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EASTERN OKLAHOMA.**

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CLAY PETROLOGY OF THE ATOKA FORMATION,
EASTERN OKLAHOMA

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BY
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Norman, Oklahoma

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CLAY PETROLOGY OF THE ATOKA FORMATION,
EASTERN OKLAHOMA

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CLAY PETROLOGY OF THE ATOKA FORMATION,
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INTRODUCTION

Purpose of Investigation

The Atoka Formation has previously been described from a general stratigraphic point of view, but both the specific stratigraphic position and the environment of deposition seem poorly defined. The present study involves a detailed investigation of clay mineralogy and petrology of these strata in order to ascertain specific mineral and chemical parameters and thereby arrive at a better understanding of the origin of these rocks. Particular attention has been focused upon the clay mineral, illite--its polytypism and structural chemistry--to determine variations with lithology, depth of burial, and geographic location. Vertical and horizontal distribution of clay minerals and their diagenetic significance as well as description and analysis of the terrigenous fraction are also included in the investigation.

Location

Exposures of the Atoka Formation are present in the Ouachita Mountains, the Arkoma Basin, the east side of the Arbuckle Mountains, and along the flanks of the Ozark Uplift. Samples were collected from

outcrops along the roads and from cores contained in the Core Library of the School of Geology and Geophysics, University of Oklahoma. The field investigation was concentrated in the Spring Mountain area and the strata exposed in the Muskogee-Porum area. The locations of the sample sites are plotted on Figure 1.

Methods of Investigation

Samples were collected from each sedimentational unit. Thin sections were cut perpendicular to bedding planes and a polarizing microscope was used for both mineral and textural investigation. Textural and structural studies of polished sections were made with a binocular microscope.

Both Norelco and Siemens x-ray units were employed for clay mineral identification and the study of polytypism. All x-ray diffraction patterns were obtained by either Norelco or Siemens x-ray diffractometers and recorders with nickel-filtered copper (K-alpha) radiation. Quantitative x-ray fluorescence analysis was performed using a Siemens x-ray unit with either a chromium or tungsten tube, and a vacuum spectrometer for chemical analysis.

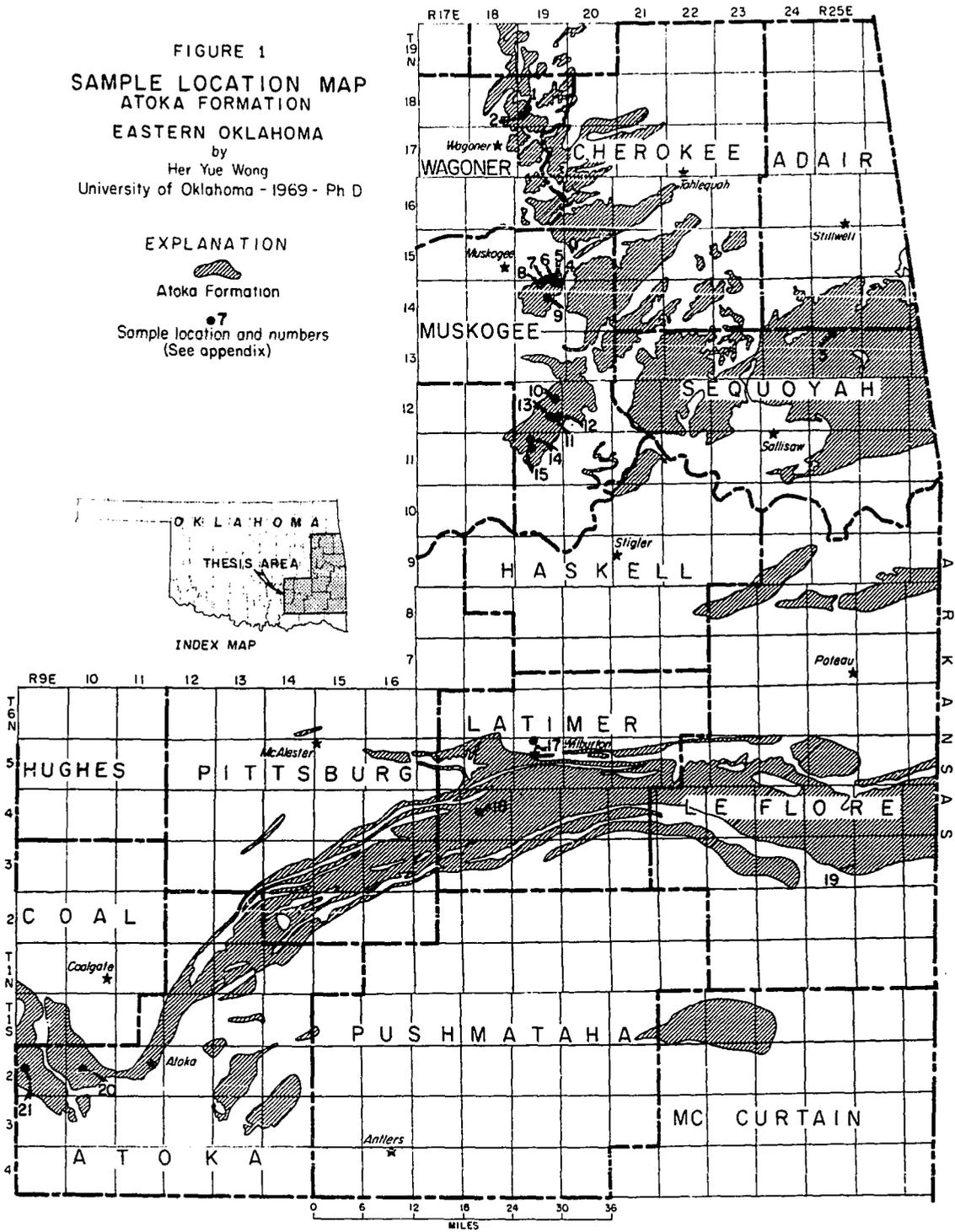
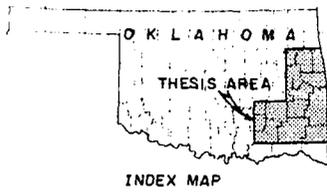
Differential thermal analysis equipment was used as a supplemental tool for clay mineral identification. This analysis of endothermic and exothermic reactions also provides some information on the structural chemistry of the clay minerals. Endothermic reactions are the result of dehydration and in some instances the loss of crystal structure whereas exothermic reactions are normally the result of the formation of new crystalline phases.

FIGURE 1
 SAMPLE LOCATION MAP
 ATOKA FORMATION
 EASTERN OKLAHOMA
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EXPLANATION

 Atoka Formation

 Sample location and numbers
 (See appendix)



0 6 12 18 24 30 36
 MILES

Emission spectrography was used to study the following trace elements; boron, vanadium, nickel, and cobalt. The quantitative analyses for these trace elements was obtained by comparing the intensity of the emission lines for each element with the intensity of standard patterns.

Several supplemental techniques were employed in the analysis of clay minerals. High temperature ovens were used for heat treatment of clay minerals. The structural changes of the clay minerals with heat treatment were used as a supplemental method for mineral identification. The ultrasonic generator was employed for dispersing the samples. A high-speed centrifuge was used for separation of selected size-fractions of clay minerals. Ethylene glycol was used for detecting the expandable clay minerals such as vermiculite and mixed-layer illite-montmorillonite. Potassium acetate was used to identify the clay minerals which will collapse to 10 \AA with this treatment.

STRATIGRAPHY

Nomenclature and Distribution

The Atoka Formation was named by Taff and Adams (1900) for exposures in Atoka County, Oklahoma, but no specific type section was defined. The Atoka Formation is exposed in the Ouachita Mountains, in the Arkoma Basin, on the east side of the Arbuckle Mountains, and along the flanks of the Ozark Uplift. The thickness of the Atoka Formation is extremely variable. The thickest sections, which will be described later, are in the Arkoma Basin. The strata are thin on both flanks of the McAlester Basin, northward toward the flanks of the Ozark Uplift, and southwestward toward the east side of the Arbuckle Mountains.

Branson (1962) stated that the Atoka Series is derived from the Atoka Formation, and in the type area, the series and formation boundaries are identical. He considered that west of Atoka, in and near the northwestern corner of Atoka County, the entire formation is present, and this area should serve as the type for both the formation and the series. In this area, the section consists of dark shale with many sandstone tongues and lenses. No detailed lithostratigraphic or biostratigraphic investigations have been published for the type area of the Atoka Formation, and therefore the unit is not well defined from either a rock stratigraphic or time stratigraphic point of view. In

gross aspect, the writer would like to consider it as a large sedimentational unit which will be explained in detail in later sections of this study.

Blythe (1959) measured a section of 130 feet in Mayes County, a section of 370 feet in Wagoner County, and a section of 500 feet in Sequoyah County. Wilson and Newell (1937) estimated the thickness of Atoka strata at about 600 feet in the Muskogee-Forum area. Groneis (1930) published a measured section from Perry County, Arkansas, where the thickness of the Atoka Formation was reported exceeding 9,479 feet. The greatest thickness of the Atoka Formation was measured by Reinemund and Danilchik (1957) to be at least 18,500 feet in the Black Fork Syncline of Scott County, Arkansas. The writer measured a section at Spring Mountain in LeFlore County of 3,590 feet and Shelbourne (1960) estimated a thickness of 6,800 feet for the Atoka Formation in the Boktukola Syncline.

Because of lithologic facies changes, extreme variability in thickness, lack of identifiable fossils in the Ouachita Mountains, and confusion from faulting and folding, exact stratigraphic correlation is still a major problem. The lower and upper boundaries are readily discernible where the Atoka Formation lies above Morrow strata and beneath the Hartshorne Formation in the Ozark Uplift area and the east side of the Arbuckle Mountains as shown in Figures 2 and 3, but the Hartshorne Formation is absent above the Atoka Formation in the Ouachita Mountains.

Internal stratigraphic correlation and geologic age are major areas of disagreement. Branson (1959) and Blythe (1959) considered the



Figure 2. Conglomerate present at the unconformity between Morrow strata and the Atoka Formation, NW $\frac{1}{4}$ Sec. 20, T. 18 N., R. 19 E., on the west shore of Fort Gibson Lake, Wagoner County, Oklahoma.



Figure 3. The Hartshorne Sandstone forms the winding ridge overlying the Atoka Formation. Direction of view is NW, SW $\frac{1}{4}$ Sec. 16, T. 16 N., R. 19 E. north of Warner, Muskogee County, Oklahoma.



Figure 4. The rocks in the lower sandstone member of the Atoka Formation at Spring Mountain section consist mainly of fine sandstone and siltstone. The picture is taken near the lower boundary of the formation, SW $\frac{1}{4}$ Sec. 23, T. 3 N., R. 25 E., along Highway 103, Spring Mountain, LeFlore County, Oklahoma.

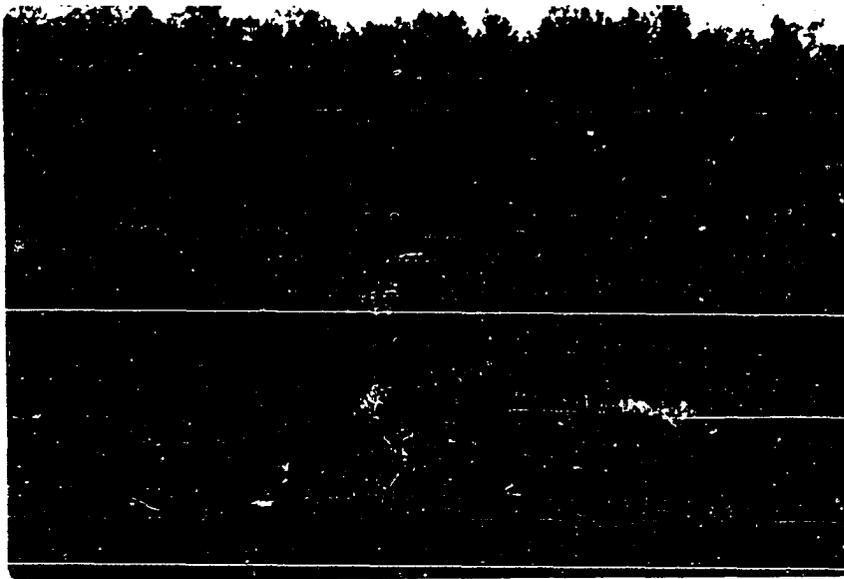


Figure 5. The rocks of the upper shale member of the Atoka Formation in the Spring Mountain section near the synclinal axis consist mainly of dark shale. Rock creep and a fault are displayed in this picture, viewing N, NW $\frac{1}{4}$ Sec. 24, T. 3 N., R. 25 E., along Highway 103, Spring Mountain, LeFlore County, Oklahoma.

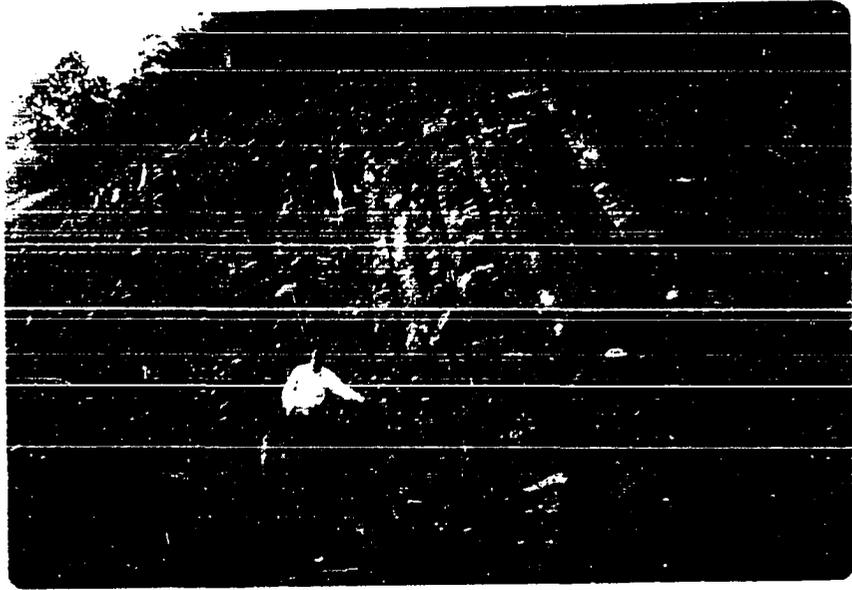


Figure 6. The so-called rhythmic strata consist of almost equal thicknesses of sandstone and shale, photograph taken near the upper boundary of the lower sandstone member, SW $\frac{1}{4}$ Sec. 24, T. 3 N., R. 25 E., along Highway 103, Spring Mountain, LeFlore County, Oklahoma.

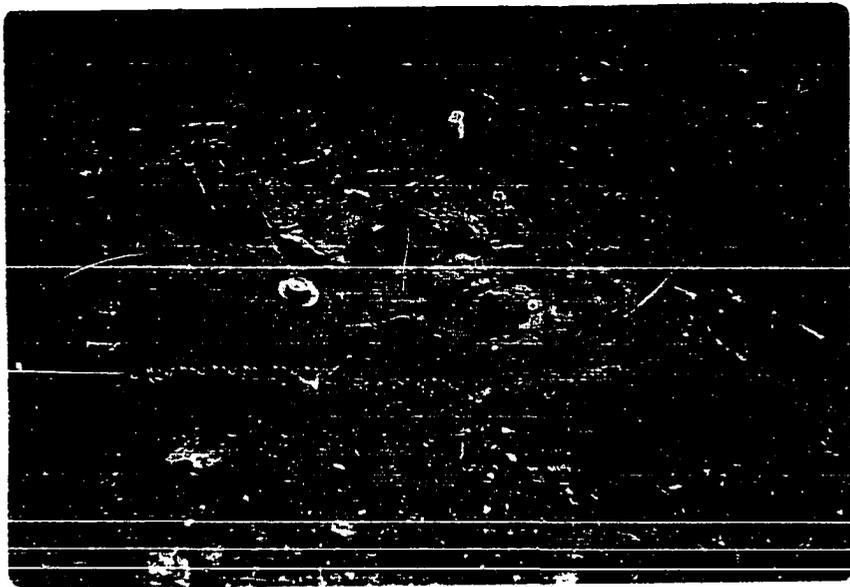


Figure 7. The thin bedded siltstone and sandstone layers form almost rectangular joints, central part of upper shale member, viewing W, NW $\frac{1}{4}$ Sec. 24, T. 3 N., R. 25 E., along Highway 103, Spring Mountain, LeFlore County, Oklahoma.

Atoka Formation in the Ouachita Mountains to be Morrowan in age and the Atoka Formation along the flanks of the Ozark Uplift to be Atokan in age. Goldstein and Hendricks (1962, p. 406) stated the following:

Diagnostic fossils are rare in the Atoka, and rocks now called "Atoka" in different parts of the Ouachitas may not be of exactly the same age.

Harlton (1959) classified the age of the Atoka Formation in the southern Ouachita Mountains as Atoka. Cline and Shelbourne (1959) believe the base of the Atoka Formation in the central Ouachita Mountains to be Morrowan in age because of the presence of sponge spicules, which are correlated with those of the Wapanucka, about 100 feet above the base of the Atoka Formation. They considered that, because the Atoka Formation is so thick, exposures in the Ouachitas must be only the lower portion of the complete sequence and the lower portions must be some part of the upper Morrowan rocks. This investigation provides little additional information on the geologic age of these strata and will therefore not be further considered.

Along the flanks of the Ozark Uplift in the Muskogee-Forum district, Wilson and Newell (1937) subdivided the Atoka Formation into six sandstone members with associated shale units. The members are in ascending order; the Coody Sandstone, the A1 Shale, the Pope Chapel Sandstone, the A2 Shale, the Georges Fork Sandstone, the A3 Shale, the Dirty Creek Sandstone, the A4 Shale, the Webbers Falls Sandstone, the A5 Shale, the Blackjack School Sandstone, and the A6 Shale. Most of the boundaries between sandstone and shale members show interfingering relationships. Blythe (1957) adopted Wilson's subdivisions for mapping the Atoka Formation in Wagoner and Mayes Counties.

Seely (1963) subdivided the Atoka Formation into two members for mapping, a basal sandy member and an overlying shaly member, in the Rich Mountain area of the Ouachita Mountains. The boundary is arbitrarily drawn as there is a gradual change from sandstone to shale with interfingering lithology.

Lithology

The rock character of the Atoka Formation on the flanks of the Ozark Uplift in Oklahoma can be traced from Sequoyah County, through Muskogee, Cherokee, and Wagoner Counties to Mayes County. At the Wagoner Pumping Station, on the shore of Fort Gibson Lake, the Atoka Formation overlies the Morrow Limestone with a limestone conglomerate in the lower portion and a chert and quartz conglomerate in the upper portion in the contact zone. Dark gray and purplish limestone layers are present above the conglomerate at this section. Blythe (1959) measured a section near the Wagoner Pumping Station.

The following general description of the lithology of the Atoka Formation is modified from a report by Wilson and Newell (1937). The Coody Sandstone Member is a massive, friable, buff sandstone with local conglomerate. The thickness ranges from 15 to 115 feet. The A1 Shale overlying the sandstone is a dark gray to greenish-gray shale. The thickness ranges from 35 to 72 feet. The Pope Chapel Sandstone Member is a hard, calcareous, greenish-gray, to buff sandstone with local cross-bedding. The thickness ranges from 10 to 20 feet. The A2 Shale is highly variable in lithologic character and thickness. It varies from black to gray to green in color, locally containing iron concretions and

limestone layers. Wilson reported a section of 85 feet in Sec. 23, T. 12 N., R. 19 E., and another section of 65 feet in Sec. 1, T. 14 N., R. 19 E. The Georges Fork Sandstone Member is a hard calcareous greenish-gray to black sandstone and the thickness ranges from 3 to 15 feet. The A3 Shale is olive-colored with limonite concretions. Wilson reported a 3-foot thick, white, fine-grained limestone at the top of A3 Shale in the NW $\frac{1}{4}$ Sec. 3, T. 14 N., R. 19 E. The Dirty Creek Sandstone is black to greenish-buff with markings of Taonurus. Wilson reported a thickness of 15 feet in T. 14 N., R. 20 E. and a thickness of 3 to 8 feet in T. 14 N., R. 19 E. The A4 Shale is greenish-gray with limonite concretions and the thickness ranges from 22 to 30 feet. The Webbers Falls Sandstone Member is actually a siltstone which is dark green to black or grayish-buff and the thickness is from 10 to 15 feet. The A5 Shale overlying the Webbers Falls Sandstone is a gray shale containing two thin limestone layers. Wilson reported a thickness of 85 feet in T. 14 N., Rs. 19 and 20 E. for the A5 Shale. The Blackjack School Sandstone Member consists of thin-bedded, buff or greenish-gray sandstone. Wilson reported a thickness of 60 to 85 feet from measurements of an aggregate section. The A6 Shale is light gray to dark gray in color and a thin coal occurs at the top of the unit in Tps. 13 and 14 N., R. 19 E. Wilson reported a thickness of 60 to 80 feet for the A6 Shale in Tps. 13 and 14 N.

