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PETROLOGY OF THE UPPER PERMIAN CLOUD CHIEF FORMATION OF WESTERN OKLAHOMA

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PETROLOGY OF THE UPPER PERMIAN CLOUD CHIEF FORMATION

OF WESTERN OKLAHOMA

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PETROLOGY OF THE UPPER PERMIAN CLOUD CHIEF FORMATION OF WESTERN OKLAHOMA

INTRODUCTION

General Statement

This investigation is a petrographic study of the Cloud Chief Formation in western Oklahoma with particular attention given to the clay mineral content of these rocks. The data obtained are used to interpret the types of source terranes, their locations and paleoclimates, as well as the environments of deposition.

Location and Geologic Setting

The Cloud Chief Formation crops-out within the Anadarko Basin, one of the largest undeformed, sediment-filled basins in North America. Although situated on the stable craton, this exceptional syncline has a maximum thickness of approximately twelve kilometers of sedimentary strata. Several positive tectonic elements define the basin. The sub-parallel Wichita-Amarillo uplift is situated on the south flank of the syncline; this uplift trends westward and continues en echelon with the Bravo Dome, an element of the Sierra Grande uplift of New Mexico. The Las Animas arch which is adjacent to the Sierra Grande uplift, borders the Anadarko Basin to the northwest. The encirclement of the syncline is completed with the Central Kansas uplift to the north, the Nemaha Ridge to the east, and the Arbuckle Mountains to the southeast.

The present investigation is confined to the area delimited by the outcrop area of the Cloud Chief Formation in west-central and western Oklahoma with the exception of a sample site in Woods County (Figure 1). The outcrop belt outlines the asymmetrical, northwest-plunging syncline of the Anadarko Basin which has a steep southern limb that dips northward about 36 feet per mile and a much broader northern limb which dips between 16 and 25 feet per mile toward the southwest.

The narrow outcrop belt on the south flank of the basin extends eastward from Beckham County where it is largely covered by Quaternary gravels. The belt crosses the axis of the syncline in eastern Washita County where it becomes broader; because resistant beds are commonly absent in this area, it is expressed as treeless, rolling hills of low relief. Isolated outcrops occur as outliers at the apex of the basin to the southeast in Caddo, Grady and Comanche Counties. The broad outcrop area on the north flank of the basin is notably dissected by the south and southeasterly flowing streams in Custer, Dewey, Roger Mills and Ellis Counties. Limited exposures occur in Blaine and Beaver Counties. More than one-half of the formation's thickness is exposed in Woods County.

Physiographically, the area lies entirely within the Central Lowlands Province of Fenneman (1931) and, for the most part, within the Western Redbed Plains of Curtis and Ham (1957).

Previous Investigations

The first published study of the red beds of Kansas and Oklahoma was by Cragin (1896) in which he named the Day Creek Dolomite for exposures in Clark County, Kansas. In 1905, the Cloud Chief

Figure 1. Index Map of Oklahoma Showing Sample Site Locations and Generalized Cloud Chief Outcrop in the Area of Investigation.

Formation was considered the "eastern area" of the Greer Formation for exposures of massive gypsum south of the Cloud Chief village in Washita County, Oklahoma. Gould (1925) considered the dominant lithology of the Cloud Chief Formation to be gypsum. Gould and Lewis indicated that (1926, p. 24) ". . . it might be well to consider the Day Creek the basal part of the Cloud Chief gypsum . . .", and attempted to correlate the Cloud Chief Formation with the Hackberry Formation of Kansas.

Sawyer (1929) stated that the Cloud Chief Formation underlies the Quartermaster Formation and overlies the White Horse Sandstone. He did not know which bed, if any, correlated with the Day Creek Dolomite of Kansas. Therefore, he concluded that for the sake of clarity it should be eliminated from stratigraphic nomenclature. Sawyer (1929) proposed that the Weatherford Dolomite be considered as the basal bed of the Cloud Chief Formation and named it for a dolomite in the vicinity of Weatherford, Custer County, Oklahoma. Thin sections of the basal dolomite were described by Suffel (1930).

Clifton (1930) noted wide lateral variations in the mineralogy of the Day Creek Dolomite and suggested that the formation name "Cloud Chief" be eliminated, particularly in northwestern Oklahoma. Evans (1931), noting that Gould did not include any sandstone above the gypsum nor adequately establish the upper limit of the unit, recommended that the Cloud Chief Gypsum be made a member of the Whitehorse Group. Buckstaff (1931), in a discussion of Evans' paper, considered this interpretation of the stratigraphic relations to be erroneous. Roth (1932) suggested demoting "Cloud Chief" from a formation name (p. 700) ". . . to be used, if at all, as a zone . . .". He later correlated the

Seven Rivers Gypsum of the Texas Panhandle with the combined Cloud Chief Formation, Whitehorse Group and Quartermaster Formation of Oklahoma.

Sellards (1933) considered the Cloud Chief Formation to be composed of those strata between the overlying Quartermaster Formation and the underlying Whitehorse Group. Green (1936) interpreted the Cloud Chief Formation as the lowest of the three stratigraphic members in the Quartermaster Formation, but altered this interpretation the following year (1937) by removing the Cloud Chief Formation from the Quartermaster Formation and making it the uppermost member of the Whitehorse Group, thereby agreeing with Evans. Schweer (1937) also agreed with this designation. Gould (1937) noted that the correlation of the upper Permian strata is a regional problem and can best be solved by regional studies. Miser (1954), Davis (1955), Myers (1959), Ham and Jordan (1961) and a number of authors of Master of Science theses at the University of Oklahoma considered the Cloud Chief Formation to be bounded by the underlying Whitehorse Group and the overlying Quartermaster Formation. Myers (1959) considered the age of the formation to be uncertain but possibly Ochoan, and he correlated it with the Taloga Formation and Day Creek Dolomite of Kansas. Ham, and others (1961) dated the Cloud Chief Formation as Ochoan, based on inter-regional correlations published by Dunbar, and others (1960). Fay (1962) suggested that the formation is the equivalent of the Seven Rivers Formation of Texas, which is in the Guadalupean Series, but he conceded that part of it may be of Ochoan age. Fay (1962) noted that no type section has been designated for the Cloud Chief Formation and, in 1965, he proposed the West Leedey site as the type section (including the U. S. Army Corps of Engineers West Leedey core). Fay also proposed a subdivision of the Cloud Chief Formation, generally following the terminology employed in Kansas. The subdivision consists, in ascending order, of the Moccasin Creek bed, the Kiger member, the Day Creek bed and the Big Basin member. He considered that both the Whitehorse Group and the Cloud Chief Formation are part of the Custerian Series as named by Roth (1932).

Purpose of Investigation

The Cloud Chief Formation is part of the Permian red beds sequence which underlies most of the western half of Oklahoma. A review of the available data concerning its stratigraphic boundaries, age, lithologic correlation, mineralogy, provenance and environment of deposition indicates that it is one of the more complicated and least understood geologic units in the state. Though controversy has been associated with many aspects of evaluating this formation within the state, little quantitative petrographic information has been forthcoming to justify the interpretations.

Petrographic methods almost invariably contribute to the solving of stratigraphic problems which have resulted from lithologic generalizations. The purpose of this investigation is to provide a detailed petrographic analysis of the Cloud Chief Formation in western Oklahoma and to utilize the data to explain its petrogenesis.

Method of Investigation

The selection of sampling locations in any investigation of large areal extent requires discretion if the detailed petrographic studies of the materials collected are not to be unreasonably time-consuming. The data accumulated must have the capability of revealing major lateral and/or vertical variations that may be present in the formation. To satisfy these requirements, a wide spacing of surface and subsurface sites was chosen. These sites depended, in part, on the availability of cores and workable exposures. Figure 1 shows the distribution of sample sites and Appendix D contains their exact locations and the sampled intervals. Selected thin section descriptions are given in Appendix C.

Approximately 175 spot samples of clastic sedimentary rock were collected in the fall of 1966. Depending upon the lithologic variations and exposure, the sample interval varied upward from 9 inches. The only horizons identifiable at most of the locations sampled are the base and the top of the formation, where present. Consequently, stratigraphic correlations were not possible but sample intervals were verified by the distance from either the top or the bottom of the formation. These distances were computed as a percentage of the total thickness of the formation in the area under consideration. Where the complete formation thickness was not observable, it was interpolated from the nearest known thicknesses.

Fifty-nine thin sections of representative samples including a broad range of size classes were examined with a petrographic microscope and described. Because the coarser fractions provided the best mineralogical data, most of the slides are of siltstones and sandstones. Mineral percentages were determined from point counts of at least 100 grains per slide. Descriptions selected to depict a range of petrographic characteristics are given in Appendix C. The immersion oil technique was utilized to differentiate mineral species with similar optical characteristics. Diffractograms of randonly-oriented, thin-sectioned samples were also utilized extensively to complement mineral identifications. Sieve analyses of several samples were made. The results were compared with the textural parameters of the same specimen as determined by optical means. The comparisons were commonly in accord. Several size classes were examined with a binocular microscope to determine surface features and roundness.

The clay mineralogy of all samples was determined by x-ray analysis of oriented clay particles. Differential thermal analysis was employed to complement the identification. More than 400 diffractograms were recorded and quantitatively evaluated. These records were preserved on strip charts and are on file in the X-ray Laboratory of the School of Geology and Geophysics. A detailed description of the techniques employed in determining the clay mineralogy is provided in Appendix A.

Acknowledgments

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LITHOLOGY

General Statement

The red beds are so named for the prevalence of brilliant reddish-brown and reddish-orange exposures. Although some beds are not inherently red in color, their outcrops are stained by the wash from the adjacent formations during weathering, which results in a uniform surficial appearance. When freshly broken, the evaporites are not red, although a few have a pinkish cast. Several zones of light greenish-gray terrigenous rocks are present throughout the stratigraphic column, especially in the sandstones, siltstones and mudstones.

The high lithologic variability of the Cloud Chief Formation is responsible for many of the difficulties in correlation and terminology noted in the section on Previous Investigations. The character of these red beds ranges from mudstones and shales to siltstones and fine-grained sandstones. The attendant lithic units include numerous beds of gypsum and some of dolomite.

The generally rapid interstratifications with nonpersistent lateral facies produce repetitious and irregular sequences which, for the most part, are not correlative over wide areas. The designation of the Cloud Chief Formations' subdivisions in the field is often as dependent upon the individual interpretation of the investigator as on any proposed standards.

No faunal evidence for the age of this formation has been discovered in the rocks investigated. Therefore the Cloud Chief Formation is here considered to be Late Permian in age and possibly Ochoan, following Ham and others (1961). The formation is stratigraphically situated between the subjacent Rush Springs Sandstone of the Whitehorse Group and the overlying Doxey Shale of the Quartermaster Formation (Miser, 1954). Subdivisions of the formation were generally not recognized over the widespread localities visited. Where observed, the upper and lower contacts of this formation seem to be conformable.

The presence of a basal gypsum or dolomite combined with the fairly consistent lithologic character of the underlying Rush Springs Sandstone allows reliable determination of this contact at most of the sites where sections were sampled. The upper contact of the formation is gradational with the darker colored and finer-grained Doxey Shale.

Surface Exposures

The dip of the Cloud Chief Formation generally approaches horizontal and deviations from this attitude are commonly less than a few feet per mile. Extensive solution of the gypsum units within the formation causes slumping and associated erratic dips. Semi-circular sinklike depressions are common and are especially noticeable on aerial photographs.

The low dips, gentle topography, erosion of upper portions, slumping and many covered intervals prohibited the sampling of complete sections. The only surface sections sampled of the entire formation were composite sections in which the upper and lower boundaries were approximately one mile apart.

In the type area of southeastern Washita County, the formation is approximately 300 feet thick. It increases in thickness to about 430 feet on the south flank of the Anadarko Basin, in eastern Beckham County. From the type area, the thickness decreases to the west and northwest and is about 170 feet thick in western Dewey County and approximately 135 feet thick in Roger Mills County.

The evaporite content of the Cloud Chief Formation is the highest of any Permian unit in western Oklahoma (Ham and Jordan, 1961). The most notable evaporite section is in the southeastern part of the Anadarko Basin. Massive gypsum and anhydrite about 100 feet thick are present at the base of the formation in southeastern Washita County and lenses of evaporites are common in the overlying sandstone and shale sequence.

The largest outlier of the formation in the vicinity of Cyril, Caddo County, was sampled. The top of the formation has been removed by erosion and the base consists mostly of evaporites interbedded with shales, siltstones and sandstones higher in the section. The gypsum is white and massively bedded at the base and occurs as lenses higher in the stratigraphic section. The sandstone is reddish-brown to pale reddish-orange, very fine grained and silty. It occurs in thin, even strata, some of which contain abundant ripple marks. Some of the siltstones have fine crossbedded laminae. Interbedded reddish-orange siltstones and reddish-brown shales are present throughout the exposed beds above the basal evaporites.

South of Elk City, Beckham County, the basal white and pinkish, massive gypsum occurs as several lenses interstratified with reddish-brown, very fine- to fine-grained sandstones. These beds are overlain by interbedded gypsiferous, hard, orange-brown, thin- to medium-bedded siltstones with pale reddish-orange silty, gypsiferous shales, and mudstones containing light greenish-gray spots. Several massive white gypsum beds with satin spar layers occur higher in the formation, interlayered with light brown mudstones and shales. Greenish-gray mudstone and siltstone zones are sporadically encountered in the predominantly pale reddish-brown siltstones. Light brown residuum covers much of the formation. Similar lithologies were observed west of Sayre, in central Beckham County, but only the uppermost portion of the formation is exposed there. It is predominantly an even-bedded, gypsiferous, reddish-brown to pale reddish-orange, silty shale and siltstone sequence. White to light gray, impure satin spar layers up to 5 inches thick are also present. The main criterion used to distinguish the Cloud Chief Formation from the overlying Doxey Shale is that it weathers to a light reddish-brown color whereas the Doxey produces a darker brown residuum.

The massive basal gypsum of the Cloud Chief Formation continues into part of Dewey County on the north flank of the basin where it is in places a double bed of gypsum and is commonly thinner. It is replaced by light-gray dolomite beds in some parts of this area. The gypsum and/or dolomite beds are overlain by reddish-brown, gypsiferous, friable, cross-bedded, very fine-grained sandstones, mudstones and fissile shales. Moderate to massive-bedded, friable, pale reddish-orange siltstones occur near the middle and top of the formation. Some of the beds are calcareous and many contain satin spar veins.

Farther to the west, in northeastern Roger Mills County, the basal gypsum is present, overlain by reddish-brown to pale reddish-orange, gypsiferous, very fine-grained sandstones with numerous lenticular gypsum layers. Randomly disseminated euhedral and subhedral selenite crystals occur in some of the exposures in the lower part of the formation. Nonresistant, interbedded, friable, fine-grained sandstone with pale reddish-brown siltstones, shales, and mudstones comprise the middle part of the formation. The upper, calcareous, moderately thick, crossbedded sandstones and siltstones stand out in relief, and thin pinkish-white limestone layers are present. The top of the formation has been removed by erosion at this site.

The top of the formation has also been removed by erosion to the north, in Woods County. The basal unit here is a quartzose dolomite with reddish-brown siltstone and crossbedded, calcareous sandstone. It is overlain by moderate reddish-brown mudstones interbedded with pale reddish-brown to pale reddish-orange siltstones and fine-grained sandstones of variable bed thickness. Greenish-gray to light gray siltstone zones sporadically occur in the section. A prominent dolomite bed caps many escarpments and buttes in the area. Greenish-gray siltstones and mudstones alternate and are replaced by medium reddish-brown shales and pale reddish-orange siltstones in the upper parts of the Cloud Chief Formation in Woods County.

Subsurface Samples

Subsurface material was studied by utilizing selected cores of the U. S. Army Corps of Engineers, which are on deposit at the School of Geology and Geophysics, Core and Sample Library. All of the cores used are 4 inches in diameter and less than 250 feet in length. The cores were selected to complement the surface sites sampled, and are generally located near the axis of the Anadarko Basin; hence, they are intermediate to most of the surface locations. Figure 1 summarizes their distribution and the exact locations of the core sites are given in Appendix D.

The lower contact of the Cloud Chief Formation is recognized in the subsurface by the characteristic massive gypsum and/or dolomite overlain by mudstones and shales, and underlain by sandstones. The upper boundary of the formation was determined by the color change from the pale reddish-brown of the Cloud Chief Formation to the darker, medium reddish-brown of the overlying Doxey Shale.

Core samples from the upper portion of the Cloud Chief Formation, and on the south side of the basin axis, were examined. The formation is predominantly a reddish-orange, moderate-bedded, micaceous siltstone with a few thin laminae and pale reddish-orange to reddish-brown, very fine-grained sandstone. Reddish-brown, gypsiferous, silty shales are interbedded with white to light gray, argillaceous, thinly laminated gypsum lenses. Satin spar veins and layers up to 2 inches thick are present. Sporadic greenish-gray zones are present, particularly in the siltstones and sandstones.

Toward the east side of the basin, in Custer County, the basal Cloud Chief lithology varies from a massive, white to light gray, mottled orange and pink, fine to coarse-grained gypsum with selenite plates to a white or pinkish, fine-grained dolomite. Pale reddish-orange, thin- to moderate-bedded, weakly indurated mudstones and siltstones are commonly present. These beds are overlain by an irregular alternation of similar lithologies with reddish-orange, friable, very fine-grained, calcareous sandstones, containing numerous greenish-gray zones and patches. Reddish-brown, blocky, weakly indurated, silty shales with thin calcite veinlets also are present.

Only the top of the Cloud Chief Formation has been cored by the U. S. Army Corps of Engineers near the axis of the basin in southeastern Roger Mills County. It consists of reddish-orange, silty shales, mudstones and sandstones. The fine-grained beds are gypsiferous with many satin spar layers and veins up to 2 inches thick. The laminations are generally thin and most of the material is weakly indurated. The sandstones are very fine-grained, silty, and contain mottled greenish-gray zones.

On the north side of the axis, in southwestern Dewey County, two beds of gypsum occur at the base of the formation, separated by a few inches of pale reddish-brown to reddish-orange, gypsiferous siltstones and mudstones. Additional white to light orange, massive gypsum occurs in thin beds and lenses higher in the section, as do satin spar veins. An interstratified sequence of reddish-brown shales and mudstones, and reddish-orange, thinly-laminated as well as crossbedded, siltstones, is a typical lithologic sequence for the Cloud Chief Formation of this area. As in the preceding cores described, sporadic greenish-gray zones are common.

Stratigraphic Trends

A few general lithologic variations are consistent enough to be discernible. Evaporites are most common in the basal portions of the Cloud Chief Formation. A number of gypsum lenses are present in the middle portion of the unit's stratigraphic section but they are relatively scarce in the upper portions. Consequently, there seems to be an overall decrease in the quantity of evaporites going up the stratigraphic column of the formation, and a distinct abundance of gypsum in its basal portion, at most surface and subsurface localities in west-central Oklahoma.

Rapid facies changes are evident at most exposures of this formation but a regular regional lateral lithologic variation exists in at least the basal portion. The thick evaporite section in the south-eastern part of the basin grades into shales, siltstones, and sandstones to the north and northwest. The thickness of the basal gypsum is reduced from hundreds of feet in Caddo County to a few feet in Roger Mills and Dewey Counties. In Woods County, the basal gypsum is virtually absent and fine-grained sandstones are present instead. The increasing abundance of the coarser detrital constituents in these directions may be locally reversed by the occurrence of gypsum or carbonate lenses, but, in general, the trend does prevail.

MINERALOGY

Terrigenous Constituents

Quartz

Sand- and silt-size quartz grains are the most abundant terrigenous constituents in all the thin sections examined. The most notable quartz features are the variety of inclusion and extinction characteristics.

The greater portion of the quartz grains (more than 60 percent) have only a few vacuoles, commonly distributed in a random fashion within the grains. Normally from 5 to 10 percent of the quartz grains contain intersecting bubble chains or planes of bubbles. Some grains contain only a few lines of vacuoles which have subparallel orientations. About 15 percent of the quartz grains in a typical slide contain idiomorphic crystalline inclusions in varying amounts. Rutile needles and other fine, hairlike inclusions are quite obvious. Apatite, tourmaline, zircon, chlorite and micas make up the remaining microlites. A few, small liquid inclusions are present.

The extinction types range from straight to composite metamorphic (Folk, 1965). The composite grains commonly show strong undulatory extinction with a strain shadow sweeping smoothly across the grain. Most of the composite quartz grains have crenulated boundaries between sub-individuals. About one-half of the composite quartz grains have elongated sub-individuals. Quartz grains with straight extinction are distinctly in the minority and "blick" extinction is rare. Quartz grains with slight undulatory extinction represent the most typical variety present.

Quartz enlargements are common in many of the thin sections examined and are commonly marked by iron stain or clay coatings on the surface of the detrital grain. The enlargements are in optical continuity with the detrital core. The overgrowths are generally not conformable with the outline of the original sand or silt grain. The overgrowths vary in thickness and in places are absent on some surfaces of the original grain. Although the majority of the quartz enlargements are angular or occur as cement, no prismatic secondary growths were noted. A number of overgrowths, however, are rounded and some of the quartz grains show two stages of enlargement. Commonly, the last secondary growth is angular whereas the first is abraded. Some grains have both rims worn by abrasion. The secondary quartz is commonly free from inclusions. Some grains have frosted surfaces, evidently due to the growth of a multitude of tiny quartz crystals. This obscures the original surface features.

Feldspar

The most abundant feldspar present is orthoclase and the least abundant is microcline. Microcline has a distinctive quadrille twinning pattern and many of the crosshatched twin lamellae are tapered. Orthoclase grains are untwinned but their refractive indices are less than that of Canadan balsam and quartz. Plagioclase shows a conspicuous twinning of parallel, multiple bands. Polysynthetic twinning is most common in the plagioclase grains but albite and pericline twinning are also abundant. The plagioclase composition is in the oligoclase-andesine range.

Alteration of the feldspar varies greatly, from clear and fresh to intensely weathered. Generally less than one-fourth of the grains are intensely altered whereas the majority of the grains are fresh or only lightly vacuolized or sericitized. The orthoclase grains are commonly the most weathered, and may show aggregate polarization. However, many grains of fresh orthoclase occur even where the greatest degree of alteration occurs in this type of feldspar. Vacuolization is the most common alteration and sericitization is second. Some chlorite and carbonate replacement of the feldspars is noted. The degree of alteration does not seem to be dependent upon the presence or lack of an enclosing orthochemical cement. Microlites are uncommon in the feldspars. A few zoned plagioclase grains are present.

Authigenic enlargements of feldspar are fairly common, especially in the coarser size classes. The majority of the enlargements are angular, but some are rounded. A few overgrowths display twinning, but most do not. Most noticeable are the untwinned overgrowths on microcline grains. Generally the enlargements are free from inclusions and have a slightly different extinction position from the core. Therefore, the enlargements are of a slightly different chemical composition than the core. (See Plate I.)

Less than one percent of all the feldspar grains are well-rounded. In most samples the majority of grains are subrounded to

Plate I

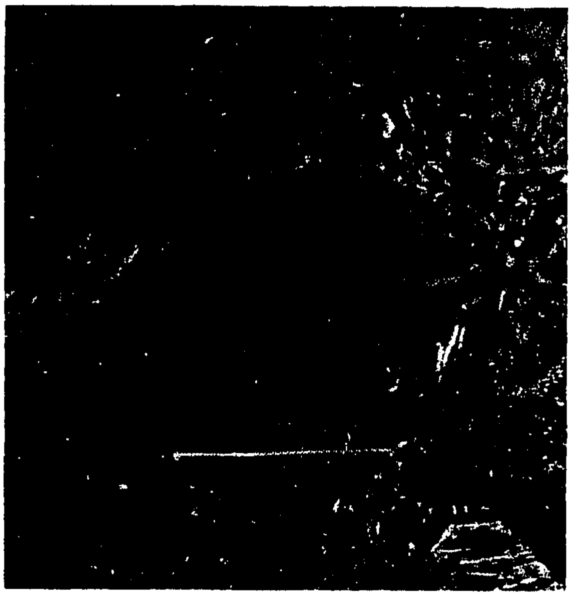
SELECTED PHOTOMICROGRAPHS

a. A subrounded quartz grain is present which contains intersecting vacuole trains. The grain is surrounded by gypsum cement. A moderately altered orthoclase grain is present on the left margin of the photomicrograph. Thin section number 993. Plane polarized light X250.

