15
Mn	.015	.015	.015	.015	.007	.015	.007	.015
B	.007	.003	.003	.007	.003	.015	.03	.03
Ba	.015	.03	.03	.03	.03	.015	.015	.07
Be	.00015	.00015	.00015	.00015	.00015	.003	.00015	.00015
Co	.0007	.0007	.0007	.0007	0	.0015	.0007	.0007
Cr	.03	.0015	.003	.003	.0015	.003	.0015	.0015
Cu	.0015	.0015	.0015	.0015	.0015	.0015	.0015	.003
Ga	.0007	.0015	.0015	.0007	.0015	.0015	.0015	.0015
La	0	0	.003	.003	.003	.003	.007	.015
Nb	0	.0015	.0015	.0015	.0015	.0015	.0015	0
Ni	.0015	.0007	.0007	.0015	.0007	.0015	.0007	.0015
Pb	.0015	.0015	.0015	Trace	.007	.0015	.0015	.0015
Sc	.007	.007	.003	.0015	.0007	.0015	.0015	.0007
Sr	.007	.03	.03	.03	.015	.015	.015	.03
V	.03	.007	.007	.007	.015	.007	.015	.015
Y	.003	.003	.003	.003	.0015	.007	.003	.003
Yb	.0003	.0003	.0003	.0003	.00015	.0007	.0003	.0003
Zr	.03	.03	.015	.015	.03	.015	.03	.015
Color	RG	BG	G	R	B	B	B	B

The samples from Courthouse Wash (table 2) contain less than 0.01 percent copper chromium, nickel, or vanadium, and therefore are not ore deposits of those or other metals. Comparison of the analyses of 5 vivid-green mudstones (56–44 to 56–48, inclusive), typical of the green zone, with those of 5 samples of the red, gray, and variegated lower zone (56–38 to 56–43, inclusive) which are used as control samples, shows that the mean content of chromium in the control samples is 0.003 percent, whereas that in the green clay is 0.0016 percent. Thus, the green clay is lower in chromium than the red and gray clays, and therefore the green color is probably not due to chromium. The green clay likewise does not contain enough chromium to be volkonskoite, the chromium-bearing variety of montmorillonite. The mean copper content of the red and gray clays is 0.0024 percent, and that of the green clay only 0.0016 percent. Hence, copper is not likely to be the cause of the green color. The mean nickel content of the controls is 0.0008 percent, and that of the green clay 0.0007 percent; nickel likewise does not seem to be the cause of the green color. Vanadium is also richer in the red and gray control samples, at 0.0075 percent mean value, than it is in the green clay, at 0.004 percent. Both gray and red samples were used as controls; the gray ones were known definitely not to be vivid green, even though the red ones might have been green but masked by a red coating. From the foregoing analyses the writer has concluded that the green clay does not owe its color to either chromium, copper, nickel, or vanadium compounds.

A similar conclusion is reached by reviewing the analytical data on the blue clays (56–93 to 56–98) and associated control specimens (56–100 to 56–104) from Lone Tree Mesa (table 3). Here, the mean cobalt content of both the blue and the control mudstones is 0.0007 percent. The mean chromium content of the control specimens is 0.0035 percent, whereas that of the blue specimens is 0.0019 percent. The mean copper content of the control specimens is 0.0015 percent and that of the blue rocks 0.0019 percent, an insignificant difference. Thus, no significant difference in the contents of these metals exists between the blue mudstones and the others, and therefore some other factor is the cause of the blue and green colors.

The most likely cause for the blue and green colors is resonance between iron in two states of oxidation in the clay-crystal structure. Supporting evidence drawn from the properties of green glauconitic mica in sandstone of the upper part of the mudstone in the Brushy Basin in the Lone Tree Mesa section is given on page 56. To explain the development of the green color, the origin of the glauconitic mica (green)—postulated to be a sequence of alteration of volcanic ash to montmorillonite to illite-glauconitic mica—is discussed in some detail below.

A zone of fine-grained clayey sandstone about 15 feet thick, colored green by its content of glauconitic mica, lies about 15 feet below the top of the Brushy Basin member on Lone Tree Mesa in the NE¼NE¼ sec. 2, T. 48 N., R. 8 W., Montrose County, Colo. (Keller, 1958). The glauconitic mica is texturally similar in this siltstone to the montmorillonite and aluminous illite in red and gray mudstones of the Brushy Basin elsewhere; it is simply a green counterpart of the other more widespread red and gray clay. The glauconitic mica is moderately pleochroic green, and its indices of refraction are 1.578 and 1.600±0.003 for X and Z, respectively; its interplanar spacings are strong at 9.97A for (001), very weak at 5.01A for (002), strong at 3.34A for (003), and moderate at 1.510A for (060) (fig. 12). It is dioctahedral and a 1–M polymorph (confirmed by Herbert Glass, oral communication, 1956).

The cause of the green color seems to be associated with the nature of the chemical compositions of clay minerals, and these two aspects will be considered together. The chemical compositions of pale-pink typical montmorillonite from the Brushy Basin (Duma Point section), green montmorillonite (Courthouse Wash section), and blue illite and green glauconitic mica (both from the Lone Tree Mesa section) are given in table 4.

Analysis 1 (table 4) is of the clay fraction (montmorillonite) of a pale-pink mudstone collected about 35 feet below the top of the Brushy Basin member on Duma Point, Grand County, Utah. Its

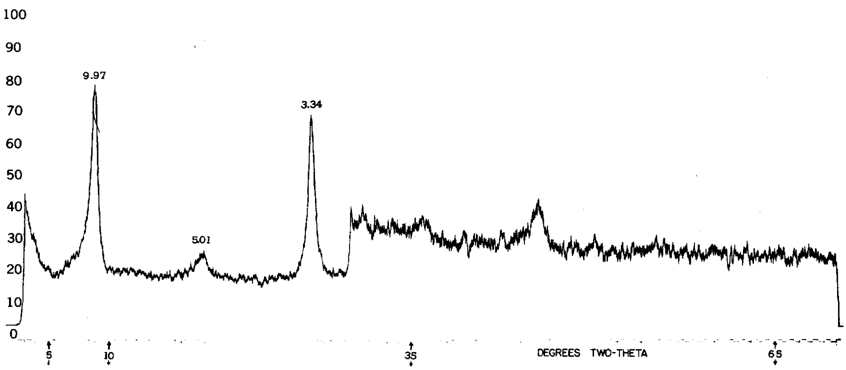

FIGURE 12.—X-ray powder diffractogram of glauconite mica from the Brushy Basin member sample (55–180) from Lone Tree Mesa section, No. 9 (117), Montrose County, Colo. The scale factor was changed at 30° two-theta to keep all parts of the diffractogram on the chart. The strong (001) and (003) reflections, and weak (002) reflection, delineate interplanar, or *d*, spacings at 9.97A, 3.34A, and 5.01A, respectively. Nickel-filtered, copper radiation.

TABLE 4.—*Chemical analyses of clay samples from the Brushy Basin member of the Morrison formation*

[All clays less than 2 microns settling-velocity diameter. Analyses, in weight percent, by Bruce Williams Laboratory; cost of analyses was defrayed by the University of Missouri Research Council]

	1	2	3	4
SiO_2	58. 40	61. 49	56. 64	49. 03
Al_2O_3	24. 16	19. 14	20. 99	17. 93
Fe_2O_3	3. 07	3. 06	3. 90	13. 11
FeO	. 35	. 32	. 66	1. 31
MgO	4. 51	2. 37	2. 65	2. 79
CaO	. 69	1. 63	. 65	. 39
Na_2O	. 51	. 51	. 45	. 10
K_2O	. 39	2. 26	7. 11	7. 84
Cr_2O_3	----------	None	----------	----------
TiO_2	. 44	. 62	. 61	1. 06
P_2O_5	. 13	. 08	. 22	. 37
Loss on ignition	7. 29	8. 47	5. 77	6. 00
	99. 94	99. 95	99. 65	99. 93

1. Pale-pink montmorillonite about 35 ft below the top of the Brushy Basin member, sample 55–223, Duma Point, Grand County, Utah.
2. Green montmorillonite (and quartz) about 20 ft above the base of the green zone, sample 56–44, Courthouse Wash, Grand County, Utah.
3. Blue illite at about the center of the Brushy Basin member, sample 55–177, Lone Tree Mesa, Montrose County, Colo.
4. Glauconitic mica about 25 ft below the top of the Brushy Basin member, sample 55–180, Lone Tree Mesa, Montrose County, Colo.

Formula of mica:
$(Al_{0.88}Ti_{0.06}Fe^{3+}_{0.68}Fe^{2+}_{0.08}Mg_{0.29})(Si_{3.40}Al_{0.60})O_{10}(OH)_2Ch_{0.95}$, computed by M. D. Foster, U.S. Geological Survey (oral communication, 1956).

field appearance indicates that it represents the kind of mudstone and montmorillonite that predominate in the Brushy Basin member over the northern part of the Colorado Plateau. The prevailing colors of the Brushy Basin here—shades of red and gray—are interpreted to indicate conditions of alteration in which the oxidation potential ranged from values high enough to permit red iron oxides to form in and on the clays, to others low enough that carbon was preserved as fragments of wood, organic trash in the sediments, and absorbed material on the clay. The composition of this clay is typical of, and accords with, that of other montmorillonites; its contents of MgO, at 4.51 percent, and K_2O at 0.39 percent are normal. Moreover, this analysis is believed to represent the typical montmorillonite alteration product of volcanic ash to mudstone in the Brushy Basin over the northern part of the Colorado Plateau.

Analysis 2 is of the clay fraction from typical green mudstone collected about 20 feet above the base of the green zone of the Brushy Basin member on Courthouse Wash. Comparing analysis 2 with 1, MgO has been lost and K_2O gained in the green clay in comparison to the normal montmorillonite (plus a small amount of quartz), but its K_2O content is larger than expected, or perhaps allowable as exchange cations, in typical montmorillonite. If the CaO, Na_2O, and K_2O are calculated as exchangeable cations, they provide 123 milliequivalents for 100 grams of clay, which is uncommonly high, especially where the clay fraction includes some free quartz; therefore part of the K_2O probably occurs in illite which may be so highly dispersed at random in the montmorillonite that the illite is not resolved on the diffraction pattern. The formula of the clay cannot be calculated with confidence from the analysis, owing to the presence of an unknown amount of free silica; so we are left with only a qualitative interpretation that some illite is present in the montmorillonite matrix. Other samples from the green zone yield patterns of mixed-layer montmorillonite-illite clays, and illite, which supports the interpretation that illite was being formed from montmorillonite. This trend is extended by the data in analysis 3.

Analysis 3 is of the clay fraction of a sample of blue to greenish-blue illite from about the center of the Brushy Basin member on Lone Tree Mesa, Montrose County, Colo. The largest difference between this analysis and Nos. 1 and 2 is the notable increase in potassium, and a slight increase in both ferrous and ferric iron in No. 3. MgO is lost with respect to No. 1 and is essentially the same (within analytical error) as in No. 2. The results of analysis 3 accord with the mineral identification of that sample as illite (potassium-rich). Despite its classification as illite, a small amount of montmorillonite is likely to be present in the illite and remain unresolved by X-ray diffraction. Such a possibility is suggested by the highly plastic nature of the wet clay in the field, and it is supported by the well-known fact that artificially mixed clays may derive high plasticity from montmorillonite added in amounts too small to be detected by X-ray. Thus, it seems reasonable that the blue illite on Lone Tree Mesa probably contains minor amounts of montmorillonite, the green montmorillonite in Courthouse Wash probably contains minor amounts of illite, and the clays of analyses 1, 2, and 3 represent steps in clay-mineral change from montmorillonite to illite. A slight gain in iron shown in the sequence becomes very large in the next analysis, No. 4.

Analysis 4 is of the clay-size fraction of glauconitic mica from a clayey sandstone about 25 feet below the top of the Brushy Basin member on Lone Tree Mesa, Montrose County, Colo. The clay is notably rich in ferric iron (but not as red ferric oxide) and high in potassium; it retains about the same amount of MgO as the other blue and green clays, but has lost MgO with respect to No. 1. Its chemical formula,

$$(Al_{0.88}Ti_{0.06}Fe^{+3}_{0.68}Fe^{+2}_{0.08}Mg_{0.29})\ (Si_{3.40}Al_{0.60})O_{10}(OH)_2Ch_{0.95}$$

is intermediate [2] between those of typical glauconite and muscovite. Thus, by strong enrichment in ferric iron an illite clay becomes transitional toward glauconite, and may be classified as another step in the clay-mineral sequence developed by the addition of potassium and iron to ash-derived montmorillonite.