Along the flanks of the Ozark Uplift, the Atoka Formation contains convolute bedding, contorted bedding, cross-bedding, graded bedding, and worm trails. In the contact portion between sandstone and shale, on the top of the shale and at the bottom of the sandstone, there are abundant iron concretions which may form discontinuous layers as

shown in Figure 8. Some iron concretions have argillaceous nuclei. The iron concretions may be formed by epigenetic processes (metharmosis) by dissolving iron from the sandstone members and precipitating it at the contact with the shale units. The precipitation would result because of the lower permeability of the shale units.

The sandstone-shale ratio is low for rock units of the Atoka Formation in the McAlester Basin. The rock character in this area was studied from core samples. Most of the shales are dark gray to black and the sandstones are light gray. Small dislocations are abundant in the shale portions showing compaction gliding surfaces. The sandstone layers are compact. The sandstone-shale ratio is low, most cores having values of less than 1. This ratio increases to 2 or more in that portion of the shelf to the north and northwest in Seminole County (Dickey and Rohn, 1955). Croneis (1930) pointed out that sandstone becomes more abundant toward the north and east in Arkansas, whereas the shale component increases southwestward into Oklahoma.

In the Rich Mountain area, the Atoka Formation was divided into a basal sandstone member and an upper shale member (Seely, 1963). The basal sandstone member consists mainly of sandstone and siltstone. The bedding varies from thinly laminated to thick bedded. The color of the sandstone varies from buff to light gray and the color of the shale layers in the basal sandstone member varies from light to dark gray. The boundary between the basal sandstone member and upper shale member is a gradational change, where the alternation of sandstone layers and shale layers becomes rhythmic. Pettijohn (1957) called these kind of strata, rhythmites. The upper shale member of the Atoka Formation



Figure 8. Iron concretions along the contact between the upper sandstone and lower shale portions of the Atoka Formation, view W, SW $\frac{1}{4}$ Sec. 5, T. 11 N., R. 19 E., near Blackjack School, Muskogee County, Oklahoma.

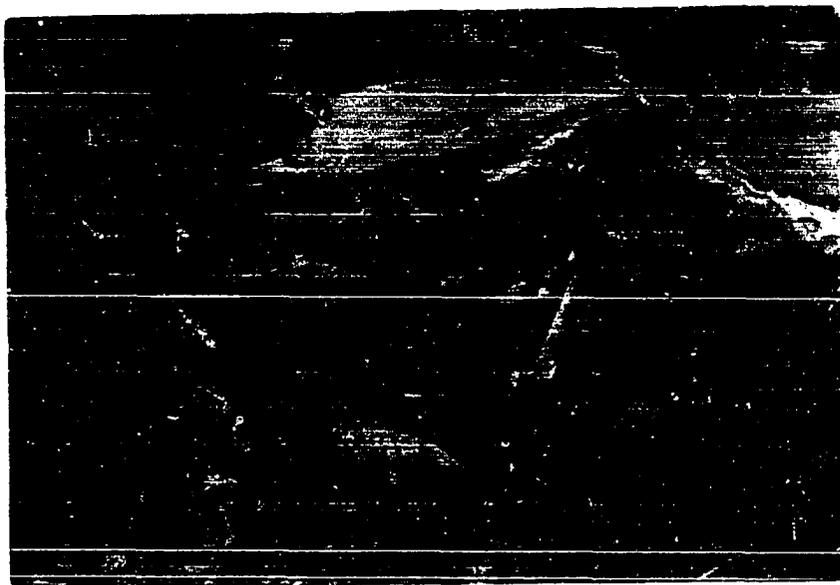


Figure 9. Abundant flute casts on bedding surfaces characterize the Atoka Formation; this view taken of a sandstone unit in the upper shale member of the Atoka Formation, SE $\frac{1}{4}$ Sec. 24, T. 3 N., R. 25 E., along Highway 103, Spring Mountain, LeFlore County, Oklahoma.

consists mainly of shale which is gray to black. The color of the sandstone layers in the upper shale member varies from buff to greenish-gray to dark gray.

Krivanek (1961) reported that the Atoka Formation in Pushmataha and Atoka Counties consists mainly of shale which is intercalated with thin-bedded sandstone. The shale of the Atoka Formation in this area is grayish-brown.

The Atoka Formation in the Ouachita Mountains contains abundant flute casts, groove casts, ripple marks, fossil bottom marks, worm trails, cross-bedding, graded bedding, convolute bedding, contorted bedding, and clay galls. All the above characteristics are well preserved in the sandstone units.

The Atoka Formation in the east side of the Arbuckle Mountains consists mainly of dark to light gray shales which are intercalated with thinner, buff to light gray sandstone layers. In the shale and siltstone portions, sandstone lenses are abundant. Clay galls in the sandstone portions are also abundant. Dannenburg (1952) studied the surface geology of Coal County and reported a 15 foot thick layer of limestone about 600 feet above the base of the Atoka Formation. Plastic deformation, worm trails, graded bedding, and iron concretions are also present in this area.

PETROGRAPHY

Seventy-five thin sections of sandstone, siltstone, shale, and limestone were prepared from rock slices cut perpendicular to bedding. The thin sections were examined optically with a polarizing microscope. The purpose of this part of the investigation was to determine the mineral content, texture, and grain-size of the terrigenous and chemical rocks. The classification and statistical analysis of sandstone and siltstone samples are based upon the system presented by Folk (1961).

The grain size is presented as an arithmetic mean obtained by measuring the longest and shortest diameters of the grains from thin sections. The size variation from microscope to sieve analysis is ignored, because, as reported by Friedman (1958), the variation between these two methods of measurement is insignificant in this size range. The graphic mean of most sandstone and siltstone units ranges from 2.88 to 5 phi. According to the Wentworth grain size scale, the size class of these units ranges from fine sand to silt.

The sorting, or standard deviation, ranges from well sorted to moderately sorted, the skewness from near symmetrical to strongly fine-skewed, and the kurtosis from leptokurtic to platykurtic. Most thin sections of the sandstone units contain a high matrix content in spite of the good sorting values in the coarse fraction. Considering that the

matrix is primarily terrigenous clay, most of the sandstone and siltstone units of the Atoka Formation are in the immature to submature stage.

Most of the quartz in the sandstones and siltstones consists of single grains, has slightly undulose extinction with few vacuoles and no microlites. The second most abundant kind of quartz consists of single grains with straight extinction, few vacuoles, and no microlites. The third most abundant kind of quartz consists of single grains with strongly undulose extinction, normally 10 to 15 degrees with some grains as high as 24 degrees. This quartz type contains few vacuoles and no microlite inclusions. A few composite grains of quartz, chert, and quartz grains containing microlite inclusions were also observed. The types of inclusions found in the quartz grains are vacuoles, rutile needles, tourmaline, and mica. Most of the quartz grains are subangular to subrounded. The characteristics of the quartz grains in the Atoka Formation show no obvious trends either stratigraphically or geographically.

Both potash feldspar and plagioclase grains are present. The potash feldspar is orthoclase and microcline. The plagioclase ranges in composition from oligoclase to andesine based upon determinations using the method of extinction angles in the albite twins cut normal to the (010) plane. The amount of potash feldspar is almost the same as that of plagioclase. More than one-half of the feldspar grains are weathered and have been partly altered to clay. In general, the size of the feldspar grains is smaller than that of quartz in the same sample. The angularity of the feldspar grains ranges from subangular to subrounded. The fresh feldspars show a higher angularity than the weathered variety.

Mica flakes are about one percent of the total mineral components in the sandstone units. Most of the mica is muscovite and only a few flakes of biotite were observed. Some of the illite may have been derived from coarse mica flakes. A few grains of coarse chlorite were noted in a few samples.

Rock fragments of shale, slate, phyllite, and schist are present primarily in the sandstone and siltstone units. The most important mineral component of the shale, slate, and phyllite fragments is illite. Some of the shale and slate fragments have been squeezed and disintegrated into individual grains of illite scattered in the interstitial spaces as a matrix.

The heavy minerals seen in thin section are tourmaline, zircon, rutile, garnet, apatite, staurolite, and mica. Weaver (1958) reported a similar suite of heavy minerals. No detailed investigation of the heavy minerals was made.

The fossil content of the rocks was examined in thin section. It consists of fragments of foraminifera, bryozoans, mollusks, brachiopods, crinoid stems and calyx plates, and siliceous sponge spicules. The only fossil fragments obtained from rocks of the Atoka Formation in the Ouachita Mountains were siliceous sponge spicules. The fossils in the Atoka Formation along the flanks of the Ozark Uplift are abundant. Wilson and Newell (1937) and Blythe (1959) reported the fossil content of the Atoka Formation in detailed reports.

The components of the matrix and cement of most of the sandstones and siltstones are clay minerals, calcite, chert, limonite, hematite, and goethite. Clay minerals are the most important components

of the matrix of the sandstones and siltstones and these include illite, kaolinite, mixed-layer illite-montmorillonite, chlorite, vermiculite, and dickite. Dickite was found in the sandstones from the exposure on Brushy Mountain in Sequoyah County. Chlorite is present in the lower portion of the Atoka Formation. This occurrence will be described in the next section of this report. Both calcite and iron oxide cementation are present locally. Chert cementation was reported by Shelburne (1960) in the Boktukola Syncline area.

The percentage of the components in the sandstone and siltstone units of the Atoka Formation varies from location to location and the range of variation can influence the classification of the rocks. According to the classification of Folk (1961), the rocks mainly lie in the range of muddy subgraywacke, feldspathic subgraywacke, and subarkose. The muddy subgraywacke and feldspathic subgraywacke rock types are the most abundant.

Mineralogically, the shales of the Atoka Formation consists of illite, kaolinite, mixed-layer illite-montmorillonite, vermiculite, chlorite, and silt-size quartz. The needle-shaped illite shows good optical orientation but kaolinite, vermiculite, and quartz do not. No secondary enlargement of illite was observed. No en-echelon orientation of illite (cataclastic structure) in the shale units was found.

A few thin sections from limestone layers along the flanks of the Ozark Uplift were studied. The limestone layers on the outcrop near the Wagoner pumping station have a high ferrous content. According to Folk's (1961) classification, the limestone layers are

recrystallized calcimicrite, and biosparrudite. No detailed investigation of the limestone units were made in this report.

The lithologic features of the Atoka Formation along the Ozark Uplift are traceable virtually throughout the entire area. The sandstone and shale units of each member are well differentiated although sandstone units may contain shale layers and vice versa. In general, the size of the grains in the sandstone portion decreases from Wagoner and Sequoyah Counties southwestward to the Muskogee-Porum area.

The base of the Coody Sandstone consists of granule to pebble-size grains but the size decreases upward to silt-size particles. The upper part of this member is actually a siltstone. Some coarse-grained sandstone lenses and bands in the siltstone portion might be formed by marine slumping. The other evidence of slumping is described in the section on lithology. In the sandstone and siltstone units, the percentage of quartz is about 75; feldspars, 1-6; rock fragments, 2-5; and matrix of detrital clay, 5-10. Most quartz grains show undulose extinction varying from 0-4 degrees and some of them show undulose extinction up to 12 degrees. Feldspar grains are both fresh and weathered. The heavy minerals are primarily tourmaline, zircon, staurolite, garnet, and mica.

The Pope Chapel Sandstone is a fine-grained sandstone. Most of the quartz is single grains with undulose extinction ranging from 0-5 degrees and some grains with undulose extinction up to 20 degrees. A few composite grains are also present. The feldspar grains are both fresh and weathered. Most of the heavily weathered feldspar grains are well rounded. The percentage of quartz is about 70-85; feldspar, 2-6;

rock fragments, 2-4; and the matrix of detrital clay minerals, 4-10. The heavy minerals are primarily tourmaline, zircon, rutile, apatite, staurolite, and mica.

The Georges Fork Sandstone is a very fine-grained sandstone. Most of the quartz is in the form of single grains with undulose extinction ranging from 0-5 degrees and some grains with undulose extinction up to 22 degrees. A few composite grains of quartz are present. Both fresh and weathered feldspar grains are present in the same sample. The percentage of quartz is about 75-85; feldspar, 3-8; rock fragments, 1-3; and the matrix of detrital clay minerals, 10-16. The heavy minerals are primarily tourmaline, zircon, staurolite, garnet, and mica.

The Dirty Creek Sandstone is a coarse siltstone. Most of the quartz is in the form of single grains with undulose extinction ranging from 0-5 degrees and some grains with undulose extinction up to 12 degrees. The proportion of fresh feldspar is smaller than weathered and kaolinized varieties. The percentage of quartz is about 35-70; feldspar, 5-15; rock fragments, 4-6; and the matrix of the detrital clay minerals, 10-40. The heavy minerals are primarily tourmaline, zircon, rutile, and mica.

The Webbers Falls Sandstone is a coarse siltstone. Most of the quartz consists of single grains with undulose extinction ranging from 0-5 degrees and some grains with undulose extinction up to 10 degrees. A few composite grains are present. Feldspar grains are both fresh and weathered. The percentage of quartz is about 30-70; feldspar, 2-10; rock fragments, 0-5; and the matrix of detrital clay, 1-15. The heavy minerals are primarily tourmaline, zircon, rutile, and mica.

The Blackjack School Sandstone is a fine sandstone. Most of the quartz consists of single grains with undulose extinction ranging from 0-5 degrees and some grains with undulose extinction up to 13 degrees. A few composite grains are present. The feldspar grains are both fresh and weathered. The percentage of quartz is about 65-70; feldspar, 3-7; and the matrix of detrital clay, 10-12.

The six shale members of the Atoka Formation along the flanks of the Ozark Uplift are similar both in mineral content and textural pattern. The mineral components of the shale units are illite, kaolinite, mixed-layer illite-montmorillonite, and silt-size quartz. Vermiculite with a high surface-charge density is present in some of the weathered samples. A small amount of chlorite is present in A1 and A2 shales. A small amount of plagioclase is also present in the shale units. Siltstone lenses varying from 2 mm to 20 mm in thickness are abundant. Most needle-shaped illite grains are optically oriented but the kaolinite and quartz grains are not. No cataclastic structures or secondary enlargement of the clay minerals were found. There is no evidence to suggest any degree of metamorphism. The illite grains that are oriented with their long axes parallel to the bedding may have been deposited by parallel flocculation rather than having been oriented by compressive stress.

The sandstone and shale units of the Atoka Formation in the Ouachita Mountains, the east side of the Arbuckle Mountains, and the Arkoma Basin are not clearly differentiated. The lithologic characteristics of the sandstone and siltstone units in the Ouachita and the east side of the Arbuckle Mountains vary from layer to layer and therefore no

fixed subdivision can be effectively applied. In general, the sandstone/shale ratio decreases southwestward, and the grain size of quartz and feldspar also decreases as the sandstone/shale proportion decreases.

In the Spring Mountain section, the grain size of quartz and feldspar ranges from medium sand to silt and the major portion is fine sand. Westward, to the south of Red Oak and southward to Atoka County, the sandstone and the siltstone units chiefly consist of grains with sizes ranging from very fine sand to coarse silt. Southwestward to the east side of the Arbuckle Mountains, the size of quartz and feldspar grains ranges from very fine sand to medium silt. Both the abundance and size of the clay galls in the sandstone and siltstone units decrease southwestward as the sandstone/shale proportion decreases. The percentage of matrix of detrital clay minerals and shale lenses in the sandstone and siltstone units increases southwestward. The appearance of silt lenses in the shale units or vice versa is abundant in the Arbuckle Mountains.

The rock fragments of the sandstone and siltstone units in the Ouachita and Arbuckle Mountains are composed of shale, slate, phyllite, and schist. The abundance and character of the quartz, feldspar, and rock fragments in the Atoka Formation in the Ouachita and Arbuckle Mountains are similar to that along the flanks of the Ozark Uplift. Kaolinization and illitization of the weathered feldspar grains are also present in these areas.

In the Ouachitas and the east side of the Arbuckle Mountains, the Atoka Formation contains no diagnostic fossils except for sponge spicules in the Spring Mountain section. Sponge spicules were found both in the

sandstone and shale units about 200 feet above the base of the Atoka Formation in Sec. 23, T. 3 N., R. 25 E.

The heavy minerals in the sandstone and siltstone units are primarily tourmaline, zircon, rutile, staurolite, apatite, garnet, and mica. This suite is similar to that in the sandstone and siltstone units along the flanks of the Ozark Uplift.

The shale units consist of clay minerals and silt-size quartz. The mineral components of the shale units are illite, kaolinite, mixed-layer illite-montmorillonite, vermiculite, and chlorite. The optical orientation of the clay minerals in the shale units of the Ouachita Mountains and the east side of the Arbuckle Mountains seems to be better developed than that along the flanks of the Ozark Uplift. Neither cataclastic structures nor secondary enlargement of clay minerals was found. The size of the illite is also similar to that along the flanks of the Ozark Uplift.

Plate I

Components Derived from High-Rank Metamorphic Source

- a. x125, Crossed nicols, Sec. 24, T. 3 N., R. 25 E. (Sample No. 19). Sample taken 2,760 feet above the base of the Atoka Formation in the Spring Mountain Section. Photomicrograph shows a good example of a mica schist fragment in sandstone.
- b. x125, Crossed nicols, Sec. 24, T. 3 N., R. 25 E. (Sample No. 19). Sample taken 1,750 feet above the base of the Atoka Formation in the Spring Mountain Section. Photomicrograph shows a quartz mica schist fragment and chlorite matrix in sandstone.
- c. x125, Crossed nicols, Sec. 24, T. 3 N., R. 25 E. (Sample No. 19). Sample taken 930 feet above the base of the Atoka Formation in the Spring Mountain Section. Photomicrograph shows a composite quartz grain derived from schist in sandstone.
- d. x125, Crossed nicols, Sec. 24, T. 3 N., R. 25 E. (Sample No. 19). Sample taken 1,340 feet above the base of the Atoka Formation in the Spring Mountain Section. Photomicrograph shows a composite quartz grain derived from metaquartzite in sandstone.
- e. x125, Open nicols, Sec. 24, T. 12 N., R. 19 E. (Sample No. 12). Sample taken from the Pope Chapel Sandstone Member. Photomicrograph shows a garnet in sandstone.
- f. x125, Open nicols, Sec. 24, T. 12 N., R. 19 E. (Sample No. 12). Sample taken from the Pope Chapel Sandstone Member. Photomicrograph shows a staurolite and detrital chlorite in sandstone.