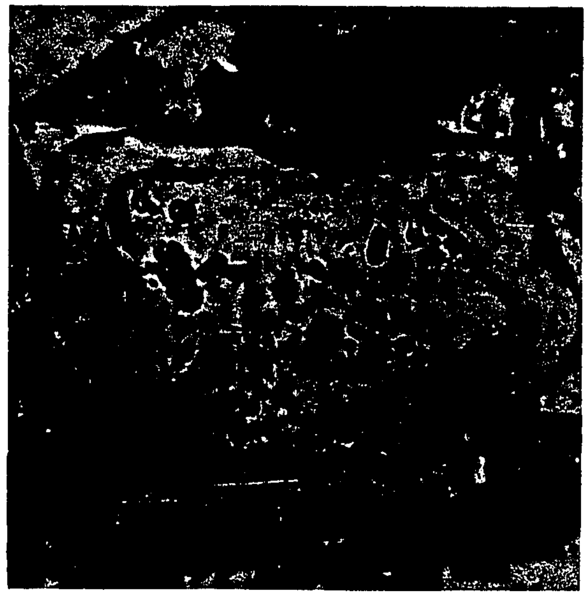
b. A subangular quartz core enclosed by two separate silica enlargements. Both the core and the first overgrowth are coated by hematite. The core contains inclusions of tourmaline, zircon, opaque material and vacuoles. The second quartz overgrowth is subrounded to the right and subangular to the left, and may itself represent two stages of quartz development. Thin section number 987. Plane polarized light X250.

c. An orthoclase core and overgrowth, both of which are subrounded and coated by iron oxides. The grain is cemented by gypsum and is in contact with quartz grains. Thin section number 984. Plane polarized light X250.

d. An angular, fresh orthoclase grain is present in the upper right portion of the picture. A rounded orthoclase grain with a thin overgrowth rim is present to the lower left. Grains are cemented by gypsum. Thin section number 982. Plane polarized light X250.

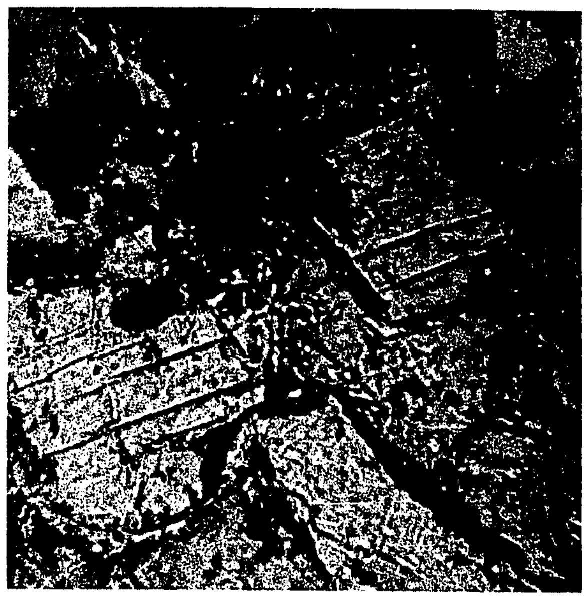


a.



b.

c.



d.

PLATE I

subangular but in a number of samples the majority of the grains are subangular to angular. Incipient overgrowths may be in part the cause of the latter grouping.

Rock Fragments

The most striking features of the rocks of the Cloud Chief Formation are the number and variety of rock particles. Metamorphic rock fragments are present in all the thin sections examined. Some of these grains consist entirely of stretched metaquartzite with sutured boundaries between sub-individuals and strongly undulatory extinction. Some rock fragments contain stretched quartz and subparallel mica, sericite, chlorite and/or opaque minerals. Some have well-defined outlines, and elongated grains of fine-grained, quartz-mica schists, quartz-chlorite schists, phyllites and fine-grained metaquartzites are recognizable; others are irregularly deformed and difficult to separate from a heavily iron-stained, argillaceous matrix. One large metaquartzite grain contains an angular plagioclase fragment.

Moderately rounded to well rounded detrital carbonate grains are present as rock fragments but generally make up less than one percent of the detrital grains in a sample. These grains are commonly polycrystalline aggregates of fine-grained material, and many have iron stained surfaces. Idiomorphic dolomite rhombohedra have formed on the surface of some of the carbonate rock fragments.

Mica

Both detrital muscovite and biotite are common accessory minerals and widespread constituents of these rocks. The varieties of biotite present include the pleochroic deep brown, tan, green, very light green to colorless types. The most common biotite is the tan to brown variety. The biotite's "crinkly" extinction is diagnostic, and the distortion of its extinction and interference figure indicates weathering to hydrobiotite. The size of the mica flakes ranges from about 45 to 150 microns. The micas have well-rounded edges. Many are disc-shaped and others are elliptical in outline. The micas seem to be about equal in abundance, but in some thin sections biotite dominates.

Chlorite

Detrital chlorite flakes are not as abundant as the micas but are as widespread in occurrence. The color of the grains varies from a moderate green to colorless. Pleochroism is common in the chlorite grains. A low iron chlorite is distinguished by its oblique extinction, a low refractive index, a positive optic sign and abnormal brown interference colors as the optic angle approaches zero (Albee, 1962). A higher iron content variety is length-slow, has a higher refractive index, a negative optic sign, and anomalous "Berlin-blue" interference colors. A few of these grains are penninite.

Some of the chlorite flakes have aggregate polarization. Some of the chlorite grains seem fibrous due to their crinkly growth form. Similar to the micas, the chlorite flakes are generally well rounded but some have distinctly angular lath shapes and others display pseudohexagonal outlines. Only a few chlorite grains are stained by iron oxides.

Opaque Minerals

Opaque accessory mineral grains are ubiquitous in the Cloud Chief Formation. The magnetite and ilmenite minerals are present as irregular masses and well-rounded grains. Both are opaque and purplish to bluish-black in reflected light. Detrital euhedra are rare. A number of the ilmenite grains are partially altered to the white substance, leucoxene. Opaque, subrounded leucoxene grains comprise from 35 to 50 percent of the opaque minerals in many of the samples described.

Heavy Minerals

Zircon. The distinctive high relief and bright, strong interference colors of zircon make it stand out in the thin sections. It is present in all slides examined. The zircons vary considerably in shape and size. The majority are moderate to well-rounded, but highly angular tetragonal prisms with pyramidal terminations occur. Few crystals contain inclusions. A number of the zircon grains are broken and subangular. A few zircon overgrowths occur on subrounded and/or broken cores of zircon. The mixing of well-rounded with euhedral zircons is common.

Tourmaline. Several varieties of tourmaline are present. Their strong pleochroism perpendicular to the polarizer and strong birefringence make them readily identifiable. The green, brown, black, blue and colorless types are present. The brown and green varieties seem to be the most abundant. A few grains of pink "watermelon" tourmaline are present. Most of the grains are worn and broken so that it is difficult to recognize any crystal form. A few grains are prismatic or subhedral.

Garnet. The high relief and isotropic nature of the garnets are their most characteristic optical features. Most of the garnets are colorless and have their surfaces etched into unique forms. Some pinkish and pale yellow grains exist. Many of the garnets are highly fractured and therefore their crystal form is obscured.

Apatite. Elongate, prismatic, transparent grains of apatite with characteristic high relief and low birefringence are most readily recognized. One hexagonal apatite grain was observed. A few subrounded and rarely well-rounded grains also occur. Apatite does not seem to be abundant in the heavy mineral suite of the specimens investigated.

Hematite. Subrounded to well-rounded detrital grains of hematite occur in many of the samples studied. The grains are deep red to black. Several are translucent but the majority are opaque. It was necessary to examine a number of the suspected opaque grains in reflected light to ascertain their identity as hematite.

Clay Minerals

General Statement

Argillaceous constituents make up almost one-half of the rocks of the Cloud Chief Formation and are present in all the lithologies examined. The clay minerals provide information about paleoclimate, source terranes and the environments of deposition. The abundance and value of the clay minerals to an interpretation of petrogenesis requires that they be thoroughly investigated.

The clay mineral identifications are based upon x-ray diffraction characteristics of the less than 4 micron equivalent spherical diameter oriented aggregates and their response to solvation with organic liquids and various heat treatments (see Appendix A for details of the technique). All the samples evaluated consist of more than one type of clay mineral and the relative proportion of each clay mineral varies from sample to sample. These mixtures can be analyzed in terms of the montmorillonite, chlorite and illite groups. The presence of interstratified clay minerals which are intimately involved with some of the main groups hinders a more detailed subdivision of the clay mineral varieties in many of the samples examined. The presence of more than one clay mineral within each sample also lessens the capabilities of differential thermal analysis as an identification aid.

Montmorillonite

The term montmorillonite is used herein as a group name for the three-layer clay minerals which expand in the c-axis direction on solvation with ethylene glycol (Plate II). This expansion varies, ranging from a maximum (001) d-spacing of 16.98 Å to less than 16 Å. The typical first order basal spacing exhibited by the nontreated samples is approximately 15.4 Å, which corresponds with the interlamellar water arrangement in two molecular layers (MacEwan, 1961). The majority of the montmorillonite present is trioctahedral, as is indicated by the 1.53 Å (060) spacing, and is suggested by the 4.58 Å (020) d-value (Plate II). The trioctahedral, expandable material is a magnesium-rich saponite (Table 1). Minor amounts of dioctahedral montmorillonite are present in some of the samples of the Cloud Chief Formation.

The variable expandability may be due to the presence of a high surface charge density montmorillonite, or an interstratification of

Plate II

SELECTED X-RAY DIFFRACTOGRAMS AND DIFFERENTIAL THERMAL ANALYSIS CURVES

a. Differential thermal analysis curve of humidified trioctahedral montmorillonite (less than 1 micron fraction).

b. Differential thermal analysis curve of humidified trioctahedral montmorillonite (less than 1 micron fraction).

c. X-ray preferred orientation diffractogram of montmorillonite, illite, chlorite and feldspar (less than 10 micron fraction) which has been placed in an ethylene glycol atmosphere for 4 hours.

d. X-ray preferred orientation diffractogram of sample c, in its natural state.

e. X-ray random orientation diffractogram of trioctahedral montmorillonite (less than 1 micron fraction), in its natural state.

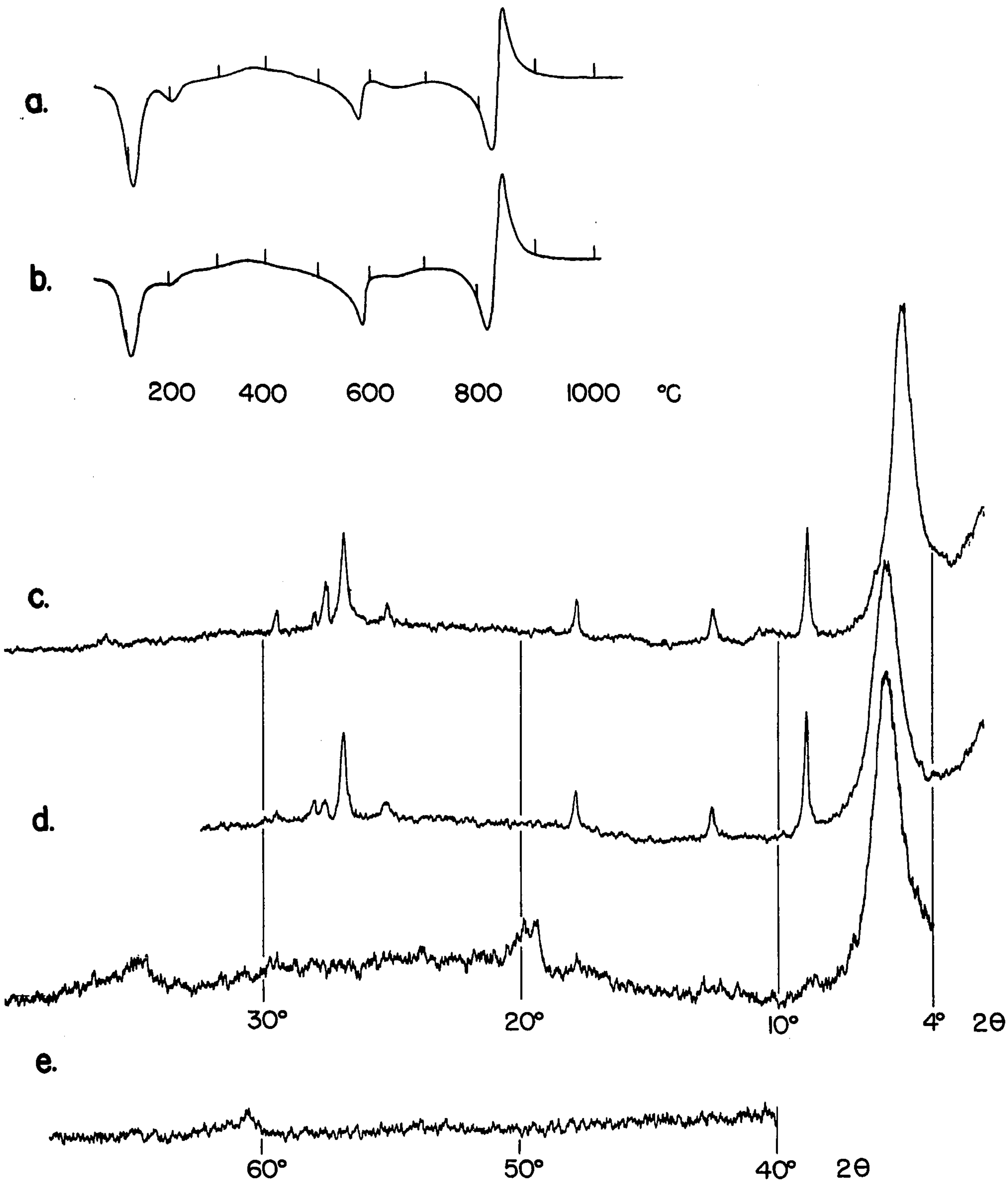


PLATE II

TABLE 1

CHEMICAL ANALYSES OF TRIOCTAHEDRAL MONTMORILLONITE AND 7 Å CHLORITE

SiO_2	TiO_2	Al_2O_3	Fe_2O_3	MgO	CaO	Na_2O	K_2O	H_2O^+	H_2O^-	Total
				Trioctahedral Montmorillonite (Saponite)						
46.06	0.68	12.01	8.01	16.39	1.35	n. d.	0.69	6.72	7.68	99.59
43.70	0.51	8.74	6.52	19.55	1.73	n. d.	1.55	5.80	11.38	99.48
44.30	0.48	9.23	6.34	19.27	1.61	n. d.	1.68	6.82	9.43	99.16
43.70	0.43	7.97	6.70	21.41	1.71	n. d.	1.29	7.08	9.78	100.07
41.60	0.31	9.85	9.24	17.98	1.52	n. d.	1.46	6.75	11.07	99.78
47.28	0.26	7.83	4.22	22.27	1.90	n. d.	0.33	5.95	9.92	99.96
44.60	0.81	10.27	6.88	17.48	1.92	n. d.	0.41	6.93	10.36	99.66
				7 Å Chlorite (Aluminum Serpentine)						
34.45	0.47	17.39	6.60	25.67	0.90	0.10	0.85	10.36	2.32	99.11
38.21	1.35	16.43	6.65	22.87	0.48	0.31	1.47	9.25	2.14	99.16

montmorillonite with vermiculite. If an interstratification exists, the ratio ranges from 5:1 to 5:2, montmorillonite:vermiculite. This estimate is based on the degree of expansion attained as compared with that expected of a pure montmorillonite. Though some layers do not expand when solvated, all of the layers do collapse to a 10 Å spacing when heated to 550° C; this indicates that the nonexpandable portion of the interstratification is a vermiculite (Walker, 1961).

Differential thermal analysis provides some additional evidence for the type of montmorillonite present (Plate II). The low temperature dehydration endotherm is typically a doublet between 90° and 220° C. The maximum displacement from the baseline is achieved at about 100° C. The minor shoulder at approximately 200° C suggests either the presence of divalent magnesium ions in the interlayer positions of the montmorillonite, or the presence of vermiculite. The amplitude of the major dewatering curve is dependent upon the degree of hydration attained by the sample prior to heating. All samples were placed in a sealed humidifier for 24 hours before being heated. Nevertheless, the temperature of the endothermic inflection, rather than the intensity of the curve, is considered the diagnostic feature in interpreting the thermograms.

The fairly sharp, asymmetrical endotherm at about 570° C represents a decomposition due to the loss of the hydroxyl groups and is considerably below the 800° C maximum dehydroxylization temperature for montmorillonites (Rich, 1964). A third endotherm occurs between 800° and 900° C and is typically followed by an exotherm which represents the final destruction of the montmorillonite lattice. Diffractometer furnace data at 1,000° C indicate that the material recrystallizes as clinoenstatite. Thermograms of specimens, size fractioned to a minimum of 0.1 microns, show an increase in the amplitude and sharpness of the high temperature exotherm with decreasing particle size. There also is an increase in the relative abundance of montmorillonite in the finer-size fractions.

Diffractograms of thermally-treated montmorillonites record the collapse of its lattice in the c_0 crystallographic direction from more than 15 Å to approximately 10 Å when heated above 300° C. Diffractometer furnace data indicate that this constriction commences at about 90° C.

Illite

Illite is identified by its (001) d-spacing of approximately 10 Å with successive basal orders of 5 and 3.33 Å (Plate II). It is a stable mineral and persists when heated to 550° C or when treated with warm, dilute (0.1 N) hydrochloric acid. Its non-expanding lattice maintains a constant d-spacing when exposed to an ethylene glycol atmosphere. Illites commonly contain more water and less potassium than do muscovites (Grim, 1953).

The illite abundance seems to increase in the less than 4 micron size fractions. Below this size the diffractograms of randomly oriented specimens are complicated by chlorite diffraction maxima. In the larger than 4 micron size fractions, the quartz reflections interfere with the illite diffraction maxima. The polymorphic variety of illite present was determinable in few specimens. The 2M type of Yoder and Eugster (1955) is considered the prevalent variety in the Cloud Chief Formation. The relatively weak (002) peak suggests a mixing of hydrobiotite with the illite. Macroscopic biotite flakes are present in all the thin sections examined.

Many samples display an asymmetrical 10 Å maximum with a tailing toward the higher d-spacings. This is probably due to randomly interspersed water layers which have replaced the leached interlayer potassium ions, and is termed a "degraded" structure.

The low temperature dewatering of illite occurs in the same general region as the corresponding evolution in montmorillonite, but does not produce the definite doublet of the latter. The second endotherm also is masked by that of montmorillonite, and the high temperature endothermic-exothermic curves occur near that of montmorillonite, but generally are not as intense.

Chlorite

The x-ray identification characteristics of normal chlorite include an integral series of diffraction maxima based upon a 14.2 Å periodicity. Upon heating to 550° C the (001) spacing shifts to approximately 13.5 - 13.8 Å with an enhancement of the first order peak; the second order peak decreases in intensity to less than one-half of the (001) maximum (Warshaw, and others, 1960). The chlorite crystal structure is destroyed when treated with warm, dilute (0.1 N) hydrochloric acid, and no x-ray diffraction lines are observed. Chlorite is not affected by solvation.

The (003) normal chlorite reflection can generally be resolved from the (002) illite peak in the nontreated sedimented samples, and it commonly is the only reflection positively identifiable as normal chlorite. The (001) reflection of normal chlorite is typically masked by the large (001) peak of montmorillonite, and the (002) reflection may be modified by the presence of a 7 Å clay mineral. The 14 Å normal chlorite peak may be discernible when the montmorillonite present is expanded by solvation, but heat treatment and the collapse of the swelling clay minerals reveal the presence of normal chlorite most distinctly. Detection of normal chlorite in heated samples is based upon the appearance of the intensified 13.8 Å peak and simultaneous decrease of the second-order peak after heating above 550° C (Plate III).

A second chlorite-type clay mineral which displays a markedly different behavior during heat treatment is present in the Cloud Chief Formation. The 7 Å maximum is not negligible after heating to 550° C for an hour but remains the most intense reflection with a second very intense peak at 3.55 Å. This mineral is a trioctahedral, 7 Å chlorite with a chemical composition analogous to a high-aluminum serpentine (Table 1). It is likely that the two types of chlorite described are representatives of two mineral series which are polymorphically related (Nelson and Roy, 1953). A chlorite-like hydrous magnesium, aluminum silicate that is considered to be authigenic by Lovett, and others (1960) occurs in both surface samples and cores in the southeastern portion of the Anadarko Basin.

Most of the chlorite-bearing specimens contain a combination of the 7 Å and the 14 Å chlorite minerals; this produces a diffractogram pattern similar to that of an iron-rich chlorite (Brindley, 1961). Orthohexagonal diffraction characteristics with relatively weak (001) and (003) peaks, and intense (002) and (004) reflections, are evident.

Plate III

SELECTED X-RAY DIFFRACTOGRAMS

a. X-ray preferred orientation diffractogram of trioctahedral 7 Å chlorite (less than 4 micron fraction) in its natural state.

b. X-ray preferred orientation diffractogram of trioctahedral 7 Å chlorite, 14 Å chlorite, hydrous magnesium aluminum silicate, illite and montmorillonite (less than 4 micron fraction) which has been heated at 500° C for 1 hour.

c. X-ray preferred orientation diffractogram of a split of sample b, which has been heated at 550° C for 1 hour.

d. X-ray preferred orientation diffractogram of a split of sample b, which has been heated at 600° C for 1 hour.

e. X-ray preferred orientation diffractogram of a split of sample b, which has been heated at 650° C for 1 hour.

f. X-ray random orientation diffractogram of trioctahedral 7 Å chlorite, quartz and feldspar (less than 10 micron fraction) in its natural state.