The most probable geologic source of the large amount of potassium necessary to add 6 or 7 percent K_2O to the mudstones in Courthouse Wash and Lone Tree Mesa is solutions from evaporites of Pennsylvanian age which have originated in salt-cored anticlines and faulted structures in nearby (within 10 miles) Paradox, Salt, and Sinbad Valleys. The source of iron in the glauconitic mica is probably within the Jurassic (or older) sediments themselves, which normally contain several percent of iron.

The transition from montmorillonite to illite includes a shift in ions, and in the loci of deficits of positive electric charge, within the clay crystals. In montmorillonite, Mg^{+2} substitutes for Al^{+3} in the octahedral layer (similar to gibbsite), whereas in illite (and glauconitic mica), Al^{+3} substitutes for Si^{+4} in the tetrahedral layer; thus the transformation of typical montmorillonite to typical illite implies substitution of a trivalent cation for magnesium, and aluminum for part (one-sixth to one-fourth) of the silicon. The exact mechanism by which such changes take place here, or elsewhere, in diagenesis is not clearly understood, but occurrences of apparently diagenetic illite are amply widespread and abundant to lend credence to the concept of transformation even though it may not be traced in detail.

The interpretation of the sequence of analyses 1 to 4 (table 4) is that volcanic ash was altered first to montmorillonite, as in analysis 1, and then toward No. 4. An alternative possibility is that the ash was altered directly to illite as found on Lone Tree Mesa (not via montmorillonite), but the evidence observed is contrary to such a possibility. First, montmorillonite is the widespread and common alteration product in the Brushy Basin member. Second, the fine silty residue of incompletely altered material that remained after the clay fraction was extracted from a blue mudstone (sample 55–171) of Lone Tree Mesa, yielded upon X-raying a diffuse montmorillonite diffractogram with only a trace of illite. These silt particles are still sufficiently unaltered to retain low indices of refraction like those of

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[2] Foster (1956, p. 66) indicates that substitution of aluminum for silicon in typical glauconite is of the order $Si_{3.67}Al_{0.33}$, and the substitution in muscovite is in the range $Si_{2.98-3.11}Al_{1.02-0.89}$, whereas in the glauconitic mica the tetrahedral substitution of aluminum for silicon. $Si_{3.40}Al_{0.60}$, is intermediate between Foster's values for glauconite and muscovite. The Al : Fe^{+3} ratio in octahedral coordination in muscovite is found by Foster to be of the order 1.9 : 0.03, and in glauconite 0.18 : 1.1–1.2, whereas in the glauconitic mica the ration Al : Fe^{+3} in octahedral coordination is of the order 0.9 : 0.7—likewise intermediate between muscovite and glauconite. For these reasons the mineral is called glauconitic mica, or ferriphengite, which would be more definitive (M. D. Foster, written communication, 1956).

fresh volcanic glass, but the particles exhibit highly birefringent shreds of clay within them that look like montmorillonite when viewed between crossed nicols under the microscope. Thus, the alteration is interpreted as proceeding from ash to montmorillonite and then to the micaceous clays.

The role of zeolites in the alteration process is difficult to assess. Analcime was observed from Lone Tree Mesa and elsewhere, but clinoptilolite (whose properties and composition are not sharply delimited), a common alteration product of volcanic ash, was not identified as a prominent constituent. Bramlette and Posnjak (1933, p. 171) suggest that clinoptilolite is commonly formed during intermediate alteration, "though it is not implied that all bentonites have gone through such an intermediate stage." Analcime is fairly common in lacustrine and subaerial deposits (Ross, 1928; Bradley, 1930; Keller, 1952), and this fact provides a basis for interpreting similar alteration of volcanic ash in the Brushy Basin member.

The cause of the blue and green colors on the clays of the Brushy Basin was tentatively attributed (p. 26, 29) to iron existing in two states of oxidation in the clay-mineral crystals. Several lines of evidence lead to this conclusion. As early as 1898, Spring (p. 202) and then years later Bancroft and Cunningham (1930) reported that artificially prepared ferrous silicate, aluminate, and borate compounds are colorless to blue, but become green upon partial oxidation. Weyl (1951) and Shively and Weyl (1951) state that when electron transfer between ions of one element in two states of oxidation (iron, for example) occurs over a considerable distance, as on the order of ten atomic diameters, the resulting oscillation of valency accounts for intensive light absorption and development of color. They noted that iron, partially oxidized from Fe^{+2} to Fe^{+3} in a compound, gives rise to a blue color, as is observed in vivianite and in artificially prepared iron hydroxides. The color of hydrated ferrous-ferric minerals tends toward green, which has long been observed in chlorite, glauconite, epidote, amphiboles, micas, and other minerals (Keller, 1953a). Hoebeke and DeKeyser (1955) attribute the green color in glauconite to the presence of Fe^{+2} in the tetrahedral silicate layers, which is a very unusual location for ferrous iron. Regardless of whether the electron transfer occurs between tetrahedrally or octahedrally coordinated ferrous-ferric pairs, the blue and green colors in clay minerals apparently derive basically from the presence of the ferrous-ferric silicate structure of the clay.

Vividly green glauconite and glauconitic mica and the blue clay (illite) on Lone Tree Mesa are potassium-bearing minerals, and the green clay at Courthouse Wash is also rich in potassium. The clay-mineral structure associated with potassium-rich aluminous clays is inferred to be especially receptive to the production of blue and green colors. Thus, the geologic conditions which resulted in addition of potassium to the montmorillonite originally at Courthouse Wash and on Lone Tree Mesa led to (1) the transformation of montmorillonite to illite and glauconitic mica, and (2) a predisposition toward the anomalous and striking blue and green coloration.

INFERENCES OF GEOLOGIC HISTORY BASED ON CLAY MINERALOGY

Clay minerals, like most other minerals, are to a certain degree indicators of the environment of their formation and may be used to infer geologic conditions present during their origin. Although a start has been made in this use of clay minerals (Millot, 1949; Grim, 1953; Keller, 1956), interpretations of geologic environments during their genesis are still only general. Furthermore, because clay minerals are clastic substances which are small and lightweight, they may be transported long distances—uphill by wind and downhill by water—and may then after deposition become lithified within environments sharply different from those under which they were formed. Thus, environments of occurrence of clay minerals may be different from environments of genesis.

Any contribution that clay minerals may make to the geologic history of the Morrison formation must be set within the framework of other geologic and petrologic evidence pertinent to its mode of origin. A fluvial origin for the Salt Wash member is well established apart from clay-mineral considerations, and there is in clay minerals nothing contradictory to that interpretation. The preponderance of typical illite in the Salt Wash is entirely compatible with Craig's (Craig and others, 1955, p. 125) conclusion that "the member was derived mainly from sedimentary rocks." The illite in the Salt Wash was likely derived from a preexisting mudstone (perhaps marine shale), and subsequently was weathered and degraded in structure prior and en route to deposition on the Salt Wash alluvial plains and fans. Much illite forms in marine sediments by the fixation of potassium within degraded three-layer clays, although it may originate also from the weathering of feldspars and other silicate minerals and glasses, and by the alteration of preexisting montmorillonite, as was postulated for the origin of the illite on Lone Tree and Blue Mesas. Illite in the mudstones of the Salt Wash member was most likely derived from the same group of sedimentary rocks that furnished the abraded sand grains in the sandstone of the Salt Wash.

The tongue of montmorillonite in the lower part of the Salt Wash member on the northwestern part of the Colorado Plateau indicates volcanic activity, apparently to the northwest, during the early stages of deposition of the Salt Wash. Sparse altered shards observed by R. A. Cadigan (oral communication, 1956) in the sandstones of the Salt Wash suggest that a relatively restricted source of volcanic detritus was available also during the later deposition of the Salt Wash. This may indicate prolonged light-intensity volcanic activity, or simply reworking of volcanic ash; independent evidence is lacking as to which is more likely.

The chlorite and mixed-layer illite-chlorite in the Salt Wash rocks may have been derived from preexisting chlorite-bearing sediments, or they may have originated by the incorporation of magnesium into a brucite interlayer within degraded three-layer clay-mineral crystals. Such conversion may have occurred even after deposition of the clay when permeability of the rocks was high enough to admit magnesium-bearing solutions. No criteria are known to the writer to decide which was the specific origin of the chloritic minerals.

The abundant montmorillonite in the Recapture member at Thoreau, N. Mex., suggests that much volcanic ash was available locally during deposition of the Recapture. Eastward from Thoreau, the montmorillonite grades into mixed-layer montmorillonite-illite and chlorite, a change which suggests either alteration of montmorillonite by potassium- and magnesium-bearing surface and ground waters, or the admixture of relatively large amounts of sedimentary-derived three-layer clay minerals with montmorillonite. Northwestward from Thoreau toward the Four Corners area, montmorillonite in the Recapture member gives way to illite and chlorite, which are likely to come from a sedimentary source. The illite and chlorite in the Recapture member are similar to those in the Salt Wash member.

Sandstones of the Brushy Basin member possess structures and textures which "indicate that they were deposited in a fluvial environment" (Craig and others, 1955, p. 157). These sandstones intertongue with mudstone, and therefore it follows that at least some of the parent material of the mudstone in the Brushy Basin was fluvially worked to a varying degree. Most of the mudstone contains subangular quartz (and feldspar) silt like some of that in the sandstones; this quartz may have been from a fresh volcanic ash fall, or it may have been transported fluvially and "may have been derived from essentially the same source area as the Salt Wash" (Craig and others, 1955, p. 157). Much of the mudstone in the Brushy Basin observed in this study shows poor sorting between clay and silt (quartz and feldspar) and therefore the writer believes that it underwent less washing by stream water than did mudstone and siltstone in the Salt Wash. Most of the mudstone in the Brushy Basin in the northern part of the Colorado Plateau is notably massive and homogeneous in structure, like the eolian loess deposits along the Missouri and upper Mississippi Rivers. This suggests ash falls which were consolidated without appreciable shifting. Certain scattered units of mudstone have short-range persistence as if they had been playa or shallow-lake deposits. Craig writes on this point (Craig and others, 1955, p. 157): "Limestone, as well as some of the clay, may have been deposited in a lacustrine environment."

The montmorillonite in the Brushy Basin member indicates in its history an interval of volcanism followed by devitrification and hydrolysis of the volcanic ash. The time and stages in the history of the Brushy Basin at which the hydrolysis of the ash occurrred can not be delimited unequivocally, but the oxidized color of the clay, its pattern of bedding, and its relation to sandstone in the Brushy Basin indicate a combination of eolian, fluvial, and lacustrine modes of deposition.

From these observations one may infer that, although fluvial conditions during deposition of the Brushy Basin were much the same as those during deposition of the Salt Wash, the amount of ash that fell during deposition of the Brushy Basin often exceeded and masked fluvial effects. At times, and in those places where fluvial action exceeded volcanic deposition, better sorted sandstones and siltstones were laid down. Presumably the source of the volcanic ash was from the northwest corner of the Colorado Plateau, because the montmorillonite predominates there. To the south, where illite, chlorite, and mixed-layer clay minerals are more abundant, stream transportation and deposition are inferred to have been more important.

Hydrolysis and argillation of the ash probably occurred to an advanced degree, almost to its present state of alteration, under subaerial, lacustrine, and shallow-ground-water conditions, during the episode of ash eruption. An oxidation potential typical of that found in present-day circulating ground water exposed to the atmosphere prevailed during the argillation of Brushy Basin rocks, as is indicated by the presence of red and purple iron oxide pigments in the rocks. Gradations between those colors and carbon grays indicate fluctuating intensities of oxidation in the zone of argillation, which are possibly correlative with fluctuations in the water table. The presence of ferrous and ferric iron within the silicate structure of the clay minerals, rather than in the oxide of iron, indicates that the oxidation was not always as intense as it would have been under conditions of laterization. Therefore partial oxidation, hydrolysis, and leaching of the ash kept pace much of the time with the rate of fall. Silica and alkali-metal and calcium ions were leached downward and were removed in part, but some dissolved silica (perhaps 10 to 20 percent of it) was flocculated within the ash beds and remained as opal, chalcedony, or microcrystalline (cherty) quartz. Uranium ions probably were released during hydrolysis and part of the uranium was removed and another part of it was precipitated within the Morrison formation. Magnesium and aluminum were relatively enriched, as the other previously mentioned elements were lost, and remained as essential constituents of the montmorillonite. Where removal of sodium, calcium, and silica by leaching did not occur, analcime and calcite may have been formed, as shown in figure 10.