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PLATE 1

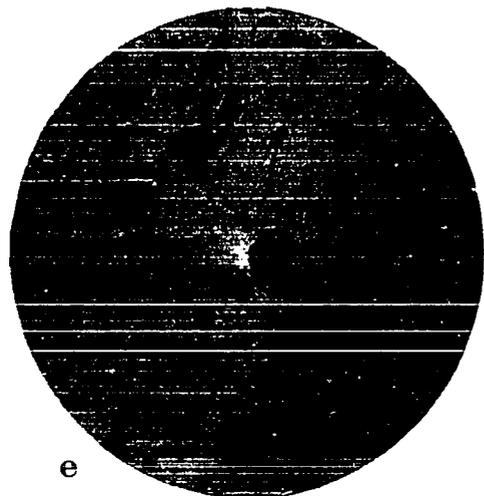
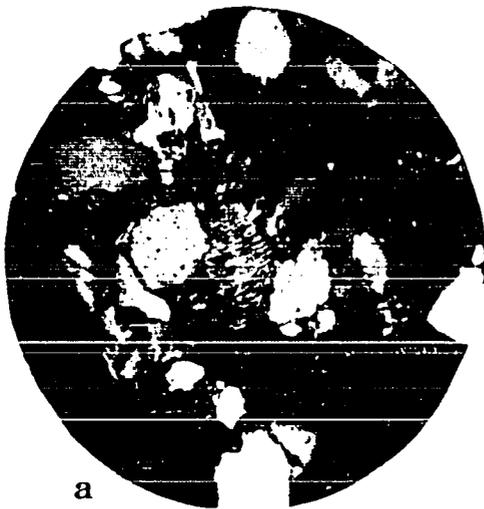


Plate II

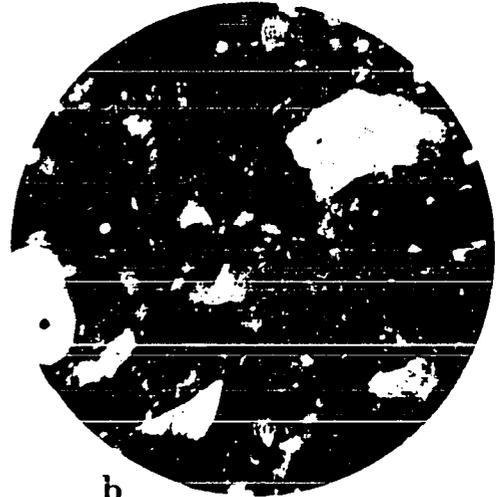
Texture of Sedimentary Rocks

- a. x125, Crossed nicols, Sec. 24, T. 12 N., R. 19 E. (Sample No. 12). Photomicrograph shows well-sorted and well rounded sand grains in the Pope Chapel Sandstone Member.
- b. x125, Crossed nicols, Sec. 23, T. 3 N., R. 25 E. (Sample No. 19). Sample taken 100 feet above the base of the Atoka Formation in the Spring Mountain Section. Photomicrograph shows three different components of quartz sand, fragments of sponge spicules, and clay minerals forming a trimodal texture.
- c. x125, Open nicols, Sec. 3, T. 14 N., R. 19 E. (Sample No. 8). Photomicrograph shows sponge spicules with the orientation of the long axis parallel to bedding planes in the Webbers Falls Sandstone Member.
- d. x50. Open nicols, Sec. 24, T. 3 N., R. 25 E. (Sample No. 19). Sample taken 2,550 feet above the base of the Atoka Formation in the Spring Mountain Section. Photomicrograph shows a convolute structure, mica forming dark bands in quartz siltstone.
- e. x125, Crossed nicols, Sec. 23, T. 3 N., R. 25 E. (Sample No. 19). Sample taken 740 feet above the base of the Atoka Formation in the Spring Mountain section. Photomicrograph shows that the orientation of illite is well developed but kaolinite and quartz show no such optical orientation.
- f. x125, Crossed nicols, Sec. 20, T. 18 N., R. 19 E. (Sample No. 1). Sample taken 144 feet above the base of the section measured by Blythe (1957, p. 132). Photomicrograph shows a good example of calcite replacing quartz.

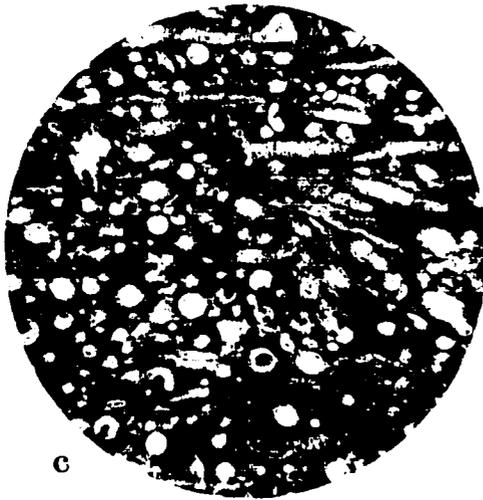
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PLATE 2



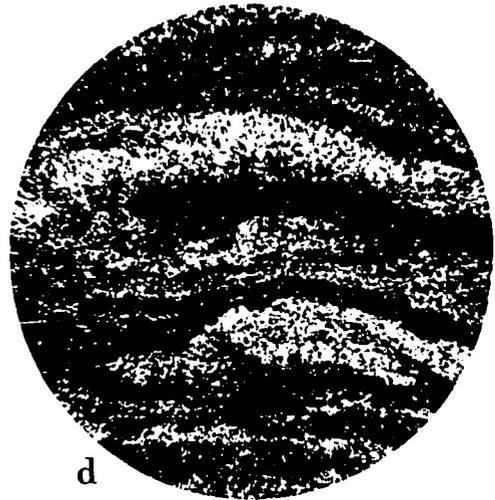
a



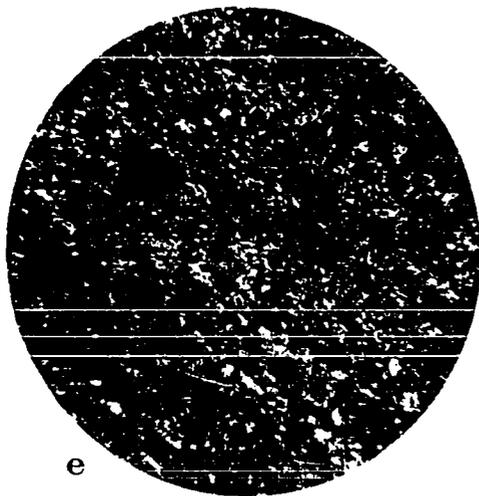
b



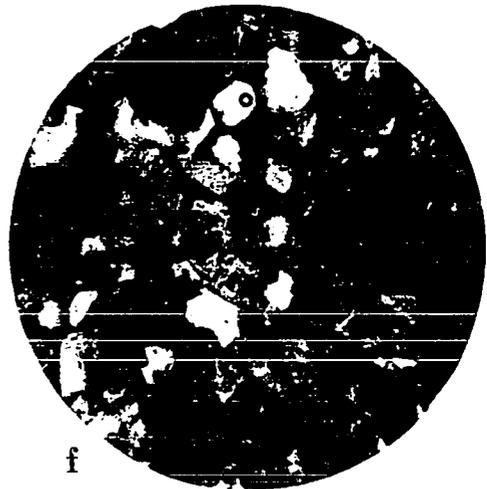
c



d



e



f

CLAY MINERALOGY

A brief introduction to the structure of clay minerals is given here and is taken largely from Grim (1968). Most clay minerals are phyllosilicates with two basic structural units, tetrahedral and octahedral layers. In the tetrahedral unit, a silicon atom in the center is surrounded by four oxygens or hydroxyls forming a tetrahedron. The silica tetrahedral groups are arranged to form a hexagonal network, which is repeated indefinitely to form a sheet with the composition, $\text{Si}_4\text{O}_6(\text{OH})_4$. The tetrahedrons are arranged so that the tips of all of them point in the same direction, and the bases of all tetrahedra are in the same plane.

In the octahedral unit, an aluminum, iron, or magnesium ion is surrounded by six oxygens or hydroxyls forming an octahedron. When aluminum is present, only two-thirds of the possible positions are filled to balance the structure, which is the basic gibbsite structure and has the formula, $\text{Al}_2(\text{OH})_6$. When magnesium is present, all the positions are filled to balance the structure, which is the basic brucite structure and has the formula, $\text{Mg}_3(\text{OH})_6$.

The basic structural unit of kaolinite and dickite consists of a single silica tetrahedral layer and a single alumina octahedral layer combined in a unit so that the tips of the silica tetrahedrons and one

of the layers of the octahedral unit form a common layer. All the tips of the silica tetrahedra point in the same direction and toward the center of the unit made by the tetrahedral and octahedral layers.

The basic structural unit of illite is a sheet composed of two silica tetrahedral layers with a central octahedral layer. The tips of the tetrahedrons in each silica layer point toward the center of the unit and are combined with the octahedral layer in a single layer with suitable replacement of OH by O. The silicons are partially replaced by aluminums and the resultant charge deficiency is balanced by potassium ions in the interlayer position of two sheets of the mica.

The basic structural unit of montmorillonite is similar to that of illite with either a lower charge density on the interlayer surface or a weaker charge owing to location of the ion substitution. The outstanding feature of the montmorillonite structure is that water, ethylene glycol, and other polar molecules, such as certain organic molecules, can enter between the unit layers, causing the lattice to expand in the c direction.

The basic structural unit of vermiculite is similar to that of illite separated by layers of water molecules occupying a definite space of 4.9 \AA which is about the thickness of two water molecules. The structure is unbalanced chiefly by substitution of Al^{+3} for Si^{+4} . These substitutions may be partially balanced by other substitutions within the mica lattice, but there is always a residual net-charge deficiency of 1 to 1.4 per unit cell. The charge deficiency is satisfied by cations which occur chiefly between the mica layers and are largely exchangeable.

In the natural mineral, the balancing cation is Mg^{++} , in some cases with a small amount of Ca^{++} also present.

The basic structural unit of chlorite consists of alternate mica-like and brucite-like layers. The layers are continuous in the a and b dimensions and are stacked in the c direction with basal cleavage between the layers. The mica-like layers are trioctahedral. The mica layer is unbalanced by substitution of Al^{+3} for Si^{+4} , and this deficiency of charge is balanced by an excess charge in the brucite layer as a consequence of substitution of Al^{+3} for Mg^{++} .

Identification

Clay minerals were identified from d-spacings obtained by x-ray diffraction procedures and endothermic-exothermic reaction peaks from differential thermal analysis. Another technique is the treatment with ethylene glycol to expand the (001) d-spacings of expandable clay minerals permitting the detection of minerals such as montmorillonite in the presence of the other 14 Å clay minerals. By this method even small amounts of montmorillonite may be detected in the presence of minerals such as vermiculite and chlorite. This method also permits the distinction between mixed-layer illite-montmorillonite and mechanical mixtures of the two minerals. The first-order x-ray diffraction peaks of illite and mixed-layer illite-montmorillonite were separated with ethylene glycol treatment for quantitative determination of the amounts of each mineral present.

Heat treatment results in the collapse of d-spacings permitting the separation of vermiculite and montmorillonite from chlorite. Samples

were sedimented on porcelain slides and placed in a high temperature oven for heat treatment for two hours. X-ray diffraction was employed for detecting the collapse immediately after heat treatment.

According to Brown (1961), the crystal structure of chlorite decomposes in warm, dilute hydrochloric acid. During HCl treatment, the solution was constantly stirred and the temperature was kept at about 80° C for about 3 hours. After treatment, chlorite was selectively dissolved in the presence of kaolinite.

According to Weaver (1958), montmorillonite and vermiculite derived from mica will collapse to 10 Å with K⁺ treatment, but those derived from non-micaceous materials will not be affected. Both potassium acetate and potassium hydroxide solution were used for the treatment. It seems that both vermiculite and mixed-layer illite-montmorillonite were not obviously affected by the treatment with potassium hydroxide.. With the potassium acetate treatment, the vermiculite and mixed-layer illite-montmorillonite collapsed to 10 Å but the vermiculite that was apparently derived from chlorite was not affected. It will be described later.

Illite

The x-ray diffraction characteristics of illite are the 9.98 Å, 4.955 Å, 3.314 Å, and 1.99 Å d-spacings obtained from sedimented slides (Fig. 10 A). It is a stable clay mineral which will not change its (001) d-spacings by ethylene glycol treatment, warm hydrochloric acid treatment, potassium acetate treatment or by heat treatment to 550° C.

Figure 10. X-ray diffraction patterns from sedimented slides.

- a. Illite from shale. Sec. 23, T. 3 N., R. 25 E. (Sample No. 19). Sample taken 250 feet above the base of the Atoka Formation in the Spring Mountain section.
- b. Illite and dickite from sandstone, Sec. 4, T. 13 N., R. 25 E. (Sample No. 3). Sample taken 240 feet above the base of the section measured by Blythe (1957, p. 113).
- c. Chlorite from sandstone, Sec. 24, T. 3 N., R. 25 E. (Sample No. 19). Sample taken 1,750 feet above the base of the Atoka Formation in the Spring Mountain section.
- d. Illite, mixed-layer illite-montmorillonite and kaolinite from shale. Sec. 24, T. 3 N., R. 25 E. (Sample No. 19). Sample taken 3,550 feet above the base of the Atoka Formation in the Spring Mountain section.
- e. Illite, vermiculite, kaolinite, dickite and mixed-layer illite-montmorillonite from weathered siltstone, Sec. 30, T. 18 N., R. 19 E. (Sample No. 2). Sample was taken 2 feet from above the road surface.



DEGREES 2θ

FIGURE 10

Figure 11. X-ray diffraction patterns with and without treatment.

- a. Illite, kaolinite, mixed-layer illite-montmorillonite and vermiculite without treatment from shale portion, Sec. 23, T. 3 N., R. 25 E. (Sample No. 19).
- b. Vermiculite and mixed-layer illite-montmorillonite collapsed to 10 Å after 450 degrees heat treatment with sample a.
- c. Chlorite and a small amount of illite without treatment from sandstone portion, Sec. 24, T. 3 N., R. 25 E. (Sample No. 19).
- d. The crystal structure of chlorite destroyed after treatment with hydrochloric acid with sample c.
- e. Mixed-layer illite-montmorillonite and vermiculite collapsed to 10 Å after treatment with potassium acetate from weathered siltstone, SE $\frac{1}{4}$ Sec. 30, T. 18 N., R. 19 E. (Sample No. 2).
- f. Mixed-layer illite-montmorillonite showing no collapse to the treatment with potassium hydroxide from shale, NW $\frac{1}{4}$ Sec. 9 T. 11 N., R. 19 E. (Sample No. 15).
- g. Illite, mixed-layer illite-montmorillonite and kaolinite without treatment from shale, Sec. 24, T. 3 N., R. 25 E. (Sample No. 19).
- h. Mixed-layer illite-montmorillonite separated from illite after treatment with ethylene glycol with sample g.

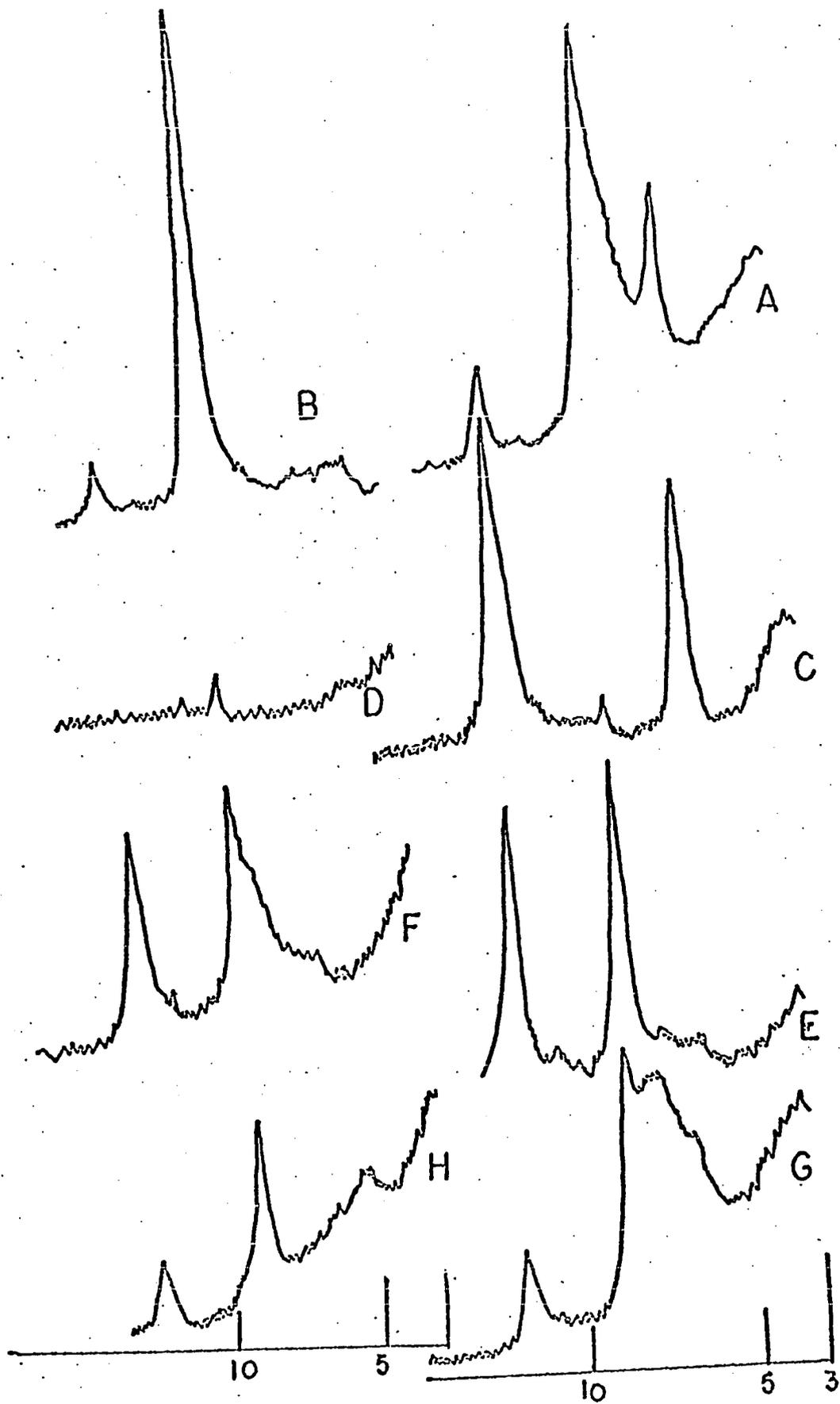


FIGURE II

Figure 12. D.T.A. patterns of clay minerals.

- a. Illite from shale portion, Sec. 23, T. 3 N., R. 25 E.
(Sample No. 19).
- b. Chlorite from sandstone portion, Sec. 24, T. 3 N., R. 25 E.
(Sample No. 19).
- c. Illite, mixed-layer illite-montmorillonite and kaolinite from
shale, Sec. 24, T. 3 N., R. 25 E. (Sample No. 19).
- d. Illite, vermiculite, mixed-layer illite-montmorillonite,
kaolinite and dickite from weathered siltstone, SE $\frac{1}{4}$ Sec. 30,
T. 18 N., R. 19 E. (Sample No. 2).
- e. Illite and dickite from sandstone, Sec. 4, T. 13 N., R. 25 E.
(Sample No. 3).