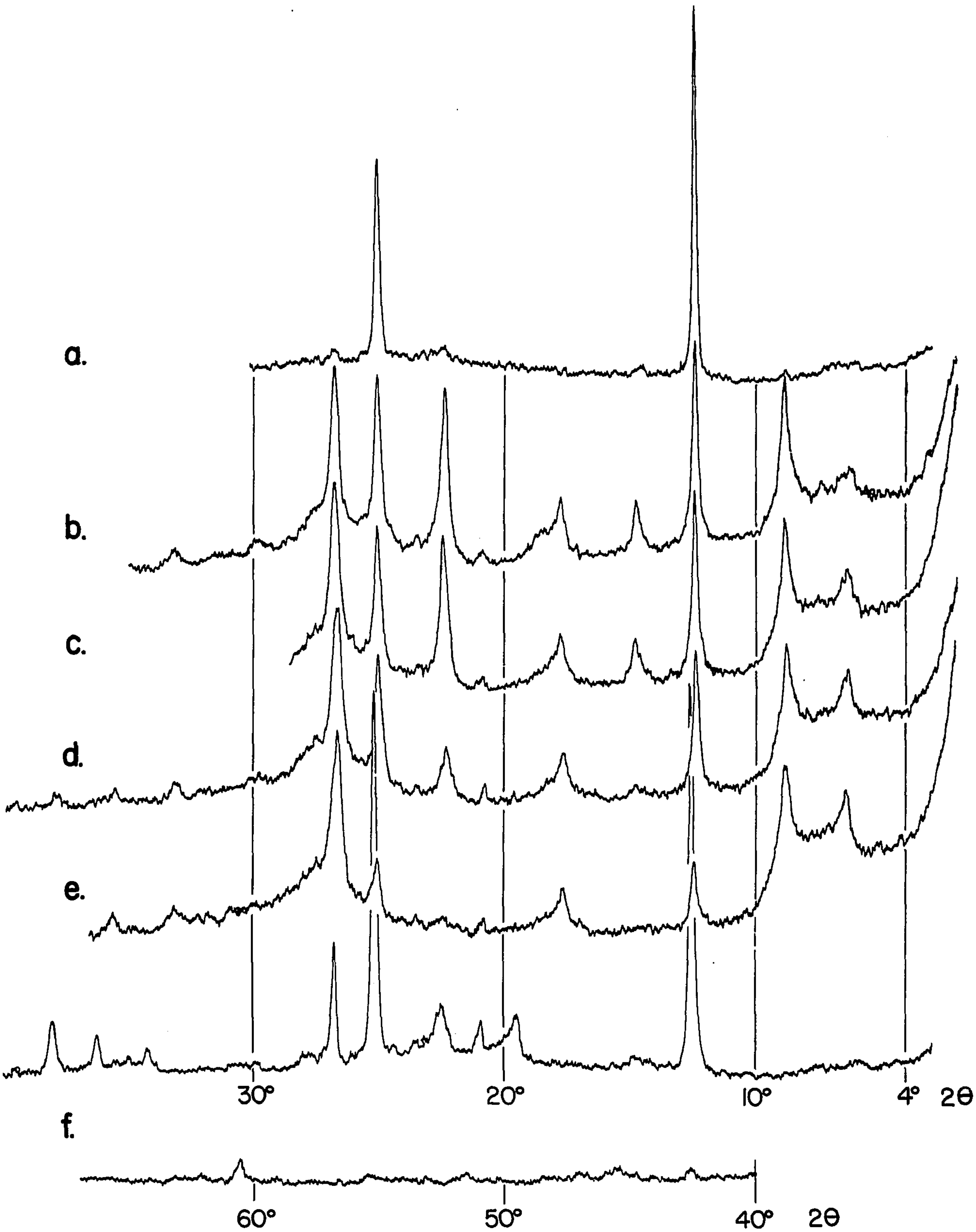


PLATE III

Table 2 lists the diffraction data for a typical sample containing a chlorite mixture of the 7 Å and the 14 Å chlorites which has been heated at various temperatures and for different durations. The ratios computed from the relative peak heights indicate that the same sample heated for a shorter time at a higher temperature can produce the same results as when heated at a lower temperature for a longer time. There is a progressive decrease of the chlorite 7 Å/14 Å ratio, as the 14 Å peak's original intensity is nearly doubled at a regular rate over the temperature range from 500° C to 650° C. A maximum intensity for the 14 Å chlorite reflection occurs between one hour of heating at 600° C and one hour of heating at 650° C. The 7 Å peak is reduced to one-fourth of its original intensity, but not at a linear rate. The first column in Table 2 shows that this diminution is most rapid when the sample is heated for one-half hour at 600° C. The diffraction furnace data listed in Table 2 reveal a 7 Å reflection persisting to over 580° C and 5 hours of heating. The increased duration of heating drastically reduced this reflection with respect to the 14 Å peak, as is indicated in the second column of the table.

Differential thermal analyses of chlorite (Plate IV) show an endothermic reaction between 550° C and 600° C. This represents the first dehydration, and involves a loss of water from the brucite layers (Brindley, 1961). The mid-region endotherm is commonly masked by the 570° C montmorillonite endotherm in the samples of the Cloud Chief Formation. The second endotherm is generally well defined at approximately 670° C and corresponds to a dehydration from the talc layer, the decomposition of the normal chlorite, and the decomposition of the aluminum

TABLE 2

RELATIVE INTENSITIES OF CHLORITE DIFFRACTION MAXIMA COMPUTED AS RATIOS
(Reflections in angstroms)

7/NT7*	7/14	14/10	7/10	T(°C)	Duration (hours)
		Samples heated in an oven on ceramic tiles			
.82	4.00	.33	1.33	500	1.0
.76	5.14	.37	1.89	500	2.0
.73	3.80	.37	1.41	550	0.5
.73	3.27	.42	1.38	550	1.0
.71	3.18	.55	1.75	550	2.0
.61	2.33	.55	1.27	600	0.5
.60	2.15	.68	1.47	600	1.0
.60	2.15	.62	1.33	600	2.0
.55	1.77	.59	1.05	650	0.5
.28	.81	.64	.52	650	1.0
.27	.75	.59	.44	650	2.0
		Samples continuously heated in diffractometer furnace			
.96	--**	--	2.25	120	1.0
.94	3.67	.48	1.76	130	1.6
.68	2.13	.48	1.03	535	4.0
.32	1.00	.54	.48	580	5.0
.04	.18	.38	.07	675	6.2

* Intensity of the 7 angstrom reflection prior to heating. All other reflections measured from heated samples.

** 14 angstrom line masked by montmorillonite.

Plate IV

SELECTED X-RAY DIFFRACTOGRAMS, DIFFERENTIAL THERMAL ANALYSIS CURVES AND A FOURIER ANALYSIS CURVE

a. Differential thermal analysis curve of a humidified 7 Å chlorite (aluminum serpentine) in the less than 1 micron fraction.

b. Differential thermal analysis curve of a humidified split of sample c.

c. X-ray preferred orientation diffractogram of a regularly interstratified chlorite-montmorillonite mixture, illite, 7 Å chlorite and 14 Å chlorite (less than 1 micron fraction) which has been placed in an ethylene glycol atmosphere for 12 hours.

d. One-dimensional Fourier synthesis from the (001) diffraction maxima of diffractogram c.

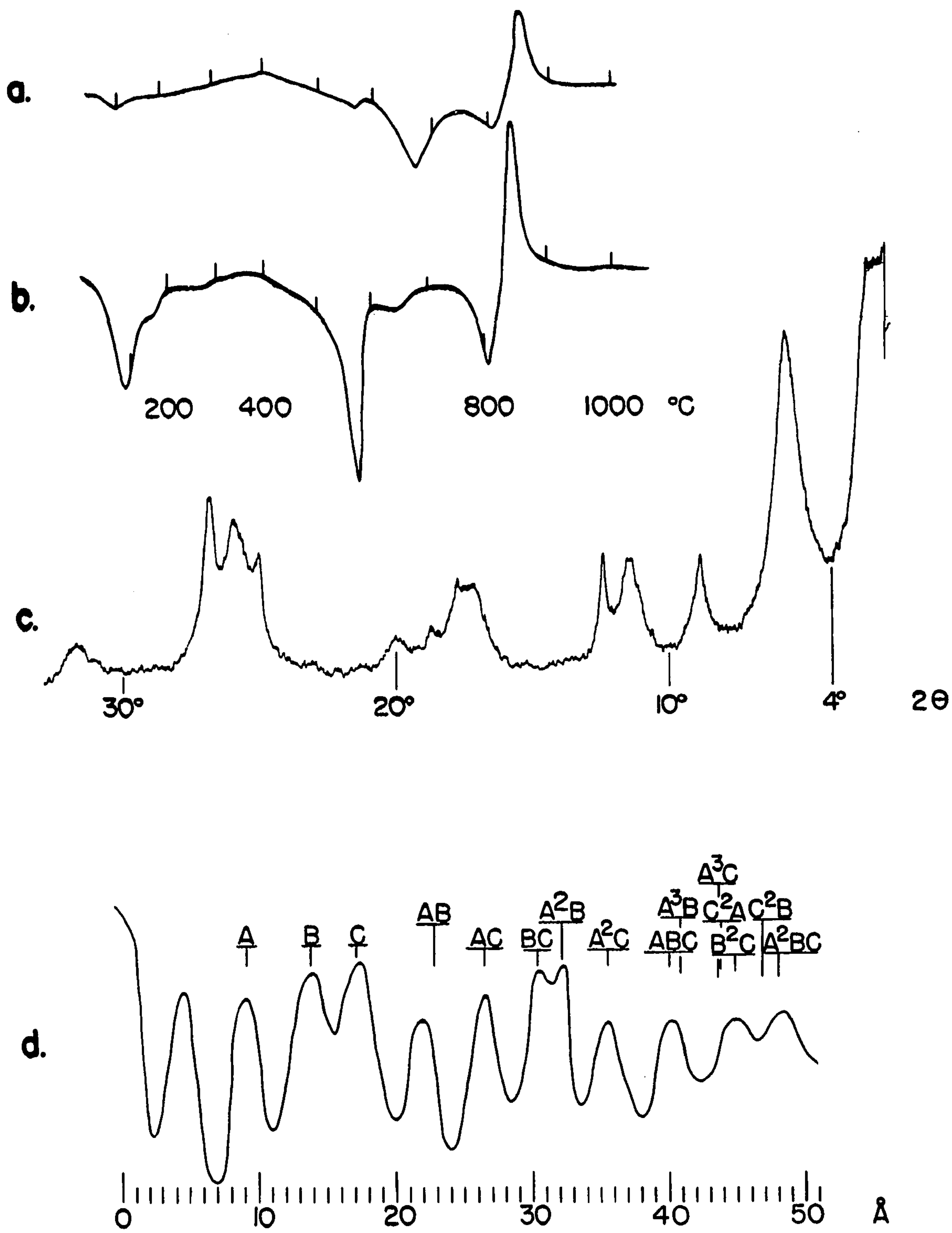

a.
b.
200
400
800
1000 °C
c.
30°
20°
10°
4°
2θ
d.
A
B
C
AB
AC
BC
A2B
A2C
A3C
A3B
C2A
C2B
ABC
B2C
A2BC
0
10
20
30
40
50
Å

PLATE IV

serpentine (Shirozu, 1958). Lattice reorganization prior to 700° C is suggested by the pronounced modifications observed on diffractometer records in this temperature range. The high temperature endotherm between 800° C and 850° C, which is closely followed by an exotherm before 900° C, is similar to the high temperature "S" curve of montmorillonite and represents the recrystallization of this material to a mixture of augite, diopside and forsterite.

Kaolinite

Clay minerals of this group are identified by strong characteristic diffraction maxima at 7.2 Å and 3.58 Å, and a (003) reflection at 2.38 Å. These diffraction maxima are unaffected by solvation or by thermal treatment to 300° C. Dependent upon grain size and kinetic factors (Roy and Osborne, 1954), collapse to a non-diffracting state occurs above the maximum hydrothermal stability temperature of 405° C. According to Brindley (1961) a thermogram of kaolinite shows an endothermic reaction near 500° C and an exothermic reaction between 900° C and 1,000° C. Warm, dilute (0.1N) hydrochloric acid treatment will not affect the basal reflections of kaolinite.

The presence of chlorites in most of the specimens investigated introduces an uncertainty into the identification of kaolinite. The basal sequence of chlorite spacings interfere with those of kaolinite. The intensity loss of the 7 Å reflection with heat treatment has not conclusively differentiated the two clay mineral groups. Attempts to attribute quantitative significance to the 7 Å peak modifications with heating have been unsuccessful. A number of heated samples, where a mixture of kaolinite with chlorite was suspected, revealed no 7 Å diffraction maxima in the diffractograms of their acid treated portions. Almost all the samples treated with acid indicated that no kaolinite is present; the single exception may be explained by the more resistant nature of dioctahedral chlorite to hydrochloric acid treatment (Schultz, 1963, and Hayashi and Oinuma, 1964).

Differential thermal analysis also indicates the absence of kaolinite by the general lack of any thermal reactions in the 900° C to 1,000° C region. Clay minerals of the kaolinite group are considered to be either absent, or to be a minor constituent of the samples tested.

Interstratified Clay Minerals

Interstratified mixtures of layer silicates may occur in a regular or random fashion. Regular alternation means that the succession of components is affected by the neighboring layers and a well-defined periodicity results. The alternation of species within a crystallite produces repeating diffraction planes at a distance equal to the sum of the c_0 axis distances of the particular components. The regular periodicity is best identified by a series of reflections at submultiples of the basal spacing. If the interstratification is not exactly regular, the (001) spacings will deviate somewhat from integral submultiples.

Randomly interstratified clay minerals have no set alternation of layers, hence layer successions are irregular. These mineral combinations produce apparent d-spacings intermediate between the normal (001) spacings of the individual components. The exact intermediate distance will depend upon the relative proportions of the components in the interstratifications. Basal spacings of either or both components may also be observed as diffraction maxima if these minerals are present as discrete entities. This situation is commonly observed in the samples of the Cloud Chief Formation.

A randomly interstratified clay mineral may produce diffraction super-orders resembling a regular succession. Such maxima are the result of a statistical averaging of the layer types in the population of layers available. The probability of a particular layer type occupying the necessary positions to obtain this succession is the same as the probability of that layer type occurring at all, i.e., a random probability. Generally, such super-order diffraction peaks are diffuse and will not produce a series of maxima at submultiples, as will a regular interstratification. It has been noted that even a moderate proportion of random interstratification can be overshadowed by the presence of a regularly interstratified material. In many instances it may not be possible to distinguish large regularly combined layer units from random interstratifications because of the high background encountered in the low angle regions of the diffractograms. Such a regular increase in intensity at the lower angles of two theta is common with interstratified clay minerals. The term "mixed-layer" is also applied to interstratified materials.

Because most of the samples investigated indicate some degree of interstratification in the clay mineral assemblage, the possibility of a regular mixed-layering being present was considered. Several samples were found to be suitable for detailed study. X-ray diffraction records of the less than 4 micron and less than 1 micron size fractions in the solvated and heated states showed super-order reflections with spacings at about 31 Å and 24 Å respectively, as well as (001) orders at regular submultiples of these first-order basal reflections. Additional super-orders are commonly present between these values, and some are as large as 40 Å, due to the presence of random interstratifications. The occurrence of discrete illite, chlorite and montmorillonite precludes reliable indexing of powder diffractograms, therefore oriented specimens were relied upon for mixed-layer identifications.

The modifications of the c_o axis distance with water loss were determined by progressive heating from room temperature to 800° C. Significant changes occurred upon heating. The spacings corresponding to diffraction lines at various temperature intervals are illustrated in Table 3. The theoretical spacings expected for integral orders of the basal reflections of a regular chlorite-montmorillonite interstratification are provided for comparison.

Table 3 also includes the diffraction lines for reflections observed from the solvated specimen whose diffractogram is illustrated in Plate IV. The presence of an expandable component is indicated by the increase in the basal spacings with solvation. Mixed-layer regularity is indicated by the consistent shift of all integral submultiples of the combined cell that is postulated from the first order d-spacing. The most expandable montmorillonites found in this area have a maximum spacing of about 16.8 Å. By adding a 14.2 Å normal chlorite (001) spacing to this, a 31 Å value is obtained. Integral orders based on a 31 Å reflection are present in the illustrated diffractogram (Plate IV). The partial chloritic character of the interstratification is revealed by

TABLE 3

BASAL REFLECTIONS FROM NATURAL, ETHYLENE GLYCOLATED AND HEATED SAMPLES (LESS THAN 1 MICRON FRACTION) CONTAINING REGULARLY INTERSTRATIFIED CHLORITE-MONTMORILLONITE

Solvated				Heated											
Theoretical		Observed		Theoretical		Observed									
						Natural		120°C		275°C		470°C		580°C	
(001)	d(Å)	d	I	(001)	d(Å)	d	I	d	I	d	I	d	I	d	I
1	31	33.46	.38	1	24			24.21	.25					23.94	.27
						17.13	.1	13.62	1.00	21.45	.19	14.16	.21	12.11	.69
2	15.5	15.5	1.00	2	12	13.83	1.0	13.29	1.00	12.5	.33	12.36	.29	11.91	.69
						9.95	.35	10.16	.69	10.05	.76	10.16	.75	10.34	.65
														10.20	.62
3	10.3	9.95	.31	3	8	8.90	.25	8.68	.50	8.05	.43	8.04	.42		
						7.17	.40	7.17	.50	7.17	.48	7.20	.33	7.21	.12
4	7.8	7.85	.35	4	6	5.34	.15	5.22	.44						
		7.14	.37			4.99	.25	5.04	.44	5.02	.67	5.05	.54	5.10	.38
						4.92	.15			4.90	.57	4.82	.38	4.91	.12
5	6.2	6.18	.02	5	4.8	4.74	.15	3.71	.38	4.79	.57	4.78	.38		
6	5.2	5.17	.29	6	4	3.58	.55	3.58	.69	3.57	.48	3.59	.33	3.59	.12
		5.00	.31												
		4.74	.13												
7	4.4	4.44	.10	7	3.4	3.51	.25			3.43	.67				
						3.35	.90	3.34	.75	3.35	1.00	3.38	1.00	3.40	1.00
8	3.9	3.88	.02												
		3.56	.43												
9	3.44	3.44	.54												
		3.33	.62												
10	3.1	3.08	.02												

the values observed for the heated sample when the collapse of the expandable material to about 10 Å produces a combined cell of about 24 Å. The disappearance of the apparent first order peak at 470° C and its re-appearance at 580° C is probably due to the modified basal intensities for normal chlorite which shows a maximum 14 Å reflection intensity in this temperature range. Discrete 7 Å and 14 Å chlorite as well as discrete illite contribute substantially to the clay mineral composition of this sample.

The thermogram interpretation of this sample (Plate IV) is complicated by the variety of clay minerals present. Montmorillonite reactions are represented by the low temperature endothermic doublet, the 570° C endotherm and the 860° C exotherm. The initial doublet is due to the removal of interlayer water, and water of cation hydration. The midregion endotherm is below that expected for a dioctahedral montmorillonite and suggests a trioctahedral nature. The presence of normal chlorite is indicated by the 640° C endotherm, which, according to Brindley (1961), represents the dehydroxylization of the talc layer.

To more thoroughly evaluate the nature of this interstratified mixture the method of Fourier transforms was applied to the solvated diffractogram of Plate IV(c). The calculations performed are described in Appendix B. By using the existing diffraction data alone it is possible to estimate the types of interstratification present in this material. W_R, the probability of finding a given interlayer spacing or the number of times the spacing occurs, is plotted in Plate IV against R, the distance along the c_o axis from any layer. Several transforms were attempted using the layer structure factor computed from the dioctahedral mica curve (Brown, 1961, p. 408) without obtaining meaningful results. The Fourier transform shown utilized the trioctahedral curve for the montmorillonite layers. To adjust for the different interlayer scattering powers in the two components, an average layer structure factor was determined.

Maxima, labeled A, B and C in Plate IV, are primary peaks which correspond to spacings between contiguous layers and represent illite, chlorite and montmorillonite, respectively. If only a regular intergrowth exists the possible successions would include A+B, B+C, and/or A+C; no A+A nor B+B successions would occur. This proceeds from the fact that in a regular interstratification a layer is required to succeed a particular layer of another type, and vice versa, to accomplish the regular alternation. For brevity the addition sign is omitted and A+A becomes AA, A+B becomes AB, or A+A+B becomes A^2B, and so on. In addition to the AB, BC, AC successions possible in a regular interlayering, maxima representative of successions with two or more intermediate layers, i.e., A^2B, AB^2, A^2C, et cetera, could be encountered. Using the three contiguous spacings the following are some of the successions possible: AA = 18 Å; BB = 28 Å; CC = 35 Å; AB = 23 Å; AC = 26.5 Å; BC = 31.5 Å; A^2B = 32 Å; A^2C = 35.5 Å; B^2A = 37 Å; B^2C = 45.5 Å; C^2A = 44 Å; C^2B = 49 Å; A^3B = 41 Å; ABC = 40 Å; and A^2BC = 49 Å. Several of these combined cells were noted on the Fourier transforms and their relative intensities are indicative of the abundance of each type of mixture present. The 4.5 Å peak is a constant feature of this type of diagram, being due to diffraction by the very large peak at the origin. It is evident from the number of maxima attributable to the successions of like layers that much random interlayering exists in this material. However, the chlorite-montmorillonite (BC) succession is the most abundant. The data indicate that random intergrowths of both illite-chlorite and illite-montmorillonite are also present, as AB and AC, and with more than one intermediate layer. The possibility of a three member interlayer system of chlorite-illite-montmorillonite is tentatively recognized on the basis of the strength of the 40 Å peak in Plate IV. However, its intensity is most likely reinforced by the 41 Å(A^3B) peak.

The method of one dimensional Fourier analysis substantiates and elucidates the interpretations which were intuitively reasoned from diffraction and differential thermal data. That is, the specimen contains a variety of interstratifications of which a regular mixed-layering of chlorite-montmorillonite is the most abundant.

Variations in the degree of regular interstratification is evident between the less than 1 micron and less than 4 micron size fractions as illustrated in Plate V(a) and V(b). The first two diffractograms were obtained from the same sample sedimented on glass slides, and each solvated for 12 hours. Both samples contain discrete chlorite, poorly expandable montmorillonite, and illite. Sample b also contains some quartz. Each has an integral series of maxima based on an appropriate 31 Å (001) spacing, but the degree of perfection of these orders is quite dissimilar. In particular, the first, second, fourth, sixth and ninth orders are different, and indicate a more regular development of mixed-layering in the finer size fractions. This is a general characteristic of the samples in which such clay mineral interstratifications occur.

Plate V

SELECTED X-RAY DIFFRACTOGRAMS AND A DIFFERENTIAL

THERMAL ANALYSIS CURVE

a. X-ray preferred orientation diffractogram of regularly interstratified chlorite-montmorillonite, montmorillonite, chlorite and illite (less than 1 micron fraction) which has been placed in an ethylene glycol atmosphere for 12 hours.

b. X-ray preferred orientation diffractogram of regularly interstratified chlorite-montmorillonite, montmorillonite, chlorite, illite and quartz (less than 4 micron fraction) which has been placed in an ethylene glycol atmosphere for 12 hours.

c. X-ray preferred orientation diffractogram of montmorillonite, chlorite, illite, mullite (ceramic tile), quartz and randomly interstratified montmorillonite-illite and chlorite-montmorillonite (less than 4 micron fraction) in its natural state.

d. X-ray preferred orientation diffractogram of sample c, which has been placed in an ethylene glycol atmosphere for 20 hours.

e. X-ray preferred orientation diffractogram of sample c, which has been heated at 650° C for 1 hour.

f. Differential thermal analysis curve of a humidified split of sample c.