In the vicinities of Courthouse Wash and Lone Tree and Blue Mesas, where potassium-rich mudstones occur, potassium ions in solution, derived from evaporites that rose in anticlinal Salt, Sinbad, and Paradox Valleys, are inferred to have combined with the products of alteration and thereby formed potassium-rich clay minerals. Examples are the green potassium-rich montmorillonite and illite at the head of Courthouse Wash and the blue illite and green glauconitic mica at Blue Mesa. The oxidation potential here was sufficient to produce predominant ferric iron in the silicate structure but not to produce ferric oxide.

In the region south from Slick Rock, Colo., where the relative amounts of montmorillonite decrease and those of illite and chlorite increase, two interpretations seem possible: (1) Enough magnesium and potassium may have been available in solution in the surface drainage to react with the hydrolyzing ash to convert montmorillonitic clay to chlorite and illite; or (2) more probably, the contribution of chlorite- and illite-bearing detritus from sedimentary rocks, such as the source area of the Westwater Canyon member, may have increased relative to the contribution of the volcanic material, whose postulated northwestern source was farther away. Thus, clay minerals in mudstones in the Brushy Basin member may be in part clay facies of the intertonguing sandstone referred to as the Westwater Canyon member.

The kaolinite in the Jackpile sandstone resembles, in a superficial way, the kaolin-rich Cow Springs sandstone near Salina, Ariz., on the Navajo Indian Reservation, and parts of the kaolin deposits in the Tuscaloosa formation of Cretaceous age in Georgia. Definitive evidence is lacking to indicate whether the kaolinitic Jackpile sandstone originated from alteration of an originally feldspathic sandstone, from clastic kaolinite washed with relatively clean quartz sand, or by deposition from ground water which migrated through the sandstone. The origin of the sandy Georgia kaolin was interpreted by Kesler (1952) to be lagoonal deposits of quartz and kaolin that had been redistributed and redeposited after the decomposition of feldspathic sands in nearby deltaic and alluvial deposits.

Probably the Jackpile kaolinite was similarly weathered from feldspathic sands, and was later redeposited with the residual quartz sand as kaolinitic sandstone.

CONCLUSIONS

This study of clay minerals in the Morrison formation has led to the following conclusions regarding relations of the clay to ore minerals and the geologic history of the formation.

CLAY MINERALS AS SPECIFIC GUIDES TO ORE

No single clay mineral, clay-mineral assemblage, or absence of clay mineral can be used as a specific and conclusive indicator of uranium ore, although kaolinite and chlorite may be correlated permissively with mineralization, and montmorillonite, as a first-cycle argillized derivative of volcanic ash, may be related to ore genesis. The discovery of kaolinite in local close association with ore minerals in sandstone of the Salt Wash member at several mineralized localities, and within mudstone of the Brushy Basin (an unusual occurrence) at the Los Ochos ore deposit, temporarily raised hopes that kaolinite might be correlated with mineralization. Such hopes were dispelled by discovery of kaolinite also in unmineralized sandstone beds in the Salt Wash member at Sapinero and Duma Point, and in unmineralized mudstone of the Brushy Basin at Sapinero. Furthermore, although kaolinite is likely to be formed in the alteration of aluminous rocks by chemically active solutions carrying ore minerals, it has also been reported as a secondarily formed clay mineral in sandstone, closely associated with mudstones that are rich in three-layer clay minerals, in regions that are chronologically and spatially far from the Morrison formation and entirely removed from uranium-bearing mineralizing solutions. Kaolinite is, therefore, not a restrictive guide to uranium ore.

Chlorite (or mixed-layer chlorite) is abundant at several ore-producing localities, particularly in those south of Lone Tree Mesa, but because chlorite is present also in nonmineralized rocks, its prevalence is probably a function of sedimentary facies rather than ore solutions.

Although clay-mineral families, identified by physical methods, cannot be used as specific guides to uranium ore on the Colorado Plateau, the possibility still remains that significant and perhaps diagnostic cationic substitutions in the clay minerals may have been brought about by mineralizing solutions. To determine the extent of such substitutions would require chemical analyses that are more costly and time consuming than direct analysis for the sought-for

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element uranium. In addition to a study of cationic substitutions, a detailed very intensive investigation of structural variations within the crystals of clay minerals near rich uranium deposits that could be contrasted statistically with the structure of clay minerals in barren areas might contribute to the geochemistry of uranium deposition. Such detailed work was beyond the scope of the subject study.

CLAY MINERALS AS SEDIMENTARY FACIES

Illite and its mixed-layer derivatives characterize the mudstones and most of the sandstones of the Salt Wash member. Most of this illite probably was derived from an illitic sedimentary-rock source. A tongue of montmorillonite, presumably derived from volcanic ash, in the Salt Wash member in the northwestern part of the Colorado Plateau indicates considerable volcanic activity while the lower part of the Salt Wash member was being deposited.

Abundant montmorillonite in the Brushy Basin member, particularly in the northern part of the Colorado Plateau, denotes very extensive eruption of ash, probably in the west. Argillation of the ash is believed to have occurred near the surface and not long after its deposition. A relatively increasing amount of mixed-layer illite and chlorite in the Brushy Basin member and its equivalent in the southeastern part of the plateau is interpreted as having a sedimentary source.

Kaolinite in the Morrison formation suggests environments of leaching: hydrothermal at Los Ochos, sedimentational in the Jackpile sandstone, and by ground water in various sandstone beds in the Salt Wash member.

RELATION OF CLAY MINERALS TO ORE GENESIS

No unequivocal evidence of a direct relation between the clay minerals and the genesis of the uranium ore was recognized. To proponents of the theory that the source of the uranium was in the sedimentary rocks, the argillation of the volcanic ash provides a mechanism by which very large quantities of uranium may have been freed from the ash and made mobile in ground water and available for ore deposition. This possibility was recognized by Waters and Granger, it finds support in Love's (1952) theory of source of uranium in volcanic ash at the Pumpkin Buttes area, Powder River Basin, Wyo., and is an important part of Gruner's (1956) hypothesis of multiple migration and accretion.

Thus, although the clay minerals in the Morrison formation neither prove nor disprove either a hydrothermal or sedimentary-rock-derived hypothesis of origin for the uranium deposits on the Colorado Plateau, they do stand as very tangible and volumetrically large permissive evidence for a source of uranium from the volcanic detritus that was parent to them. Indeed, the amount of uranium-bearing hydrolysates that were counterparts of the countless tons of clay formed during argillation of the ash was so large and so widespread geographically that it would require an incredibly efficient process of leaching to remove them cleanly and completely and not leave at least some fraction of them as ore deposits in the nonmarine host rocks where they were released.

DETAILED DESCRIPTION OF SAMPLES

The following pages contain individual descriptions of clay-bearing samples, their locations in the stratigraphic sections, and identifications of the clay minerals, in more detail than was desirable in the body of the report. The stratigraphic-section numbers of the writer are followed by numbers, in parentheses, used in the original stratigraphic investigation (Craig, 1959). Likewise, unit numbers referred to in some of the sections are the same as those used in the original stratigraphic descriptions. One more set of numbers, those in parentheses following each clay-mineral identification, for example (55–270), refers to the writer's sample numbers.

Pine Creek section, No. 1 (159); Garfield County, Utah; sec. 13, T. 34S., R. 2E.; unmineralized

Morrison formation, Brushy Basin member:
- Top mudstone in the Brushy Basin member (Craig's unit 56), light-greenish-gray mudstone; clay mineral is montmorillonite (55–259).
- Upper two-thirds of Craig's unit 56, a purplish-gray claystone; montmorillonite predominates, but a zone 5 to 6 ft. thick near the lower part of 56 contains chiefly mixed-layer illite-montmorillonite (55–258, 55–257).
- Lowest part of Craig's unit 56, a gray-green sandy clay; montmorillonite is the clay mineral (55–256).

Morrison formation, Salt Wash member:
- Top zone in Salt Wash (Craig's unit 53), a red clayey siltstone; contains mixed-layer montmorillonite-chlorite and a small amount of illite (55–255).
- Lowest part of Salt Wash, Craig's unit 51; clay minerals are illite and mixed-layer chlorite-illite (55–254).

Hanksville section, No. 2 (88); along Utah Highway 24, Wayne County, Utah; sec. 18, T. 28S., R. 11E., and sec. 13, T. 28S., R. 10E.; unmineralized

Morrison formation, Brushy Basin member, 262.6 ft. thick:
- Unit 15, pinkish-gray mudstone; weathers to a frothy surface; montmorillonite is dominant (55–263).
- Unit 14, red mudstone zone intercalated with gray mudstone; frothy weathered surface; montmorillonite is dominant (55–264).
- Near base of unit 14, mottled mudstone, grayish- to purplish-red; montmorillonite comprises the clay (55–265).

Morrison formation, Brushy Basin member—Continued

Basal conglomerate in the Brushy Basin, possibly transitional with Salt Wash member; clay-sized fraction yields a strong X-ray diffraction pattern of montmorillonite (55–266).

Morrison formation, Salt Wash member:

Unit 10, lower part, red and green siltstones; the clay-sized fraction contains illite and quartz (55–267).

Unit 6, specimen is from a silty green mudstone directly beneath a sandstone ledge at about the center of the Salt Wash member; its weathered surface is slightly frothy; the clay-sized fraction comprises montmorillonite and quartz (55–268).

Unit 3, specimen is from a tan to greenish-gray mudstone split in the major conglomeratic sandstone in the lower part of the Salt Wash member in this section; it contains illite (55–269).

Unit 2, a red-green mottled clayey sandstone about 20 ft. above the gypsum bed that is basal (unit 1) Salt Wash member; illite is the clay mineral (55–270).

Little Cedar Mountain-Buckhorn Flat section, No. 3 (24); Emery County, Utah; secs. 34 and 35, T. 18 S., R. 9 E., and secs. 2 and 3, T. 19 S., R. 9 E., unmineralized.

Cedar Mountain formation, 419 ft. thick (not shown on pl. 1):

About 20 ft. below Dakota sandstone, estimated 400 ft. above the base of the Cedar Mountain formation, sample from a gray silty clay slope which weathers to a moderately frothy surface. Clay minerals in it are montmorillonite and probably small amount of chlorite.

Spot sample from a thick gray shaly mudstone series which characterizes the upper part of the Cedar Mountain formation (above the topmost sandstone). It is impure mixed-layer montmorillonite (55–249). A sample from a purplish phase (containing $CaCO_3$ nodules) of this mudstone series contains the same kind of mineral as in the gray shale (55–250).

Claystone, 100 ft. (estimated) above base of Cedar Mountain formation; hard, flinty, granular; contains illite-montmorillonite mixed-layer clay mineral, but most clay-sized particles are quartz.

Morrison formation, Brushy Basin member:

Eight samples from upper 245 ft. of Brushy Basin (writer's units 23–26 inclusive). Samples were selected from beds or zones showing different topographic expressions in the bare well-exposed faces of the mudstone. Mudstone varies in sand and silt content, and although generally gray, it may be colored light shades of green, red, and purple. Its texture ranges from very fine grained smooth flinty surfaces to mealy and sandy rough surfaces. It assumes, in a general way, a pattern of benches or steps in which the steep risers are siliceous and the flat treads are more argillaceous. Siliceous beds may be rich in quartz and silt grains, or may contain chalcedonic or cherty cement, both of which resist erosion.

Typical montmorillonite is dominant in all of these mudstone samples, but several samples show slightly mixed-layered structure. Apparently any differences in color, texture, and resistance to weathering in the mudstones of the upper part of the Brushy Basin here are due to the presence of minerals other than clays (55–240 to –246, inclusive; 56–14).