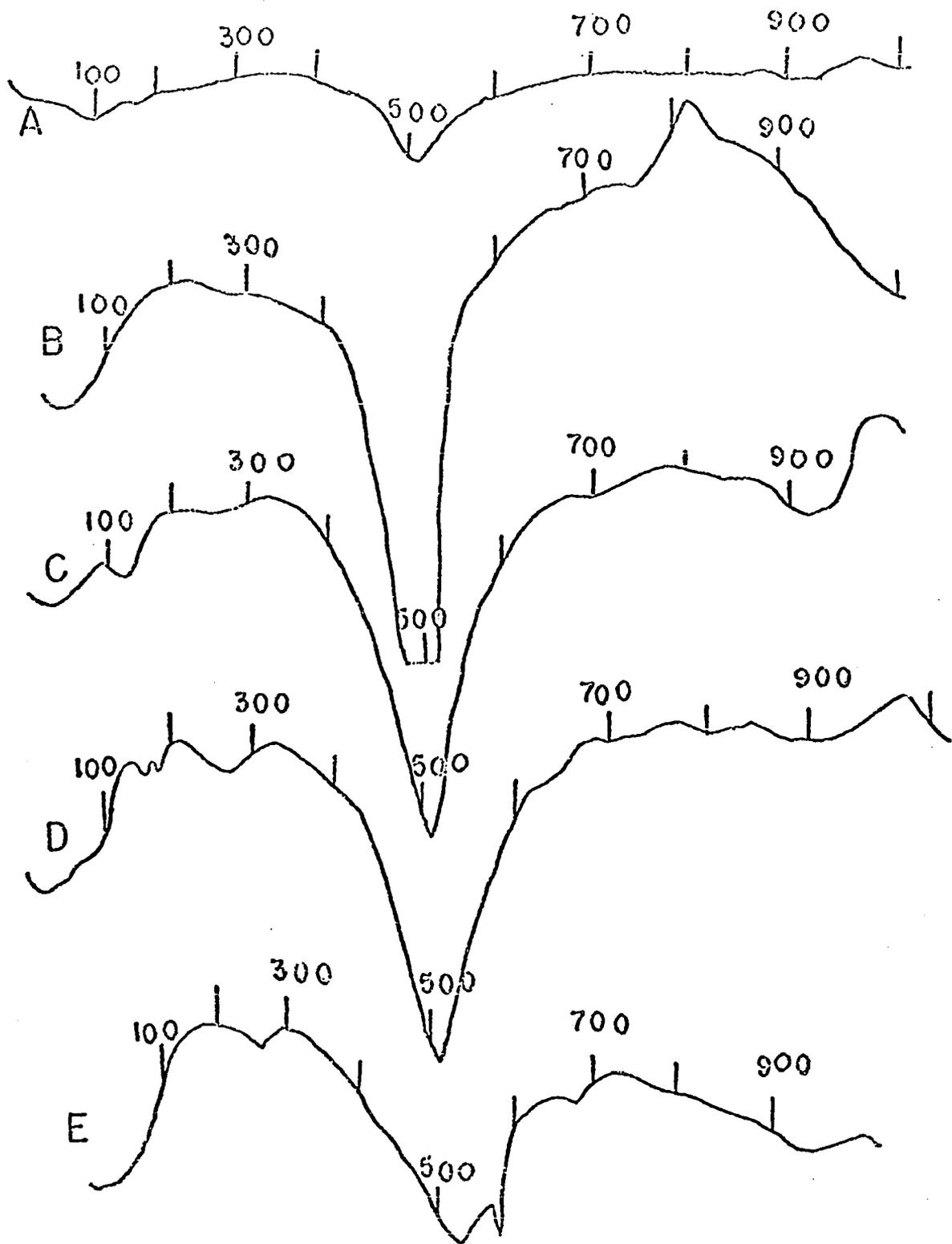


FIGURE 12

Grim and Bradley (1940, 1951) in studying differential thermal curves of illite showed an endothermic reaction corresponding to the loss of interlayer water at about 100° C, a second endothermic reaction beginning at 450° to 500° C, with a peak at 550° to 650° C corresponding to the loss of OH lattice waters, a third slightly endothermic reaction between about 850° and 950° C, and commonly an exothermic reaction between 900° and 1000° C. According to Brown (1961) the exothermic reaction is a spinel phase. Wong (1965) studied the Beavers Bend illite and found that the D.T.A. pattern showed no significant reaction.

In the Atoka Formation, the illite D.T.A. pattern shows an initial endothermic peak around 100° to 130° C. The second endothermic peak, which is the main peak of the curve, is around 510° to 520° C, and the third endothermic peak is around 910° to 920° C. The last endothermic peak is immediately followed by an exothermic peak at around 960° C (Fig. 12 A).

From D.T.A. patterns, the illite of the Atoka Formation is similar to the samples used by Grim and Bradley (1940, 1951) but different from the Beavers Bend illite. The illite of the Atoka Formation is finer grained than the Beavers Bend illite as determined by thin section study. The former shows poorer crystallinity and contains more water than the latter and therefore the reactions to heat of the former are more sensitive than the latter.

Kaolinite

The x-ray diffraction characteristics of kaolinite are the 7.15 Å, 3.75 Å, 2.56 Å and 2.33 Å d-spacings from a powder sample. It

is a stable clay mineral which does not change its d-spacings with either ethylene glycol or warm hydrochloric acid treatment, but the crystal structure can be destroyed by heating to 550° C for as much as 2 hours.

According to Grim (1953), differential curves of kaolinite show an endothermic reaction corresponding to the loss of OH water beginning at 400° C, and for well-crystallized kaolinite the peak is at about 600° C. An exothermic reaction is at about 950° C corresponding to the formation of mullite and/or gamma alumina. In the Atoka Formation, the kaolinite shows an endothermic reaction between 500° to 600° C and the peak is at about 540° C. The exothermic peak is at 980° C. Judging from the temperatures of the reaction peak, the crystallinity of the kaolinite of the Atoka Formation is fairly good. From microscopic study, the kaolinite which is silt size is slightly larger than illite.

Dickite

Dickite is a polytype of the kaolinite group. The x-ray diffraction characteristics of dickite are the 7.15 Å and 3.58 Å d-spacings (Fig. 10 B). Because only small amounts of dickite occur in the compact sandstone portion, it is difficult to obtain a pure mineral separated by size fraction and therefore no detailed x-ray diffraction peaks have been obtained. Dickite is a stable mineral which does not change d-spacings with ethylene glycol treatment. No effect has been observed by treatment with warm hydrochloric acid or potassium acetate.

The differential thermal curve of dickite is similar to that of kaolinite but the temperature of the endothermic peak for the reaction corresponding to the loss of OH water is higher for dickite.

Grim (1953) pointed out that the major endothermic peak is about 100° C higher than that of kaolinite. The dickite of the Atoka Formation shows an endothermic reaction between 660° and 700° C with the peak at 680° C. An exothermic reaction occurs between 970° and 1000° C with the peak at about 985° C (Fig. 12 E).

Mixed-Layer Illite-Montmorillonite

The mixed-layer illite-montmorillonite in the Atoka Formation is mechanically mixed with illite and has a prominent x-ray diffraction peak at about 12.5 \AA (Fig. 10 D). The extent of the hump depends upon the amount of mixed-layer illite-montmorillonite mixed with illite. It can expand to 14 \AA with ethylene glycol treatment (Fig. 11 H). It collapses to 10 \AA and intensifies the 10 \AA peak of illite with potassium acetate treatment. The intensity increase occurs because the potassium ion collapses some of the (001) structure. The treatment with the potassium hydroxide solution shows that the reaction is insensitive. The differential thermal curve shows that the mixed-layer illite-montmorillonite is similar in character to ordinary illite, except for the intensity of the first endothermic reaction.

Weaver (1958) considered that montmorillonite and vermiculite derived from mica would have a high interlayer charge and therefore may be fixed by potassium ions and contract to 10 \AA . Hower and Mowatt (1966) showed that the relationship between percent expandable montmorillonite layers increasing with decreasing fixed interlayer cations in illite and illite-montmorillonite is linear. Chen (1968) found that the montmorillonite derived from volcanic ash shows incomplete collapse after potassium fixation.

Judging from the characteristics, the mixed-layer illite-montmorillonite of the Atoka Formation is probably derived from illite or muscovite by substituting interlayer water for potassium ions. Actually, the characteristics of illite, degraded illite, mixed-layer illite-montmorillonite, and montmorillonite are transitional in the Atoka Formation.

Chlorite

The x-ray diffraction characteristics of chlorite are the 14 Å, 7 Å, 4.7 Å, and 3.5 Å d-spacings (Fig. 10 C). It does not expand with ethylene glycol treatment and will not collapse with potassium acetate treatment. Treatment with hydrochloric acid will destroy the crystal structure of chlorite to the extent that it shows no x-ray diffraction peaks.

Grim (1953) pointed out that little or no low temperature endothermic reaction indicates an absence of interlayer or absorbed water in chlorite, but very fine grained chlorites may have some interlayer water in some clay minerals. On the differential thermal curve, a sharp endothermic reaction is between 500° and 700° C and a second endothermic reaction at about 800° C. This peak is followed immediately by a sharp exothermic peak. According to Brown (1961), the first endothermic reaction corresponds to the loss of water from brucite layers and the second endothermic reaction corresponds to the loss of water from mica layers, and the exothermic reaction corresponds to the formation of olivine.

The chlorite of the Atoka Formation shows no significant endothermic reaction below 400° C. A major endothermic reaction takes

place between 400° and 600° C and the endothermic peak is at about 500° C. A small endothermic peak is at about 750° C. Following the second endothermic peak, a small exothermic peak is at about 820° C (Fig. 12 B).

The shift of endothermic and exothermic peaks to lower temperatures than that indicated by Grim (1953) may be due to poorer crystallinity or finer size. From the microscopic study, the size of the chlorite is finer than illite.

Vermiculite

The x-ray diffraction characteristics of vermiculite are the strong 14 \AA peak, and weak second, third, and fourth order peaks. Owing to the small amount of vermiculite in the mixture of other clay minerals, all peaks except 14 \AA are not discernible. With heat treatment to 450° C, most vermiculites shift their 14 \AA peak to 10 \AA , but some shift to 11.6 \AA . Most vermiculites do not expand with treatment by ethylene glycol and only a few samples expand to 15.3 \AA . With potassium acetate treatment, vermiculite collapses to 10 \AA except those derived from chlorite which are not affected.

The vermiculite of the Atoka Formation shows dual initial endothermic peaks, one at about 160° C and the other at about 180° C, followed by a peak at about 270° C (Fig. 12 D). The other reaction peaks above 270° C are unclear due to the mixture with other clay minerals. The D.T.A. pattern of vermiculite from the Atoka Formation is the same as that shown by Grim (1963).

There are two kinds of vermiculite in the Atoka Formation. One is considered to have been derived from chlorite and the other from mixed-layer illite-montmorillonite. The former is associated with chlorite and is not affected by potassium acetate treatment whereas the latter is associated with mixed-layer illite-montmorillonite and will collapse to 10 \AA° with potassium acetate treatment.

DISTRIBUTION OF CLAY MINERALS

Procedures for Semi-Quantitative Estimation

The clay mineral suites in the sandstone and shale portions of the Atoka Formation are similar throughout the entire formation but the percentage of each clay mineral varies from place to place and from layer to layer. In order to find out the significance of this variation, a semi-quantitative estimation of each clay type was made in accordance with the methods reported by Johns, Grim, and Bradley (1954), Freas (1962), and Gibbs (1967). The areas under the first-order diffraction peaks are multiplied by a factor of 3 for illite, 1 for kaolinite, 1 for dickite, 1 for montmorillonite, 1 for vermiculite, and 2 for mixed-layer illite-montmorillonite. Chlorite was estimated from the ratio of chlorite and kaolinite using the diffraction peaks described in the quantitative method developed by Gibbs (1967). This method uses the ratio of the diffraction peaks $3.52 \text{ \AA} / 3.58 \text{ \AA}$.

The illite content was determined from the 10 \AA peak after ethylene glycol treatment which separates illite from mixed-layer minerals. The mixed-layer illite-montmorillonite was obtained by subtracting the broad peak of the mixture of illite and mixed-layer illite-montmorillonite to illite. Vermiculite was obtained from the 14 \AA peak. In the presence of chlorite, vermiculite was obtained by subtracting

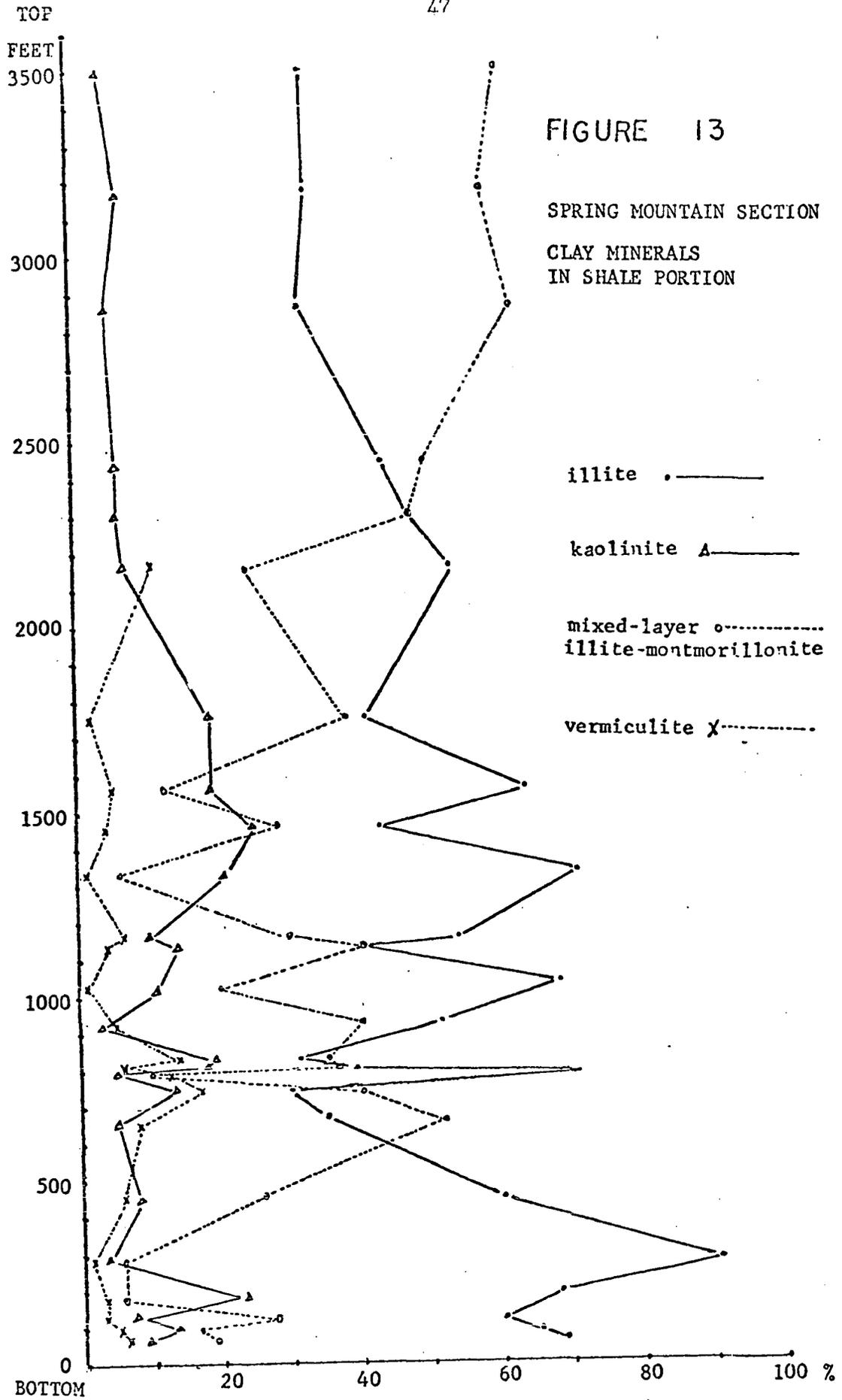
the original 14 Å peak to the 14 Å peak after heat treatment to 450° C. Kaolinite was obtained from the 7 Å peak. In the presence of chlorite, kaolinite was obtained after treatment with hydrochloric acid to dissolve the chlorite. Chlorite was obtained from the curve of the ratio of the 3.52 Å/3.58 Å peaks.

Vertical Distribution of Clay Minerals

In the Spring Mountain area, the percentage of clay minerals shows marked variation vertically. The percentage of clay minerals shows such extreme and apparent erratic variations that it is almost impossible to describe in detail. The clay minerals in the shale portion consist of illite, kaolinite, mixed-layer illite-montmorillonite, and vermiculite. A few samples of shale contain a trace amount of chlorite.

The variation of clay minerals in the shale portion has been semi-quantitatively estimated and is shown in Figure 13. The vermiculite content decreases as mixed-layer illite-montmorillonite increases upward. The vermiculite, which appears to be related to surface and ground water weathering, may be derived from mixed-layer illite-montmorillonite.

The clay minerals in the sandstone portion consist of illite, chlorite, kaolinite, vermiculite, and mixed-layer illite-montmorillonite. Chlorite is present in the sandstones of the lower portion of the Atoka Formation from the base up to 2,000 feet in the Spring Mountain section. At about 1,750 feet above the base, there is a layer of green sandstone in which chlorite is more than 90 percent of the total clay mineral content. The sandstone portion from 2,000 feet above the base up to the top of the formation contains no chlorite.



In the Muskogee-Porum district, the section of the Atoka Formation is a composite section from six sandstone members and their overlying shale members from different locations. Chlorite is present in the Coody, Pope Chapel, and Georges Fork Sandstone Members. In the Pope Chapel Sandstone Member there is a layer of green sandstone in which chlorite is more than 90 percent of total clay mineral content. This chlorite-rich layer in Pope Chapel Sandstone Member is considered to be the same layer as that described previously at about 1,750 feet above the base in the Spring Mountain section. There is no chlorite in the Dirty Creek, Webbers Falls, and Blackjack School Sandstone Members. In the shale portion, only the A1 and A2 Shale Members bear a trace amount of chlorite. The clay minerals in the sandstone portion consist of illite, chlorite, kaolinite, mixed-layer illite-montmorillonite, and vermiculite. The semi-quantitative estimation of clay minerals in both the sandstone and shale portions in the Muskogee-Porum area is shown in Figure 14.

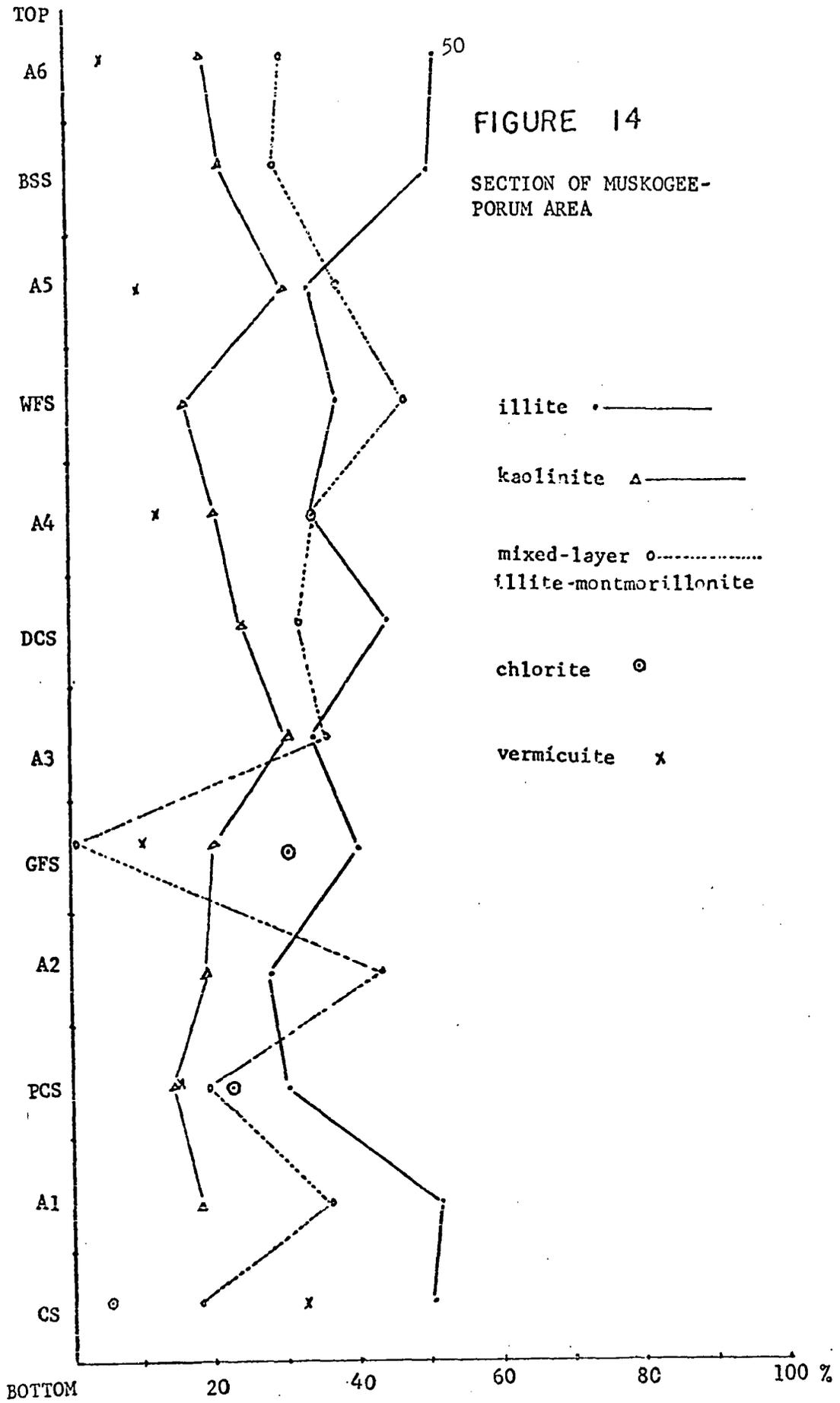
Horizontal Distribution of Clay Minerals

The writer considers that the clay mineral suites of the Atoka Formation may be used for physical correlation. The clay mineral suites in the strata of the Atoka Formation in the Muskogee-Porum area can be traced northward to correlative strata in Wagoner and Mayes Counties and southward to correlative strata in Sequoyah County without significant change in clay minerals.