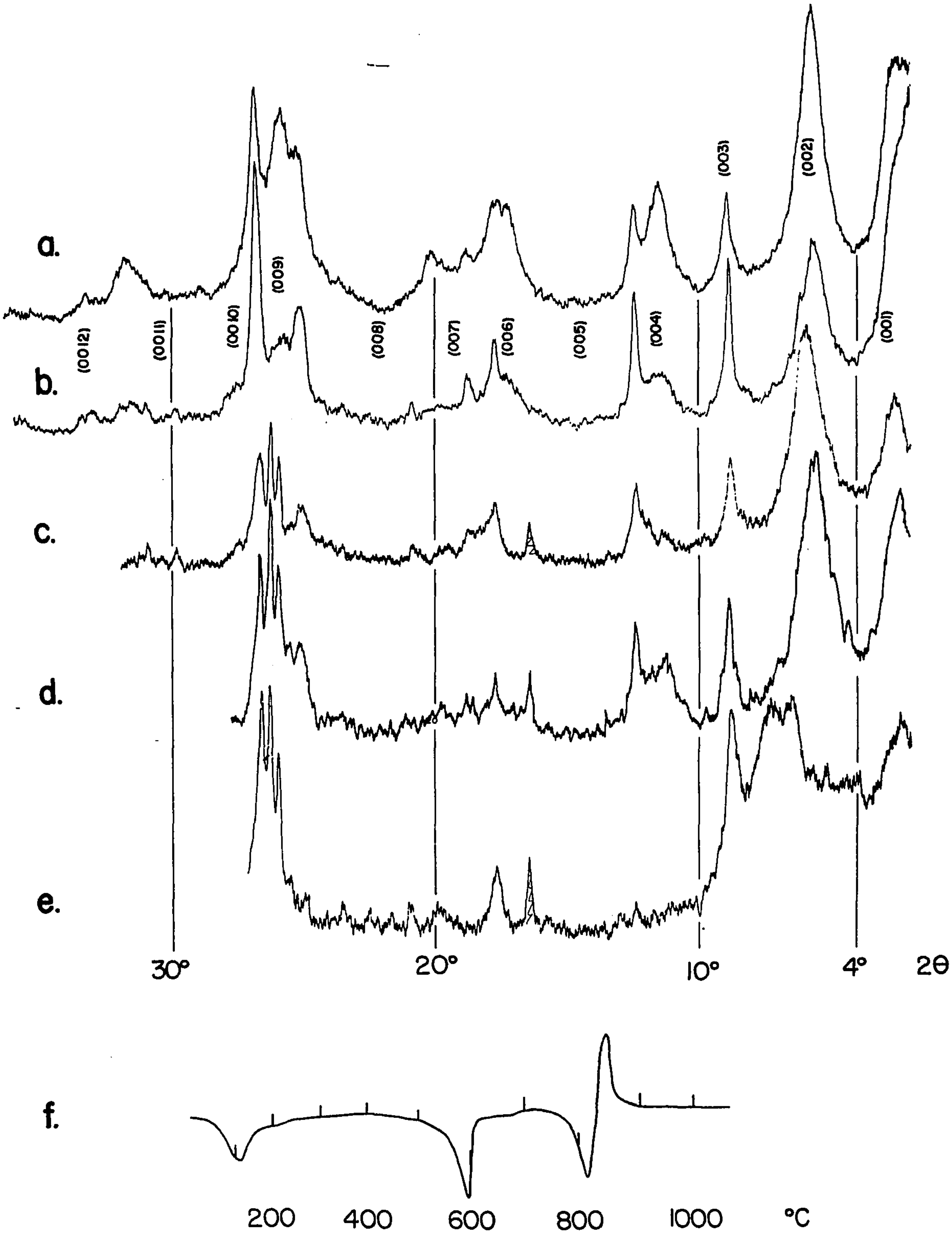

a.
b.
c.
d.
e.
(0012)
(0011)
(0010)
(009)
(008)
(007)
(006)
(005)
(004)
(003)
(002)
(001)
30°
20°
10°
4°
2θ
f.
200
400
600
800
1000
°C

PLATE V

Randomly interstratified chlorite-montmorillonite with minor regular interstratification of the same combination makes up part of the clay mineral assemblage illustrated in Plate VI. The nontreated sample on both the platinum plate and ceramic tile show super-orders in the diffraction records. When heated to 250° C, the large montmorillonite peak collapses and is replaced by a diffuse series of maxima at approximately 13 Å. Random interstratification between the 7 Å chlorite peak and a 10 Å mineral produces the 8.31 Å diffraction line which becomes progressively less visible on heating. This behavior is in accord with chlorite heating characteristics. At 550° C the (001) chlorite peak has been enhanced as shown by the 14 Å line for the discrete normal chlorite. Therefore, the 14 Å/10 Å normal chlorite-dehydrated montmorillonite random interstratification becomes evident at about 12 Å. The intensity of this peak corresponds well with the normal chlorite peak modifications on heating. Heating from 550° C to 650° C removes the 7 Å and 8 Å maxima and displaces the 14 Å and 12 Å peaks to 13.6 Å and 11.6 Å respectively, and slightly decreases their intensities. The 11.6 - 12 Å reflection continues to maintain its broad character. The mixed-layer basal spacing indicates approximately equal amounts of the chlorite and montmorillonite constituents. The presence of discrete montmorillonite as well as an expandable component in the interstratification is indicated in the solvated diffractogram. The slight 12 Å line can result from a random mixed-layering of 10 Å and 14 Å clay minerals, and the possibility of chlorite-illite interlayering is not ruled out. The randomly interstratified solvated montmorillonite-illite does not produce an intermediate diffraction maximum at approximately 12 Å

Plate VI

SELECTED X-RAY DIFFRACTOGRAMS

a. X-ray preferred orientation diffractogram of montmorillonite, 7 Å chlorite, 14 Å chlorite, randomly interstratified chlorite-montmorillonite, quartz and illite (less than 4 micron fraction) at room temperature on a platinum plate.

b. X-ray preferred orientation diffractogram of sample a, which has been heated to 250° C.

c. X-ray preferred orientation diffractogram of sample a, which has been heated to 550° C.

d. X-ray preferred orientation diffractogram of montmorillonite, 7 Å chlorite, 14 Å chlorite, illite and randomly interstratified chlorite-montmorillonite (less than 4 micron fraction) on a ceramic tile (mullite peak evident) in its natural state.

e. X-ray preferred orientation diffractogram of sample d, which has been placed in an ethylene glycol atmosphere for 20 hours.

f. X-ray preferred orientation diffractogram of sample d, which has been heated at 650° C for 1 hour.

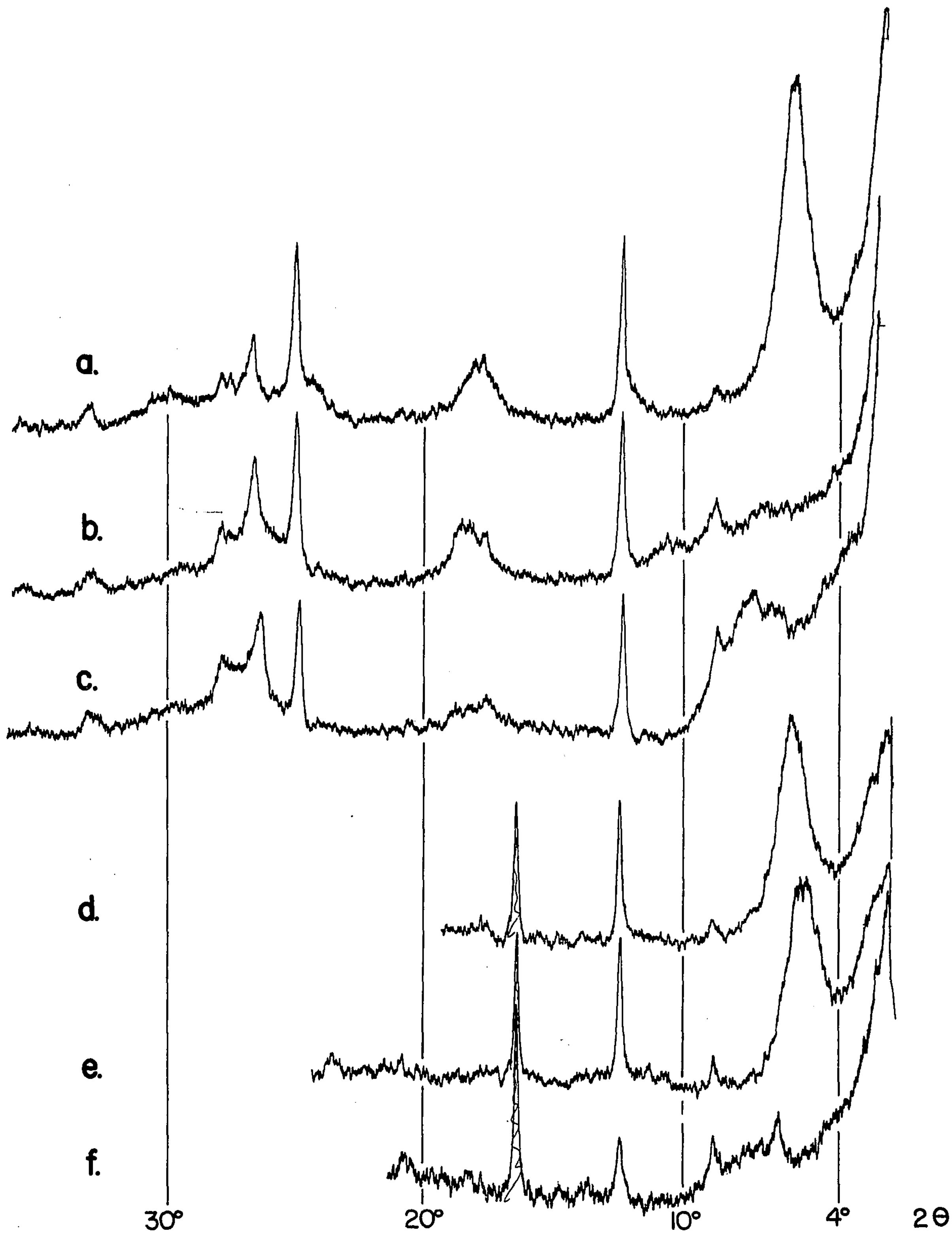


PLATE VI

(Reynolds, 1967), therefore such a peak is indicative of a regular mixed-layering.

Plate V(c-e) exemplifies the characteristics of a similar material with more well defined super-orders. Numerous quartz and mullite reflections are present. Separate illite, montmorillonite and chlorite are also present. The nontreated 33.72 Å spacing could consist of a 10+10+14 Å layer stacking. The corresponding solvated peak shows an expansion to 36.96 Å, and therefore consists of a 10+10+17 Å clay mineral stacking. Neither reflection is accompanied by an integral series of submultiples. Therefore, the mixed-layering is randomly stacked. The 7.87 Å reflection, which is quite evident in the ethylene glycolated sample, is a combination of the second order chlorite and first order illite basal reflections. The increase in the 7.87 Å reflection is somewhat artificial, being due to a different scale factor setting on the recorder for the solvated sample, and partly due to the second order from the intense (001) montmorillonite reflection. The slight 12 Å peak on the same diffractogram represents a random 10/14 Å combination (or 10/16 Å); the 24 Å super-order could also be due to a 10+14 Å stacking. The presence of discrete normal chlorite and a mixed-layering of chlorite and montmorillonite is indicated on the sample heated to 650° C, for 1 hour. The large montmorillonite first-order reflection collapses to about 10 Å. Some of this clay mineral is randomly interstratified with the intensified first-order chlorite peak to produce a 12 Å(10/14 Å) reflection. The 36.96 Å super-order could represent a random stacking of the 13.6 Å chlorite layers with a

9.98 Å illite, or collapsed montmorillonite layer. The recorder setting for diffractograms "c" and "d" in Plate V are the same.

Interstratified mixtures are common in the clay mineralogy of the Cloud Chief Formation. Only a fraction of these mixtures are regular alternations, and typically consist of a chlorite-montmorillonite combination. The regular mixed-layering is seemingly better developed in the finer clay fractions (less than 1 micron). A variety of random interstratifications is present which includes chlorite-montmorillonite, chlorite-illite, illite-montmorillonite and, possibly, chlorite-illite-montmorillonite. Some of the randomly interstratified clay materials contain more than one intermediate layer, as indicated by Fourier analysis.

Orthochemical Constituents

Gypsum

Gypsum occurs in the Cloud Chief Formation as bedded deposits, individual selenite crystals, vein filling, and as cement. It commonly is present as a mozaic of subparallel, fibrous, subhedral crystals with well-defined margins. It is generally devoid of impurities except for a few "floating" detrital grains. Its gray color and wavy extinction closely resemble strained, composite quartz. The cement also occurs in subhedral aggregates with an uneven grain. No anhydrite was recognized.

Carbonates

Much of the carbonate present is micrite. Microcrystalline dolomite is a common cementing agent in the formation. A few, thin dolomite beds are present. Many, large, idiomorphic dolomite rhombohedra also occur throughout the formation. Calcite is present as cement, but to a lesser extent than dolomite. It commonly occurs as microcrystalline calcite, but some sparry calcite cement is present. A number of feldspars and, to a lesser extent, quartz grains are partially replaced by carbonate. Highly iron-stained, argillaceous, carbonate intraclasts are present in several of the mudstones and shales examined. The intraclasts would more properly comprise the allochemical constituents.

Hematite

Thin hematite coatings on detrital grains and disseminated hematite stain in the finer fractions are common in this red bed sequence. The presence of hematite staining is universal in many of the examined samples. Accumulations of hematite occur in the angular space between detrital grains, nearest their contacts. Only a few contacts are devoid of the red coating at the boundary. The iron oxide coating is uniform on many of the grains, but a number of grains have their thinnest coatings on their protruberances. Furthermore, some of the grains have no stain on their corners and nodes. Hematite stain is recognizable beneath and on the surface of overgrowths on a number of single grains. In some portions of the rocks studied hematite is the sole binding agent which results in weakly-indurated lithic units.

PETROLOGY

General Statement

The petrographic evidence indicates that the rocks of the Cloud Chief Formation are the product of multiple sources. The major contributions came from plutonic sources. The influence of a metamorphic terrane is obvious; most of the rocks are subgraywackes. Several lines of evidence indicate a recycling of pre-existing sedimentary materials, some of which were red beds. A sporadic volcanic influence is also suggested.

The clay mineral assemblage provides evidence of a semi-arid to arid paleoclimate. The variable expandability of some 14 Å clay minerals suggests a series of climatic fluctuations. Variable feldspar alteration either supports a change in climate or is due to tectonic instability. A regional compilation of the mineralogy of these rocks points to different geographic source areas. Variability is a prominent aspect in the geologic history of rocks of the Cloud Chief Formation.

The highly variable lithologic character of the formation is reflected on a microscopic scale in many of the samples studied. The inhomogeneity is particularly evident in the mudstones and finer siltstones. Laminae of silt grains are interlayered with either argillaceous bands or hematite-stained carbonate intraclasts. Microscopic cut and fill sedimentary structures occur, outlined by minute placers of heavy minerals (Plate VIII). Delicate cross-bedding, and truncations, are present in the fine laminae. Many of the thin layers are disrupted by microfissures. Some lenses of detrital grains do not extend the length of the thin section before pinching to a fine edge. It would be difficult to sample a single sedimentation unit of this inhomogeneous material for a meaningful grain size analysis.

In determining the provenance of these rocks an attempt has been made to minimize the effect of the depositional environment and/or post-depositional alteration. All point counts utilized varietal types of a single mineral.

All alterations that have taken place at the site of deposition are considered diagenetic, with the exception of mechanical reworking by currents. Weathering is not considered as part of diagenesis. Authigenesis is the in situ formation of new minerals and is considered a diagenetic process. Additions to primary minerals, such as overgrowths, are authigenic in a restricted sense, and are termed "secondary".

Provenance

Parent Terrane

Plutonic sources. The major detrital constituent present in the rocks of this formation is quartz. The most abundant type of quartz present has slightly undulose extinction and typically contains only a few scattered vacuoles, and even fewer microlites. Although this variety of quartz is ascribable to different source rocks, a granitic parent terrane is strongly suggested (Krynine, 1946).

Even though only a small number of quartz grains contain crystalline inclusions, the variety of the microlites indicates that more than one source material has contributed to these sediments. No relationship between the size of the quartz grains and the type of microlite included was noted.

The most abundant feldspar variety present is orthoclase (Plate VII). Orthoclase and microcline are the dominant feldspars in granites and gneisses. Therefore, a plutonic source rock is a possible provider of the prevalent species of feldspar in the Cloud Chief Formation.

Metamorphic sources. Metamorphic rock fragments occur in all of the samples examined and ordinarily comprise more than 5 percent of the detritus. According to the classification of Folk (1965) a rock with such a rock fragment-rich framework composition is a subgraywacke.

Metaquartzite fragments are the most abundant positive metamorphic type present. The rocks also contain a variety of well-rounded, elongated, and subrounded, irregular, quartz-bearing schist fragments (Plate IX). Micaceous schist and phyllite rock fragments are less common. These particles were undoubtedly furnished by the erosion of a metamorphic area. It is also likely that the principal provider of the omnipresent micas are the metamorphic rock suites. The disintegration of the soft phyllite and micaceous rock fragments could account for some of the argillaceous matrix, in particular the illite. The small population of quartz grains with rutile needles and other hairlike inclusions is a minor component of the terrigenous constituents. However,

Plate VII

SELECTED PHOTOMICROGRAPHS

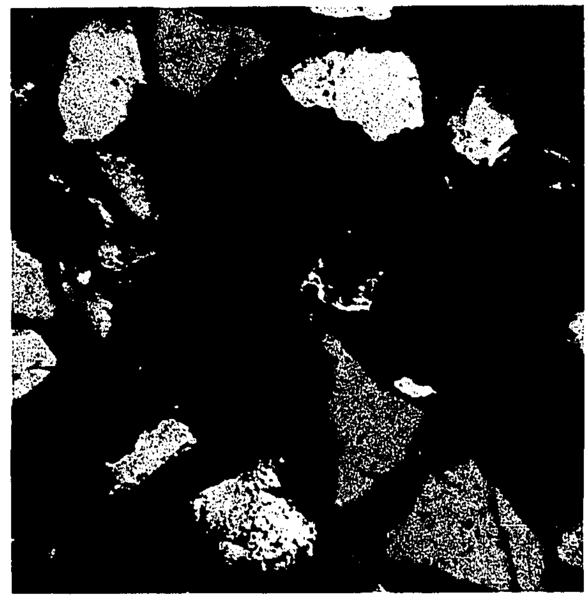
a. A large, angular, fresh orthoclase grain (center) is next to a subrounded quartz grain (upper right). A quartz-sericite-opaque rock fragment is adjacent to the orthoclase grain to the left. Thin section number 1020. Crossed nicols X100.

b. A plagioclase grain with polysynthetic twinning is present in the center of the photomicrograph. An angular quartz grain occurs below and to the right of the plagioclase grain. Thin section number 1035. Crossed nicols X100.

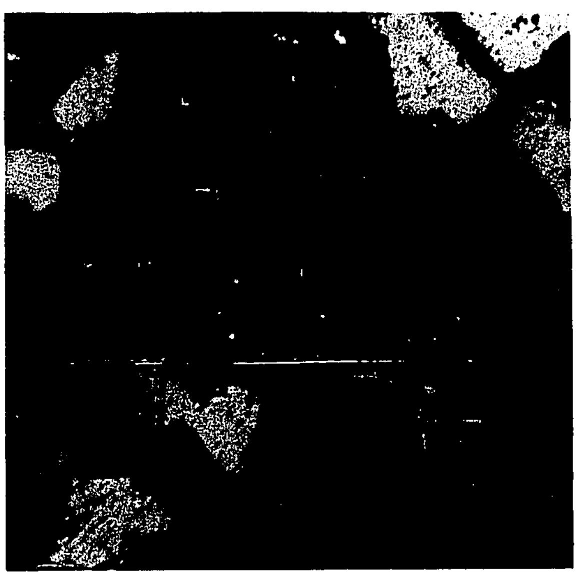
c. A lightly altered plagioclase grain is present to the left of center. Directly below this grain is an angular quartz grain. An elongated quartz-chlorite schist fragment with some opaque material is present to the right of center. Thin section number 993. Crossed nicols X100.

d. The angular, lightly altered feldspar grain to the left of center has an angular feldspar overgrowth with a slightly different optical orientation. In the lower right corner is a round, iron-coated carbonate rock fragment composed of microcrystalline dolomite. A subrounded, semicomposite quartz grain at partial extinction occurs in the upper left corner of the photomicrograph. Thin section number 987. Crossed nicols X100.

a.



b.



c.

d.

PLATE VII

Plate VIII

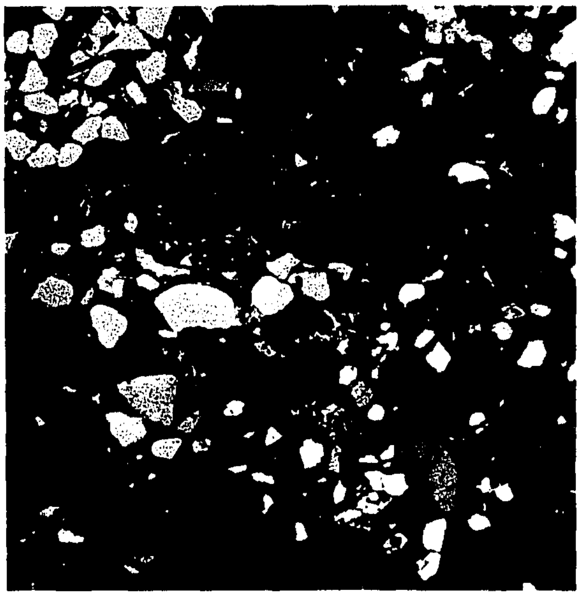
SELECTED PHOTOMICROGRAPHS

a. A large, well-rounded metaquartzite fragment occurs slightly to the left and above center. This grain is magnified in photomicrograph b. At approximately one-half the distance to the right margin of the picture from the metaquartzite grain is a composite quartz grain at partial extinction. Thin section number 1035. Crossed nicols X100.

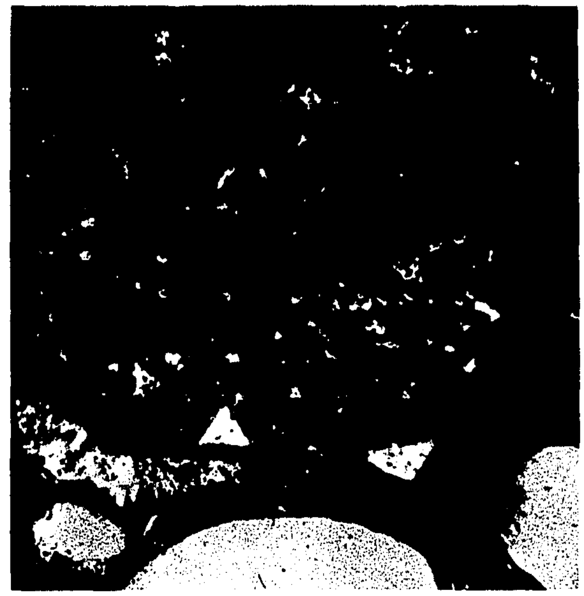
b. The metaquartzite grain in photomicrograph a, occupies the upper two-thirds of this picture. The bright, triangular fragment at the lower margin of the grain is feldspar, indicating that the grain is a metasedimentary rock fragment. Note the composite quartz grain adjacent to the metasedimentary rock fragment. Thin section number 1035. Crossed nicols X250.

c. A bent flake of muscovite mica occupies the center of the photomicrograph. An elongated chlorite-mica-quartz schist rock fragment is present to the right of the bent part of the muscovite grain. An angular grain of orthoclase felsdpar is present at the right center margin of the picture. A dark, horizontal biotite flake showing maximum pleochroism is present directly to the left of the muscovite flake. Note the angularity of some of the quartz grains. Thin section number 1020. Plane polarized light X100.

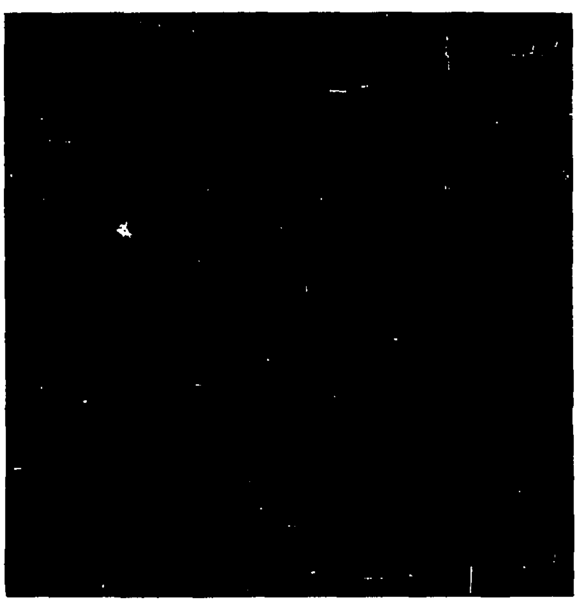
d. Placers of heavy minerals in the siltstone show the fine cross-laminations present. Ilmenite, magnetite and opaque grains are the prevalent heavy minerals in the dark laminae. Thin section number 1005. Plane polarized light X25.