Morrison formation, Brushy Basin member—Continued

44 and 62 ft. above base, unit 22, silty mudstone weathers in irregular and patchy patterns to a frothy and hackly surface over about 20 ft. of stratigraphic interval; about two-thirds montmorillonite, and one third mixed-layer illite (56–12, –13).

16 ft. above base, unit 22, hackly to frothy weathering; mixed-layer illite and montmorillonite in about equal amounts (56–11).

10 ft. above base, unit 22, clayey sandstone forming the vertical face of a bench; mixed-layer montmorillonite-illite (55–237). Bluish silty clay at top of bench; montmorillonite, slightly illitic (55–238).

Morrison formation, Salt Wash member:

102 ft. above base of formation, unit 20(?), gray mudstone; mixed-layer illite, some chlorite (55–236).

87 ft. above base, sandstone unit 17, gray-green sandy mudstone; illite, and mixed-layer montmorillonite in about equal amounts (56–9).

61 ft. above base, gray sandy mudstone; illite (56–7).

51 ft. above base, gray mudstone; illite (56–8). A sequence of mudstones weathering to alternating hackly to frothy surfaces extends from 35 ft. to 71 ft. above the base of the Salt Wash. Those mudstones which weather to a frothy surface are montmorillonitic, and those which weather to a hackly surface are illitic.

41 ft above base, unit 12, gray mudstone; weathers to frothy to hackly surface; montmorillonite (55–235).

35 ft above base, unit 10, gray silty mudstone; montmorillonite, slightly mixed-layer probably with illite (56–5).

21 ft above base, unit 10, gray silty claystone; weathers to a grainy surface; illite, broad peak (56–4).

10 ft above base, unit 10, gray claystone; weathers to a slightly frothy surface; illite, slightly mixed-layer probably with montmorillonite (55–233).

6 ft above base of Salt Wash member, unit 10, gray claystone; weathers to slightly granular surface; illite (56–3).

Summerville formation (not shown on pl. 1):

Top of Summerville formation, unit 9, red silty claystone; illite and quartz (55–232). Gray claystone; weathers to grainy surface; illite (56–2).

Curtis formation (not shown on pl. 1):

Spot sample collected near top of Curtis formation, greenish silty clay; mixed-layer illite and some chlorite (55–247).

San Rafael River Bridge section, No. 4 (178); along a wash northeastward from the highway bridge in sec. 27, T. 22 S., R. 14 E., Emery County, Utah; mineralized

Morrison formation, Brushy Basin member, 430 ft thick (Baker, 1946):

Sample representative of the uppermost lithologic unit in the Brushy Basin member, a variegated silty mudstone; the clay mineral is well-developed montmorillonite (55–15).

176 ft above base of Brushy Basin, red laminated mudstone; montmorillonite (55–14).

172 ft above base, white fine-grained sandstone; clay-sized fraction contains chiefly montmorillonite, and a trace of kaolinite (55–13).

152 ft above base, brownish-gray mudstone along the approximate strike from a prospect opening about a quarter of a mile away; typical montmorillonite (55–12).

Morrison formation, Brushy Basin member—Continued

104 ft above base, light-gray to pink mudstone; weathers to a frothy surface; montmorillonite (55–11).

70 ft above base, red mudstone; composed of typical montmorillonite (55–10).

Reddish mudstone zone 34 ft thick, at base of Brushy Basin member; montmorillonite is the chief clay mineral, but a slight amount of illite is also present (55–9).

Morrison formation, Salt Wash member, 207 ft thick (Baker, 1946):

Top unit of Salt Wash; a gray massive crossbedded conglomeratic sandstone unit 16 ft thick, which is referred to the lowermost part of the Brushy Basin by Craig (oral communication, 1955). The clay fraction of a sample from this unit contained montmorillonite and a small amount of quartz (55–8). The common prevalence of montmorillonite in the Brushy Basin, and of illite in the Salt Wash, lends support to Craig's interpretation of this unit as Brushy Basin.

45 ft below top of Salt Wash a red shaly mudstone; illite (55–7).

50 ft below top, a gray sandstone; the clay-sized fraction contains illite and mixed-layer montmorillonite-chlorite in about equal amounts (55–6).

60 ft below top, a 7-ft shale unit; sample is a gray calcareous sandy clay; the clay mineral is illite (55–5).

70 ft (estimated) above base of Salt Wash member, a variegated mudstone split; the clay-sized fraction contains illite and quartz (55–4).

54 ft above base, light-gray fine-grained sandstone contains chiefly illite and a small amount of mixed-layer chlorite-montmorillonite (55–3).

20 ft above base of Salt Wash member, a mottled red-green silty mudstone; chiefly illite and a small amount of mixed-layer chlorite-montmorillonite (55–2).

Smith Cabin section, No. 5 (near 186); Emery County, Utah; sec. 33, T. 20 S., R. 14 E.; unmineralized (not shown on pl. 1)

Morrison formation, Brushy Basin member:

White hard resistant bed, about 4 ft thick, just north of Cottonwood Wash, in the lower third of the Brushy Basin member. Silicified volcanic ash, contains small flakes of biotite; clay mineral is montmorillonite.

Gray claystone below the hard layer, massive at top and fissile below; montmorillonite and a small amount of kaolinite(?) (55–229). Shard fragment observed in thin section.

Duma Point section, No. 6(64); Grand County, Utah, sec. 19, T. 23 S., R. 18 E., unmineralized

The Duma Point section begins near the type locality of the Salt Wash member and continues eastward, upslope through the Brushy Basin member.

Morrison formation, Brushy Basin member:

Sample collected 290 ft above base of Brushy Basin member represents a 5-ft zone at top of member which is light purplish-gray mudstone, frothy weathering, and forms steps or benches. The flat tread of the step, least resistant to erosion, is composed dominantly of montmorillonite (56–56); the thin section shows about 5 percent of the section to be quartz silt grains. The steep to vertical riser of the step contains about 10 percent quartz silt grains; the clay minerals in it are montmorillonite, about 85–90 percent; mixed-layer illite, about 10–15 percent (56–55).

Morrison formation, Brushy Basin member—Continued

Upper 190 ft of member chiefly mudstone with a few thin discontinuous fine-grained interspersed sandstone lenses. The color is variegated, and changes over short distances vertically and horizontally. Steps or benches stand out in the bare exposures of the mudstone, but they incline and gradually merge laterally into benches at other elevations, just as the colors grade laterally, one into the other. Almost all the mudstone weathers to a frothy surface, some of it more intensely developed than the other. Nine samples (including 56–55 and –56, described above) were collected from this upper mudstone, and all of them were composed dominantly of montmorillonite (55–222, –223, –224, –225, –220; 56–53, –54). A thin lens of hard white silicified ash also contains montmorillonite as the dominant clay mineral (55–221).

155 ft above base of Brushy Basin, a pinkish layer (55–218) which weathers to a frothy surface is associated with a white hard flinty layer (55–219) which weathers to a less frothy more hackly texture. Both contain dominantly montmorillonite (shown as one zone on pl. 1), but the white rock shows vestiges of shards and is partly silicified, which accounts for its hackly weathering.

114 ft above base, red siltstone overlying the sandstone of sample 55–216; montmorillonite is dominant, slight amount of kaolinite(?) (55–217).

105 ft above base, pale-red prominent sandstone, medium fine-grained, about 15 ft thick: clay fraction is about four-fifths mixed-layer chlorite-illite and one-fifth illite-chlorite (56–52).

54 ft above base, gray sandy mudstone unit; montmorillonite about two-thirds, and illite one-third (55–216).

Lowest mudstone in Brushy Basin member, gray, silty, semiflinty fracture, montmorillonite about 60 percent, mixed-layer illite about 40 percent (55–215).

Morrison formation, Salt Wash member:

Top mudstone in Salt Wash, 214 ft above its base, mottled red-greenish, very silty, calcareous; mixed-layer montmorillonite with chlorite, about two-thirds of clay fraction; illite about one-third (55–214).

180 ft above base, a mottled pink mudstone within sandstone above and below; illite strongly developed, slight amount of kaolinite (55–213).

About 170 ft above base, mudstone split in upper 50-ft-thick sandstone unit; gypsiferous olive-gray shaly sandy mudstone; illite strongly developed; chlorite in small to moderate quantity (55–212).

About 100 ft above base, sample taken from upper two-thirds of 79-ft thick mudstone, a light reddish-gray shaly mudstone; illite and a trace of chlorite (55–211).

45 ft above base, lower part of 79-ft mudstone, gray silty clay; mixed-layer illite (55–210).

25 ft above base, sandstone from the lowest thick sandstone of the Salt Wash; clay fraction consists of about equal amounts of chlorite and illite, both mixed layer (56–59).

20 ft above base, gray silty clay; illite and quartz abundant in clay-sized fraction (55–209).

Summerville formation (not shown on pl. 1):

Top mudstone layer red and bluish-gray mottled shaly mudstone; illite and small amount of kaolinite (55–208).

Courthouse Wash section, No. 7 (43): Grand County, Utah; sec. 24, T. 24 S., R. 20 E; unmineralized, but near mineralized district

This section is reached by turning east, off U.S. Highway 160, about half a mile north of the entry to Arches National Monument, and driving about 1½ miles eastward.

Burro Canyon formation.

Morrison formation, Brushy Basin member:

310 ft above base of member, 15 ft below the top; sample 56–49, representative of the upper 40 to 50 ft, of variegated red, gray, and green mudstone; montmorillonite makes up 80 to 90 percent of the clay; the remainder is mixed-layer illite and a small amount of quartz.

294 ft above base; bluish-green sandy mudstone; montmorillonite constitutes about three-fourths of the clay mineral; mixed-layer illite-montmorillonite, about one-fourth (56–48).

242 ft above base, light bluish-green mudstone weathering to frothy surface, representative of about 50 ft; montmorillonite makes up about four-fifths of the clay, illite about one-fifth (56–47).

190 ft above base, blue-green mudstone, weathers to distinctly frothy surface; montmorillonite about 90 percent, illite about 10 percent (56–46).

164 ft above base, greenish sample from a prominent bench; montmorillonite alone predominates (56–45).

153 ft above base, mudstone from a blue-green silty vertical bench; weathers to a frothy surface; montmorillonite and quartz (56–44).

138 ft above the base; this is the lowermost part of the greenish upper part; variegated red and green; weathers to a frothy surface; montmorillonite randomly mixed with chlorite (56–43).

112 ft above base, red mudstone in association with a gray fine-grained partly silicified limestone which fractures and oxidizes to angular brown gravel; mudstone contains montmorillonite and clay-size quartz (56–42).

96 ft above base, greenish-gray mudstone; weathers to frothy surface; montmorillonite (56–41).

51 ft above base, red and intercalated green and gray mudstone; weathers to frothy surface; typical montmorillonite diffractogram (56–40).

33½ ft above base, gray mudstone sample, typical of a zone from 15 to 50 ft above base; montmorillonite (56–39).

7 ft above base, mudstone weathers to slightly frothy surface; mixed-layer montmorillonite-illite about one-fifth of the clay (56–38).

Basal mudstone of section, pinkish-gray, silty; slightly mixed-layer montmorillonite makes up about three-fourths of clay fraction; illite, which has a broad range in basal spacing, makes up the remaining one-fourth (56–37).

Thick sandstone immediately below mudstone sample 56–37, taken as zero datum (base of Brushy Basin member or top of Salt Wash); the clay fraction is composed of about equal parts of montmorillonite and kaolinite (56–36).

Yellow Cat section, No. 8 (231); Grand County, Utah; near common corner of T. 22 S., R. 21 E., T 23 S., R. 22 E., mineralized

This section, located in the Yellow Cat mining district (Dane, 1935) about 8 miles south of U.S. Highway 50 and 7 or 8 miles east of Thompsons, Utah, was measured by Carl Koteff.

Morrison formation, Brushy Basin member:

296 ft above base of Brushy Basin, greenish-gray mudstone; composed of mixed-layer illite having widely variable basal spacing, and probably a slight amount of kaolinite (56–83).

260 ft above base, variegated red, yellow, gray, sandy mudstone; mixed-layer montmorillonite-illite and probably some kaolinite (56–82).

220 ft above base, gray mudstone; weathers to slightly frothy surface; clay minerals mixed-layer montmorillonite and mixed-layer illite (56–81).

204 ft above base, a light-colored slightly bluish-gray mudstone occurring in steps and benches; weathers to frothy surfaces; montmorillonite is dominant; a slight amount of kaolinite present (56–80).