The clay mineral suites at the Spring Mountain section can be used as a standard for correlation with outcrops in different locations. The clay minerals from units exposed in the outcrops along Highway 2 near

Figure 14. Clay minerals from the section in the Muskogee-Porum area.

- CS: Coody sandstone (Sample No. 4).
- A1: A1 shale (Sample No. 4).
- PCS: Pope Chapel sandstone (Sample No. 12).
- A2: A2 shale (Sample No. 11 and 6).
- GFS: Georges Fork sandstone (Sample No. 5).
- A3: A3 shale (Sample No. 10).
- DCS: Dirty Creek sandstone (Sample No. 13).
- A4: A4 shale (Sample No. 7).
- WFS: Webbers Fall sandstone (Sample No. 8).
- A5: A5 shale (Sample No. 14 and 15).
- BSS: Blackjack School sandstone (Sample No. 14).
- A6: A6 shale (Sample No. 9).



the top of Fine Mountain and along the road about two miles south of Red Oak underlying the Hartshorne Sandstone are similar to the clay mineral suites in the upper shale member at the Spring Mountain section. The core in Sec. 4, T. 5 N., R. 19 E., from a depth of 6,680 feet to 7,180 feet contains a significant amount of chlorite. This is considered to be the primary criterion to identify the strata as equivalent to the lower sandstone member at the Spring Mountain section and the strata lower than the Georges Fork Sandstone Member in the Muskogee-Forum area.

DISCUSSION OF ILLITE

Polytypism and Chemistry

In 1937, Grim, Bray, and Bradley defined the term illite as follows (in Brown, 1961, p. 208):

It is not proposed as a specific mineral name, but a general term for the clay mineral constituents of argillaceous sediments belonging to the mica group.

The mica type minerals have the same kind of basic structure with six stacking directions along the c axis. Yoder and Eugster (1954, 1955) and Smith and Yoder (1956) classified the polytypism of micaceous minerals. This classification, based upon the stacking of basic units along the c axis, contains the following types: 1M, 2O, 2M₁, 2M₂, 3T, and 6H.

Samples from the shale portion of the Atoka Formation were separated into several size fractions by using decantation methods for the size coarser than one micron and continuous centrifuging methods (Kerns, 1967) for the size fractions smaller than one micron.

It is unfortunate that some mixed-layer illite-montmorillonite is mechanically mixed with illite in these samples. It is impossible to separate this mixture by the size fraction method. It is fortunate that the mixed-layer illite-montmorillonite does not seriously affect the x-ray pattern except for the 10 Å⁰ peak. In the coarse fractions, larger

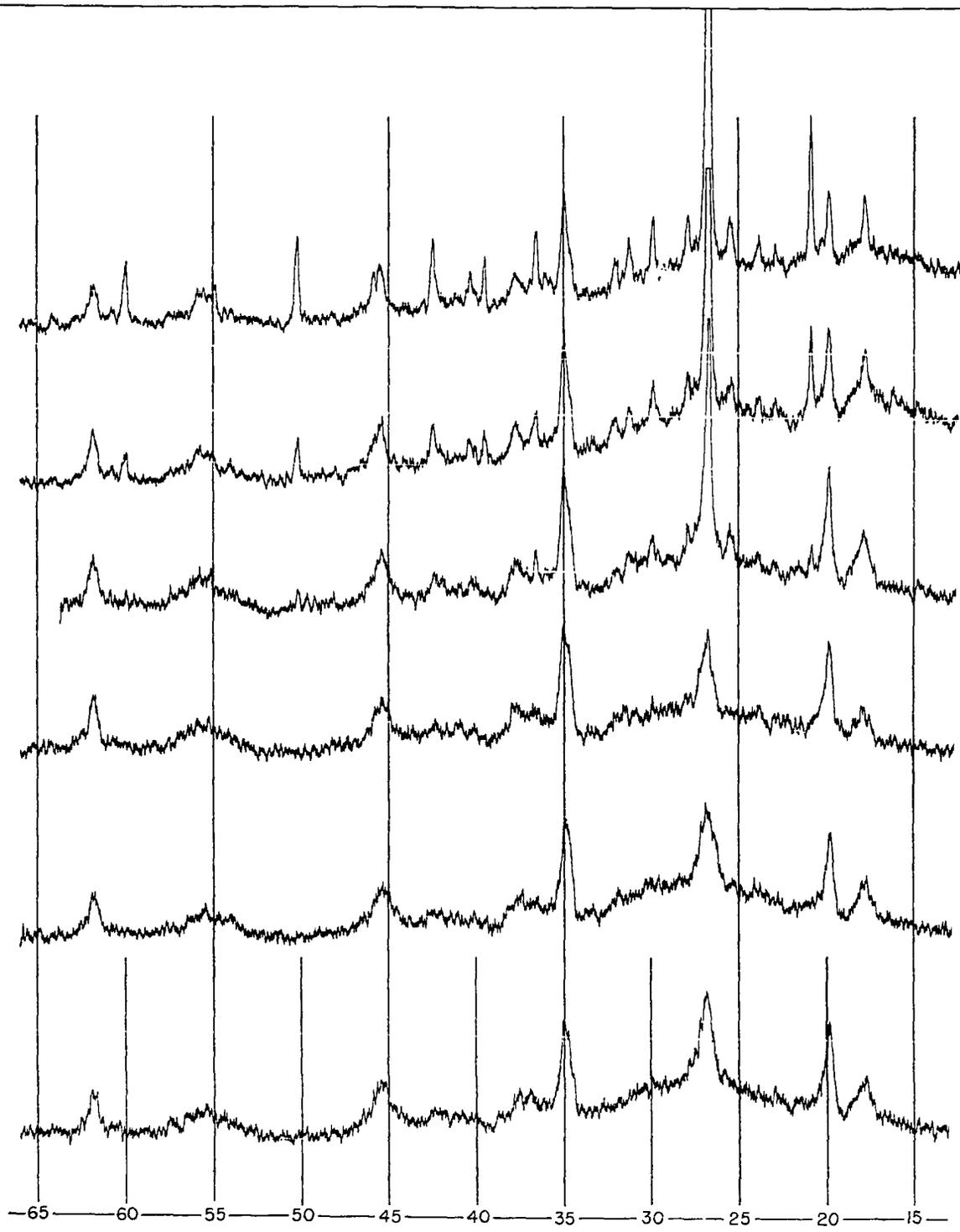
than $\frac{1}{2}$ micron, quartz is always mechanically mixed with the clay minerals but in finer fractions, smaller than $\frac{1}{2}$ microns, the quartz content is almost eliminated.

The x-ray diffraction data obtained from illite minerals of the Atoka Formation in various fractions are listed in the Appendix. In comparing these data with the data published by Yoder and Eugster (1954, 1955), Smith and Yoder (1956), and Brown (1961), the polytypism of the illite mineral in the Atoka Formation includes $2M_1$, $1M_1$ and $1M_2$ (Fig. 15). The coarse-size fractions, larger than $\frac{1}{2}$ micron, are chiefly composed of $2M_1$. The finer size fractions, smaller than $\frac{1}{2}$ micron, are chiefly composed of $1M_1$. The finest size fraction obtained, 1/8-1/16 micron, is chiefly composed of $1M_2$. Hower, Hurly, Pinson, and Fairbairn (1963) reported a similar size-related polytypism from the Sylvan Shale. The different polytypism of illite minerals of the Atoka Formation might be derived from a heterogeneous source or merely reflect the expected effects of particle size on the stacking configuration.

The classification of the octahedral layers into dioctahedral and trioctahedral is based upon the value of the (060) spacing. The peaks of the x-ray diffraction patterns show that the values of the (060) for illite range from 1.4968 Å to 1.5055 Å with an average of 1.5011 Å. The peak height ratio of 002/001 is about 0.5 and 004/001 about 0.25. According to the intensity curves of Grim, Bradley, and Brown (1951, in Grim 1953, p. 96), the dioctahedral layers of illite range from $2Al^{+3}$ to $1\frac{1}{2}Al^{+3}\frac{3}{2}Fe^{+3}$ on the graph (Fig. 16) of the octahedral layer for a dioctahedral mica.

Figure 15. Polytypes of illite versus particle size in microns.

- A. 6-3
- B. 3-1
- C. 1-1/2
- D. 1/2-1/4
- E. 1/4-1/8
- F. 1/8-1/16



DEGREES 2θ

FIGURE 15

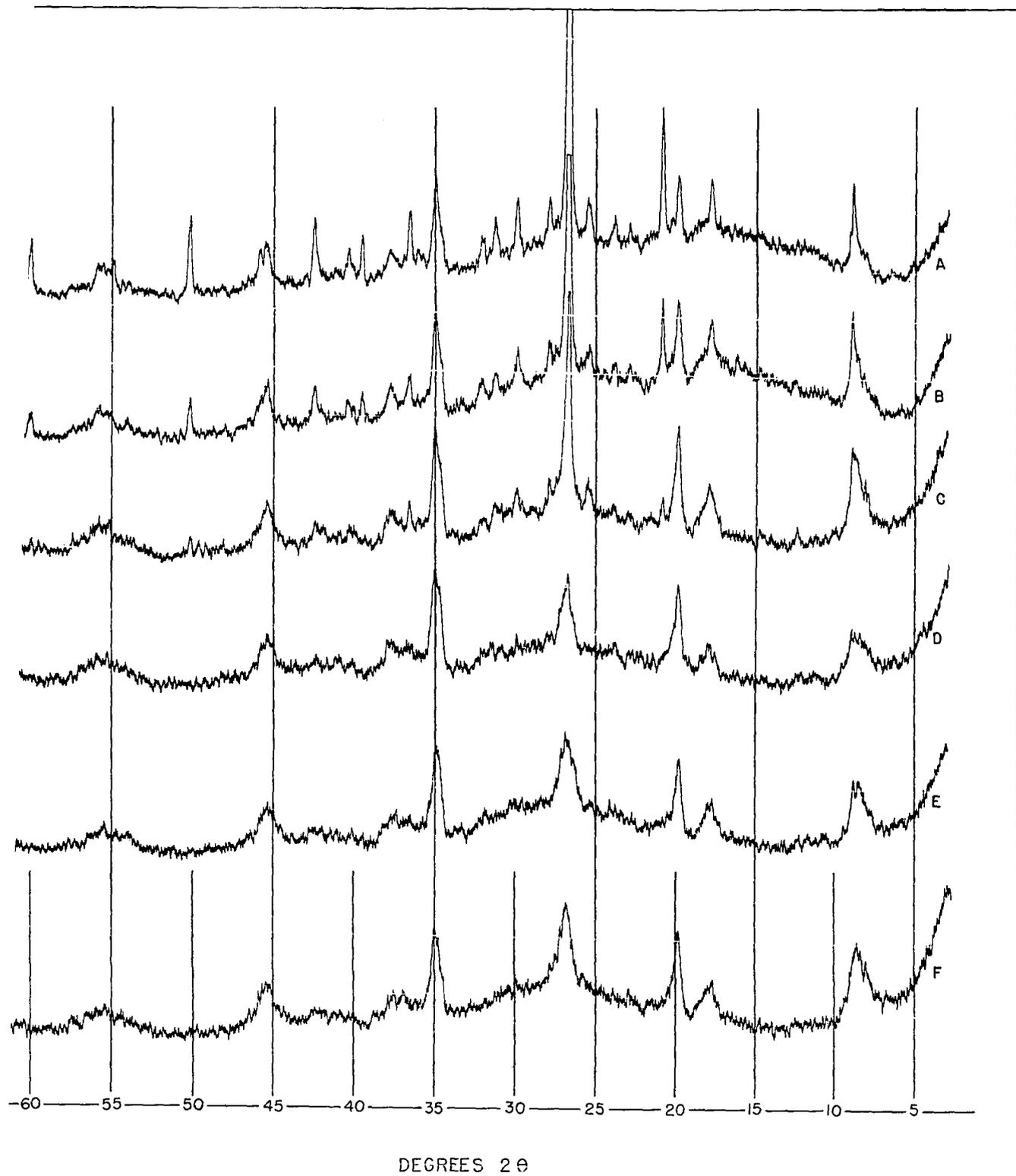


FIGURE 15

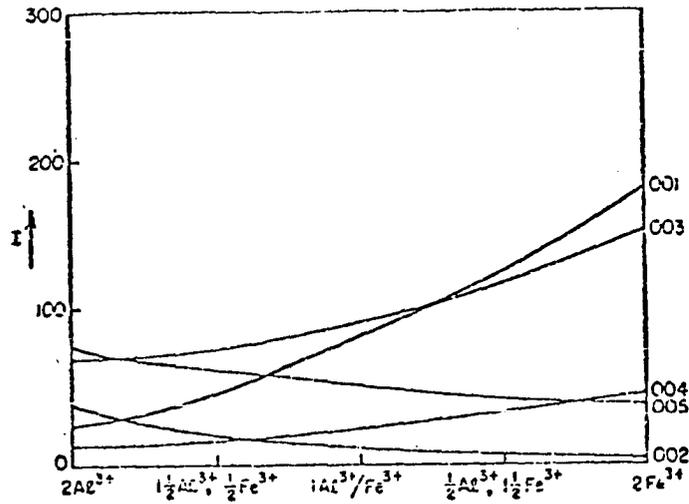


Figure 16. Graph showing the change of the (00l) reflections with varying composition of the octahedral mica (From Grim, Bradley and Brown, 1951; Grim, 1953, p.96).

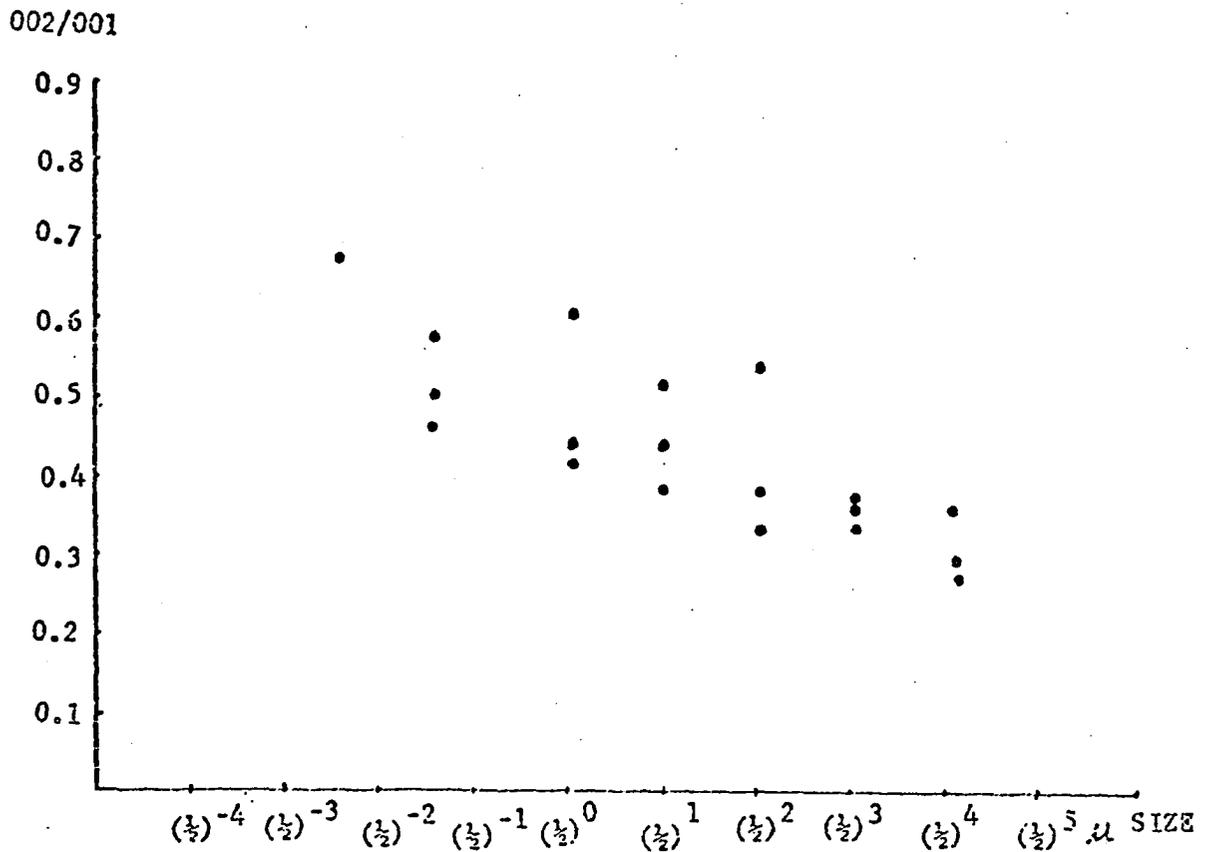


Figure 17. Peak height ratio vs. size

As the size fraction of the illite in the Atoka Formation decreases, the peak height ratios of 002/001 and 004/001 decrease (Figs. 17 and 18). This means that the iron content of the octahedral layer for dioctahedral illite increases as the size decreases. The chemical analysis of the illite shows that $\text{Fe}_2\text{O}_3/\text{Al}_2\text{O}_3$ increases as the size decreases (Fig. 19). The chemical data confirm that the change of the peak-height ratio is chiefly affected by the iron content in various size fractions rather than crystallinity.

The mixed-layer illite-montmorillonite contains less potassium than illite. The mixed-layer mineral has a slight tendency to be more concentrated in the finer fractions and therefore the potassium content should theoretically decrease as size decreases. It is postulated that the finer fractions which have larger surface areas for the absorption of ions can pick up potassium ions and incorporate them into the inter-layer positions easier than the coarser fractions. Therefore, the chemical data of the $\text{K}_2\text{O}/\text{Al}_2\text{O}_3$ ratio in various fractions are similar.