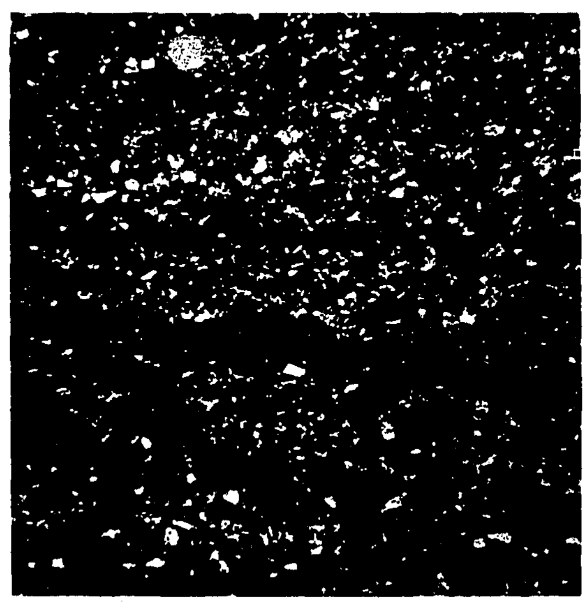
a.



b.



e.



d.

PLATE VIII

Plate IX

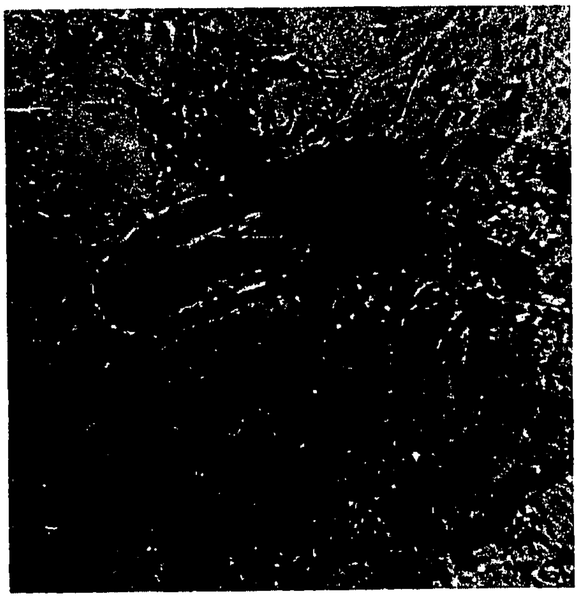
SELECTED PHOTOMICROGRAPHS

a. An elongated quartz-chlorite-opaque schist rock fragment enclosed by gypsum cement. Thin section number 933. Plane polarized light X250.

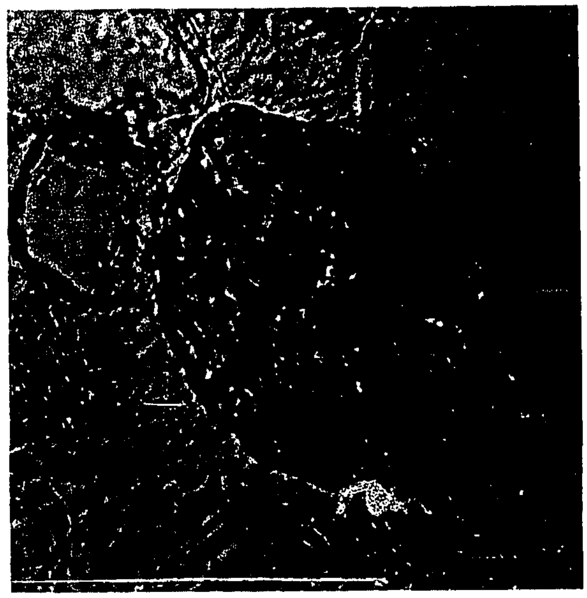
b. A subrounded quartz-chlorite-mica-opaque schist rock fragment in gypsum cement. Thin section number 933. Plane polarized light X250.

c. A well-rounded, medium sand grain of quartz accentuates the bimodal size distribution of the sedimentary particles. Note the wide variation in the particle shape of the silt grains. Thin section number 1035. Crossed nicols X25.

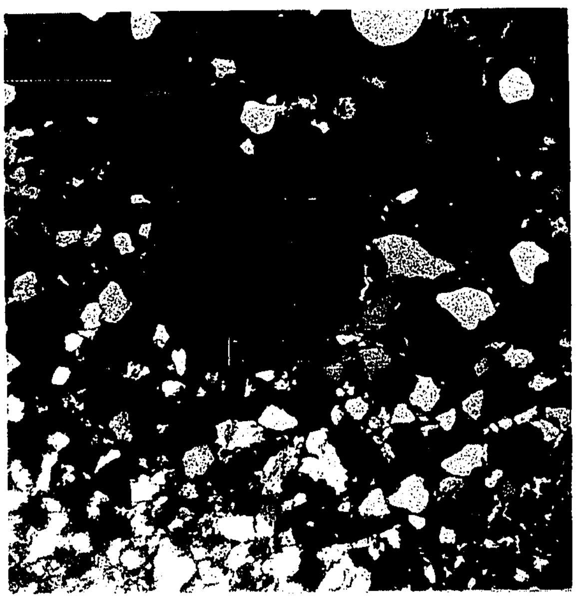
d. A vein filling of subparallel gypsum crystals has wedged out and "floated" a quartz grain. The quadrille twinning of microcline is evident in the grain in the lower central portion of the photomicrograph. Note the size of the microcline grain compared to that of most of the quartz grains present. Thin section number 984. Crossed nicols X25.



a.



b.



c.

d.

PLATE IX

are genetically significant as metamorphic indicators, according to Folk (1965).

Generally less than 10 percent of the quartz grains have composite or strongly undulose extinction. Although these extinction characteristics are not absolutely unequivocal evidence for a metamorphic source rock, they do lend support to this conclusion. Chlorite, though volumetrically minor, is a persistent constituent in the formation. It has widespread occurrence as well-worn detrital flakes in west-central Oklahoma. These chlorite flakes were most likely derived from a metamorphic terrane. The normal, 14 Å clay size chlorite probably resulted from the disintegration of the megascopic chlorite grains and chlorite-bearing schists.

The presence of "watermelon" pink tourmaline grains is considered a metamorphic indicator by Krynine (1946a). The widespread occurrence of garnet also implies a metamorphic influence. The large, well-worn zircon grains are anomalously associated with finer-grained clastics in many of the thin sections examined. A few fractured by well rounded zircon cores have equally well-rounded zircon enlargements. These grains may be the product of a metasedimentary source. Positive evidence for metasedimentary contribution is put forth by the inclusion of an angular felsdpar fragment in a well-rounded, stretched composite metaquartzite sand grain (Plate VIII).

Volcanic sources. The most abundant feldspars expected in the detritus of a granite source are orthoclase and microcline. Orthoclase is the most abundant feldspar in the Cloud Chief Formation. However, microcline is invariably the least abundant feldspar and plagioclase is the second most prominent feldspar variety. In some samples plagioclase equals or is slightly more plentiful than orthoclase. The high percentage of plagioclase, relative to orthoclase, points to a volcanic source rock. The presence of a few zoned plagioclase crystals lends support to this possibility. However, no indisputable, embayed, volcanic quartz grains were noted.

The ratio of muscovite to biotite varies throughout the formation. Broadly speaking, muscovite is the most prevalent variety present. This relationship is expected if the micas were derived from the disintegration of schists and gneisses. However, the sporadic increase in biotite, which in a few instances exceeds the amount of muscovite present by a factor of two, lends credence to a volcanic influence. The mixing of worn zircon grains with euhedral, prismatic zircons may be due to multiple sources which include volcanic source materials.

Montmorillonite is consistently the most abundant clay mineral present. Weaver (1959) considers the high montmorillonite content of the Permian sedimentary rocks to be an indication of contemporary volcanism. Dioctahedral montmorillonite is typically the major clay mineral component of bentonite deposits whereas trioctahedral montmorillonite is the most abundant expandable 14 Å clay mineral in the Cloud Chief Formation. The montmorillonite is also intimately mixed with quartz, feldspar, rock fragments and mica grains, indicating that it is detrital. Consequently, if it was originally deposited as a volcanic ash fall it has since been reworked; the bulk of the dioctahedral montmorillonite (if any was originally present) has undergone a removal of iron and/or aluminum and a concurrent increase in the magnesium ion content of its octahedral layer, thereby developing a trioctahedral clay mineral.

Sedimentary sources. Evidence of reworking, in general, documents a sedimentary source for much of these rocks. The "floating" appearance of detrital grains in microcrystalline dolomite cement suggests that some of the original framework was made up of unstained carbonate grains that have been recrystallized and are no longer observable. Nevertheless, the worn, iron-stained carbonate grains noted could only have been the result of a disintegration and reworking of older carbonate beds. It is doubtful that these soft, soluble particles would survive lengthy transportation. They therefore must have been derived from within the basin.

Multicycle development is recorded in the double quartz overgrowths, both of which are worn by abrasion. This determined the minimum number of times the sediments have been reworked. The high compositional maturity of the heavy minerals present necessitates prolonged abrasion and weathering to remove the less stable constituents and concentrate the ultrastable varieties which are the most abundant in the Cloud Chief Formation. A recycling of these grains from older sediments is quite plausible. A few well-rounded secondary zircon enlargements with worn, highly fractured cores attest to the reworking of this material. Such detritus probably underwent several cycles of erosion and deposition to produce the broken, well-worn tourmaline and zircon grains noted.

Grains of translucent and opaque hematite are fairly common in these rocks. This may be due to a re-organization of iron oxide in the environment of deposition, but many of the grains are too well rounded to be considered anything but detrital in origin. They represent the accumulation of hematite into aggregates in pre-existing materials. Many of the quartz overgrowths have developed over hematite coatings, and some of the double overgrowths nearly envelop two such coatings. Furthermore, a significant number of the iron-stained, detrital grains have thinner coatings or no iron oxides on their nodes and corners. The coating was removed by abrasion during transportation. Many grain contacts show no interruption of the hematite coatings on the adjacent grains. These observations confirm the conclusion that at least some, and possibly the majority, of the iron-stained detritus is the result of a reworking of older sedimentary red beds.

When compared to the quartz grains, the feldspars are notably more angular and commonly have approximately the same mean grain size. There are no anomalously large, well-rounded grains of feldspar similar to those in the bimodal quartz detritus. Angular feldspar enlargements are fairly common in some of the rocks of this formation and indicate that conditions during transportation and deposition favored feldspar development rather than its reduction. It is possible that this is the reason for the large size of these grains as compared to the quartz grains. However, if many of the clastic particles have undergone extensive abrasion, as is indicated by the shape of most of the quartz and heavy mineral grains, the softer, cleavable feldspar grains should be relatively smaller than the associated quartz grains. But, this is not the case. The explanation may rely upon a different rock type for the source of much of the feldspar content. The exposure of local environments to erosion could have provided the angular feldspar grains which were mixed with the more rounded, reworked quartz detritus. More feldspar grains lack a hematite coating than do quartz grains. This is either because the feldspar constituents were not derived from red beds, or because they were deposited after the principal distribution of the iron oxides had occurred.

It has been noted that the quartz-bearing metamorphic rock fragments are more abundant than the micaceous schists and phyllite grains. This is undoubtedly due to the higher resistance to abrasion of the quartz-bearing particles. Nevertheless, it seems unlikely that the soft mica-chlorite-sericite schistose rock fragments that are present would have survived the long abrasion necessary to form the number of well-worn quartz grains with which they are associated. Therefore, a mixing of metamorphic materials with reworked pre-existing sedimentary materials is postulated.

The majority of the detrital quartz grains present are subrounded, yet a considerable range in particle shapes exists within most samples. Some contain subangular, very-fine sand grains mixed with well-rounded, medium silt grains. More typically, the same size class of grains has great variation in particle shape, ranging from well-rounded to angular. Textural inversions such as these indicate either that the high roundness of some of the grains is inherited from older sedimentary rocks, or that multiple sources have contributed materials, or both.

The degree of sorting is somewhat variable. In some samples there are anomalously large, well-rounded quartz sand grains associated with much finer silt grains. This bimodal size distribution may be the result of a mixing of products from different environments, or a function of multiple sources. The large, well-rounded sand grains may be flood plain, beach bar, aeolian or other material which has been reworked and deposited in a low energy environment with associated fine detritus. Such a bimodal break would be expected between tidally influenced estuarine clastics and the fluvial materials, which are much coarser.

Climate and Tectonism

The least complicated approach to interpreting the clay mineral assemblage of the Cloud Chief Formation is to consider the less than 4 micron material as detrital. The available evidence indicates that clay minerals do respond to different environments of weathering (Weaver, 1959). The climate will determine the type of weathering and, therefore, the alteration of the clay minerals. Consequently, the nature of the clay mineral suite provides a tool in the interpretation of the climatic conditions at the source area.

Illite is present in all samples investigated but its abundance varies. No definite vertical nor lateral trends are discernible in its quantitative variation. Lithologic changes do not seem to affect the distribution of the illite. Due to weathering, some of the potassium ions have been leached out of their interlayer positions and have been replaced by water molecules, which allows a slight expansion of the structure. This expansion produces the asymmetrical (001) peak with a characteristically ragged low angle side. These are termed "degraded" illites. Many of the illites, however, are well crystallized.

Trioctahedral montmorillonite is the most abundant clay mineral in the formation. It may be the result of the weathering of 10 Å mica-type minerals (Guven and Kerr, 1966). The montmorillonite probably came from the B and C soil horizons of the source area (Keller, 1956). The trioctahedral montmorillonite may also be the product of the weathering of biotite (Walker, 1950), or other ferromagnesium minerals, in the soil of the source area. A climate where precipitation is less than the potential evaporation concentrates magnesium, calcium, iron and other cations which may combine with the silicon-oxygen-aluminum sheet structures to form montmorillonite (Rich, 1964).

A partial alteration of chlorite has produced the interstratified chlorite-montmorillonite material that is common in the formation. The amount of interstratified clay minerals seemingly increases with decreasing particle size, which also suggests that the finer material is an alteration product of the coarser crystallites. Some of the "brucite-like" sheets were removed and replaced by water, forming a partially expandable structure. Instead of water, hydroxide material may be present between certain layers, giving mica-chlorite interstratifications, rather than the chlorite-montmorillonite mineral. A number of bleached biotite grains occur microscopically and may contribute to the formation of chlorite-montmorillonite mixed-layering by undergoing alteration with incomplete leaching of magnesium and calcium.

Discussing the origin of mixed-layer clay minerals with regard to entropy and free energy, Zen (1967) notes that the commonly present water molecules decisively contribute to the free energy balance of the system. Their presence allows mixed-layer formation to be favored by low temperatures, such as those encountered in surface weathering. The slight increase in the surface material's clay mixed-layer content over that of the core samples supports this view. However, in a comparison of surface and core samples a reasonable qualitative agreement of clay mineral assemblages was found. Slight quantitative variations were present. Therefore, no significant alteration (besides an increase in the mixed-layered minerals at the surface sites) of the clay minerals is indicated.

The weathering in the source area was not thorough enough to create kaolin-like clay minerals. The general lack of kaolinite in the samples examined indicates that the weathering environment was such that it did not remove all the readily soluble cations. Furthermore, the incomplete removal of the feldspar from the source rock implies a low intensity weathering process, or rapid transportation and burial. The clay mineral assemblage consists of montmorillonite, illite, chlorite and several interstratified mixtures of these minerals; such an assemblage is chemically stable only in an environment in which potassium, sodium, calcium and magnesium ions are preserved in the weathering zone. An arid to semi-arid climate with poor ground water circulation and concomittant retention of the soluble ions is responsible for the immature weathering of the clay minerals.

Because the extent of alteration of the clay minerals depends upon the length of time available and the intensity of weathering, the alteration imprint is controlled by the tectonic stability of the source area as well as by the prevailing climatic conditions. The presence of reworked sediments and the repetitious nature of the strata indicates that cyclic sedimentation has occurred. Cyclic sedimentation processes are due to either tectonic activity or climatic fluctuations, or both. The moderate sorting of the sands and silts suggests slight tectonic instability and, perhaps, the introduction of reworked material from different environments.

The apparent uniformity of the montmorillonite content in the formation is refuted where the high expansion clay minerals are distinguished from the poorly expandable montmorillonite. These different types are erratically distributed throughout the formation. The non-uniform character of the expandable clay minerals could be due to climatic fluctuations. The reworked nature of much of this formation is germane. Certainly the clay mineral assemblage now present could have been partially or entirely developed in a weathered zone at any of the several stages possible in the erosion and redeposition of this material. This significantly enhances the materials' chances of encountering different weathering environments, if some changes of climatic conditions had occurred.

Orthoclase seems to be the most intensely weathered type of feldspar present, but each species commonly exhibits a wide range of alteration. The majority are either fresh or only slightly weathered, and either subrounded or subangular. The existence of some subrounded but fresh feldspars in these rocks indicates an arid climate and tectonic quiescence. The mixture of fresh with intensely weathered feldspar grains, combined with the persistent angularity of these grains, suggests some tectonic activity and a less arid, more temperate climate. Therefore, mild fluctuations in both climate and tectonic stability are postulated from the texture and alteration of the feldspars.

Location of Sources

It is difficult to attempt to restrict the source area of the upper Permian red beds to a single region when the Anadarko Basin is nearly encircled by positive tectonic elements, many of which were active in the Permo-Pennsylvanian interval. To the west, the Sangre de Cristo and Wet Mountains were tectonically active well into Permian time as indicated by the adjacent continental arkosic sediments and the thin cover of Middle to Late Permian clastics resting directly on the core complex of the Apishapa uplift of southeastern Colorado (Osborne, 1956). The Central Kansas uplift may be genetically related to the disturbances in the west.

As early as 1921, the detritus of the Cyril Gypsum was thought to have been derived from the north and west (Reeves). The base of the formation, with its massive gypsum beds and subjacent sandstones of the Rush Springs is the most correlative portion of the formation in western Oklahoma. The evaporites are most abundant to the east and southeast, and they grade into dolomites, sandstones and mudstones to the west and north. Only 3 feet of basal gypsum is present in Ellis County and the evaporites are entirely replaced by sandstone sequences to the north, in Woods County.

General trends in the mineralogy of the Cloud Chief Formation are suggested from a computation of the mean percentages of the metamorphic rock fragments and feldspars in the thin sections examined.

Because of their inferior hardness the micaceous metamorphic rock fragments and cleavable feldspar grains are more susceptible to abrasion than are the quartz grains and consequently are more rapidly depleted from the assemblage of mineral grains during transportation and recycling. The rapid abrasion of these grains may work in reverse and increase the percentage of soft metamorphic rock fragments present with respect to the quartz content by concentrating the abraded fragments in the finer size classes. Because the majority of the metamorphic rock fragments are metaquartzites and a variety of quartz-bearing schists, it is probable that their diminution is only slightly hastened as compared with the associated quartz grains. Nevertheless, the finer grained rocks studied provided less mineralogical data concerning the metamorphic rock fragments and feldspars, and their percentages are highly erratic. Consequently, the percentages utilized were computed from only the coarse silt and very fine sand size classes.

The surface sample site number 1 in Ellis County contains the lowest mean percentage (4 percent) of metamorphic rock fragments and the highest mean percentage (11 percent) of feldspars in the thin sections examined. The largest relative amount of metamorphic rock fragments computed (13 percent) occurs in site number 2, south of Elk City, in Beckham County; the second highest amount (11 percent) occurs at sample site number 3, west of Sayre, also in Beckham County. The lowest feldspar content (2 percent) occurs near Clinton at site number 4 in Custer County. Considering the extremes, therefore, there is a suggestion of metamorphic rock fragment increase to the south-southeast and an increase in feldspar to the north-northwest. The westward arkosic nature of the upper Permian strata of Kansas lends support to a western, granitic source area (Swineford, 1955). Lower Permian formations are also arkosic to the west of Oklahoma (Cunningham, 1961).

Mean percentages and ranges representing the sum of the thin sections from each sample site are listed in Table 4. The wide difference in mineral content of samples from even the same locality finds expression in the varied ranges listed. The vertical mineralogic distribution is similarly irregular. The feldspar content seems to decrease going up the section but this trend is upset by some singularly high, fresh feldspar percentages in the upper one-half of the formation. The suggested pattern could be the result of the sampling. Some of the intermediate locations disrupt the postulated trends but most of the figures provide positive support for it.

The erratic nature of the mineralogic data available dictates that caution be used in postulating regional trends. Nevertheless, there is an indication of a granitic influence to the west and northwest. This corroborates well with the general increase in coarse detritus in the same directions and also with the arkosic upper Permian strata of Kansas. The suggested increase of the rock fragment content to the south and southeast requires a metamorphic terrane in those directions.

A reconstructed shoreline to the east of Weatherford, in Custer County, during the time of deposition of the Cloud Chief strata is postulated by Ham and others (1961) on the basis of isobar values. Tanaka and Davis (1963) also consider a landmass to the east of Caddo County the most logical explanation for the lithologic variations observed in that area. The Nemaha Ridge exists to the east as a subsurface feature

Table 4

REGIONAL VARIATIONS IN THE PERCENTAGE OF METAMORPHIC ROCK FRAGMENTS AND FELDSPAR

	Metamorphic Rock Fragments		Feldspar				
	Mean	Range	Mean	Range	Microcline	Plagioclase	Orthoclase
1**	4%*	3-5%	11%	4-21%	5%	33%	62%
2.	13%	1-16%	2%	1-4%	--	35%	65%
3.	11%	6-18%	8%	3-14%	16%	41%	43%
4.	6%	1-16%	2%	1-4%	29%	38%	33%
5.	7.5%	6-11%	5.5%	3-7%	9%	52%	38%
6.	7%	6-9%	5%	4-6%	11%	43%	46%
7.	10%	3-28%	6%	3-12%	12%	44%	44%
8.	8%	1-22%	8%	2-16%	6%	33%	61%

	Feldspar							
	Alteration				Abrasion			
	Fresh	Light	Moderate	Intense	Round	Subround	Subangular	Angular
1.	22%	36%	24%	18%	1%	30%	41%	28%
2.	54%	30%	12%	4%	-	19%	49%	32%
3.	27%	48%	17%	8%	4%	40%	38%	18%
4.	35%	42%	15$	10%	1%	64%	22%	13%
5.	57%	14%	29%	-	-	29%	57%	14%
6.	15%	57%	17%	11%	4%	59%	29%	8%
7.	29%	42%	8%	21%	4%	29%	50%	17%
8.	15%	54%	17%	14%	-	29%	50%	21%

* Figures represent the average percentage of total detrital grains except under feldspar species, and alternation and abrasion, which represent the average percentage of the feldspar content.

** Locations of sample sites are listed in Appendix D.

but its effect on the sedimentation in the Anadarko Basin during Permian time could only have been minor. The Ozark uplift to the northeast lacks a significant metamorphic terrane and is considered an unlikely source area for these materials (Huffman, 1958). Fay (1962) suggests that the large, well-rounded sand grains of the Cloud Chief Formation in Blaine County have been derived from the south and southeast.

The closest positive tectonic areas to the south and southeast of the basin are the Arbuckle and Wichita Mountains. The Arbuckle Mountains underwent a Late Pennsylvanian (Virgin) deformation (Ham, 1956) and were probably covered by sediments during Permian time. Even though the Wichita-Amarillo uplifts may be genetically related to the Permo-Pennsylvanian mountain ranges of southern Colorado and northern New Mexico, they did not directly contribute to the sediments of the Cloud Chief Formation because the Wichita Mountains were submerged by the close of the Pennsylvanian period (Becker, 1930). Considering the reworked nature of much of the formation, it is possible that some of the detritus was indirectly derived from the Wichita Mountains (Ham and others, 1964).