168 ft above base, a reddish mudstone zone about 22 ft thick; weathers to a frothy surface; montmorillonite (56–79).

145 ft above base, a white sandstone 6 ft thick; montmorillonite and quartz in the clay fraction (56–78).

135 ft above base, gray to pinkish mudstone; weathers to a frothy surface; montmorillonite (56–77).

120 ft above base, variegated, interbedded mudstone and clayey siltstone; mudstone weathers to frothy surface, siltstone weathers to rounded knobby surfaces; clay mineral in both rocks is montmorillonite (56–75).

105 ft above base, a reddish to white fine-grained sandstone ledge, 3 to 4 ft thick; mixed-layer, montmorillonite-chlorite (56–74).

103 ft above base, reddish sandy mudstone; weathers to slightly frothy surface; clay minerals are montmorillonite and illite in about equal amounts (56–72).

74 ft above base, variegated red, green, purple, mudstone; weathers to moderately frothy surface; clay fraction rich in quartz, and contains a small amount of montmorillonite (56–73).

50 ft above base, a gray to pink mudstone zone 25 ft thick; weathers to very frothy surface; montmorillonite (56–71).

30 ft above base, a fine-grained light-gray sandstone, 11.5 ft thick; clay fraction is mixed-layer montmorillonite-chlorite (56–70).

Morrison formation, upper part of Salt Wash member:

Specimens from upper, thick sandstone unit of the Salt Wash member. A friable coarse conglomeratic sandstone zone at the top contains a clay fraction composed of mixed-layer chlorite-montmorillonite, and quartz (56–69). A reddish medium-grained muddy sandstone below it contains a mixture of about equal amounts of chlorite and montmorillonite (56–68).

Reddish mudstone beneath upper sandstone unit contains mixed-layer montmorillonite-chlorite and mixed-layer illite-montmorillonite (56–67).

Second (downward from top) thick sandstone and subjacent red-gray mottled mudstone in the Salt Wash contain, respectively, mixed-layer chlorite and quartz in the clay-sized fraction of the sandstone (56–66), and mixed-layer illite and a trace of chlorite in the mudstone (56–65).

Morrison formation, upper part of Salt Wash member—Continued

Third (downward from top) thick sandstone and subjacent greenish mudstone unit of the Salt Wash; about 60 ft below the second sandstone. The clay fraction of the sandstone contains mixed-layer chlorite (56–63) and minor amounts of illite. This unit is exposed in the center of the anticlinal structure in the Yellow Cat district, but does not represent the base of the Salt Wash member.

Lone Tree Mesa section, No. 9 (117); Montrose County, Colo.; secs. 2 and 3, T. 48 N., R. 18 W.; near mineralized area

Morrison formation, Brushy Basin member:

Generally greenish to grayish-green silty to sandy mudstone comprises the upper 40 ft of the Brushy Basin member at this locality. Uppermost 15 ft. is pale to yellowish green, but the next 15 ft. downward is composed of blue-green to pale blue-green clayey sandstone and sandy mudstone that contain greenish glauconitic mica (55–180). This greenish zone grades downward into a bluish-green zone and thence to a bluish zone below.

415 ft above base, a light-bluish silicified volcanic ash, exhibiting shard structure in thin secion. The clay-sized fraction contains illlite having a wide range of basal spacing (56–91).

393 ft above the base, a blue grainy clayey siltstone; shows in thin section about 10 percent platy glauconitic mica. The clay-sized fraction is illite (56–92).

388 ft above base, a mudstone lens 5 ft below, but within, the siltstone from which sample 56–92 was collected; illite is dominant; trace of chlorite (56–93).

363 ft above base, a reddish mudstone zone; illite having a wide range in basal spacing is the major clay mineral, but slight amounts of mixed-layer montmorillonite and mixed-layer chlorite are also present (56–94).

333 ft above base, a zone 25 ft to 30 ft thick, of silicified volcanic ash(?) interbedded with a lenticular coarse conglomeratic sandstone; the clay-sized fraction is chiefly illite and a slight amount of mixed-layer montmorillonite-chlorite (56–95).

308 ft above base, a light bluish-gray mudstone; contains about equal amounts of illite having a wide range in basal spacing, and mixed-layer chlorite (56–96).

278 ft above base, a lenticular red mudstone zone about 3 ft thick; illite predominates, but clay-sized quartz is prominent (56–97).

210 ft above base, grayish to pinkish mudstone; contains illite and quartz (56–98).

178 ft above base, a grayish clayey fine-grained sandstone; clay-sized fraction is composed of illite having a wide range of basal spacing, a slight amount of mixed-layer chlorite-illite, and quartz (56–99).

168 ft above base, red mudstone zone; illite predominates (56–100).

148 ft above base, a greenish mudstone; weathers to slightly frothy surface; illite is the chief clay mineral, but a small amount of mixed-layer chlorite is also present (56–101).

102 ft above base, bluish-gray mudstone; illite and mixed-layer chlorite-illite (56–102).

75 ft above base, a zone of alternating bluish thin silty and clayey layers in which the clay is the most intense blue. In thin section, quartz silt, secondary carbonate and analcime, and clay minerals are observed (fig.

Morrison formation, Brushy Basin member—Continued

10) (55–174). The clay-sized fraction of the siltstone contains dominantly illite and a minor amount of mixed-layer chlorite. The clayey layers contain illite and abundant montmorillonite (55–173).

40 to 45 ft above base, a zone of sandy to clayey bluish mudstone; montmorillonite constitutes more than half of the clay minerals present, the remainder being mixed-layer illite and a small amount of chlorite (55–170, –171, –172).

20 ft above base, a mottled red-green silty mudstone; illite predominates; a minor amount of chlorite (55–169).

5 ft above a conglomeratic sandstone 4 ft thick interpreted as lowest part of member is a grayish-green silty mudstone; it contains dominantly illite and small amounts of montmorillonite and chlorite (55–168).

Morrison formation, Salt Wash member:

Highest thick ledge in the Salt Wash member; clay-sized fraction contains mixed-layer chlorite and quartz (56–103).

Mudstone zone below top thick sandstone, red and slightly green mottled; contains mixed-layer illite and a small amount of kaolinite(?) (55–183).

Middle zone of Salt Wash member; one sandstone and one mudstone sample taken at the same elevation but in adjacent overlapping lenses of sandstone and mudstone. Mudstone contains mixed-layer illite-chlorite (56–104), whereas clay fraction of sandstone contains kaolinite in considerable amount and a little mixed-layer chlorite (56–105).

Sandstone from near top of lowest thick sandstone ledge in Salt Wash. Clay fraction consists of about one-half kaolinite, one-fourth illite, and one-fourth quartz (56–106).

Mudstone split about 8 ft above base of Salt Wash; clay minerals are dominantly illite and a slight amount of chlorite (55–185).

Dolores group section, No. 10 (56); Montrose County, Colo.; secs. 19, 20, 23, and 30, T. 48 N., R. 17 W.; mineralized

The Dolores group section was sampled along the road from the base and south edge of Atkinson Mesa, on the northeastern edge of Uravan, Colo., to the top of the mesa.

Burro Canyon formation (not shown on pl. 1):

20 ft above base of Burro Canyon formation, a greenish-gray siltstone split in the bottom sandstone; contains mixed-layer illite-chlorite, a small amount of kaolinite(?), and a trace of montmorillonite (55–201).

Morrison formation, Brushy Basin member:

50 ft (estimated) below top of Brushy Basin member (316 ft above base), a mottled red and greenish-gray silty mudstone; contains kaolinite and degraded illite in about equal quantities and a trace of montmorillonite (55–200).

270 ft (estimated) above base, a reddish silty mudstone; contains montmorillonite and mixed-layer illite (very wide span in basal spacings) in about equal quantities, and a small amount of kaolinite (55–199).

220 ft (estimated) above base, a mottled gray-green and reddish, slightly shaly mudstone; contains chiefly montmorillonite and minor amounts of mixed-layer illite, and kaolinite (55–198).

175 ft (estimated) above base, a red silty mudstone; contains dominantly mixed-layer illite-chlorite and probably a minor amount of kaolinite (55–197).

Morrison formation, Brushy Basin member—Continued

110 ft (estimated) above base, bluish-green silty mudstone; montmorillonite is dominant; a small amount of illite is also present (55–196).

60 ft. above base of Brushy Basin member, mottled gray to light-reddish fine silty mudstone; clay fraction is about four-fifths montomorillonite and one-fifth illite (55–195).

Basal mudstone of Brushy Basin; gray; weathers to somewhat frothy surface; clay is about three-fourths montmorillonite and one-fourth illite having a wide range in basal spacings (55–194).

Morrison formation, Salt Wash member:

Top sandstone in Salt Wash member. Sample was taken from a clayey sandstone layer; the clay fraction contains chlorite and quartz (56–108). Sample from a mixed, pink and gray-green, clay mudstone split in the top sandstone contains illite (55–193).

Mudstone interval between top thick sandstone and middle sandstone yielded a mottled red and gray-green siltstone; clay minerals are dominantly mixed-layer illite and a trace of kaolinite(?) (55–192).

Middle or second (downward) thick sandstone ledge; clay-sized fraction of sandstone is composed of about equal amounts of illite and chlorite (55–203). A reddish mottled silty mudstone from a split in the middle sandstone contains dominantly illite (55–191).

Mudstone interval between lowest and middle thick sandstone ledges yields a pinkish-gray silty mudstone that fractures like a semiflint clay; the clay mineral is dominantly illite (55–190).

From lower thick sandstone ledge in Salt Wash member; a mudstone split in the upper part of the ledge contains mixed-layer illite ((55–189). A pair of samples collected from a sandstone, and its counterpart in a mudstone within 3 ft. of the sandstone, yielded from the sandstone a clay fraction composed of about two-thirds kaolinite and one-third illite (56–107s), and from the mudstone chiefly illite having a wide range of basal spacings and a small amount of mixed-layer chlorite (56–107 cl).

Summerville formation (not shown on pl. 1):

Upper mudstone in Summerville contains dominantly illite.

Skein Mesa section, No. 11 (182), Bull Canyon district; Montrose County, Colo.; secs. 16 and 17, T. 46 N., 19 W., unmineralized

At this section, the Salt Wash member was sampled in a wash about a quarter of a mile east of Skein Spring Reservoir, and the Brushy Basin member about 2 miles east of the reservoir. This locality is near the location of Union Mines Development Corp. section, No. 16.

Burro Canyon formation (not shown on pl. 1):

Mudstone about 50 ft (estimated) above base of Burro Canyon formation (the lower unit of which is a conglomerate); illite is strongly developed (56–156).

Morrison formation, Brushy Basin member (400 ft thick):

395 ft above base of Brushy Basin member, 5 ft below the Burro Canyon formation, a green mudstone; contains mixed-layer illite-chlorite (56–155).

345 ft above base, a green mudstone spotted with a small amount of red; montmorillonite and quartz constitute the clay fraction (56–154).

295 ft above base, a sample representing a pink mudstone zone 70 to 80 ft thick; montmorillonite is strongly developed (56–153).

Morrison formation, Brushy Basin member—Continued

215 ft above base, a lens of yellowish-brown friable sandstone about 18 ft thick; clay-sized fraction is composed of illite and mixed-layer chlorite-illite in about equal amounts (56–152).

180 ft above base, a reddish claystone from a mudstone zone consisting of intercalated beds which weather to alternately frothy and nonfrothy surfaces; clay minerals are montmorillonite and illite in about 3:2 ratio (56–151).

145 ft above base, a gray mudstone which weathers to a frothy surface; clay is mixed-layer montmorillonite-illite (56–149).

75 ft above base, light greenish-gray mudstone (56–147); contains illite and minor chlorite.

57 ft above base, a conglomeratic sandstone; clay-sized fraction yields no clay minerals, only quartz (56–146).

45 ft above base, pink mudstone; contains illite (56–145).

20 ft above base, a light-red fine-grained sandstone; clay-sized fraction yields weak illite and chlorite diffraction patterns (56–144).

5 ft above base, reddish-brown siltstone; clay-sized fraction yields quartz and iron oxide, but no identifiable clay mineral (56–143).