Trace Elements

The trace element boron has been used in the study of paleosalinity. The site of boron in the crystal lattice in various clay minerals has been investigated but no firm conclusions have been reached. Stubican (1960, in Hawkins and Roy, 1963) found that boron definitely enters the lattice of clay. Barsukov (1958) believes that boron substitutes for tetrahedrally-coordinated aluminum rather than for silicon. According to Degens (1965), only dioctahedral micas incorporate boron in significant quantities into their structure and the boron substitutes for aluminum in the tetrahedral

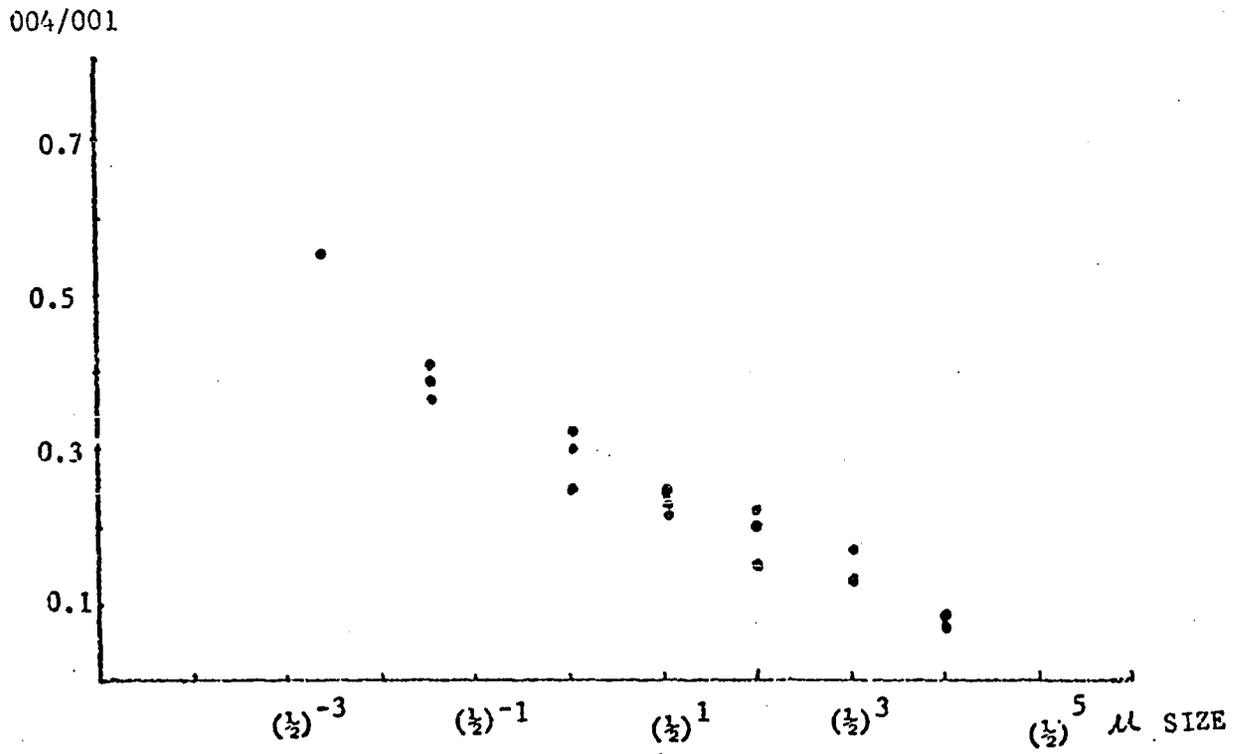


Figure 18. Peak height ratio vs. size

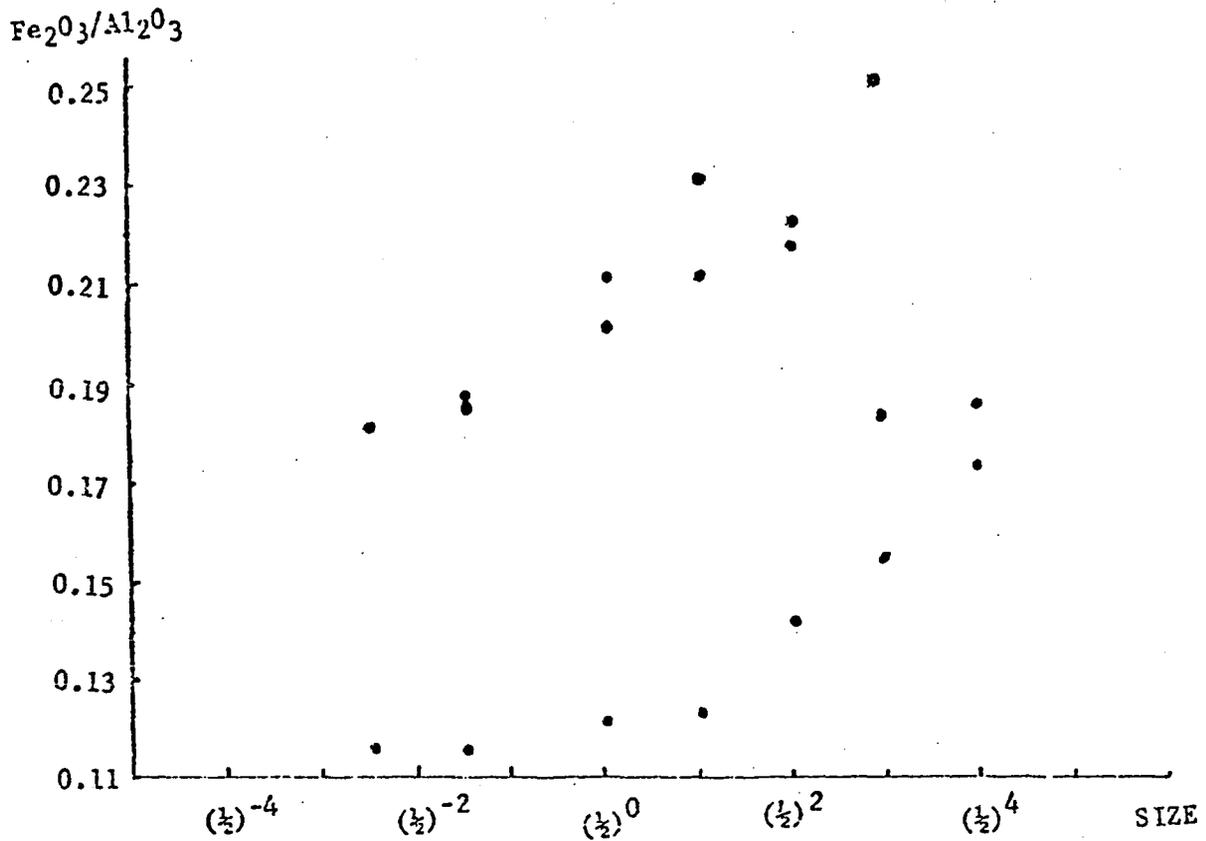


Figure 19. Fe₂O₃/Al₂O₃ ratio vs. size

position. Harder (1961), Frederickson and Reynolds (1960), and Walker (1963, 1964) believe that boron is incorporated only or chiefly, in the illite clays. Levinson and Ludwick (1966), and Shaw and Bugry (1966) believe that boron is indicative of paleosalinity in a variety of argillaceous sediments rather than only in illitic clay.

Landergren (1964) found that the abundance of boron was greater in the finer fractions. Levinson and Ludwick (1966, p. 857) speculated on the incorporation of boron into argillaceous sediments and stated the following:

Finer fractions of argillaceous sediments usually contain boron because more surface area is offered for absorption. Furthermore, any colloidal-sized precipitates, in contrast to the above absorbed type, would be expected to be found in the finest-sized fractions.

The samples of shale from the Atoka Formation, which are composed overwhelmingly of illite, a small amount of mixed-layer illite-montmorillonite and quartz, were studied by separating into various size fractions. These size-fractions are the same as those for the polytypism study. This investigation shows that the boron content increases as the particle size decreases (Fig. 20). From x-ray patterns, the coarser size fractions contain some quartz which may dilute the content of boron. Because the theory of boron substituting for aluminum is favored by most recent workers, the increase of boron content may be related to the increase of aluminum content (Fig. 21). The correlation coefficients between boron and aluminum oxide of various particle sizes range from 0.6 to 0.7. When the boron content of each size fraction is divided by aluminum oxide content of the same fraction and the result multiplied by the average value of aluminum oxide, the increase of boron content in the finer size-

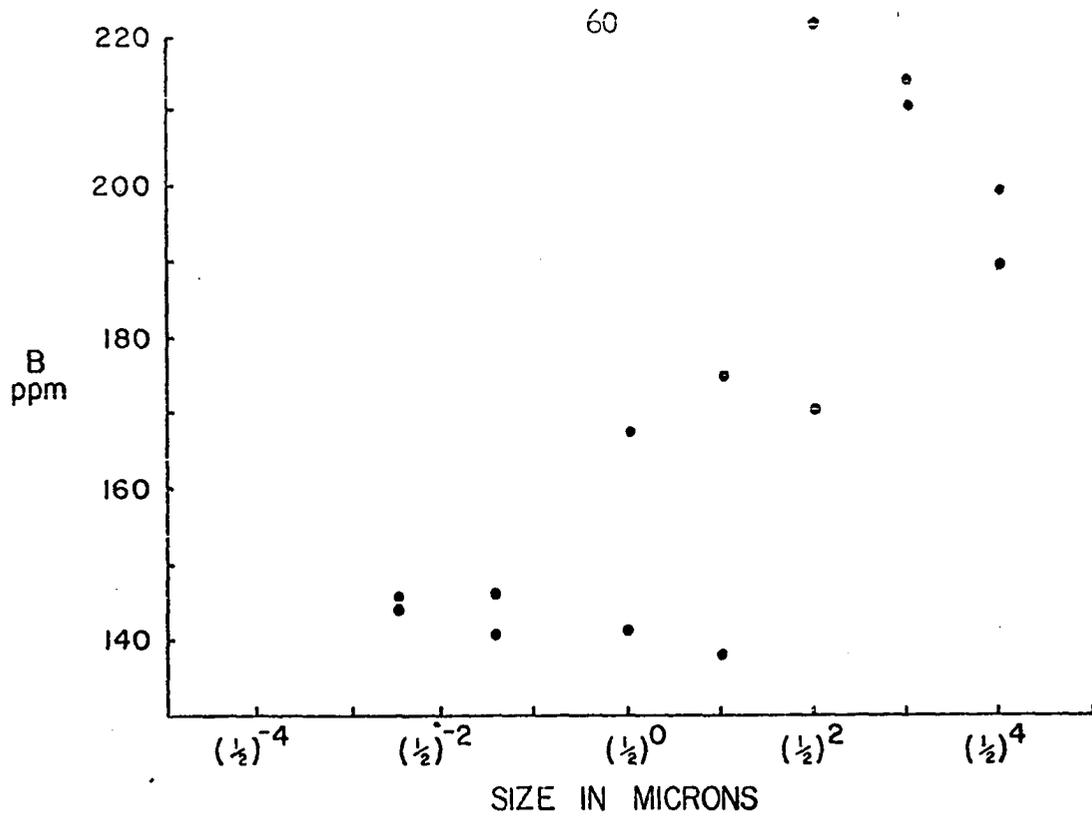


Figure 20. Boron content vs. size

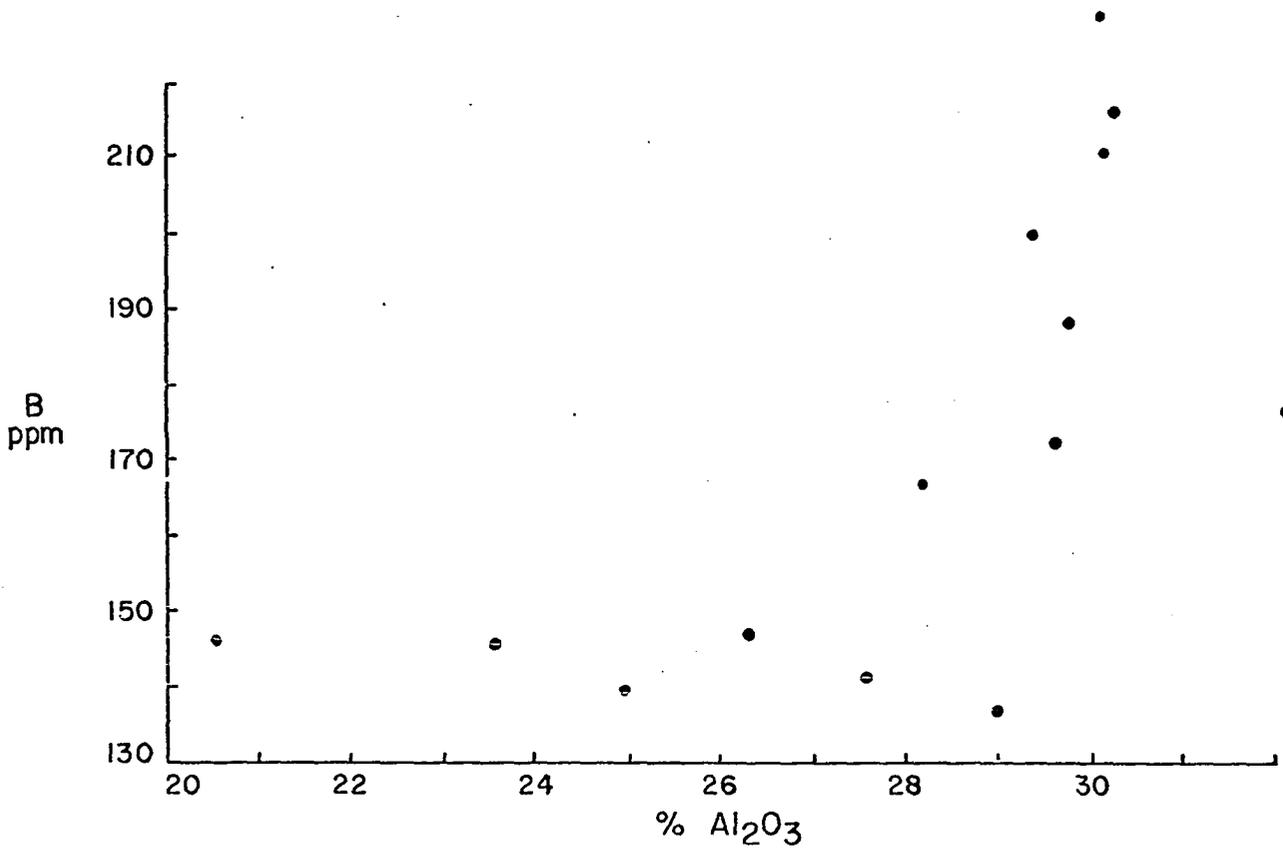


Figure 21. Boron content vs. Al₂O₃ content

fractions is not apparent. Therefore, the increase of boron in the finer fractions is chiefly due to the increase in the content of clay minerals in the finer fraction. From the above point of view, it would not seem to be reasonable to accept the theory of colloidal size precipitates or direct incorporation of boron into the crystal lattice of clay minerals at the site of deposition. It would be more reasonable to suppose that the boron content is absorbed on the surface of the clay particles first and then the ion would migrate into the crystal lattice of clay minerals and substitute for aluminum. The effect of diagenesis would result in a more homogeneous distribution of boron ions in various size-fractions of clay minerals.

The trace elements of vanadium, nickel, and cobalt in the argillaceous sediments were studied by Goldschmidt (1954) and Potter, Shimp and Witters (1963) for paleosalinity. The amounts of these elements also increase with decreasing size (Figs. 22, 23, and 24). The chemical character of V, Ni, and Co are also close to Fe. Although the contents of these trace elements increase with increasing iron oxide content (Figs. 25 and 26), the correlation coefficients show a great variation. Therefore, the contents of V, Ni, and Co may not be completely related to the iron in the clay minerals. Degens (1965) believes that these trace elements are associated with organic matter of porphyrins. It seems that the abundance of organic matter is greater in finer fractions in the shale of the Atoka Formation.