The most plausible source of the metamorphic rock fragments are the Ouachita Mountains of southeastern Oklahoma, which extend in the subsurface below the Cretaceous overlap through the Llano area of Texas, to the Marathon salient and into northern Mexico. The Ouachita orogeny is dated by Melton (1930) as post-Early Permian in southeastern Oklahoma. This deformation probably continued longer in the western part of the geosynclinal belt. The orogenic activity may be Late Permian in age in northern Mexico where the Ouachita belt contains variable metamorphosed facies (Flawn, and others, 1961). This would provide a late Permian limit to the oldest age of the Cloud Chief Formation.

The frontal zone of the Ouachita belt consists of a thick sequence of Mississippian-Pennsylvanian clastics. The prevalent clay mineral is illite but chlorite is also present. The frontal zone has a higher feldspar content, with an increase in micas and chlorite, in the vicinity of the Llano area. It is broadly developed in the Marathon region. The heavy mineral suite of the frontal zone consists of zircon, apatite, tourmaline, chlorite veinlets, magnetite and ilmenite. Garnet is not abundant in the frontal zone. However, the Precambrian or Early Paleozoic interior zone of the Ouachita Mountains contains abundant phyllite, schist, slate, metaquartzite and marble. Therefore, the metamorphic rock fragment trend, the widespread occurrence of detrital chlorite grains, and consistent illite content of the Cloud Chief Formation can best be attributed to the erosion of the Ouachita structural belt which is situated to the south and southeast of the Anadarko Basin.

Environment of Deposition

The abundance of fine-grained particles in the Cloud Chief Formation suggests low energy levels of transportation. The largest detrital grains found are medium to fine sand, and these are rather uncommon. The well-rounded sand and silt grains implies either prolonged weathering and washing of the detritus, or a multicycle development. Lengthy transportation from distant sources would increase the abrasion of these particles. Sediments on a marine shelf, especially on the stable craton, would be expected to be mineralogically mature, presumably because they have passed through the shoreline zone. Thus argillaceous rock fragments and unstable minerals would not be in great abundance. The maturity of the heavy minerals present and the notable lack of nonquartz-bearing rock fragments fortifies this explanation.

The micas have been subjected to long abrasion by gentle bottom currents to produce their disc-like shapes. The opaque and heavy minerals are commonly found randomly distributed in the rocks of the Cloud Chief Formation. However, many fine placers of these grains have been noted. An individual lamina is typically a few grains thick and some are only a single grain in thickness. Delicate cross-laminations are common. Prolonged gentle current action of uniform intensity is a prerequisite for the fine laminae of tourmaline, zircon, ilmenite, magnetite, leucoxene and hematite that occur throughout the formation. Even-bedded, ripple-marked silt and very fine sand indicate quiet water deposition.

Frequent interruptions of the "gentle current" environment have occurred. Angular carbonate intraclasts and intraformational breccias (Tanaka and Davis, 1963) document a higher energy environment and turbulent conditions. The repetitious interbeds of shale, siltstone and sandstone suggest cyclic sedimentation. The reworked detritus supports a fluctuation of the marginal marine sea. The changes could be due to climatic and/or tectonic fluctuations. Evidence for both influences has been previously reviewed.

Massive beds of gypsum attest to the highly saline character of the depositional environment. The lenticular nature of many of the gypsum deposits suggests a series of isolated basins, barely connected with the sea. Evaporation of sea water in a restricted environment requires an arid climate to produce the abundant sulfate accumulations. The general lack of fauna may be due to the penesaline conditions. If alteration of the clay minerals continued at the site of deposition, illite and chlorite are typical of materials deposited in supersaline basins (Millot, 1953).

Carroll (1953) considers the euhedral zircon enlargements to be indicative of estuarine conditions. Evidence of a quiet water, gentle current environment must be reconciled with the frequent turbulent conditions indicated as well as the influxes of sand bar and floodplain material which produce the anomalous size distribution in these rocks. A tidal flat origin is postulated. The associated sediments tend to be marginal marine and susceptible to tidal influences and sea level fluctuations with attendant turbulent conditions. Estuarine embayments may be isolated to develop supersaline basins. Barrier islands, or bars, and floodplains are in proximity to the quiet water, gentle current environment. Sediments deposited in such an area would be expected to bear the imprint of mixed environments which would not persist for long distances, thus resulting in many lateral facies.

Diagenesis

Authigenesis

The angular feldspar overgrowths are secondary because it is unlikely that the cleavable rims would have undergone transportation without being worn. The angular quartz overgrowths and quartz overgrowth cement are also a secondary development. A source for the silica enlargements from pressure solution during compaction is belied by the absence of pitting or suturing of the quartz grains at their points of contact. This would indicate an intrastratal origin for the silica cement; it was probably introduced from silica-bearing waters. Zircon enlargements are secondary and probably formed in an acidic environment (Carroll, 1953). This may indicate a deltaic contribution.

Many carbonate rock fragments and enclosing carbonate cement are uniformly recrystallized to microcrystalline dolomite. The outline of the detrital carbonate grains are set off by their hematite coatings. Another secondary development is the growth of euhedral dolomite rhombohedra. A few generations of gypsum development are recorded by cross-cutting relationships and different crystal habits. Obvious secondary gypsum growth is pointed out where detrital grains are wedged out and "floated" by fibrous gypsum vein filling (Plate IX). The lathlike selenite crystals found on the surface are probably due to a reorganization of the gypsum in the Recent weathered zone. A number of the ilmenite grains show partial alteration to leucoxene. This authigenic product is probably the result of alteration by intrastratal carbonate solutions. Many of the ilmenite grains have been completely transformed to leucoxene and these white grains are common in the formation.

The random occurrence of more heavily iron-stained areas in irregular patches suggests a post-depositional redistribution of iron oxide. In a few thin sections the iron staining seems to be more concentrated in the vicinity of several magnetite and ilmenite grains. However, the greenish-gray sedimentary rocks do not differ in mineralogy from their reddish-brown counterparts. The coarser, more permeable strata most likely allowed leaching by groundwater or intrastratal solutions whereas the greenish-gray patches may be the result of the local oxidation of small particles of organic matter.

Post-depositional alteration may affect the composition of the clay minerals. In determining whether the detrital or diagenetic influences have prevailed, it is more difficult to assess the possible results attributable to an authigenic origin of the clay minerals, because the geologic processes involved are less well understood. A few of the clay minerals present in the Cloud Chief Formation are authigenic and others may be of that origin.

The euhedral, rectangular and hexagonal chlorite crystals are probably authigenic, because it is unlikely that they would have undergone lengthy transportation without developing more rounded crystal outlines. Authigenic hydrous, magnesium, aluminum silicate occurs in several surface samples from Caddo County (Lovett and others, 1961). The euhedral chlorite crystals seem to be slightly more abundant in the coarser siltstones and very fine-grained sandstones than in the mudstones and shales examined. This mineral may be authigenically formed by intrastratal solutions permeating the coarser sedimentary rocks.

The trioctahedral 7 Å aluminum serpentine is widely and irregularly distributed but is seemingly more abundant in the southeastern part of the Anadarko Basin where the gypsum deposits are thickest. This 7 Å clay mineral also seems to be more or less concentrated in the basal portion of the formation and between one-half and three-fourths of the distance to the top of the formation. No significant relationship between the 7 Å clay mineral occurrence and a particular lithology was recognized. The mineral occurs from clay size particles to sizes greater than 80 microns. It is possible that the 7 Å aluminum serpentine is authigenic.

The interstratified chlorite-montmorillonite is considered a weathering product from the source area. It was formed by a partial removal of the "brucite-like" layers and subsequent replacement by water. This replacement is thought to have occurred in an environment where leaching was incomplete and substantial quantities of calcium, iron and magnesium ions were left in the soil zone. However, it is possible that degraded trioctahedral structures such as biotite and chlorite could absorb the necessary cations from sea water to form an authigenic chlorite-montmorillonite interstratification (Raup, 1966).

Walker (1967) has shown that in situ post-depositional alteration of ferro-magnesium minerals provides iron oxide pigmentation and forms clay minerals in an arid environment. The magnesium-rich expandable trioctahedral clay mineral present in the samples investigated may be the authigenic product of such an alteration. The only ferro-magnesium mineral grains noted in the Cloud Chief Formation are biotite and chlorite. The absence of altered pyroxenes and amphiboles could be due to their instability and early removal from these sediments. However, this condition is such that it also removes the evidence for the postulated in situ alteration.

Secondary developments have occurred but the evidence available is too weak to postulate any significant authigenesis. Widespread authigenic effects are not demonstrable.

Paragenesis

Some quartz overgrowths are iron stained and some are not. Therefore, some may have formed before iron staining occurred. The quartz overgrowths are commonly free from included matter even where enclosed by carbonate or gypsum cement. If the overgrowths had precipitated after the formation of the cement, some of the carbonate would probably be included within the quartz enlargements. The quartz rims are therefore pre-cementation. Because the detritus is reworked, the iron staining and secondary growths could have occurred at any stage in the recycling.

A few feldspar overgrowths enclose moderately altered feldspar cores; the secondary enlargements are not altered. Therefore, the detrital cores were either altered prior to deposition or, if altered at the site of deposition, prior to the formation of their overgrowths. Many of the feldspar overgrowths are not coated with hematite. They therefore must have formed after its distribution. The redistribution of iron oxide at the site of deposition is indicated by the accumulations of hematite between grains, in the narrow corners near their points of contact, and by the random distribution of iron oxide stain through irregular areas.

The subparallel arrangement of the micas is the only expression of bedding in some of the samples examined. However, the mica flakes are randomly oriented in most of the specimens. This could be due to contemporaneous slumping at the deposition site or by compaction of a high fluid contact sediment. It may also be the result of a disruption of the fine stratification by a later growth of chemical cements.

Where gypsum is the dominant cement is usually encloses the detrital grains and their hematite coatings, whereas the gypsum is not stained by the hematite. Therefore, the gypsum was developed after the staining and was probably precipitated after burial of these sediments. Up to four generations of gypsum development are recognized. The lack of impurities in the gypsum crystals also suggests its formation after burial of the framework grains. Fractured, hematite-coated quartz grains which have been wedged apart by development of interstitial gypsum are present. This also indicates the later development of this mineral.

In a few thin sections where gypsum and carbonate cement occur together, the manifest order of development is that the carbonate was formed after the gypsum. This is shown by the crosscutting relationships. However, in many slides, the paragenetic relationships between the gypsum and carbonate cementing agents are not discernible. More than one generation of carbonate formation is evident in slides where recrystallization to microcrystalline dolomite has affected both the hematite-stained carbonate rock fragments and the enclosing carbonate cement. Lateral gradation into arenaceous dolomite suggests that the original carbonate cement was related to the environment at the depositional site. Euhedral dolomite rhombohedra extending across both carbonate cement and gypsum vein filling indicates that they were late in forming.

CONCLUSIONS

The Cloud Chief Formation consists of an interstratified sequence of mudstones, shales, siltstones and fine-grained sandstones with associated gypsum and carbonate lenses and beds. Combined with nonpersistent lateral facies, this sequence produces a repetitious and irregular series which, for the most part, is not correlative over wide areas in west-central Oklahoma. The majority of the rocks are feldspathic subgraywackes. Metaquartzite and mica-chlorite-schist fragments are present in all the thin sections examined. Orthoquartzites, subarkoses, shales and mudstones are also common.

Portions of the quartz and feldspar content indicate a plutonic source whereas the rock fragments, stretched composite quartz, detrital chlorite and some heavy minerals provide evidence for a metamorphic contribution. The sporadic increases in plagioclase and biotite, as well as the presence of prismatic zircon and zoned plagioclase suggests a volcanic source. Worn carbonate rock fragments and double quartz overgrowths give positive evidence of reworking. The rounded zircon overgrowths and the high compositional maturity of the heavy minerals also point to a multicycle development.

Some of the reworked material was derived from pre-existing red beds as shown by the detrital hematite grains and the many rounded quartz enlargements over hematite-coated cores. Some of the eroded quartz grains from previous red beds have had the iron oxide coatings removed from their corners and protruberances by abrasion. A portion of the detritus is not iron stained and either was not derived from red beds or was deposited after the principal distribution of the iron oxides had taken place.

The diversity of source types and textural inversions confirm the multiple source origin of the Cloud Chief Formation. An increase in the feldspar content to the northwest in the Anadarko Basin corroborates well with the increase in coarse detritus in the same direction. The probable granitic source to the west is the Ancestral Rocky Mountains of Colorado and New Mexico. The increased metamorphic rock fragment content to the southeast necessitates a metamorphic parent terrane in that direction. The Ouachita Structural Belt is considered the most likely source for the widespread chlorite and metamorphic rock fragments present. Because some of the formation is a reworked deposit there is the possibility that the Wichita Mountains indirectly contributed material to the sedimentary rocks of the Cloud Chief Formation.

The clay mineral assemblage is qualitatively uniform throughout west-central Oklahoma, and consists primarily of trioctahedral montmorillonite, illite, chlorite and interstratified mixtures of these minerals. Kaolinite is notably absent. An arid to semi-arid climate with poor ground water circulation and concomittant retention of the soluble ions is responsible for the immature weathering of the clay minerals. The trioctahedral montmorillonite may be the weathering product of 10 Å mica-type minerals and/or volcanic ash falls. The interstratified chlorite-montmorillonite is due to incomplete weathering of chlorite where some of the brucite-like layers have been removed and replaced by water. This results in a partially expandable structure. Minor modifications due to weathering in the Recent epoch are observable in the interstratified clay minerals. Significant authigenic effects have not been developed.

Delicate laminae and disc-like flakes of mica indicate prolonged abrasion by gentle currents of uniform intensity. Abundant fine-grained particles attest to the low energy transportation levels. The site of deposition, therefore, involved quiet water conditions. Yet, sporadic turbulent conditions have produced anomalous bimodal size distributions and random influxes of sand bar, aeolian and floodplain material. Isolated basins of evaporation also must have existed to develop the many lenses of gypsum present. The postulating of a marine, tidal flat environment reconciles the mixing of depositional environments that is evident. This would be, principally, a quiet water, low energy environment, but it would be susceptible to marginal marine fluctuations and tidal influences. Such influences would produce turbulent conditions. The introduction of eroded sand bar and floodplain materials could result during the higher energy phases. Its shallow estuaries could become restricted and develop the supersaline basins necessary to produce the thick evaporite deposits present in the Cloud Chief Formation.

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APPENDIX A

CLAY MINERAL ANALYSES

General Statement

Both surface and subsurface samples of sandstones, siltstones, shales and mudstones were collected from 10 locations in west-central Oklahoma. These samples were analyzed to determine the clay mineralogy of the Cloud Chief Formation. The exact sample locations are given in Appendix D.

Sample Preparation

The materials investigated were disaggregated, sieved and dispersed in distilled water by an ultrasonic transducer (Powertron Autosonics, model PA-3001). Repeated dispersal, followed by differential settling according to Stoke's Law provided the particles with a less than 4 micron equivalent spherical diameter. These suspensions were sedimented on ceramic plates and glass slides, then dried in an oven at 60° C prior to x-ray analysis. This preparation enhances the basal diffraction maxima by orienting the c_o crystallographic axes of the clay minerals normal to the slide. Ten samples from surface site number 4 were further size-fractioned into 1/2-1, 1/4-1/2, 1/8-1/4, and 1/16-1/8 micron portions by continuous-flow centrifugation using a Lourdes (model

LCA-1) super-centrifuge. Size limitations were determined by adjusting the centrifuge speed and/or flow rate. The less than 1 micron suspended clay particles were centrifuged with a flow rate of 5 minutes per liter at 3,000 r.p.m. to release the 1/2-1 micron fraction. The suspension was then centrifuged at 6,000 r.p.m. using a flow rate of 5 minutes per liter to release the 1/4-1/2 micron fraction. The remaining suspension of clay from this step in the size fractionation was centrifuged at 12,000 r.p.m. with a flow rate of 5 minutes per liter to release the 1/8-1/2 micron fraction. In the final step, the remainder of the suspension was centrifuged at 12,000 r.p.m. with a flow rate of 20 minutes per liter to release the 1/16-1/8 micron particles. Attempts to beneficiate the samples to monomineralic composition employed this technique.

Analytical X-ray Techniques

X-ray analyses were performed on wide-angle North American Phillips (Norelco) vertical, or Siemens-Halske horizontal, diffraction equipment. Nickel-filtered copper (K-alpha) radiation was used at a setting of 35 KV and 18 MA. A 1° slit system was employed on the Norelco diffractometer with a 0.006 inch scatter slit. A one millimeter collimating slit and 0.2 millimeter receiving slit were used on the Siemens unit. A variable wedge close to the sample slide reduced the scatter slit for low angle two-theta analysis on the Siemens diffractometer. The goniometer was scanned at 1° two-theta per minute and scintillation counters provided detection of diffracted quanta. The Norelco recorder time constant was set at 4 seconds for all samples analyzed but the multiplier value and scale factor were varied to produce optimum chart resolution. Records are maintained as diffractograms on strip charts.

X-ray analyses were made before and after the sample was solvated in an ethylene glycol atmosphere at 60° C for at least 2 and not more than 20 hours. Subsequent treatment involved heating the specimens to either 550°, 600° or 650° C for an hour prior to being x-rayed again. Continuous heating and x-ray analyses were accomplished for select samples on a Stone diffractometer furnace. Acid treatment was employed on splits of 15 samples to identify kaolinite in the presence of chlorite. This treatment was generally avoided to eliminate the possible chemical changes effected by acid reactions. Sodium hexametaphosphate was employed to disperse flocculated samples. A solution of 2.5 grams of peptizer per liter sufficed to dispese most flocculated samples.

Diffractograms were obtained over an angular range sufficient to include the strongest (001) diffraction lines of the four major clay mineral groups. A knowledge of the basal spacings is required to assign the clay minerals to these groups; therefore, preferred orientation specimens were prepared. The (hkl) reflections obtained from samples with random orientation are necessary to differentiate polymorphs, i.e., layer lattice minerals consisting of the same units stacked in a variety of ways. The spacing of the (060) reflection was used to distinguish dioctahedral from trioctahedral clay minerals.

Differential Thermal Analyses

Select samples were examined by differential thermal analysis on a Robert L. Stone model 13M furnace and recorder, employing a heating rate of approximately 10° C per minute. The unit has an Inconel Sample holder. The standard is alpha alumina. The purging gas utilized is helium. The thermocouples are made of a platinum-rhodium alloy. However, clay mineral identifications were accomplished primarily through the comparison and evaluation of the x-ray data of the nontreated, solvated and heated sample preparations.

Quantification Methods

In order to evaluate the potential of using clay mineral assemblages to zone the Cloud Chief Formation, or to detect a characteristic mineralogical pattern within the area, a method of comparing clay mineral assemblages is needed. The use of intensities or integrated peak areas to quantitatively interpret diffractograms depends not only upon the concentrations of clay minerals but their particle size, crystal perfection, degree of crystal orientation, chemical composition and the presence of amorphous substances. In most cases these factors cannot be controlled. To avoid the necessity of introducing internal standards, which could interfere with the resolution of the minerals present, the area under each diffraction peak was approximated by utilizing the product of the peak intensity and its width at one-half height (Freas, 1962). This technique assumes that the intensity of the reflection of a given mineral is related to its abundance. By using relative peak area approximations (Taylor and Norrish, 1962) instead of absolute measurements, many of the difficulties arising from the numerous aforementioned variables are eliminated. This technique is considered to be semi-quantitatively reliable.

After measuring the peaks, several ratios were calculated utilizing the diffractograms from the solvated and heated samples. The two basic ratios derived from the solvated samples are the montmorillonite to montmorillonite plus illite ratio, and the interstratified species, as shown by superorders below 5° two-theta, divided by the same figure plus illite. From the heated specimens, a series of 4 ratios utilized a combination of the collapsed montmorillonite plus illite sum at approximately 10 Å as the common denominator. The numerators measured are in the 14 Å, 7 Å, 12 Å and superorder regions, to determine the 14 Å and 7 Å chlorites, the $001_{10}/001_{14}$ interlayered material and the interlayering producing c_o axis cells in excess of 16 Å. A number of other diffraction features were measured and compared, including the change in the 7 Å peak from the nontreated to the heated conditions, the montmorillonite and interstratified clay minerals in the nontreated samples, any discernible interstratified material in the 12 Å region on the solvated diffractograms, and the degree of expandability recorded from the solvated samples. But the six ratios first described above provide the most useful semiquantitative indicators of the clay mineralogy investigated.

APPENDIX B

FOURIER ANALYSES

General Statement

The cosine transform utilized is essentially the Patterson projection on the c_o axis of the crystallites. Its values are proportional to the mean number of layers at a distance, R, from any arbitrary layer chosen as the origin. This form of function gives a peak at the origin.

Transform Equation

The transform equation and explanation of the terms are (MacEwan, 1956, p. 106):

$$W_R = \sum_s i(s) \cos (d'R) \qquad \text{where,} \quad d' = 360/d_s,$$

$$i(s) = I_s/\theta_s \, |F|^2_{eff}, \text{ and } \quad |F|^2_{eff} = \left(|F_1|_{p_1} \cdot |F_2|_{p_2} \right)^2$$

The observed intensity for each diffraction maximum is I_s. The effective layer structure factor of a single layer is $|F|^2_{eff}$ as computed for equal proportions (p_1=p_2) from existing curves (Brown, 1961, p. 408). An exact alternation of the chloritic and montmorillonoid components would only be possible if they were present in equal amounts within the interstratified mineral.

The angular intensity factor (Lorentz, polarization, geometrical) is Θ and is taken from the International Table for X-Ray Crystallography (5.2.5A, p. 268). The spacing in angstroms measured from the diffractograms is d_s and d' is the computed reciprocal spacing. The perpendicular distance from any layer of the phyllosilicates is R. The five terms with maximum I_s were used in the series summation. The resulting curves were further modified for a Gaussian decrease from the origin by the function $e^{-1/2\,\sigma^2 R^2}$.

APPENDIX C

THIN SECTION DESCRIPTIONS

General Statement

A total of 59 thin sections were examined in detail and 20 of these are described on the following pages. The thin sections were studied to determine the mineral composition, texture and fabric of the rocks of the Cloud Chief Formation. Paragenetic indications and evidence of cementation or alteration were noted and interpreted. The petrographic nomenclature and format for thin-section descriptions used follows that of Folk (1965). Roundness determinations were made by comparison with Krumbein's chart (1941). The fabric (grain to grain contacts) terminology of Adams (1964) is used. Color assignments were made by comparison with the Rock Color Chart (1963). Percentages cited were computed from point counts of at least one hundred detrital grains per thin-section. Varietal types of quartz and feldspar were counted. Grain sizes were measured with a calibrated occular micrometer. Several samples were checked by sieving. All thin sections are on file by accession number at the School of Geology and Geophysics, X-ray Laboratory.

Format

I. ACCESSION NUMBER AND SAMPLE SITE. Refer to Appendix D for the vertical location of the thin section within the stratigraphic section and the geographic location of the sample site.

II. ROCK NAME: Grain size; prevalent orthochemical cement, textural maturity, name of rock.

III. MEGASCOPIC DESCRIPTION: Sedimentary structures, color, induration, prominent constituents, rock type.

IV. MICROSCOPIC DESCRIPTION:

A. Texture. Grain size (extreme, 16-84%, mean), distribution, general grain shape, textural maturity.

B. Authigenic cements. Type and percentage estimate of total amount, relative distribution, paragenic relations noted.

C. Mineral composition.

1. Quartz: type and percentage of total detrital grains, fabric and percentage of total quartz grains, grain shape and percentage of total quartz grains, inclusion types and abundance estimate.

2. Rock fragments: type and percentage of total detrital grains.

3. Feldspar: type and percentage of total detrital grains, alteration and percentage of total feldspar, grain shape and percentage of total feldspar.