Morrison formation, Salt Wash member (about 370 ft thick):

270 ft (estimated) above base of Salt Wash member, a red mudstone, 14 ft thick, just below base of top massive sandstone unit in the Salt Wash; mixed-layer illite is present (56–142).

245 ft above base, top of third massive sandstone ledge, a light-gray sandy mudstone; clay fraction is mixed-layer chlorite (56–141).

175 ft above base, a gray mudstone split, 14 ft thick, beneath third sandstone; clay mineral is illite having a wide range in basal spacings (56–140).

151 ft above base, about 10 ft below top of the second massive sandstone (second rim) in the Salt Wash member, a light purplish-gray silty mudstone; contains illite and chlorite in about equal amounts (56–139).

121 ft above base, about 15 ft below second massive sandstone of the Salt Wash; 2 samples, taken about 100 yards apart, of mottled red-green silty mudstone yield illite and quartz in both (56–138, –137).

75 ft above base of Salt Wash, in first sandstone rim; clay fraction shows only quartz (56–136).

Bachelor Draw section, No. 12, Bull Canyon district; Montrose County, Colo.; southwest corner sec. 1, T. 45N., R. 8W.; mineralized

Morrison formation, Brushy Basin member:

380 ft above base of Brushy Basin member, just below contact with Burro Canyon formation; greenish-gray mudstone; contains mixed-layer illite-chlorite and chlorite-illite in ratio of about 3:2 (56–133).

355 ft above base, a red-green banded mudstone; contains mixed-layer illite-chlorite clay mineral (56–132).

257 ft above base, a red mudstone representative of most of the section from 70 ft below to 25 ft above the sample; yields mixed-layer illite and kaolinite in ratio of about 3:1 (56–131).

185 ft above base, a crossbedded sandstone layer about 40 in. thick; clay-sized fraction contains chiefly quartz and a minor amount of illite showing a wide range in basal spacing (56–129).

155 ft above base, bluish-gray mudstone; mixed-layer montmorillonite-illite and illite-montmorillonite (56–128).

Morrison formation, Brushy Basin member—Continued

90 ft above base, gray speckled conglomeratic sandstone; clay-sized fraction is chlorite (56–127).

63 ft above base, dark-gray fine-grained sandstone; clay fraction is mixed-layer chlorite-illite (56–125).

35 ft above base, a green mudstone; contains well-developed illite (56–124).

Just above base of Brushy Basin member; a light-red clayey sandstone; clay-sized fraction is mixed-layer illite-chlorite (56–123).

Morrison formation, Salt Wash member (334 ft thick):

304 ft above base of Salt Wash member, a sample from near top of third sandstone yields in its clay-sized fraction quartz and mixed-layer chlorite; a little illite probably intermixed (56–122).

255 ft above base; a gray sample from top of mudstone just below third sandstone composed of well-developed illite (56–121). Another sample from this mudstone (28 ft thick) is composed of illite having a wide range in basal spacing (56–120).

222 ft above base, near top of second sandstone, a light reddish-brown siltstone; no clay mineral (only quartz) identifiable in the clay-sized fraction (56–119).

168 ft above base, near top of mudstone split, a mottled red-green mudstone; contains chiefly illite and a minor amount of chlorite (56–118).

36 ft above base, a greenish-gray shaly mud split about 4 in. thick; contains illite and quartz (56–117).

32 ft above base, in lower thick sandstone unit; clay-sized fraction shows only quartz—no clay mineral (56–116).

Dry Creek anticline section, No. 13 (61), Bull Canyon district; Montrose County, Colo.; NE¼ sec. 20 and sec. 19, T. 45N., R. 16W.; unmineralized

The Dry Creek anticline section was sampled on the northeast side of the valley.

Morrison formation, Brushy Basin member (440 ft thick):

3 ft below top, 437 ft above base of Brushy Basin member, a green mudstone; contains slightly mixed-layer illite and a minor amount of kaolinite (56–174).

390 ft above base, red and green mudstone; contains illite and kaolinite(?) (56–173).

343 ft above base, mottled grayish-blue and red mudstone; illite chiefly, and a little chlorite (56–172).

285 ft above base, red-green variegated silty mudstone; montmorillonite, accompanied by a slight amount of kaolinite (56–171).

245 ft above base, a reddish-gray mudstone representative of the zone from 30 ft below to 10 ft above the sample; some mixed-layer montmorillonite and illite (56–170).

215 ft above base, a crimson-red zone about 1 ft thick (it is thicker on Skein Mesa and in the Klondike region); montmorillonite strongly developed (56–169). Description of the sample collected in the Klondike region (56–177) follows this stratigraphic section.

185 ft above base; this sample represents a red silty mudstone zone extending 25 ft higher; mixed-layer chlorite, and illite, are present in about 2:1 ratio (56–167).

133 ft above base, a light-gray mudstone; chiefly montmorillonite accompanied by a slight amount of mixed-layer illite (55–166).

Morrison formation, Brushy Basin member—Continued

125 ft above base, a quartzite rib; clay fraction contains kaolinite and quartz (56–165).

100 ft above base, a gray mudstone; mixed-layer montmorillonite and mixed-layer illite in about equal amounts (56–164).

Basal sandstone, light reddish-gray, carbonate-cemented; clay-sized fraction is dominantly quartz and minor amounts of chlorite(?) (56–163).

Morrison formation, Salt Wash member (280 ft thick):

270 ft above base of Salt Wash member, a tan sandstone, representative of the top massive sandstone; clay-sized fraction composed of quartz and a slight amount of chlorite(?) (56–162).

225 ft above base, reddish mudstone between second and third sandstones; illite (56–160).

145 ft above base, second massive sandstone in Salt Wash; clay-sized fraction contains montmorillonite, illite, and a small amount of quartz (56–159).

120 ft above base, a mudstone split between first and second massive sandstones; illite, having a wide range in basal spacings (56–158).

15 ft above lowest exposure of Salt Wash, sample is from lowest massive sandstone; clay-sized fraction contains illite and mixed-layer chlorite in about equal amounts (56–157).

Bright red zone in the Klondike region

A faulted tilted section of the Morrison formation, in which the Brushy Basin member contains a conspicuous red (moderate red, 5*R* 5/4) zone, 15 ft or more thick, is exposed in the so-called Klondike region, in the central part of T. 43 N., R. 16 W. (not shown on pl. 1). The brilliant red color of the claystone and associated red chert makes this zone sharply conspicuous against the gray rocks of the region. The red zone is present also on Skein Mesa and on the valley sides of Dry Creek. Shards of volcanic ash, replaced by silica and red iron oxide, are well preserved at this locality (fig. 11*B*) (56–177). The clay mineral in the red mudstone is well-developed montmorillonite (56–175).

Slick Rock section, No. 14 (184); San Miguel County, Colo.; secs 28 and 33, T. 44 N., R. 18 W.; mineralized

The Slick Rock section sampled for this study represents only a part of section 184 measured by Craig in 1948.

Burro Canyon formation:

Samples collected from Craig's units 57, 54, and 53, which included the interval in the Burro Canyon formation from 50 to 85 ft below the top of it, contain illite and quartz in the clay fractions (55–24, –25, –26). The lowest sandstone (Craig's unit 47) in the Burro Canyon formation contains dominantly kaolinite and a slight amount of illite in its clay fraction (55–27). The occurrence of kaolinite in sandstone, associated with three-layer clay minerals in accompanying mudstone, repeats in the Burro Canyon what has been found also in other associated sandstones and mudstones.

Morrison formation, Brushy Basin member:

8 to 10 in. below base of Burro Canyon formation, a pinkish-gray laminated claystone; contains chiefly illite, a small amount of mixed-layer montmorillonite, and quartz (55–44).

Morrison formation, Brushy Basin member—Continued

330 ft (estimated) above base of Brushy Basin, hard conchoidally fracturing pinkish-gray claystone; montmorillonite predominates, and small amounts of illite and quartz are present (55–43).

315 ft (estimated) above base, in center of Craig's unit 45, mottled red-green claystones; about equal amounts of mixed-layer illite-montmorillonite and mixed layer montmorillonite-illite (55–42).

270 ft (estimated) above base, lower red zone in Craig's unit 45, a pinkish-gray claystone, fractures conchoidally; montmorillonite and mixed-layer illite-mortmorillonite in about equal amounts (55–41).

220 ft (estimated) above base, near top of Craig's unit 44, greenish hard shale; contains montmorillonite and mixed-layer illite-montmorillonite in about equal amounts (55–40).

140 ft (estimated) above base, grayish-white shale; weathers to very frothy surface; montmorillonite dominates clay-mineral fraction and some mixed-layer illite-montmorillonite is also present (55–38).

95 ft (estimated) above base, in lower 15 ft of Craig's unit 44, green hard claystone; illite, the major clay mineral, is accompanied by a small amount of chlorite (55–37).

65 ft (estimated) above base, Craig's unit 43, greenish gray siltstone; clay fraction contains mostly illite accompanied by a small amount of chlorite (55–36).

35 ft (estimated) above base, Craig's unit 42, mottled reddish-green calcareous siltstone; clay fraction contains illite and quartz (55–35).

Morrison formation, Salt Wash member:

Craig's unit 39, which he placed with reservation in the Salt Wash member. Illite dominates in the clay fraction of the mottled red-green siltstone; presence of illite lends support to referring it to the Salt Wash member (55–34).

Upper thick sandstone, ore-bearing, Craig's unit 38; clay fraction contains illite and chlorite in about equal amounts (55–33).

265 ft. (estimated) above base, from a mudstone zone below uppper ore-bearing sandstone (Craig's unit 37), mottled red-green silty mudstone; illite predominates (55–32).

135 ft. (estimated) above base, from a thick mudstone (Craig's unit 32), a red-green spotted silty mudstone; mixed-layer illite (and probably some chlorite) and quartz make up the clay-sized fraction (55–31).

Clay partings in Craig's unit 29, interpreted by Craig in 1948 to be the basal sandstone of the Salt Wash member; red silty laminated clay; chiefly illite, a minor amount of kaolinite, and quartz constitute the clay fraction (55–30).

Mudstone in Craig's unit 27, originally referred to upper part of the Summerville but now considered by Craig (oral communication, 1955) to be Salt Wash; mottled red-green silty mudstone; illite and some quartz make up the clay-sized fraction (55–29).

Lower McElmo Canyon section, No. 15 (124); Montezuma County, Colo.; sec. 30, T. 46 N., R. 18 W.; unmineralized

Morrison formation, Brushy Basin member (about 200 ft. thick):

Mudstone, about 4 ft. thick, at or above top of Brushy Basin member (L. C. Craig, oral communication, 1955) and just below a "peanut brittle" conglomerate; a soft grayish clayey mudstone (Craig's unit 74, in his section 124); contains illite, mixed-layer chlorite-montmorillonite, and koalinite in about equal amounts (55–58).

Morrison formation, Brushy Basin member—Continued

125 ft (estimated) above base of Brushy Basin; Craig's unit 71, grayish-green claystone; composed of well-defined mixed-layer chlorite-montmorillonite (55–57).

Craig's unit 70, composite sample; a light-gray partly silicified very fine grained siltstone; contains chiefly mixed-layer chlorite with a slight amount of illite, and kaolinite in about equal quantities; a slight amount of muscovite (55–56).

Craig's unit 68, composite sample; greenish silt-clay; contains mixed-layer montmorillonite-chlorite (55–55).

Lowermost claystone in Brushy Basin, Craig's unit 67; clay mineral is mixed-layer montmorillonite-chlorite (55–54).

Morrison formation, Westwater Canyon member (79 ft thick):

13 ft below top of Westwater Canyon member, Craig's unit 65, greenish-gray sandy clay; weathers to a frothy surface; montmorillonite (55–53).

25 ft below top of Westwater Canyon member, lower part of Craig's unit 65; clay fraction contains illite, chlorite, and much quartz (55–52).

Lowest part of Westwater Canyon (Craig's unit 63); composite sample collected across a variegated exposure about 2 ft thick; illite and mixed-layer chlorite having a wide range in basal spacings (55–51).

Morrison formation, Recapture member (117 ft thick):

In middle of Recapture member (exact location not determinable); grayish mudstone; mixed-layer illite, probably associated with montmorillonite (55–50).

Lowest unit of Recapture member, Craig's unit 51, reddish-gray mudstone; illite, and a minor amount of kaolinite (55–49).