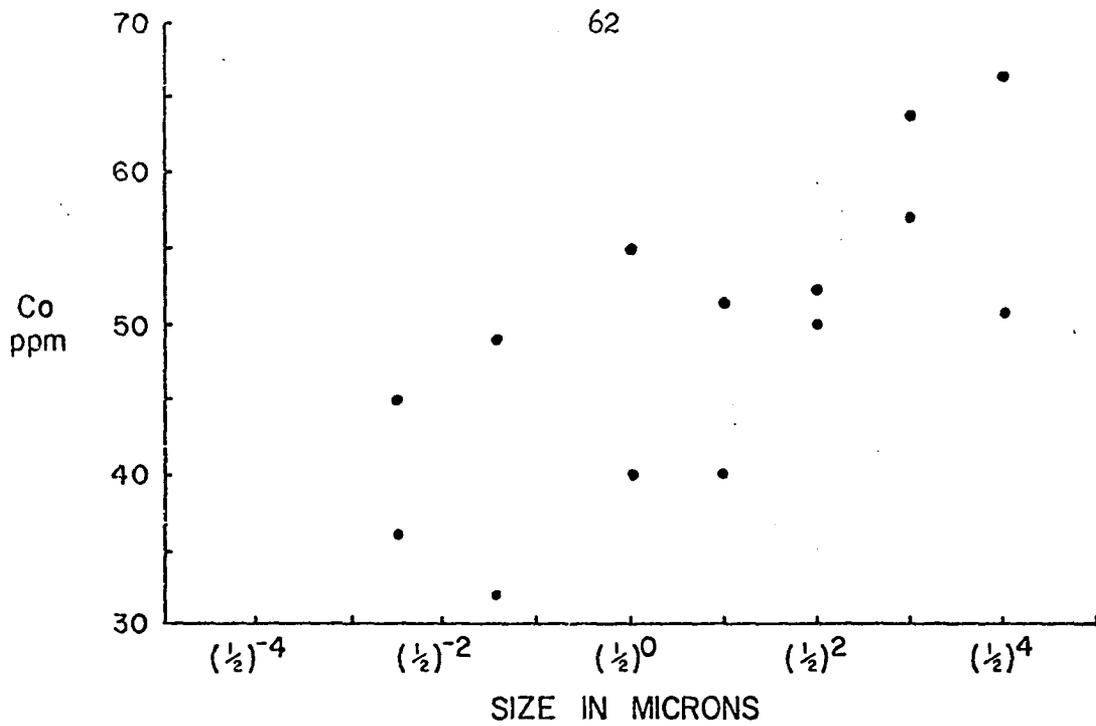


Figure 22. Cobalt content vs. size

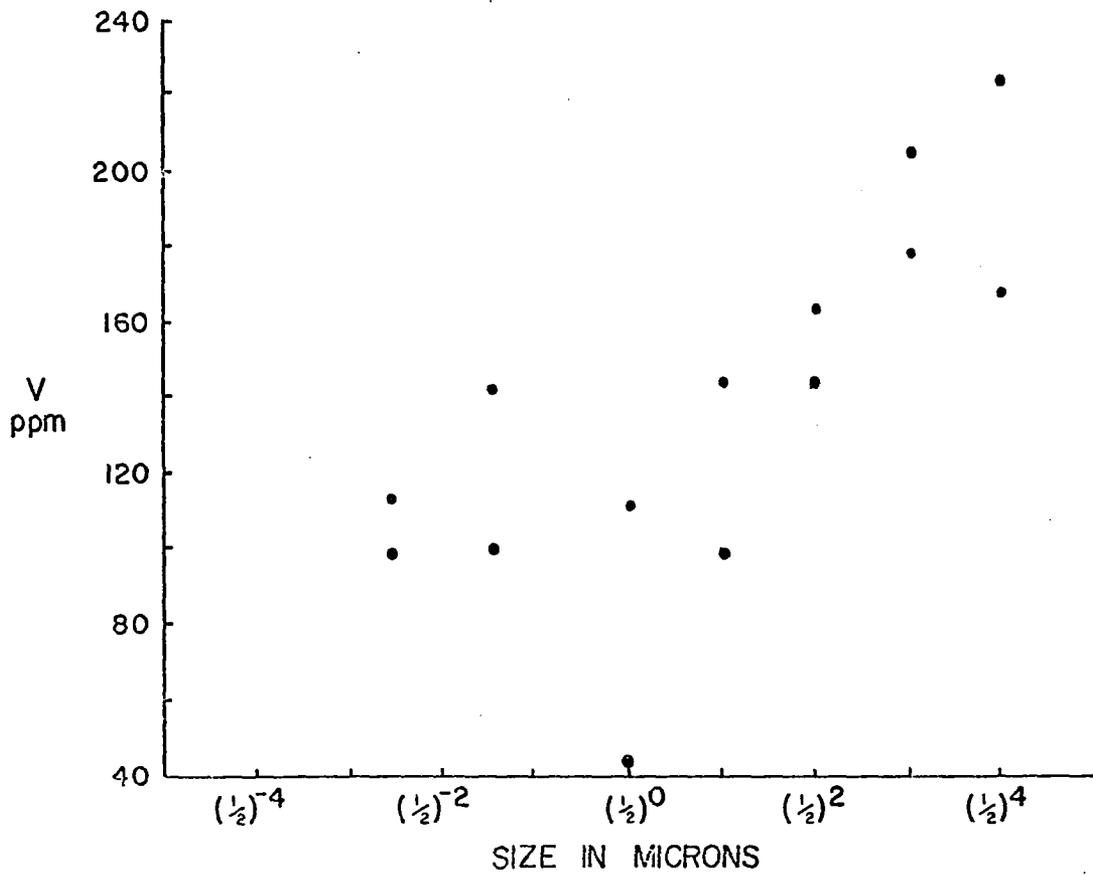


Figure 23. Vanadium content vs. size

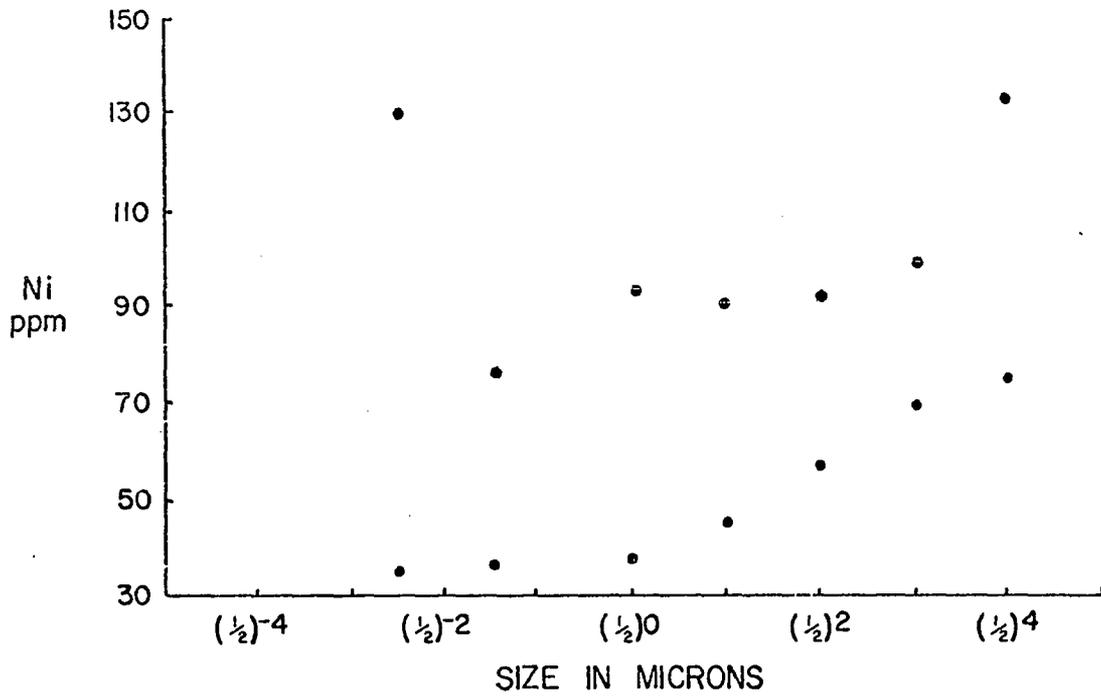
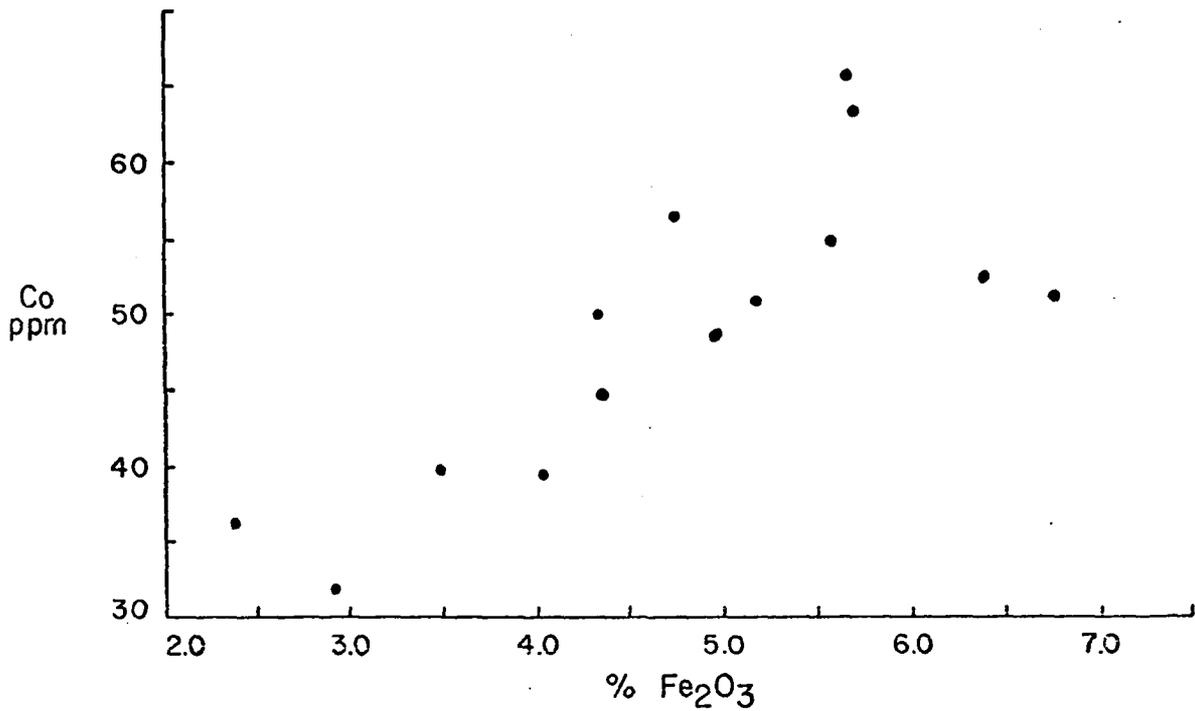


Figure 24. Nickel content vs. size

Figure 25. Cobalt content vs. Fe_2O_3 content

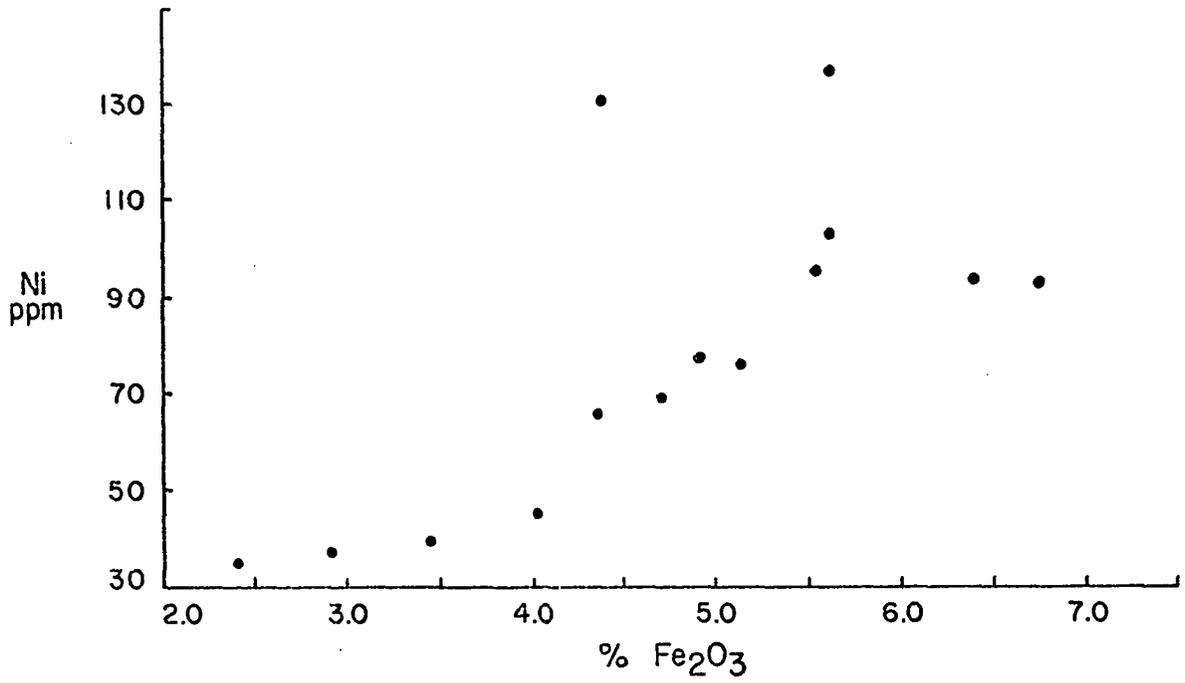


Figure 26. Nickel content vs. Fe₂O₃ content

DIAGENESIS AND WEATHERING

Accumulation, compaction, diagenesis, lithification, folding, and faulting may cause changes in sediments in both mineral composition and texture. Intrastratal solution and alteration by groundwater and surface weathering can also affect these rock properties.

Most illite, which is the main component of the clay minerals in the Atoka Formation, is considered to be essentially detrital in origin and only a very small amount is considered to be authigenic. Mixed-layer illite-montmorillonite may pick up potassium ions, which may either be present in the site of deposition or be carried in by groundwater or formation water to form illite. From Figure 13, the increase in illite and the related decrease in mixed-layer illite-montmorillonite can be interpreted as reflecting the change of mixed-layer illite-montmorillonite into illite.

The abundance of vermiculite seems to be related to the degree of weathering. The intensively weathered samples normally have a higher vermiculite content, especially in the weathered sandstone units with high chlorite contents. Therefore, the appearance of vermiculite cannot be used as a criterion for establishing stratigraphic position in the Atoka Formation. The vermiculite derived from the sandstone units in which the clay minerals are composed of chlorite will not collapse to 10 Å with potassium acetate treatment, but the vermiculite derived from

non-chlorite-bearing rocks will collapse to 10 \AA with the same treatment. Weaver (1958) considered the former type as having a low surface charge density and the latter as having a high surface charge density. The samples from the core at a depth between 6,750-7,180 feet from the Atoka Formation in Latimer County contain no vermiculite of either variety.

The chlorite of the Atoka Formation is a high iron chlorite, with a $\text{Fe}_2\text{O}_3/\text{MgO}$ ratio of about 10:1 based upon chemical analysis. The intensity of the (001) peak is normally mixed with vermiculite which may intensify the 14 \AA peak. The (060) reflection is 1.5418 \AA which is the value for a trioctahedral chlorite. From a microscopic study, the size of the chlorite fragments range from fine silt to clay. The clay-sized particles of chlorite are normally filling the interstitial positions between the sand grains. Both Weaver (1958) and the writer believe that the chlorite in the Atoka Formation is detrital rather than authigenic in origin.

Kaolinite is derived primarily from detrital material and only a minor amount is of authigenic origin. It seems that the content of kaolinite increases as the degree of weathering increases. The kaolinite content in the section in the Muskogee-Porum area is higher than at the Spring Mountain section. Thin section studies indicate that the alteration of feldspar into kaolinite, due to the effect of weathering, is a normal relationship in the Atoka Formation. A small amount of dickite in the sandstone units along the flank of Ozark Uplift area is considered to be detrital in origin.

During the diagenetic process, clay minerals are forced to fill the interstitial position by compressional forces and form a sort of

cement in the sandstone units. The shale portion shows that the Atoka Formation has no cataclastic textures which is obviously developed in the core area of the Ouachita Mountains. No secondary enlargement of clay minerals was observed, and the orientation of the clay minerals is only slightly developed. Most needle-shaped illite is preferentially oriented with its a-b axes parallel to the bedding plane, but most kaolinite, chlorite and silt-sized quartz grains are not optically oriented. The orientation of illite could result from parallel flocculation. The secondary rearrangement is less significant. Folding and faulting in the Atoka Formation seems to have had little effect on the texture of the rock. The main factor influencing the diagenesis is compression by the overburden. Weaver (1961) used the relative sharpness of the illite in 10 \AA reflection for determining the rank of low grade metamorphism. He used the values of $10 \text{ \AA}/10.5 \text{ \AA}$ ratio for the rocks in the Ouachita fold belt. It is unfortunate that the illite of the Atoka

TABLE 1

	Average Sharpness Ratio
Low-grade Metamorphism	12.1
Weak to Very Weak Metamorphism	6.3
Incipient to Weak Metamorphism	4.5
Incipient Metamorphism	2.3
Unmetamorphosed Stanley	2.3
Unmetamorphosed Atoka	1.8

(After Weaver (1961, p. 159)).

Formation is mixed with mixed-layer illite-montmorillonite. Therefore, the sharpness ratio is greatly influenced and the $10 \text{ \AA}/10.5 \text{ \AA}$ is not the true value of illite reflections. Weaver's sharpness ratio may be applicable to the Ouachita fold belt, but is not a universal principal which is applicable anywhere. After treatment with ethylene glycol to separate the mixed-layer minerals, the sharpness ratio is greatly increased. Thirteen samples were treated with ethylene glycol and the average of the sharpness ratio was 4.15. Weaver's concept of classifying low-grade metamorphism may be applicable, but the data need to be reexamined.

Thin section studies indicate that feldspar grains are both weathered and fresh. The weathering of the feldspar grains might have occurred either before deposition or after present exposure. The weathered feldspar grains may alter into illite or kaolinite depending upon the K^+ concentration in the environment. In the weathering process, the iron content may be put into solution and migrate through the permeable sandstone members to the upper surface of the shale members. The change of environment may cause the precipitation of iron oxide in that position to form iron concretions. Many concretions at the same level can form a layer of limonite. This kind of syngenetic product of iron concretions can even be used for tracing the boundaries of members, especially along the flank of the Ozark Uplift.

In the limestone layers of the Atoka Formation along the flank of the Ozark Uplift, sparry calcite forming as a cement in the rock is a post-depositional process. Grain-growth and grain-diminution of calcite by recrystallization are observable. The formation of syntaxial rims around crinoidal fragments is abundant. Veins of sparry calcite in the

limestone layers and calcareous sandstone units are quite common. The calcite replaces quartz sand in the calcareous sandstone or sandy limestone due to a change in the environment to higher pH conditions. Siliceous veins are also observed in limestone and shale portions.

SEDIMENTATION

The sedimentary rocks in a local area may not reflect the character of the entire formation. Therefore, in order to analyze these parameters, a greater areal extent is normally considered. Seely (1963) classified the main theories regarding the depositional environments of the Atoka Formation in the Arkoma Basin into two types: (a) a shallow-water deposition in a deltaic environment and (b) a below-wave-base deposition with turbidity currents.

The evidence in this study would favor the theory of deposition in a deltaic environment. This evidence is as follows:

(1) Graded bedding, cross bedding, current marks, flute casts, groove casts, and laminations can be formed by deltaic deposition either in a marine or fluvial environment.

(2) Turbidity currents, wave-ripple marks, and convolute bedding can be formed by deltaic deposition, especially in the marine environment.

(3) Particle size, clay gill content, and sand/shale ratio decrease westward in conformance with the current direction.

(4) Rapid changes in the color of shale at a constant stratigraphic level is common in the Spring Mountain section. This is a common feature in modern deltaic environments.

(5) Carbonaceous debris in the shale and siltstone portions of the lower part of the Atoka Formation is abundant.

(6) The shift in current direction (Fig. 27) might be due to a shift in the river course.

(7) It is normal in deltaic deposition to have a volume of sediments with complicated facies changes and thickness variations from location to location, depending upon changes in the distributary pattern.

(8) Channel sands and coal streaks in Arkansas reported by Scull (1961), are important pieces of evidence for continental sedimentation.

The sediments comprising the Atoka Formation in the Ouachita Mountains are considered to have been deposited near a river mouth. Therefore, a large volume of sediments was deposited in this area. The characteristics of sediments are the same as the deltaic environment mentioned above. Except siliceous sponge spicules, no diagnostic fossils have been found, although worm-trails are abundant.

Along the flank of the Ozark Uplift, wave-ripple marks, limestones, and fossils, including brachiopods and crinoids, indicate that the depositional environment was a near-shore, marine, non-deltaic, marginal depositional facies where less terrigenous sediments were contributed. Scull (1961) compared the southern one-half of the Atoka Formation as being similar to the Mississippi delta and the northern one-half as being similar to the depositional environment near Florida.

From a study of the trace elements of boron and vanadium, the depositional environment of the shale of the Atoka Formation at the Spring Mountain section was a low salinity marine environment (Fig. 28). The

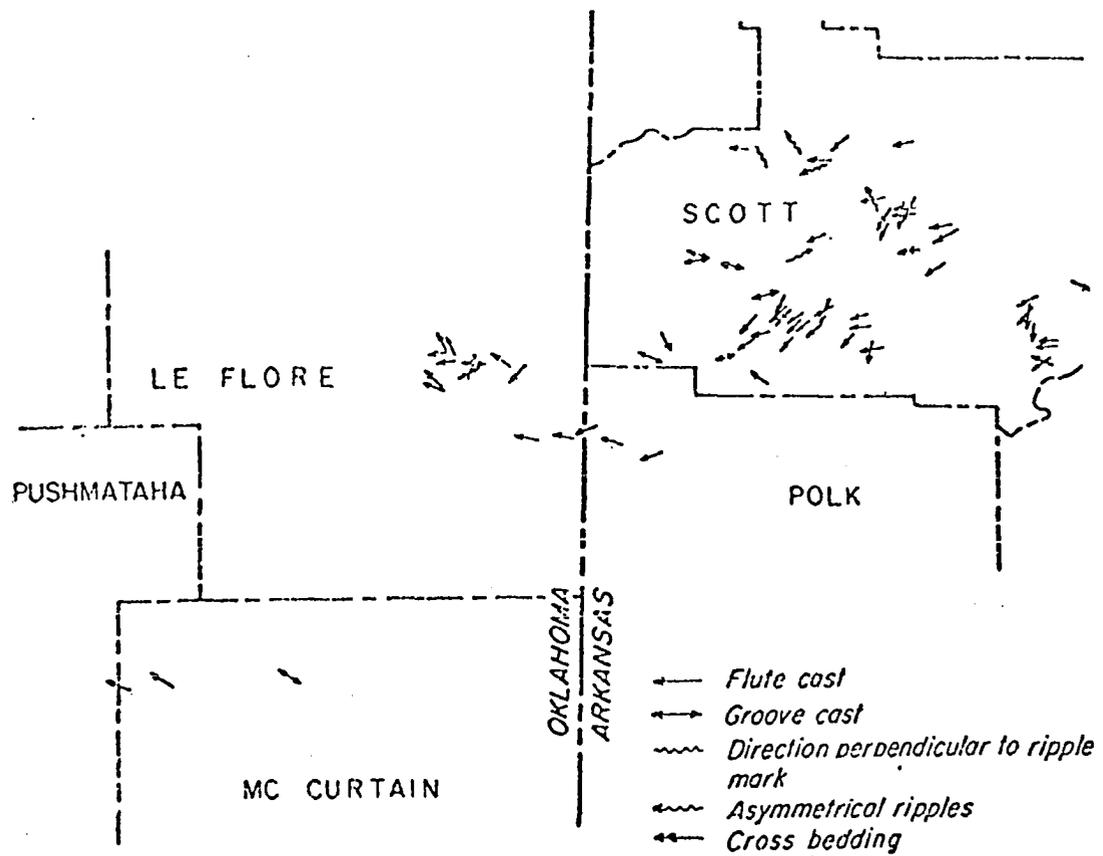


Figure 27. Map of Atoka current indicators. Each symbol represents a single observation. Observations are those of Seely (1963), of Shelburne (1960), and of Reinemund and Danilchik (1957).

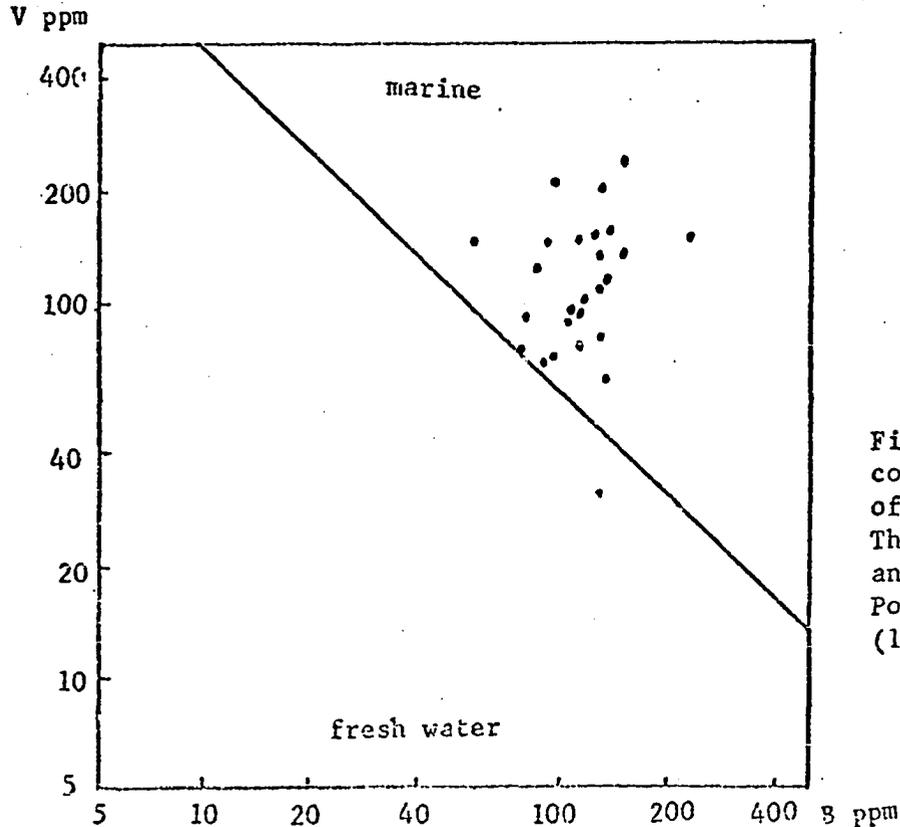


Figure 28. Plot of B and V concentrations in 27 samples of the Atoka shale. The boundary between marine and fresh water is after Potter, Shimp and Witters (1963, p.680).

existence of large amounts of mixed-layer illite-montmorillonite indicates that the water in the depositional environment of the Atoka Formation may have been deficient in potassium.