4. Miscellaneous terrigenous grains: type and percentage of total detrital grains.

D. Remarks.

Thin Section Descriptions

I. 980, sample site 3.

II. Coarse-grained siltstone; gypsum and dolomite cemented, submature, quartzose subgraywacke.

III. Thinly laminated, pale reddish orange (10 R 6/6), gypsiferous, arenaceous, well-indurated, coarse-grained siltstone.

IV. A. Grain size: extreme, clay to 2.25 ∅, 16-84%, 6 to 3.25 ∅, mean, 4 ∅; poorly sorted, bimodal; textural inversion with wide rounding variation in all size classes; submature.

B. 1. Gypsum cement comprises over 80%; widely distributed throughout the entire slide, encloses iron-stained detrital grains.

2. Dolomite cement is minor; occurs in localized patches; microcrystalline with a few euhedral rhombohedra; crosscut gypsum cement.

3. Quartz overgrowths, less than 2%; restricted to a few grains; clear and angular, commonly over iron oxide coated detrital cores.

4. Feldspar overgrowths, less than 1%; uncommon; angular and generally not over iron-stained cores and not iron-stained in turn.

C. 1. Quartz: common, 9%; undulose, 68%; composite, 2%; stretched composite, 2%; total 81%; free grains, 62%; fixed grains, 29%, floating grains, 9%; 9% well-rounded, 39% subrounded, 43% subangular, 9% angular; less than 6% have inclusions except minor bubbles, about 4% have bubble planes, few with fine, hairlike inclusions, less than 10% with microlites of micas, chlorite, zircon, tourmaline and opaques.

2. Rock fragments: metaquartzite, 5%; quartz-mica schist, 2%; quartz-chlorite-mica schist, 2%; carbonate, 2%; total, 11%; schist fragments elongated.

3. Feldspar: orthoclase, 1%; microcline, 1%; plagioclase, 2%; total, 4%; 12% fresh, 64% slightly altered, 24% moderately altered; 4% rounded, 52% subrounded, 36% subangular, 8% angular.

4. Ilmenite, magnetite, hematite, leucoxene, 2%; micas and chlorite, 1%; tourmaline, zircon, garnet, apatite, rutile, 1%; total, 4%; minor subparallel orientation of platy minerals to bedding.

D. Feldspar grains have a mean grain size equal to quartz grains and range from fresh to moderately altered, and subrounded to angular, within each mineral species. Dolomite rhombohedral overgrowths on quartz grains.

I. 982, sample site 3.

II. Coarse-grained siltstone; gypsum and dolomite cemented, submature, feldspathic subgraywacke.

III. Platy, pale reddish orange (10 R 6/6), moderately indurated, gypsiferous, micaceous, coarse-grained siltstone.

IV. A. Grain size: extreme, clay to 2.5 Ø, 16-84%, 6 to 3.5 Ø, mean, 4.25 Ø; moderately sorted; textural inversion with wide rounding variation in most size classes; submature.

B. 1. Gypsum cement, more than 85%; present in most interstices; encloses iron-stained grains; also occurs as vein filling.

2. Dolomite cement, minor; irregularly distributed as microcrystalline masses; partially replacing gypsum.

3. Quartz overgrowths, less than 1%; only between a few grains; generally clear and angular; several over iron coatings; few coated with iron oxides.

4. Feldspar overgrowths, minor; free from inclusions and typically untwinned.

C. 1. Quartz: common, 9%; undulose, 49%; composite, 3%; stretched composite, 7%; total, 68%; free grains, 84%, floating grains, 11%, fixed grains, 5%; 11% well rounded, 58% subrounded, 24% subangular, 7% angular; more than one-half contain minor vacuoles, some with criss-crossing vacuole trains, less than 10% contain microlites.

2. Rock fragments: metaquartzite, 7%; quartz-mica-chlorite schist, 4%; phyllite, 2%; quartz-mica schist, 3%; carbonate, less than 2%; total, 18%.

3. Feldspar: orthoclase, 3%; microcline, 4%; plagioclase, 5%; total, 12%; 25% fresh, 75% slightly altered; 42% subrounded, 50% subangular, 8% angular.

4. Miscellaneous terrigenous grains: Micas and chlorite, 1% (mostly biotite); magnetite, ilmenite, leucoxene, tourmaline, zircon, hematite, 1% (mostly leucoxene); total, 2%.

D. Mean feldspar grain size (3.5 Ø) is larger than that of quartz. A few zoned feldspar grains. "Watermelon" pink tourmaline noted. Anomalously large zircons present. Rounded zircon overgrowths occur. Subparallel orientation of micas to laminae somewhat evident. Well-rounded quartz grain with hematite coating covered by overgrowth. Several angular feldspar overgrowths, some on worn inner cores.

I. 983, sample site 3.

II. Coarse-grained siltstone; gypsum and dolomite cemented, submature, feldspathic subgraywacke.

III. Platy, yellowish gray (5 Y 8/1), moderately indurated, gypsiferous, micaceous, coarse-grained siltstone.

IV. A. Grain size: extreme, clay to 2.25 ϕ, 16-84%, 5 to 3.5 ϕ, mean, 4.15 ϕ; poorly sorted, bimodal; slight textural inversion; submature.

B. 1. Gypsum cement most prevalent; well distributed throughout the thin-section; some large (70-150 microns) patches of gypsum mosaic.

2. Dolomite cement, minor; isolated patches; some microcrystalline sections seem to replace gypsum; rhombohedral overgrowths on detrital grains having crosscutting relationships with both gypsum and dolomite cement.

3. Quartz overgrowths, minor; mostly free from inclusions without growth stages; commonly angular but a few rounded rims present.

4. Feldspar overgrowths, minor; generally untwinned and free from inclusion but a few slightly vacuolized; mostly angular; some being replaced by carbonate.

C. 1. Quartz: common, 8%; undulose, 44%; composite, 8%; stretched composite, 12%; total, 72%; free grains, 82%; fixed grains, 13%, floating grains, 5%; 24% well-rounded, 47% subrounded, 22% subangular, 7% angular; majority have slight vacuolization, less than 5% highly vacuolized, less than 5% contain microlites.

2. Rock fragments: metaquartzite, 12%; quartz-chlorite schist, 3%; phyllite, 2%; mica schist, 1%, carbonate, 1%; total, 19%.

3. Feldspar: orthoclase, 3%; microcline, 4%; plagioclase, 4%; total, 11%; 13% fresh, 87% slightly altered; 20% well-rounded, 47% subrounded, 27% subangular, 6% angular.

4. Miscellaneous terrigenous grains: micas and chlorite, 1%; tourmaline, zircon, leucoxene, magnetite, ilmenite, 1%; total, 2%.

D. In the absence of hematite stain, the scarcity of clay becomes evident. Bimodal distribution especially obvious with a minor amount of large (220 microns), well-rounded quartz grains. A large, well-rounded zircon overgrowth on a rounded but fractured core. Some unusually angular heavy minerals (apatite) mixed with predominantly well-rounded heavy minerals.

I. 984, sample site 3.

II. Very fine-grained sandstone; gypsum and carbonate cemented, submature, subarkose.

III. Blocky, yellowish gray (5 Y 8/1) with pale reddish brown (10 R 5/4) mottling, well- to moderately-indurated, gypsiferous, very fine-grained sandstone.

IV. A. Grain size: extreme, clay to 2.25 Ø, 16-84%, 4.5 to 3.25 Ø, mean, 3.85 Ø; moderately sorted; more than one-half subrounded; submature.

B. 1. Gypsum cement most abundant; well distributed throughout the thin-section; especially prevalent in the vicinity of gypsum veinlets; interlocking subhedral mosaics and fibrous patches.

2. Dolomite cement, minor; irregular patches of microcrystalline cement, commonly secondary to gypsum.

3. Quartz overgrowths, minor; clear and angular binding a few grains; some rounded enlargements.

4. Feldspar overgrowths, minor; generally not twinned; typically clear; few are rounded.

C. 1. Quartz: common, 35%; undulose, 37%; composite, 10%; stretched composite, 3%; total, 85%; free grains, 87%, fixed grains, 8%, floating grains, 5%, some concave-convex contacts; 6% well-rounded, 59% subrounded, 31% subangular, 4% angular; about one-half are slightly vacuolized, a number of clear grains and a minor amount contain inclusions of tourmaline, zircon, micas and opaques.

2. Rock fragments: metaquartzite, 3%; quartz-mica-chlorite schist, 2%; phyllite, 1%; quartz-chlorite schist, 1%; total, 7%.

3. Feldspar: orthoclase, 2%; microcline, 3%; plagioclase, 3%; total, 8%; 7% fresh, 74% slightly altered, 19% moderately altered; 18% well-rounded, 52% subrounded, 19% subangular, 11% angular; alteration mostly vacuolization and sericitization with some carbonate replacement and chloritization.

4. Miscellaneous terrigenous grains: leucoxene, sericite, opaques, zircon, tourmaline, micas, trace amounts.

D. Broken hematite-coated quartz grain displaced by later gypsum growth. A euhedral dolomite rhomb extending into gypsum vein mosaic. Irregular iron oxide staining on many grains with none on some. Many intersections of grain boundaries have hematite accumulations in corners. A wide variation in shape occurs in the microcline and plagioclase species. Feldspar mean grain size approximates that of quartz. Some grains have both their cores and overgrowths iron-stained. Many detrital grains "floating" in gypsum cement.

I. 985, sample site 3.

II. Coarse-grained siltstone; gypsum and dolomite cemented, mature, feldspathic subgraywacke.

III. Blocky, pale reddish orange (10 R 6/6), gypsiferous, coarse-grained siltstone with some one-quarter inch satin spar veinlets.

IV. A. Grain size: extreme, clay to 2.5 Ø, 16-84%, 5 to 3.75 Ø, mean, 4.35 Ø; moderate to well sorted; slightly more subrounded than subangular; mature.

B. 1. Gypsum cement, most common; well distributed throughout the thin-section; fibrous anhedral interlocking satin spar veinlet mosaics.

2. Dolomite cement, less than 25%; commonly heavily hematite-stained and in irregular patches; some intraclasts of microcrystalline carbonate cemented iron oxides and clay; a few euhedral dolomite rhombohedra.

3. Quartz overgrowths, minor; most are free from inclusions and angular; some slightly vacuolized and some rounded.

C. 1. Quartz: common, 10%; undulose, 46%; composite, 7%; stretched composite, 9%; total, 72%; free grains, 61%; fixed grains, 23%, floating grains, 16%; 12% well-rounded, 33% subrounded, 31% subangular, 24% angular; majority contain minor bubbles, some in chains; few sericitized grains and grains with inclusions are in the minority.

2. Rock fragments: metaquartzite, 9%; mica schist, with opaques, 4%; quartz-mica-chlorite schist, 2%; phyllite, less than 1%; total, 16%.

3. Feldspar: orthoclase, 2%; microcline, 3%; plagioclase, 5%; total, 10%; 35% fresh, 51% slightly altered, 14% moderately altered; 28% subrounded, 57% subangular, 15% angular; the low orthoclase count may be due to some of these being counted as strained quartz; feldspar weathering seems normal when comparing species but a wide range of alteration exists within each species.

4. Miscellaneous terrigenous grains: micas, sericite, ilmenite, magnetite, leucoxēne, detrital hematite, chlorite, 2%; biotite and muscovite about equally abundant.

D. Hematite coatings thinnest on grain protruberances. Feldspar mean grain size only slightly less than that of quartz.

I. 986, sample site 3.

II. Coarse-grained siltstone; dolomite cemented, submature, feldspathic subgraywacke.

III. Massive-bedded, moderate reddish brown (10 R 4/6), moderately indurated, silty mudstone.

IV. A. Grain size: extreme, clay to 3.5 ϕ, 16-84%, 6 to 4 ϕ, mean, 5 ϕ; moderately sorted; majority of grains subrounded or subangular but a wide variation of shape within major size classes; submature.

B. 1. Dolomite cement, most prevalent; widely distributed throughout slide; commonly heavily hematite stained; microcrystalline; few large euhedral to subhedral rhombohedra present.

2. Gypsum cement, minor; occurs as fibrous to subhedral masses in irregular patches.

C. 1. Quartz: common, 8%; undulose, 51%; composite, 8%; stretched composite, 6%; total, 73%; free grains, 65%, floating grains, 30%, fixed grains, 5%; 5% well-rounded, 41% subrounded, 45% subangular, 9% angular; majority either clear or with minor vacuolization and sericitization; minor amount with inclusions of tourmaline, zircon, mica, opaques and apatite.

2. Rock fragments: metaquartzite, 6%; quartz-mica schist, 7%; phyllite, 2%; quartz-chlorite and/or opaques, 1%; total, 16%.

3. Feldspar: orthoclase, 2%; microcline, 1%; plagioclase, 3%; total, 6%; 18% fresh, 32% slightly altered, 45% moderately altered, 5% intensely vacuolized, sericitized and chloritized; 50% subrounded, 32% subangular, 18% angular.

4. Miscellaneous terrigenous grains: micas, hematite, ilmenite, leucoxene, magnetite, sericite, interstitial clay, less than 3%.

D. Two generations of carbonate formation. Shape of quartz grains ranges from well-rounded to angular in the 4 to 5 Ø class. Hematite on nodes and corners of grains is abraded. At least two periods of iron staining evident. Mica flakes most common in clay-carbonate masses. Intensely iron-stained carbonate mud gall intraclasts common. Mean feldspar grain size slightly larger than that of quartz.

I. 987, sample site 4.

II. Very fine-grained sandstone; dolomite cemented, submature, borderline subarkose/subgraywacke/orthoquartzite.

III. Blocky, pale reddish-orange (10 R 6/6), moderately indurated, micaceous, silty, fine-grained sandstone.

IV. A. Grain size: extreme, clay to 2.25 Ø, 16-84%, 4.75 to 3.25 Ø, mean, 4 Ø; poorly sorted, bimodal; majority of grains are subrounded or subangular; even in the fine sand class both well-rounded and angular grains occur; submature.

B. 1. Dolomite cement, most abundant; widely but irregularly distributed as microcrystalline material, partially hematite stained; some euhedral rhombohedra, uncoated and with crosscutting relationships to previous carbonate cement.

2. Quartz overgrowths, minor; clear and angular with many hematite coatings outlining the detrital cores; some enlargements rounded.

C. 1. Quartz: common, 18%; undulose, 62%; composite, 4%; stretched composite, 2%; total, 86%; free grains, 86%, remainder fixed grains; 2% well-rounded, 65% subrounded, 30% subangular, 3% angular; most are free of inclusion or contain only a few scattered bubbles or sericite inclusions, a small percentage are moderately vacuolized and less than 20% contain inclusions of tourmaline, mica, zircon, rutile and, rarely, small liquid-filled cavities.

2. Rock fragments: metaquartzite, 2%; quartz-mica schist, 2%; phyllite, 1%; carbonate, 2%; total, 7%; most carbonate fragments are well-rounded with hematite-stained surfaces.

3. Feldspar: orthoclase, 2%; microcline, 1%; plagioclase, 2%; total, 5%; 26% fresh, 48% slightly altered, 12% moderately altered, 14% intensely altered, commonly sericitization or vacuolization; 4% moderately well-rounded, 48% subrounded, 32% subangular, 16% angular; about 45% of the feldspars have angular overgrowths that do not bind other grains.

4. Miscellaneous terrigenous grains: leucoxene, ilmenite, hematite, zircon, tourmaline, hematite, micas, chlorite, 2%; clay, trace.

D. A few chert fragments may be present. The feldspar mean grain size is about the same as that of quartz.

I. 990, sample site 8.

II. Argillaceous; carbonate cemented, immature, siliceous shale.

III. Platy, pale reddish orange (10 R 6/6), weakly indurated, silty shale.

IV. A. Grain size: extreme, clay to 4.25 ϕ, 16-84%, clay to 6 ϕ, mean, 8 ϕ; poorly sorted, highly inhomogeneous; more than one-half of the slide is composed of heavily iron-stained, calcareous clay and sericite hash; silt-sized particles are mostly angular to subangular; immature.

B. 1. Carbonate cement, entirely; microcrystalline and heavily stained dolomite; many large, euhedral rhombohedra irregularly distributed.

C. 1. Quartz: common, 12%; undulose, 30%; composite, 2%; stretched composite, less than 1%; total, 45%; mostly free and floating grains, 5% well-rounded, 5% subrounded, 40% subangular, 50% angular; mostly clear or with few inclusions.

2. Rock fragments: metaquartzite, less than 1%; phyllite, less than 1%; total, 1%.

3. Feldspar: orthoclase, less than 2%; microcline, less than 1%; plagioclase, less than 1%; total, 2%; all feldspar counted is slightly vacuolized, subangular and in the coarse silt class.

4. Clay: intensely iron-stained, calcareous clay, sericite and mica hash compose about 50% of the thin-section.

5. Miscellaneous terrigenous grains: magnetite, ilmenite, leucoxene, hematite, chlorite (clinochlore), tourmaline, zircon, 1%.

D. Inhomogeneous. Silt laminae interstratified with fine-grained carbonate hash. Micas oriented subparallel to some laminae.

I. 991, sample site 4.

II. Coarse siltstone; dolomite cemented, submature, orthoquartzite.

III. Blocky, pale reddish brown (10 R 5/4), moderately indurated, calcareous, micaceous, coarse-grained siltstone.

IV. A. Grain size: extreme, clay to 3.25 ∅, 16-84%, 5 to 3.75 ∅, mean, 4.45 ∅; moderately sorted; mostly subrounded to subangular; submature.

B. 1. Dolomite cement, most prevalent; microcrystalline and iron-stained to varying degrees within the thin section; a few euhedral dolomite rhombohedra are present.

2. Quartz overgrowths, very minor; clear and angular; few actually bind grains; some have minor inclusions of vacuoles or sericite.

C. 1. Quartz: common, 14%; undulose, 69%; composite, 9%; stretched composite, less than 1%; total, 92%; free grains, 88%, remainder are fixed grains; 3% well-rounded, 38% subrounded, 32% subangular, 27% angular; most grains contain only minor bubbles, irregularly disseminated, minor amounts of clear grains and grains with included tourmaline, rutile, zircon, apatite and micas.

2. Rock fragments: carbonate, 2%; metaquartzite, less than 1%; phyllite and quartz-mica-chlorite schist, trace amounts; total, 3%.

3. Feldspar: orthoclase, less than 1%; microcline, 1%; plagioclase, 1%; total, 3%; 14% fresh, 45% slightly altered, 32% moderately altered, 9% intensely altered; 45% subrounded, 32% subangular, 23% angular; approximately 30% have angular overgrowths; no fresh orthoclase was found.

4. Miscellaneous terrigenous grains: leucoxene, ilmentite, magnetite, sericite, tourmaline, zircon, apatite and, rarely, chlorite, about 2%.

D. A mixture of well worn and subhedral heavy minerals. Wide variation in grain shape in all major size classes, from well-rounded to angular. Several chlorite grains are subhedral to euhedral with rectangular and pseudohexagonal outlines. Other flakes are disc-like.

I. 993, sample site 8.

II. Very fine-grained sandstone; gypsum cemented, mature, feldspathic subgraywacke.

III. Thin-bedded, light greenish gray (5 GY 8/1) with slight pale reddish orange (10 R 6/6) mottling, moderately well indurated, gypsiferous, silty, very fine-grained sandstone.

IV. A. Grain size: extreme 8 to 2.25 Ø, 16-84%; 4.5 to 3.25 Ø, mean, 3.9 Ø; medium well sorted; majority subrounded; mature.

B. 1. Gypsum cement, most prevalent; well distributed throughout slide; interlocking subhedra and fibrous aggregates; more than one period of formation/recrystallization.

2. Dolomite cement, trace; rare, isolated patches; microcrystalline.

3. Quartz overgrowths, trace; very few clear, angular enlargements, some with minor inclusions of sericite or bubbles.

C. 1. Quartz: common, 13%; undulose, 28%; composite, 10%; stretched composite, 12%; total, 63%; 82% free and floating grains, 18% fixed grains; 8% well-rounded, 52% subrounded, 33% subangular, 7% angular; with variation within each principal size class; most are either free from inclusions or contain minor vacuoles; less than 5% contain rutile and/or a variety of microlites.

2. Rock fragments: metaquartzite, 12%; quartz-mica-opaque schist, 7%; quartz-chlorite schist, 2%; phyllite, less than 2%; total, 22%.

3. Feldspar: orthoclase, 9%: microcline, 1%; plagioclase, 4%; total, 14%; 9% fresh, 59% slightly sericitized or vacuolized, 18% moderately altered, 14% intensely altered; 57% well-rounded, 30% subangular, 13% angular.

4. Miscellaneous terrigenous grains: leucoxene, ilmenite, magnetite, tourmaline, zircon, micas, chlorite, garnet, apatite, 1%.

D. Several myrmekite grains noted.

I. 994, sample site 8.

II. Medium-grained siltstone with abundant carbonate cemented argillaceous material; dolomite cemented, immature, mudstone.

III. Blocky, pale reddish orange (10 R 6/6), moderately indurated, micaceous, silty shale.

IV. A. Grain size: extreme, clay to 3.5 Ø, 16-84%, 8 to 4 Ø, mean, 6 Ø; poorly sorted; mostly subangular; immature.

B. 1. Dolomite cement, most prevalent; well distributed throughout major portions of the slide; microcrystalline with very few euhedral rhombohedra; variably iron stained.

2. Quartz overgrowths, trace; clear and angular on a few isolated grains.

3. Feldspar overgrowths, trace; without inclusions and very few binding grains; most not iron stained.

C. 1. Quartz: common, 14%; undulose, 37%; composite, 8%; stretched composite, 1%; total, 60%; 98% free or floating grains; 20% subrounded, 22% angular, 58% subangular; a single rounded overgrowth noted; less than 25% slightly vacuolized, minor amount contain inclusions of tourmaline, mica, zircon, hair-like matter and, rarely, liquid inclusions with "dancing bubbles."

2. Rock fragments: metaquartzite, 1%; phyllite, 1%; quartz-mica-chlorite-opaque schist, 1%; total, 3%.

3. Feldspar: orthoclase, 2%; microcline, less than 1%; plagioclase, 1%; total, about 3%; 30% fresh, 30% slightly altered, 20% moderately altered, 20% intensely sericitized and/or vacuolized; 30% subrounded, 40% subangular, 30% angular.

4. Miscellaneous terrigenous grains: clay, mica, chlorite, zircon, tourmaline, leucoxene, ilmenite, magnetite, hematite, about 33%.

D. Intensely iron-stained, dolomite cemented clay hash and mica make us about one-third of the rock. Inhomogeneous with silt concentrations and laminae occur.

I. 995, sample site 7.

II. Silty argillite; calcite cemented, immature, orthoclase feldspathic, mudstone.

III. Blocky pale reddish orange (10 R 6/6), weakly indurated, silty shale.

IV. A. Grain size: extreme, clay to 3.5 Ø, 16-84%, clay to 6 Ø, mean, 8.5 Ø: poorly sorted; most grains subangular to angular but a wide variation in shape exists within each principal size class; immature.

B. 1. Calcite cement, most prevalent; irregular, patchy distribution as microcrystalline calcite and abundant sparry calcite vein filling; microgranular calcite variably iron stained; vein filling does not significantly contribute to bonding.

2. Gypsum cement, trace; small, local occurrence as fibrous grains.

C. 1. Quartz: common, 7%, undulose, 19%; composite, 9%; stretched composite, 2%; total, 37%; 98% are free or floating grains; 4% rounded, 21% subrounded, 32% subangular, 43% angular; most are clear or very slightly vacuolized; some are moderately vacuolized or contain rutile and microlites of tourmaline and mica; a few intensely altered quartz grains.

2. Rock fragments: metaquartzite, 2%; phyllite, less than 1%; mica-quartz and mica-quartz-chlorite schist, less than 1%; total, 3%.

3. Feldspar: orthoclase, 2%; microcline, 1%; plagioclase, 1%; total, 4%; about 25% fresh and remainder only slightly sericitized and vacuolized; about 25% subrounded and remainder subangular.