Morrison formation, Salt Wash member (101 ft thick):

20 to 25 ft below top of Salt Wash member, a reddish mudstone split in Craig's sandstone unit 50; contains mixed-layer illite-chlorite and quartz in the clay-sized fraction (55–48).

Approximately in center of Salt Wash member (Craig's unit 49), a mudstone lens in the sandstone; clay-sized fraction is composed of illite and quartz (55–47).

30 ft (estimated) above base (Craig's unit 48), reddish silty mudstone; illite (55–46).

1 to 2 ft above base of Salt Wash member (Craig's unit 46), mottled red mudstone; mixed-layer illite-chlorite having wide range in basal spacings is well developed (55–45).

Oak Creek section, No. 16 (151); San Juan County, N. Mex.; secs. 12 and 13, T. 29 N., R. 21 W.; mineralized

Burro Canyon formation:

Mudstone near base of Burro Canyon formation, green clay; composed of montmorillonite and quartz (55–74).

Morrison formation, Brushy Basin member (86 ft thick):

5 ft below top, 81 ft above base of Brushy Basin member, light-pink claystone; montmorillonite is well developed (55–73).

Near center of Brushy Basin member, gray conspicuous silty mudstone zone; thin section shows volcanic shards replaced by carbonate, clay-sized fraction is composed of montmorillonite and small amount of quartz (55–71). Sandstone in lower part of this zone contains analcime, clay, and quartz; montmorillonite is the clay mineral present (55–72). A layer of pink tripolitic rock below the sandstone contains well-developed mixed-layer montmorillonite (55–70).

Morrison formation, Brushy Basin member—Continued
- 10 ft above base of Brushy Basin member, lowermost light greenish-gray sandy mudstone unit; composed of about two-thirds montmorillonite and one-third mixed-layer illite-montmorillonite (55–69).

Morrison formation, Westwater Canyon member (265 ft thick):
- 230 ft above base of Westwater Canyon, greenish-gray sandy mudstone; montmorillonite (55–68).
- 98 ft above base, a greenish claystone lens in an argillaceous sandstone; contains illite and chlorite in about equal amounts; both clay minerals show a wide range in basal spacings (55–67).
- 43 ft above base, a spotted green and red silty mudstone split in the sandstone; contains illite and chlorite, similar to those in sample 55–66.
- 10 ft above base of Westwater Canyon member, a green sandy mudstone having purplish-red spots; contains illite and mixed-layer chlorite-illite in about equal amounts (55–65).

Morrison formation, Recapture member (192 ft thick):
- 175 ft to 180 ft above base of Recapture member, a spotted red-green shaly mudstone in the upper mudstone unit; illite and chlorite in about equal amounts (55–64).
- 75 ft above base, a red mudstone split in the sandstone unit; contains illite showing a wide range in basal spacing (55–63).
- 14 ft above base of Recapture member, red mudstone; illite and quartz (55–62).

Morrison formation, Salt Wash member (220 ft thick):
- 210 ft above base of Salt Wash member, a spotted red-green silty-shale parting in the sandstone; clay fraction is mixed-layer illite-chlorite having a wide range in basal spacing (55–61).
- Center (estimated) of Salt Wash; sample collected along the road leading toward Cortez-Gallup highway, a reddish-gray clayey siltstone occurring in the sandstone; clay fraction is chiefly illite and a minor amount of chlorite (55–75).
- 20 ft to 25 ft above base, a mudstone split in the sandstone; contains illite (55–76).

Thoreau section, No. 17 (207); McKinley County, N. Mex.; sec. 13, T. 14 N., R. 13 W.; unmineralized

The Thoreau section was sampled in the cliffs on both sides of New Mexico Highway 56 and about 6 miles northeast of Thoreau. Specimens were collected from the Recapture, Westwater Canyon, and Brushy Basin members of the Morrison formation on the east side of the highway, and from the Bluff sandstone on the west side. Prospect drilling was in progress at the Thoreau section in August 1955, but at that time no extensive mineralization had been reported from the district.

Morrison formation, Brushy Basin member (86 ft thick):
- 2 ft below top of Brushy Basin member, 84 ft above base, a sample from a slightly pinkish, clayey sandstone (unit 24 of section 207 described by Craig and Freeman); clay-sized fraction contains montmorillonite and kaolinite in about equal amounts (55–82).
- 47 ft above base (unit 24), mixed red and green mudstone; well-developed montmorillonite (55–81). A friable coarse-grained sandstone underlies the mudstone: clay minerals in the sandstone are chiefly montmorillonite and minor amounts of illite and kaolinite (55–80).

Morrison formation, Brushy Basin member—Continued

36 ft above base, a mudstone pocket in the lower part of sandstone (unit 23); contains light-gray silty fissile mudstone; mixed-layer illite-montmorillonite and montmorillonite-illite in about equal amounts (55–79).

5 ft above base, a gray sandy clay in unit 22; dominantly montmorillonite and a minor amount of illite (55–78).

Morrison formation, Westwater Canyon member (181 ft thick):

173 ft above base of Westwater Canyon member, a tan clayey friable sandstone; clay fraction is montmorillonite (56–192).

150 ft above base, light-brown sandstone; clay-sized fraction is chlorite and a minor amount of quartz (56–191).

120 ft above base, grayish-red clayey sandstone; clay fraction is kaolinite and a minor amount of chlorite (?) (56–190).

75 ft above base, reddish-brown siltstone; clay minerals are mixed-layer chlorite-montmorillonite and kaolinite in about equal amounts (56–189).

50 ft above base, light-brown sandy mudstone; clay mineral is chlorite (56–188).

30 ft above base, a white-speckled pinkish-gray friable sandstone; clay-sized fraction is composed of mixed-layer chlorite and a small amount of kaolinite (probably from the light-colored grains) (56–187).

Morrison formation, Recapture member (209 ft thick):

Top unit is Recapture member, a light-gray friable clayey sandstone; chiefly montmorillonite, and a small amount of mixed-layer illite (56–196).

30 ft below top (base of Recapture member not exposed and cannot be used as a reference measuring point), mottled red-green sand; clay-sized fraction is composed dominantly of montmorillonite and a minor amount of kaolinite(?) (56–195).

60 ft below top, light-gray friable sand; contains montmorillonite in clay fraction (56–194).

75 ft below top, light greenish-gray sandy clay; composed mainly of montmorillonite and a minor amount of kaolinite (56–193).

125 ft (estimated) below top, greenish-gray; sandy montmorillonite and kaolinite in ratio of about 2:1 (56–197).

160 ft (estimated) below top, greenish-gray clay (56–198); similar to sample 56–197 taken above.

Bluff sandstone (147 ft thick):

2 ft below top of sandstone, light-gray friable sandstone; clay-sized fraction, small in amount, contains montmorillonite and quartz (56–202).

57 ft below top, light-gray sandstone; clay-sized fraction contains chiefly montmorillonite and a minor amount of kaolinite and quartz (56–201).

107 ft below top, gray sandstone; clay-sized fraction contains mixed-layer montmorillonite-chlorite and quartz (56–200).

142 ft below the top, greenish-gray sandstone; clay-sized fraction contains chiefly montmorillonite and a minor amount of kaolinite and quartz (56–199).

Haystack Butte section, No. 18 (92); McKinley County, N. Mex.; secs. 7 and 18, T. 13 N., R. 10 W.; unmineralized section in a mineralized region

Dakota sandstone.

Morrison formation, Brushy Basin member, upper mudstone tongue (74 ft. thick according to R. E. Thaden, oral communication, 1956):

Upper 5 ft. of Brushy Basin member; may be mixed with some shale of overlying Dakota sandstone; grayish-green clayey sandstone; clay-sized

Morrison formation, Brushy Basin member, upper mudstone tongue—Continued
fraction contains mixed-layer montmorillonite-chlorite and kaolinite (from Dakota?) in about equal amounts (56–222).

59 ft. above base of this tongue, greenish-gray mudstone; montmorillonite and slight amount of randomly mixed chlorite (56–221, –220).

43 ft. above base, pink mudstone pellets in orange-colored sandstone; clay-sized fraction contains a small amount of mixed-layer chlorite-montmorillonite and much quartz (52–219).

Morrison formation, Westwater Canyon member, upper tongue (42 ft. thick):

38 ft. above base of this tongue, a sample of sandstone that appears lithologically typical of this tongue; clay-sized fraction contains mixed-layer chlorite-montmorillonite (56–218).

Morrison formation, Brushy Basin member, lower mudstone tongue (12 ft. thick):

8 ft. above base of this tongue, light-tan mudstone; well-developed montmorillonite (56–217).

Morrison formation, Westwater Canyon member, lower tongue (120 ft. thick):

83 ft. above base, light-reddish-brown clayey sandstone; clay-sized fraction contains mixed-layer chlorite and quartz (56–216).

48 ft. above base, reddish-brown sandstone slightly speckled with lighter colored grains of clay; clay fraction is composed of montmorillonite and kaolinite in about equal amounts (56–215).

5 ft. above base of Westwater Canyon member, reddish-brown sandstone; clay fraction is similar to sample 56–215 above: montmorillonite, kaolinite, and quartz (56–214).

Morrison formation, Recapture member (232 ft. thick):

5 ft. below top, a greenish mudstone; illite having a wide range in basal spacing (56–213).

202 and 157 ft. above base of member, red and gray silty sandstones, respectively; their clay-sized fractions are almost entirely quartz and possibly a trace of montmorillonite (56–212, –211).

111 ft. above base, pale-pink silty sandstone; clay-sized fraction is chiefly quartz, and a minor amount of illite (56–210).

57 ft. above base, a red to gray mudstone layer; contains mixed-layer illite-chlorite (56–209).

45 ft. above base of Recapture member, light-red clayey sandstone; clay fraction contains chlorite that has varying basal spacings (56–208).

Bluff sandstone (116 ft. thick):

At the top, red siltstone; contains dominantly montmorillonite and a minor amount of kaolinite (56–206).

78 ft. above base of formation, red siltstone; contains montmorillonite (56–205).

56 ft above base, light-red sandstone; clay-sized fraction is chiefly montmorillonite and a minor amount of chlorite (56–204).

4 ft above base of Bluff sandstone, pinkish-gray siltstone; dominantly montmorillonite accompanied by minor amounts of kaolinite (56–203).

Laguna section, No. 19 (103); Valencia County, N. Mex.; (A), *NW¼ sec. 28, T. 10 N., R. 5 W.; and* (B), *at the Jackpile mine; mineralized*

Part *A:*

Morrison formation, Jackpile sandstone of local usage:

65 ft above base of Jackpile sandstone, unit 13, a pale-pink silty mudstone pocket in the sandstone; contains kaolinite and a minor amount of illite (55–119).

Morrison formation, Jackpile sandstone of local usage—Continued

25 ft above base of Jackpile, unit 13, a light-tan mealy coarse-grained sandstone; clay-sized fraction consists of kaolinite and a small amount of quartz (55–118).

Morrison formation, Brushy Basin member:

360 ft above base and 10 ft below top of Brushy Basin member, in unit 12, a greenish-gray siltstone; mixed-layer illite showing wide basal spacing (55–117).

290 ft above base, unit 12, red mudstone; montmorillonite and mixed-layer illite montmorillonite in about equal amounts (55–116).

233 ft above base, in unit 8, green sandy shaly mudstone which weathers to a frothy surface; montmorillonite, having a wide range of basal spacing (55–115).

175 ft above base, in unit 6, dark reddish-gray mudstone; contains chiefly illite and a minor amount of mixed-layer montmorillonite-illite (55–114).

150 ft above base, in unit 6, gray-green mudstone which weathers to a frothy surface; montmorillonite slight mixed-layer, and illite (55–113).

100 ft above base, near top of unit 5, bluish-gray mudstone and green mud pellets from sandstone beneath weather to a frothy surface; mixed-layer montmorillonite-illite (55–112).

30 ft above the base, unit 4, pale-pink to reddish mudstone; contains well-developed montmorillonite (55–111).

Morrison formation, Westwater Canyon member:

35 to 40 ft (estimated) above base of Westwater Canyon member, in unit 3, a thin light-greenish-gray silty mudstone split; mixed-layer illite and montmorillonite in about 3:2 ratio (55–109).

About 25 ft above base; tan earthy sandstone speckled with white sand-sized grains; clay-sized fraction contains montmorillonite and kaolinite in about 2:1 ratio (55–110).

Near base of the Westwater Canyon member, a mudstone pod within the sandstone; red, conchoidally fracturing claystone; mixed-layer chlorite-montmorillonite and a moderate amount of illite (55–108).

Morrison formation, Recapture member:

Two samples collected from upper part (the only exposed part) of Recapture member, unit 2: a gray mudstone which contains mixed-layer montmorillonite and mixed-layer illite-montmorillonite in about equal amounts (55–107); and a red to purple mudstone about 4 ft lower in the section which contains mixed-layer chlorite-montmorillonite (55–106).

Part *B*, Samples at the Jackpile mine; collected by permission of the Anaconda Co. and through courtesy of Lee Wiley, geologist of the Anaconda Co., in the opencuts of the Jackpile mine.

Dakota sandstone:

Black fissile shale in basal part of Dakota; kaolinite and quartz (55–93).

Morrison formation, Jackpile sandstone of local usage:

1 ft below base of Dakota sandstone, a greenish clayey sandstone; clay fraction consists of mixed-layer illite-chlorite chiefly, and a small amount of kaolinite (55–94).

11 ft below Dakota, greenish to brownish partly oxidized mudstone layer, ranging from 1 to 24 in. in thickness, some veins of gypsum in the clay; chiefly illite and a minor amount of mixed-layer chlorite (55–95).

Morrison formation, Jackpile sandstone of local usage—Continued

15 ft below Dakota, light-greenish chalky friable sand; thin section shows clay films wrapped around the sand grains; clay-sized fraction contains chiefly mixed-layer montmorillonite-chlorite and a small amount of kaolinite (55–96). A more friable and slightly whiter zone than 55–96, but in the same bed of Jackpile sandstone; clay-sized fraction contains kaolinite and dickite (55–97) which was identified by differential thermal analysis. This is the only dickite found in the samples of Jackpile sandstone that were collected.

Mudstone in lowest level (August 1955) of Jackpile mine, 6 to 9 ft below ore zone, greenish-gray mudstone; contains mixed-layer montmorillonite-chlorite and a small amount of kaolinite(?) (55–104). A red silty mudstone 10 to 11 ft below ore zone; montmorillonite having a wide range in basal spacings which collapse normally upon heating (55–105).

Mesa Gigante section, No. 20; Valencia County, N. Mex.; sec. 34, T. 11 N., R. 3 W., Canyoncito Navajo Indian Reservation; unmineralized

Dakota sandstone:

Lower part of Dakota sandstone, zone 16, contains coaly or carbonaceous clay; chiefly montmorillonite, slightly mixed-layer, and a moderate amount of kaolinite (56–246). (Sample location not shown on pl. 1.)

Morrison formation, undifferentiated (about 270 ft thick):

2 to 6 in. below Dakota, gray silty mudstone, zone 15; contains montmorillonite and mixed-layer illite (56–245).

208 ft above base of Morrison formation, undifferentiated zone 14, light-gray mudstone which weathers to a frothy surface; montmorillonite is strongly developed (56–244).

176 ft above base, top of zone 13, grayish-green sandstone; clay-sized fraction contains montmorillonite and a minor amount of kaolinite (56–243).

158 ft above base, a mudstone in zone 13; dominantly montmorillonite and a small amount of mixed-layer illite (56–242).

132 ft above base, zone 12, tan sandstone speckled with white grains; clay-sized fraction contains montmorillonite, kaolinite in slightly lesser amount, and quartz (56–241). Kaolinite probably is present in the white grains.

131 ft above base, near top of zone 11, gray mudstone weathering to a frothy surface; well-developed montmorillonite (56–240).

88 ft above base, at bottom of zone 11, gray mudstone; dominantly montmorillonite (56–239).

76 ft above base, zone 10, light-tan sandstone speckled with off-white grains; clay-sized fraction contains montmorillonite and mixed-layer chlorite (56–238).

65 ft above base, zone 9, a tan coarse-grained sandstone; clay-sized fraction contains montmorillonite and small amounts of chlorite and kaolinite(?) (56–237).

53 ft above base, in middle of zone 8, gray mudstone weathering to a frothy surface; montmorillonite is dominant (56–235).

15 ft above base of undifferentiated Morrison which overlies Bluff sandstone, in zone 6, grayish-tan mudstone; montmorillonite (56–234).

Bluff sandstone (122 ft present, base unexposed):

17 ft below top of Bluff sandstone, zone 2, buff sandstone; clay-sized fraction contains montmorillonite and quartz (56–233).

Bluff sandstone—Continued
67 ft below top, zone 1, grayish-tan sandstone; clay-sized fraction contains kaolinite and mixed-layer illite-chlorite in about equal amounts (56–232).
At base of exposed part of Bluff sandstone, characterized by planar-type bedding; clay-sized fraction is composed of montmorillonite (slightly mixed-layer) and quartz (56–231).

South Canyon section, No. 21 (188); Garfield County, Colo.; sec. 2, T. 6 S., R. 90 W.; unmineralized

The section in South Canyon is the northeasternmost locality sampled. L. C. Craig collected four specimens; no swelling clays were observed in the entire section.

Morrison formation, Brushy Basin member (or stratigraphic equivalent of Brushy Basin):
210 ft above base of Morrison formation; mixed-layer illite-chlorite (LC–11–56).
Morrison formation, Salt Wash member (or stratigraphic equivalent of Salt Wash):
160 ft above base; illite moderately to strongly developed (LC–10–56).
115 ft above base; illite strongly developed (LC–9–56).
6 ft above base; illite strongly developed (LC–8–56).

Sapinero section, No. 22 (179); Gunnison County, Colo.; sec. 23, T. 49 N., R. 4 W., unmineralized

Burro Canyon formation:
Lowermost mudstone; contains illite, kaolinite, and quartz (55–136).
Morrison formation, Brushy Basin member:
Sample taken 18 in. from top of a thick mudstone series which is overlain by a conspicuous conglomeratic sandstone interpreted to be base of Burro Canyon formation. Sample is a light blue-gray hard flintlike silty mudstone; contains illite and a subordinate amount of kaolinite (55–135).
233 ft above base of Brushy Basin member, light bluish-gray silty mudstone typical of upper mudstone zone; montmorillonite and a slight amount of kaolinite(?) (55–134).
180 ft above base, a sandy to soft mealy light bluish-gray mudstone; dominantly montmorillonite and a trace of kaolinite (55–133).
144 ft above base, sandy variegated mudstone; dominantly montmorillonite and a minor amount of kaolinite (55–132).
82 ft above base, a mottled red-green mudstone zone intercalated with thin sandstone layers; mixed-layer montmorillonite constitutes about three-fourths and kaolinite about one-fourth of the clay minerals in the mudstone (55–131).
60 ft above base, a gray fine-grained clayey sandstone containing about 25 percent clay interstitial to the sand grains; clay fraction is composed of kaolinite and quartz (55–130).
40 ft above base, greenish-gray silty mudstone; fractures conchoidally; mainly illite, a small amount of chlorite, kaolinite(?), and quartz (55–129).
Basal(?) mudstone Brushy Basin, about 265 ft above base of Salt Wash member, reddish calcareous, and silty; mixed-layer illite and chlorite in about equal amounts (55–128).

Morrison formation, Salt Wash member:

250 ft (estimated) above base of Salt Wash, reddish mudstone; mixed-layer illite and subordinate kaolinite (55–127).

230 ft (estimated) above base, reddish-brown mudstone; mainly illite accompanied by slight amounts of both chlorite and kaolinite (55–126).

190 ft (estimated) above base, reddish-gray mudstone; illite is clay mineral (55–125).

100 ft (estimated) above base, mottled green and red mudstone which contains layers of thin algal (*Echinochara spinosa*, identified by R. E. Peck, U.S. Geological Survey) limestone; illite constitutes clay mineral (55–124).

75 ft (estimated) above base, tan sandstone; clay fraction contains illite (55–123).

35 ft (estimated) above base, reddish-gray mudstone; illite predominates (55–122).

15 ft (estimated) above base, reddish mudstone; mixed-layer illite and quartz (55–121).

Basal sandstone of Salt Wash member, clay-sized fraction is dominantly illite, and contains a small amount of chlorite and quartz (55–120).

Los Ochos section, No. 23; Saguache County, Colo.; T. 47 N., R. 2 E.; mineralized, probably by hypogene solutions

The Los Ochos samples were taken, by permission of the Gunnison Mining Co., from their diamond-drill core SDE No. 15 (60° inclination). The geologic formation present at the top of the hole cannot be identified with certainty, but Morrison lithology was recognized in the top of the core recovered at a depth of 47 ft in the hole. The best stratigraphic control on the core is the top of the sandstone, at a depth of 242 ft, which was assigned to the Salt Wash member by L. C. Craig.

Diamond-drill core SDE No. 15:

0 to 47 ft, no core available.

47 to 69 ft; core starts in Morrison formation but stratigraphic position is not known; light-gray to tan mudstone. Silicified ribs at 51, 61, and 65 ft.

50 ft, sample G–1; illite is strong to dominant, chlorite(?) also present.

61 ft, G–2; moderate kaolinite, and a clay mineral(?) not recorded by X-ray until specimen is heated to 550°C, after which a 10A peak like that of illite-mica, or collapsed montmorillonite, is developed.

69 to 72.5 ft, dark reddish-brown silty mudstone.

71 ft, G–3; no clearly recorded clay mineral until specimen is heated to 550°C, after which a broad 10A (may signify illite, mica, or collapsed montmorillonite) arch is registered.

72.5 to 85 ft, white to very pale orange mottled fine- to medium-grained sandstone; abundant white interstitial material.

81 ft, G–4; kaolinite.

85 to 105 ft, variegated transition zone; light-gray silty mudstone, mottled and striped mudstone, and dark reddish-brown silty mudstone.

100 ft, G–5; quartz, but no clay mineral identifiable.

105 to 128 ft, variegated zone, and leached pale yellowish-orange to white porous oxidized silicified fine-grained sandstone.

125 ft, G–7; kaolinite; sample G–6 was lost in transit.

Diamond-drill core SDE No. 15—Continued

128–167 ft, light-gray silty to sandy claystone.

135 ft, G–8; kaolinite, and a deteriorated illite structure.

141 ft, G–9; kaolinite.

167 to 172 ft, light-gray silicified mudstone.

170 ft, G–10; kaolinite, and an additional small peak (probably degraded illite) in the diffractogram at 10A after heating specimen to 550°C.

172 to 180 ft, oxidized mudstone; lower part hard, probably silicified; tiny dark powdery spots and seams of sulfide minerals, and white seamlets and vugs.

177 ft, G–11; kaolinite strongly developed, minor illite.

180 to 200 ft, light-gray very fine grained mottled sandy mudstone, and dark-redish-brown sandy mudstone.

185 ft, G–12; illite, probably degraded, as shown is a broad arch at 10A in the diffractogram.

200 to 216 ft, light-gray fine-grained sandstone to siltstone containing small dark-gray seams; vug and seam fillings of white material.

204 ft, G–13; illite and kaolinite in about equal amounts.

209 ft, G–14; mixed-layer or deteriorated illite, originating probably from leaching action of solution.

216 to 234 ft, strongly brecciated material otherwise similar to that in the interval 200 to 216 ft.

224 ft, G–15; well-crystallized illite, or possibly sericite which was developed in the brecciated zone.

234 to 238 ft, light-gray fine-grained clayey sandstone; fractured but not silicified and lacks sulfides.

236 ft, G–16; illite or sericite well developed.

238–242 ft, dark reddish-brown clayey siltstone.

240 ft, G–17; illite is dominant.

242–261 ft, sandstone, medium- to fine-grained, brittle, lightly silicified; some pyrite in fractures. Called sandstone of Salt Wash, but lack of bedding admits possibility of it being Entrada sandstone. Craig (written communication, 1956) assigns it to Salt Wash member.

248 ft, G–18; does not yield clay minerals.

260 ft, G–19; illite and a trace of chlorite.

261 ft, G–20; siliceous; does not yield a clay-mineral fraction.

Basal 1 ft of sandstone, highly quartzitic. Sharp contact apparent.

261 to 266 ft, weathered schist.

Note.—Uranium production in this district is reported to be from Brushy Basin and Salt Wash members along fractures or fault zones.

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INDEX

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