4. Variably iron-stained, calcareous clay and sericite hash, 55%.

5. Miscellaneous terrigenous grains: leucoxene, ilmenite, magnetite, tourmaline, zircon and micas, 1%.

D. Sparry calcite fissure filling separates subrounded to angular, calcareous mud intraclasts. Silt and sand segregated into local bands and pods. Biotite approximately twice as abundant as muscovite.

I. 996, sample site 7.

II. Coarse-grained siltstone; calcite cemented, submature, rounded carbonate fragments, subgraywacke.

III. Massive-bedded, pale reddish orange (10 R 6/6), weakly indurated, quartzose, coarse-grained siltstone.

IV. A. Grain size: extreme, clay to 2.75 Ø, 16-84%, 5 to 3.5 Ø, mean, 4.25 Ø; moderately sorted; wide variation of grain shape in very fine sand and coarse silt classes; submature.

B. 1. Calcite cement, most prevalent; irregularly distributed in patches through less than one-half of the thin-section; microcrystalline and variably iron stained.

2. Gypsum cement, trace; very few local spots of fibrous gypsum.

C. 1. Quartz: common, 18%; undulose, 59%; composite, 8%; stretched composite, 2%; total, 87%; majority are free or floating grains; 12% well-rounded, 31% subrounded, 28% subangular, 29% angular; most are free from inclusions or contain only a few vacuoles, about 25% either moderately to intensely vacuolized or contain microlites of zircon, tourmaline, micas, and/or opaques.

2. Rock fragments: metaquartzite, 2%;, quartz-mica schist, 3%; quartz-mica-chlorite schist, 2%; phyllite, 1%; carbonate, 2%; total, 10%.

3. Feldspar: orthoclase, 2%; microcline, less than 1%; plagioclase, less than 2%; total, 4%; 44% fresh, 27% slightly altered, 12% moderately altered. 17% intensely altered; mostly vacuolization with some sericitization and replacement by carbonates; 4% well-rounded, 11% subrounded, 48% subangular, 37% angular.

4. Miscellaneous terrigenous grains: zircon, apatite, garnet, tourmaline, leucoxene, ilmenite, magnetite, micas, chlorite, 1%.

D. Angular zircon grains mixed with well-rounded zircons. Textural inversion with subangular fine sand and angular very fine sand quartz grains.

I. 1008, sample site 8.

II. Coarse-grained siltstone; dolomite cemented, mature, orthoquartzite.

III. Cross-bedded, finely laminated, light greenish gray (5 GY 8/1) with moderate reddish brown (10 R 4/6) mottling, well indurated, coarse-grained siltstone.

IV. A. Grain size: extreme, clay to 3.5 Ø, 16-84%, 5.5 to 4 Ø, mean, 4.75 Ø; well sorted; mature.

B. 1. Dolomite cement, mostly prevalent; well distributed throughout the thin-section as microcrystalline aggregates; variably iron stained.

2. Quartz overgrowth, minor; isolated grains with clear, angular enlargements; few have any vacuoles.

C. 1. Quartz: common, 21%; undulose, 65%; composite, 4%; stretched composite, 1%; total, 91%; free grains, 92%; 3% well-rounded, 44% subrounded, 26% subangular, 27% angular; most slightly vacuolized, about 10% clear, small amount with moderate vacuolization or contain microlites or mica, apatite, tourmaline, zircon or opaques.

2. Rock fragments: metaquartzite, 1%; quartz-sericite-chlorite-opaque schist, 2%; total, 3%.

3. Feldspar: orthoclase, 3%; microcline, trace; plagioclase, 1%; total, 4%; 20% fresh, 40% slightly altered, 30% moderately altered, 10% intensely sericitized and vacuolized; 10% subrounded, 55% subangular, 35% angular.

4. Miscellaneous terrigenous grains: leucoxene, ilmenite, magnetite, hematite, less than 1%; micas and chlorite, less than 1%; zircon, tourmaline, apatite, garnet, 1%; total, 2%.

D. Hematite staining seemingly extends out from concentrations of a few opaque grains. Textural inversion with both round and angular coarse silt and medium silt. No difference noted in the mineralogy of the iron stained zones when compared with the greenish-gray portions of the thin section.

I. 1010, sample site 1.

II. Coarse-grained siltstone; dolomite cemented, mature, subarkose.

III. Thin-bedded, moderate reddish brown (10 R 4/6), moderately indurated, slightly friable, quartzose, coarse-grained siltstone.

IV. A. Grain size: extreme, clay to 3.25 ϕ, 16-84%, 4.75 to 3.75 ϕ, mean, 4.25 ϕ; well sorted; mature.

B. 1. Dolomite cement, most common; irregularly distributed through over one-half of the thin section; microcrystalline, variably iron stained; few euhedral rhombohedra; two generations of development after gypsum formation.

2. Gypsum cement, minor; irregularly distributed in rare, isolated patches of fibrous aggregates.

3. Quartz overgrowths, minor; very few isolated grains with clear and angular enlargements; most covering iron stained surfaces; most enlargements are uneven and some have the overgrowth developed on only one side of the grain.

4. Feldspar overgrowths, minor; random distribution on isolated grains; generally not iron stained; clear and angular.

C. 1. Quartz: common, 14%; undulose, 60%; composite, 7%; stretched composite, 1%; total, 82%; free grains, 76%, floating grains, 18%, fixed grains, 6%; 9% well-rounded, 48% subrounded, 36% subangular, 7% angular; over 75% either clear or slightly vacuolized, less than 10% contain a variety of inclusions.

2. Rock fragments: metaquartzite, 1%; quartz-mica-opaque schist, 3%; quartz-sericite, 1%; total, 5%.

3. Feldspar: orthoclase, 4%; microcline, 1%; plagioclase, 3%; total, 8%; 15% fresh, 41% slightly sericitized, vacuolized or replaced by carbonates, 22% moderately altered, 22% intensely altered; 4% well-rounded, 33% subrounded, 52% subangular, 11% angular.

4. Miscellaneous terrigenous grains: micas, 1%; hematite, 1%; tourmaline, zircon, apatite, ilmenite, leucoxene, magnetite, chlorite, 1%; total, 3%.

D. Unlike the quartz grains with overgrowths, the feldspar overgrowths do not cover iron stained surfaces and generally are not in turn iron stained.

I. 1012, sample site 1.

II. Coarse-grained siltstone; dolomite cemented, detrital hematite grains, mature, quartzose subgraywacke.

III. Cross-bedded, finely laminated, moderate reddish brown (10 R 4/6) to pale reddish brown (10 R 5/4), well indurated, quartzose, coarse-grained siltstone.

IV. A. Grain size: extreme, clay to 3.25 Ø, 16-84%, 5.5 to 3.5 Ø, mean, 4.5 Ø; well sorted but inhomogeneous; subrounded to subangular; mature.

B. 1. Dolomite cement, most abundant; well distributed throughout the thin-section; microcrystalline; variable iron stained; late crystallization.

2. Gypsum cement, minor; irregular patch of fibrous and subhedral aggregates.

3. Quartz overgrowths, minor; a few angular, clear overgrowths on isolated grains; few are rounded.

4. Feldspar overgrowths, minor; very few angular, clear enlargements, commonly untwinned.

C. 1. Quartz: common, 19%; undulose, 61%; composite, 4%; stretched composite, 1%; total, 85%; more than 75% are fixed grains; 10% well-rounded, 52% subrounded, 25% subangular, 13% angular; more than 50% contain minor bubble inclusions, less than 20% are clear, some are moderately vacuolized and some contain inclusions of mica, tourmaline, zircon, opaques and/or apatite.

2. Rock fragments: metaquartzite, 1%; quartz-mica schist, 2%; quartz-sericite schist, less than 1%; quartz-sericite-opaque schist, 1%; total, 5%.

3. Feldspar: orthoclase, less than 2%; microcline, less than 1%; plagioclase, 2%; total, 4%; 18% fresh, 29% slightly altered, 37% moderately altered, 16% intensely sericitized, vacuolized and chloritized; 31% subrounded, 40% subangular, 29% angular.

4. Miscellaneous terrigenous grains: leucoxene, ilmenite, magnetite, hematite, 2%; tourmaline, zircon, apatite, micas, chlorite, garnet, clay, 2%; total, 4%.

D. Mean feldspar grain size approximates that of quartz. Euhedral, prismatic zircon grains mixed with well worn zircon grains. Chlorite with "crinkly" extinction. Minor chert possibly present.

I. 1016, sample site 2.

II. Coarse-grained siltstone; dolomite cemented, submature, feldspathic subgraywacke.

III. Thin-bedded, moderate reddish brown (10 R 4/6), weakly indurated, friable, coarse-grained siltstone.

IV. A. Grain size: extreme, clay to 3.25 Ø, 16-84%, 5.5 to 4 Ø, mean, 4.75 Ø; moderately sorted; mostly subangular; submature.

B. 1. Dolomite cement, most of binding agent; irregularly distributed through less than one-half of the slide; microcrystalline patches.

2. Gypsum cement, minor; isolated areas of fibrous and subhedral interlocking crystals.

3. Quartz overgrowths, very minor; only on a few grains; clear and angular; some do not cover entire grain; commonly over hematite coating.

4. Feldspar overgrowths, trace; clear and angular enlargements; commonly not twinned and without inclusions.

5. Iron oxide cement, minor; widely distributed but volumetrically minor.

C. 1. Quartz: common, 18%; undulose, 36%; composite, 12%; stretched composite, 5%; total, 71%; free grains, 41%; fixed grains, 59%; 39% well-rounded, 44% subangular, 17% angular; most are either clear or contain only a few vacuoles, some moderately vacuolized and a minority with inclusions of mica, rutile, tourmaline, opaques and zircon.

2. Rock fragments: metaquartzite, 5%; quartz-chlorite schist, 4%; quartz-mica schist, 3%; quartz-sericite-opaque schist, 2%; total, 14%.

3. Feldspar: orthoclase, 4%; microcline, trace; plagioclase, 2%; total, 6%; 46% fresh, 43% slightly altered, 8% moderately altered, 3% intensely sericitized or vacuolized; 23% subrounded, 38% subangular, 39% angular.

4. Miscellaneous terrigenous grains: ilmenite, leucoxene, magnetite, 2%; micas, sericite, 3%; clay, 3%; tourmaline, zircon, apatite, chlorite, garnet, less than 2%; total, 9%.

D. Feldspar mean grain size slightly less than that of quartz. Most feldspar overgrowths not iron stained whereas most quartz overgrowths are stained. Few carbonate cemented, clay intraclasts.

I. 1019, sample site 1.

II. Coarse-grained siltstone; dolomite cemented, submature, orthoclase subarkose.

III. Blocky, pale reddish brown (10 R 5/4), moderately indurated, coarse-grained siltstone.

IV. A. Grain size: extreme, clay to 4 Ø, 16-84%, 5.5 to 4.25 Ø, mean, 4.75 Ø; moderately sorted; mostly subangular, submature.

B. 1. Dolomite cement, most abundant; well distributed throughout the thin-section; microcrystalline.

2. Quartz overgrowths, trace; isolated grains randomly distributed; commonly clear and angular though some have minor vacuoles.

C. 1. Quartz: common, 11%; undulose, 48%; composite, 6%; stretched composite, 1%; total, 66%; fixed grains, 89%; free grains, 11% mostly in hematite/carbonate/clay hash; 12% well-rounded, 27% subrounded, 41% subangular, 20% angular; most clear or contain minor vacuoles, some moderately vacuolized, minority with tourmaline, zircon, mica, or opaques microlites.

2. Rock fragments: metaquartzite, 1%; quartz-mica-opaque schist, 2%; carbonate, 2%; total, 5%.

3. Feldspar: orthoclase, 18%; microcline, trace; plagioclase, 3%; total, 21%; 34% fresh, 37% slightly altered, 12% moderately altered, 17% intensely sericitized, vacuolized or replaced by carbonate; 20% subrounded, 34% subangular, 46% angular.

4. Miscellaneous terrigenous grains: mica and clay, 4%; hematite, 2%; leucoxene, ilmenite, magnetite, zircon, tourmaline, apatite, chlorite, 2%; total, 8%.

D. Feldspar mean grain size approximates that of quartz. Carbonate rock fragments are iron coated and recrystallized to a microgranular texture which is uniform with subrounded dolomite cement.

I. 1020, sample site 7.

II. Coarse-grained siltstone; dolomite cemented, submature, feldspathic subgraywacke.

III. Blocky, pale reddish orange (10 R 6/6), weakly indurated, quartzose, coarse-grained siltstone.

IV. A. Grain size: extreme, clay to 3.5 Ø, 16-84%, 4.75 to 3.75 Ø, mean, 4.25 Ø; moderately sorted; subrounded to subangular; submature.

B. 1. Dolomite cement, most prevalent; irregularly distributed in patches through over 50% of the thin section; microcrystalline and variably stained; few euhedral rhombohedra, commonly not stained.

C. 1. Quartz: common, 9%; undulose, 22%; composite, 14%; stretched composite, 12%; total, 57%; most are fixed grains; 5% well-rounded, 41% subrounded, 33% subangular, 21% angular; most free from inclusions or contain only a few vacuoles; some with rutile needles or other microlites.

2. Rock fragments: metaquartzite, 12%; quartz-mica schist, 9%; quartz-mica-chlorite-opaque schist, 5%; phyllite, 2%; total, 28%.

3. Feldspar: orthoclase, 5%; microcline, 2%; plagioclase, total, 12%; 21% fresh, 19% slightly sericitized or vacuolized, 13% moderately altered, 47% intensely altered; 7% well-rounded, 47% subrounded, 33% subangular, 13% angular.

4. Miscellaneous terrigenous grains: leucoxene, ilmenite, magnetite, tourmaline, zircon, chlorite, garnet, 1%; micas, clay, 2%; total, 3%.

D. Feldspar mean grain size approximates that of quartz. The only well-rounded feldspar grains counted are microcline. A wide range in alteration of plagioclase and orthoclase with both fresh and intensely sericitized/vacuolized grains within each species.

I. 1031, sample site 5.

II. Coarse-grained siltstone; gypsum cemented, immature, subgraywacke.

III. Blocky, moderate reddish brown (10 R 4/6), moderately to weakly indurated, silty, gypsiferous shale.

IV. A. Grain size: extreme, clay to 2.75 Ø, 16-84%, clay to 3.75 Ø, mean, 4.75 Ø; poorly sorted; mostly subrounded to subangular; immature.

B. 1. Gypsum cement, most prevalent; concentrated in veinlets as subhedral, interlocking mosaic.

2. Dolomite cement, common; irregularly distributed in intensely hematite-stained patches as microcrystalline aggregates; concentrated in hematite/clay hash.

C. 1. Quartz: common, 10%; undulose, 52%; composite, 8%; stretched composite, 3%; total, 73%; majority are free or floating grains; 12% well-rounded, 58% subrounded, 20% subangular; most grains clear or slightly vacuolized, some with tourmaline, zircon, opaque, mica or chlorite inclusions.

2. Rock fragments: metaquartzite, 3%; quartz-mica schist, 2%; quartz-mica-chlorite-opaque schist, 1%; total, 6%.

3. Feldspar: orthoclase, less than 1%; microcline, trace; plagioclase, less than 1%; total, 1%; 57% fresh, 14% slightly sericitized, vacuolized or chloritized, 29% moderately altered; 29% subrounded, 57% subangular, 14% angular.

4. Clay and micas, 18%.

5. Miscellaneous terrigenous grains: hematite, leucoxene, ilmenite, magnetite, 1%; zircon, apatite, tourmaline, garnet, chlorite, 1%; total, 2%.

D. Angular zircon grains mixed with well-rounded zircon grains. Many of the quartz grains are not coated with hematite. Intraclasts of intensely iron-stained argillaceous material partially cemented by dolomite. Some translucent, well worn hematite grains.

APPENDIX D

THIN SECTION LOCATIONS

Accession Number	Location	Vertical Distance*
980	NW/4, SE/4,SW/4, sec. 21, T. 10 N., R. 23 W.	- 5'
981	NW/4,SE/4,SE/4, sec. 16, T. 11 N., R. 26 W.	-21'
982	NW/4,SE/4,SW/4, sec. 21, T. 10 N., R. 23 W.	-33'
983	NW/4,SE/4,SW/4, sec. 21, T. 10 N., R. 23 W.	-35'
984	NW/4,SE/4,SW/4, sec. 21, T. 10 N., R. 23 W.	-57'
985	NW/4,SE/4,SW/4, sec. 21, T. 10 N., R. 23 W.	-76'
986	NW/4,SE/4,SW/4, sec. 21, T. 10 N., R. 23 W.	-124'
987	NW/4,NW/4,SE/4, sec. 9, T. 12 N., R. 16 W.	+111'
988	NW/4,SE/4,SW/4, sec. 21, T. 10 N., R. 23 W.	-133'
989	NW/4,SE/4,SW,4, sec. 21, T. 10 N., R. 23 W.	-147'
990	NW/4,SE/4,SW/4,SE/4, sec. 7, T. 16 N., R. 20 W.	+97'
991	NW/4,NW/4,SE/4, sec. 9, T. 12 N., R. 16 W.	+80'
992	NW/4,SE/4,SW/4,SE/4, sec. 7, T. 16 N., R. 20 W.	+69'
993	NW/4,SE/4,SW/4,SE/4, sec. 7, T. 16 N., R. 20 W.	+63'
994	NW/4,SE/4,SW/4,SE/4, sec. 7, T. 16 N., R. 20 W.	+61'
995	SE/4,SE/4,SW/4, sec. 1, T. 15 N., R. 17 W.	+41'
996	SE/4,NW/4,SW/4, sec. 1, T. 15 N., R. 17 W.	+34'
997	SW/4,SW/4,NE/4,SE/4, sec. 6, T. 15 N., R. 20 W.	+14'
998	SE/4,SE/4,NW/4, sec. 36, T. 13 N., R. 17 W.	+13'
999	NW/4,SE/4,SW/4,SE/4, sec. 7, T. 16 N., R. 20 W.	+88'
1000	NW/4,SE/4,SW/4,SE/4, sec. 7, T. 16 N., R. 20 W.	+75'
1001	SW/4,SW/4,NE/4,SE/4, sec. 6, T. 15 N., R. 20 W.	+18'
1002	NW/4,NW/4,SE/4, sec. 9, T. 12 N., R. 6 W.	+108'
1003	SE/4,SE/4,NW/4, sec. 36, T. 13 N., R. 17 W.	+10'
1004	NW/4,NW/4,NE/4,SE/4, sec. 6, T. 12 N., R. 16 W.	-129'
1005	SW/4,SW/4,SW/4, sec. 18, T. 10 N., R. 23 W.	- 9'
1006	NW/4,NW/4,SE/4, sec. 5, T. 10 N., R. 21 W.	-19'
1007	SW/4,NW/4,SE/4, sec. 4, T. 10 N., R. 24 W.	-40'
1008	SE/4,SE/4,NE/4, sec. 32, T. 17 N., R. 20 W.	-43'
1009	NE/4,SE/4,NW/4, sec. 26, T. 18 N., R. 22 W.	+92'
1010	NE/4,SE/4,NW/4, sec. 26, T. 18 N., R. 22 W.	+86'
1011	SW/4,NW/4,SW/4, sec. 22, T. 9 N., R. 21 W.	-110'
1012	NE/4,SE/4,NW/4, sec. 26, T. 18 N., R. 22 W.	+67'
1013	SE/4,SW/4,SW/4, sec. 16, T. 28 N., R. 18 W.	+37'
1014	SE/4,SW/4,SW/4, sec. 16, T. 28 N., R. 18 W.	+39'

Accession Number	Location	Vertical Distance*
1015	NE/4,SE/4,NW/4, sec. 26, T. 18 N., R. 22 W.	+63'
1016	SW/4,SW/4,SW/4, sec. 1, T. 8 N., R. 21 W.	+10'
1017	SW/4,SW/4,SW/4, sec. 18, T. 10 N., R. 23 W.	-11'
1018	SE/4,SW/4,SW/4, sec. 16, T. 28 N., R. 18 W.	+38'
1019	NE/4,SE/4,SW/4, sec. 26, T. 18 N., R. 22 W.	+67'
1020	SE/4,NW/4,SW/4, sec. 1, T. 15 N., R. 17 W.	+113'
1021	SE/4,NW/4,SW/4, sec. 1, T. 15 N., R. 17 W.	+58'
1022	SE/4,NW/4,SW/4, sec. 1, T. 15 N., R. 17 W.	+84'
1023	SE/4,NE/4,SW/4, sec. 1, T. 15 N., R. 17 W.	+110'
1024	SE/4,NW/4,SW/4, sec. 1, T. 15 N., R. 17 W.	+100'
1025	SE/4,NW/4,SW/4, sec. 1, T. 15 N., R. 17 W.	+47'
1026	NW/4,SE/4,SW/4, sec. 32, T. 14 N., R. 23 W.	+134'
1027	NW/4,SE/4,SW/4, sec. 32, T. 14 N., R. 23 W.	+104'
1028	NW/4,SE/4,SW/4, sec. 32, T. 14 N., R. 23 W.	+97'
1029	NW/4,SE/4,SW/4, sec. 32, T. 14 N., R. 23 W.	+73'
1030	NW/4,SE/4,SW/4, sec. 32, T. 14 N., R. 23 W.	+65'
1031	NW/4,SE/4,SW/4, sec. 32, T. 14 N., R. 23 W.	+76'
1032	NW/4,SE/4,SW/4, sec. 21, T. 10 N., R. 23 W.	-13'
1033	NW/4,SE/4,SW/4, sec. 21, T. 10 N., R. 23 W.	-16'
1034	NW/4,SE/4,SW/4, sec. 21, T. 10 N., R. 23 W.	-37'
1035	NW/4,SE/4,SW/4, sec. 21, T. 10 N., R. 23 W.	-57'
1036	NW/4,SE/4,SW/4, sec. 21, T. 10 N., R. 23 W.	-73'
1037	NW/4,SE/4,SW/4, sec. 21, T. 10 N., R. 23 W.	-84'
1038	NW/4,SE/4,SW/4, sec. 21, T. 10 N., R. 23 W.	-145'

Sample Sites

Sample Site	Location
1	NE/4,SE/4,NW/4, sec. 26, T. 18 N., R. 22 W. (surface).
2	Sec. 1, T. 8 N., R. 21 W., to sec. 5, T. 10 N., R. 21 W. (surface).
3	NW/4,SE/4,SW/4, sec. 21, T. 10 N., R. 23 W. (core) and SW/4,SW/4,SW/4, sec. 18, T. 10 N., R. 23 W (surface).
4	NW/4,NW/4,NE/4,SE/4, sec. 6, T. 12 N., R. 16 W. (core) and SE/4,SE/4,NW/4, sec. 36, T. 13 N., R. 17 W. (core).
5	NW/4,SE/4,SW/4, sec. 32, T. 14 N., R. 23 W. (core).
6	NW/4,SE/4,SE/4, sec. 16, T. 11 N., R. 26 W. (core).
7	SE/4,NW/4,SW/4, sec. 1, T. 15 N., R. 17 W. (core).
8	NW/4,SE/4,SW/4, sec. 7, T. 16 N., R. 20 W. (core) and SE/4,SE/4,NE/4, sec. 32, T. 17 N., R. 32 W. (surface).
9	SE/4,SE/4,SE/4, sec. 17, T. 28 N., R. 18 W. to SE/4,SW/4,NE/4, sec. 4, T. 28 N., R. 18 W. (surface).
10.	NW/4,NE/4,NE/4, sec. 15, T. 5 N., R. 10 W. to SW/4,NE/4,NE/4, sec. 32, T. 6 N., R. 10 W. (surface).

* When positive, the distance indicates the number of feet from the base of the formation; when negative, the distance indicates the number of feet from the top of the formation.