The upward decrease in the sand/shale ratio and the carbonaceous content at the Spring Mountain section indicates that the depositional environment was transgressive. Scull (1961) divided the Atoka Formation into a lower, middle and upper division for convenience in interpretation. This subdivision would seem to have no stratigraphic significance. The writer would prefer to divide the Atoka Formation into upper and lower units, marked by the presence and absence of chlorite in the sandstone portions. The disappearance of chlorite could reflect a change in source material or a reduction in the relief of the source area where chlorite might be exposed to longer periods of weathering and might alter to other, more stable clay minerals.

According to Folk (1961) the condition of feldspar grains provides information to aid in the interpretation of the climate and relief of the source area during periods of weathering and transportation. Both fresh and weathered feldspar grains are present in the sandstone units of the Atoka Formation. The size of the feldspar grains decreases upward. These characters indicate that the climate in the source area was temperate to warm and humid, and the relief of the source area changed from rugged to flat.

The clay mineral content in the shale portion is rather constant from the bottom to top. The clay content of the sandstone is different with a high chlorite content in the lower units and no chlorite in the upper. The chlorite in the sandstone portion is associated with high-rank

metamorphic rock fragments and minerals, including schist, phyllite, slate, metaquartzite, garnet, and staurolite. Scull provided the following description of the depositional history (1961, p. 151):

The southern Appalachian folded belt was strongly positive early in the Pennsylvanian. Great sheets of gravel and coarse sands were deposited in the Black Warrior basin adjacent to the uplift and even large volumes of finer debris were carried westward (Mellen 1947) along the axis of the developing Atoka trough.

Therefore, the chlorite could be derived from the green schist area on the southwest side of the Appalachian Mountains. Near the end of the time during which the lower part of the Atoka Formation was deposited, the topographic relief was reduced and the drainage system altered. Therefore, the unstable high iron chlorite may not have been available or it might have been altered to another kind of clay mineral during weathering.

The appearance of large quantities of mixed-layer illite-montmorillonite would suggest that the material might be intensively weathered before transportation to the site of deposition. The mixed-layer minerals might have been derived from the shales in the source area.

The sediments deposited in the northern one-half of the area may have been partly contributed from a river to the south, especially those clay minerals that may be widely spread, and partly derived from the north where the coarse sediments such as conglomerate, granule sands, and chert, may have originated. According to Blythe (1959), chert pebble conglomerates in the area near Wagoner were derived from outcrop areas of the "Boone" chert in the Ozark Uplift. From a study of the clay minerals,

the sediments of the Atoka Formation along the flank of the Ozark Uplift would suggest that they could not have been derived from the Ouachita Mountains. The most obvious evidence is that the chlorite in the core area of the Ouachita Mountains is a high magnesium chlorite whereas the chlorite in the Atoka Formation is a high iron chlorite.

SUMMARY AND CONCLUSIONS

The rocks of the Atoka Formation consist of shale, sandstone, siltstone, and a few limestone layers. From a textural study, it may be concluded that the rocks have undergone no metamorphism. Authigenic minerals and secondary grain enlargement are insignificant throughout the formation.

The grain size of quartz ranges from fine sand to silt. The mineralogical classification of the sandstone lies mainly in the muddy subgraywacke, subarkose, and feldspathic subgraywacke classes. The feldspathic subgraywacke is the most abundant. The limestone layers include recrystallized calcimicrite and sandy biosparrudite.

The clay minerals of the Atoka Formation are illite, chlorite, kaolinite, mixed-layer illite-montmorillonite, vermiculite, and dickite in order of general decreasing abundance. The vermiculite is considered to be an authigenic weathering product. The vermiculite derived from chlorite will not collapse to 10 \AA after treatment with potassium acetate, but that derived from illite or mixed-layer minerals will readily collapse to 10 \AA with the same treatment. A small amount of authigenic illite and kaolinite as diagenetic products are present but have no quantitative significance.

The high iron chlorite is considered to have been derived from high-ranked metamorphic rocks and the source area may have been on the

southwest side of the Appalachian Mountains. The polytypism of the illite includes $2M_1$, $1M_1$, and $1M_d$ which would indicate that the source materials were complicated and heterogeneous.

The size-fraction study indicates that the $2M_1$ illite is concentrated in the size-fraction coarser than 0.5 microns and the $1M$ illite is concentrated in the size-fraction finer than 0.5 microns. The octahedral layer of the illite is dioctahedral with a high aluminum content but with an increasing iron content in the finer fractions. The chlorite is a high-iron, trioctahedral variety.

The study of the vertical stratigraphic distribution of the clay minerals reveals that chlorite is present in the sandstone units in the lower Atoka Formation, from the base up to 2,000 feet at the Spring Mountain section. This section may be physically correlated to the section in the Muskogee-Porum area in the sandstone units from the Coody Sandstone Member to the Georges Fork Sandstone Member. The presence or absence of chlorite may reflect a change of source material.

No change in the polytypism of the illite by diagenetic mechanism has been observed. The decreasing mixed-layer illite-montmorillonite content with depth could reflect alteration into illite by diagenetic processes.

The increase in the boron content in the finer size-fractions is related to the abundance of aluminum content rather than only size variation. The explanation of this phenomenon is that the boron is absorbed on the surface of the clay mineral first and then migrates into the lattice site, instead of direct incorporation or precipitation as a gel. The relative abundance of aluminum and boron has a correlation

coefficient of about 0.6-0.7. Therefore, the theory of the substituting of boron for aluminum is reasonable. The contents of V, Ni, and Co seem not to be related to the elements in the crystal lattice of clay minerals.

The orientation of illite grains seems to be chiefly caused by parallel flocculation rather than by secondary reorientation as a diagenetic process. The sharpness ratio of the $10 \text{ \AA}/10.5 \text{ \AA}$ peaks as proposed by Weaver (1961) is not of significant value in the Atoka Formation because the appearance of the mixed-layer minerals significantly reduces the ratio value. The sharpness ratio of illite in the 10 \AA reflection may be obtained only after treatment with ethylene glycol which will separate the mixed-layer minerals from illite.

The deposition of the Atoka Formation in the southern one-half of the Arkoma Basin was in a deltaic environment and the northern one-half was in a shallow water, non-deltaic, marine, near-shore environment. The sediments contributed to the delta are from the east and northeast and the northern one-half is partly from the north and partly from the river which built the delta westward.

The upward decrease of light color sandstone and siltstone units and increase of dark color shale units of the Atoka Formation at Spring Mountain section indicate that the depositional environment was a transgressive delta.

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APPENDICES

TABLE 2

PERCENTAGE OF CLAY MINERALS FROM SHALE PORTION
AT THE SPRING MOUNTAIN SECTION

Base	Illite	Kaolinite	Illite- Montmorillonite	Vermiculite
0-86 86 ft	68	9	19	4
86-118 32 ft	65	13	17	5
118-138 20 ft	60	7	28	5
138-223 85 ft	68	23	6	3
223-303 80 ft	92	3	4	1
303-459 156 ft	60	8	26	6
459-672 218 ft	Covered			
672-692 20 ft	35	5	52	8
692-739 47 ft	30	13	40	17
739-775 36 ft	73	5	10	12
775-821 46 ft	39	18	37	6
821-854 33 ft	32	19	35	14
854-928 74 ft	52	3	40	5

TABLE 2--(Continued)

Base	Illite	Kaolinite	Illite- Montmorillonite	Vermiculite
928-1031 103 ft	68	11	20	1
1031-1141 110 ft	41	14	41	4
1141-1160 19 ft	54	10	30	6
1160-1328 168 ft	72	21	6	1
1328-1486 158 ft	43	25	28	4
1486-1581 95 ft	64	19	12	5
1586-1782 201 ft	41	19	38	2
1782-2182 400 ft	54	7	24	15
2182-2319 137 ft	47	6	47	
2319-2454 135 ft	44	6	50	
2454-2558 104 ft				
2558-2581 23 ft				
2581-3513 932 ft	F 32 H 34 I 34	15 7 5	63 59 61	

TABLE 3

PERCENTAGE OF CLAY MINERALS FROM THE MUSKOGEE-PORUM AREA

Top	Illite	Kaolinite	Illite- Montmorillonite	Chlorite	Vermiculite
Shale A6	46	19	30		5
Blackjack School Sandstone	50	21	29		
Shale A5	33	30	37		10
Webbers Falls Sandstone	37	16	47		
Shale A4	34	20	34		12
Dirty Creek Sandstone	44	24	32		
Shale A4	34	30	36		
Georges Fork Sandstone	40	20		30	10
Shale A2	28	19	43		10
Pope Chapel Sandstone	30	14	19	22	15
Shale A1	46	18	36		
Coody Sandstone	45		18		32

TABLE 4
CHEMICAL DATA

Size microns	SiO ₂ %	Al ₂ O ₃ %	K ₂ O %	Fe ₂ O ₃ %	MgO %
<u>Sample 5b Illite</u>					
6	67.65	20.50	4.81	2.39	1.07
6-3	61.72	24.98	5.92	1.90	1.48
3-1	55.62	28.12	6.76	3.44	1.91
1-1/2	52.00	32.18	7.14	4.00	2.38
1/2-1/4	50.50	30.10	7.11	4.32	2.14
1/4-18	50.42	30.16	7.11	4.72	1.98
1/8-1/16	50.80	29.40	7.04	5.10	1.80
<u>Sample 2c Illite</u>					
6	62.00	23.61	4.03	4.32	1.06
6-3	57.40	26.34	5.18	4.92	1.84
3-1	54.52	27.52	5.28	5.52	1.83
1-1/2	51.40	29.08	5.46	6.72	2.00
1/2-1/4	44.47	29.60	5.55	6.42	1.80
1/4-1/8	44.00	30.18	5.78	5.62	2.04
1/8-1/16	50.83	29.91	5.79	5.61	2.62
<u>Sample 1b Illite</u>					
6-3	58.00	26.12	4.97	4.90	1.64
3-1	54.42	27.32	5.16	5.32	1.71
1-1/2	50.67	29.32	5.48	6.20	2.05
1/2-1/4	50.30	29.07	5.65	6.50	2.04
1/4-1/8	48.62	28.62	5.79	7.19	2.10
<u>Sample 20 Chlorite</u>					
Bulk	41.80	19.61	4.20	24.8	2.42

TABLE 5
TRACE ELEMENTS

Sample No.	Boron ppm	Vanadium ppm	Nickel ppm
1a	78	78	37
2a	90	160	94
3a	115	108	46
4a	148	115	43
5a	91	75	26
6a	180	136	29
8a	120	134	57
9a	85	98	90
10a	160	148	59
11a	110	99	73
12a	57	150	54
13a	182	250	54
14a	106	180	85
15a	95	94	39
16sh	110	83	39
17a	106	95	116
18a	95	215	54
19a	128	160	90
20a	134	87	59
21a	142	70	45
22a	136	29	26
23sh	95	80	25
24a	132	75	27
26a	126	210	92
26c	120	114	66
26e	225	154	28
26g	106	186	51
26i	150	140	47

Note: Numbers refer to samples collected from the Spring Mountain section and are arranged from bottom to top of section.

TABLE 6
TRACE ELEMENTS

Size microns	Boron ppm	Vanadium ppm	Nickel ppm	Cobalt ppm
<u>Sample 5b Illite</u>				
6	146	113	34	36
6-3	140	142	35	32
3-1	167	112	37	40
1-1/2	176	143	44	40
1/2-1/4	227	162	65	50
1/4-1/8	210	178	69	57
1/8-1/16	198	166	75	51
<u>Sample 2c Illite</u>				
6	146	97	130	45
6-3	147	99	76	49
3-1	142	42	94	55
1-1/2	137	99	92	52
1/2-1/4	171	142	92	53
1/4-1/8	215	205	102	63
1/8-1/16	189	225	134	66

TABLE 7
RATIO VALUES

Size microns	$\text{Fe}_2\text{O}_3/\text{Al}_2\text{O}_3$	$\text{K}_2\text{O}/\text{Al}_2\text{O}_3$	$\text{B}/\text{Al}_2\text{O}_3 \times 27.977^*$
<u>Sample 5b Illite</u>			
6	0.1166	0.2345	199.252
6-3	0.1160	0.2370	156.811
3-1	0.1223	0.2414	166.155
1-1/2	0.1243	0.2219	153.006
1/2-1/4	0.1435	0.2362	210.974
1/4-1/8	0.1565	0.2357	166.827
1/8-1/16	0.1734	0.2395	188.425
<u>Sample 2c Illite</u>			
6	0.1829	0.1707	173.010
6-3	0.1868	0.1967	156.112
3-1	0.2007	0.1919	144.361
1-1/2	0.2310	0.1978	131.803
1/2-1/4	0.2169	0.1975	161.623
1/4-1/8	0.1852	0.1915	199.308
1/8-1/16	0.1876	0.1936	176.797

*27.977: average value of Al_2O_3 .

TABLE 8
 INDEX OF d-SPACINGS OF THE POLYTYPISM OF ILLITE
 IN VARIOUS SIZES
 (microns)

A 6-3	B 3-1	C 1-1/2	D 1/2-1/4	E 1/4-1/8	F 1/8-1/16
10.0480	10.0480	10.0480	10.0480	10.0480	10.2810
4.9828	4.9828	4.9552	4.9707	4.9552	4.9828
4.4681	4.4615	4.4615	4.4838	4.4770	4.4770
3.8833	3.8833	3.4930	3.5900	3.5201	3.3264
3.7231	3.7231	3.3264	3.3264	3.3264	2.5672
3.4930	3.5210	3.1977	2.5672	2.5672	2.4358
3.3264	3.3264	2.9882	2.4887	2.4044	2.3982
3.1977	3.1977	2.8488	2.3799	1.9976	2.1353
2.9882	2.9882	2.7968	2.2485	1.6980	1.9955
2.8666	2.8666	2.5672	2.2012	1.6779	1.6584
2.7968	2.7883	2.3799	2.1365	1.6584	1.5011
2.5672	2.5672	2.1317	1.9976	1.5011	
2.4551	2.4551	1.9976	1.6612		
2.3799	2.3799	1.6639	1.6447		
2.2378	2.2378	1.6474	1.5011		
2.1207	2.1207	1.5011			
1.9935	1.9935				
1.6723	1.6639				
1.6723	1.6639				
1.6474	1.6478				
1.5011	1.5011				

Formula Used for Linear Correlation Coefficient

$$r = \frac{n \sum_{i=1}^n xy - \left(\sum_{i=1}^n x_i \right) \left(\sum_{i=1}^n y_i \right)}{\sqrt{\left[n \sum_{i=1}^n x_i^2 - \left(\sum_{i=1}^n x_i \right)^2 \right] \left[n \sum_{i=1}^n y_i^2 - \left(\sum_{i=1}^n y_i \right)^2 \right]}}$$

x and y are two variables.

r is correlation coefficient.

LIST OF SAMPLE LOCALITIES

Sample No. 1

SW $\frac{1}{4}$ SW $\frac{1}{4}$ NW $\frac{1}{4}$ Sec. 20, T. 18 N., R. 19 E.

Proceed north on U. S. Highway 69 from Wagoner city limits for 3.2 miles. Turn east on section line road for 3 miles, then north for 0.5 miles.

The Atoka Formation is exposed on the bank of Fort Gibson Lake near the Wagoner Pumping Station. A section was measured at this location by Blythe (1957, p. 132).

Sample No. 2

SE $\frac{1}{4}$ NW $\frac{1}{4}$ SE $\frac{1}{4}$, Sec. 30, T. 18 N., R. 19 E.

Proceed north on U. S. Highway 69 from Wagoner City limits for 3.2 miles. Turn east on section line road for 2.2 miles, then southeast for 1 mile.

The Blackjack School Member of the Atoka Formation is exposed on both sides of the road. The exposure of buff sandstone is about 4 feet thick.

Sample No. 3

Sec. 4 and 5, T. 13 N., R. 25 E.

The Atoka Formation is exposed on both sides of U. S. Highway 56 from the border of Sequoyah and Adair Counties to Brushy Mountain. A section was measured along the highway by Blythe (1957, p. 113).

Sample No. 4

NW $\frac{1}{4}$ NW $\frac{1}{4}$ NE $\frac{1}{4}$, Sec. 1, T. 14 N., R. 19 E.

Proceed south on State Highway 2 from Muskogee City Limits for 1 mile. Turn east on paved section line road for 8.5 miles.

The Coody Sandstone member and the overlying A1 Shale are exposed on the southside of the section line road. The exposure includes 15 feet of buff-gray sandstone and 1 foot of overlying gray shale.

Sample No. 5

NW $\frac{1}{4}$ NW $\frac{1}{4}$ NE $\frac{1}{4}$, Sec. 2, T. 14 N., R. 19 E.

Proceed south on State Highway 2 from Muskogee City Limits for 1 mile. Turn east on paved section line road for 7.5 miles.

The Georges Fork Sandstone member is exposed on the southside of the section line road. The exposure of buff sandstone is about 10 feet thick.

Sample No. 6

SW $\frac{1}{4}$ SW $\frac{1}{4}$ SW $\frac{1}{4}$, Sec. 35, T. 15 N., R. 19 E.

Proceed south on State Highway 2 from Muskogee City Limits for 1 mile. Turn east on paved section line road for 7 miles.

The A2 Shale is exposed on the north side of the section line road. The exposure of gray shale is about 20 feet thick.

Sample No. 7

NE $\frac{1}{4}$ NW $\frac{1}{4}$ NW $\frac{1}{4}$, Sec. 3, T. 14 N., R. 19 E.

Proceed south on State Highway 2 from Muskogee City Limits for 1 mile. Turn east on paved section line road for 6.7 miles.

The A4 Shale is exposed on the south side of the section line road, about 0.25 miles east of the bridge (tributary to Cooly Creek). The exposure of gray shale is about 4 feet thick.

Sample No. 8

NW $\frac{1}{4}$ NW $\frac{1}{4}$ NW $\frac{1}{4}$, Sec. 3, T. 14 N., R. 19 E.

Sample No. 8 (Continued)

Proceed south on State Highway 2 from Muskogee City Limits for 1 mile. Turn east on paved section line road for 6 miles, then turn south on unpaved section line road for 900 feet.

The Webbers Falls Sandstone member is exposed on the slope of the hill. The exposure of buff-gray sandstone is about 10 feet thick.

Sample No. 9

SE $\frac{1}{4}$ NE $\frac{1}{4}$ NE $\frac{1}{4}$, Sec. 15, T. 14 N., R. 19 E.

Proceed south on State Highway 2 from Muskogee City Limits for 1 mile. Turn east on paved section line road for 7 miles, then turn south on unpaved section line road for 2 miles, then turn west for 0.1 mile, and then turn south for 0.3 mile.

The A6 Shale is exposed on the east side of the road, near the warning sign of the Bell Telephone System. The exposure of dark gray shale is about 3.5 feet thick.

Sample No. 10

NE $\frac{1}{4}$ NE $\frac{1}{4}$ NE $\frac{1}{4}$, Sec. 14, T. 12 N., R. 19 E.

Proceed east on U. S. Highway 64 from Warner City Limits for 2.5 miles. Turn north on unpaved section line road for 2 miles, and then west for 180 feet.

The A3 Shale is exposed on the southside of the section line road. The exposure of gray shale is about 10 feet thick.

Sample No. 11

NE $\frac{1}{4}$ NE $\frac{1}{4}$ NE $\frac{1}{4}$, Sec. 26, T. 12 N., R. 19 E.

Proceed east on U. S. Highway 64 from Warner City Limits for 2.5 miles.

The A2 Shale is exposed on the corner of the intersection of U. S. Highway 64 and the section line road. The exposure of gray shale is about 1 foot thick from the bottom of the ditch.

Sample No. 12

SW $\frac{1}{4}$ SW $\frac{1}{4}$ SE $\frac{1}{4}$, Sec. 24, T. 12 N., R. 19 E.

Proceed east on U. S. Highway 64 from Warner City Limits for 3 miles.

The Pope Chapel Sandstone member is exposed on the banks of Georges Fork Creek. The exposure of the light gray sandstone is about 15 feet thick.

Sample No. 13

SW $\frac{1}{4}$ SW $\frac{1}{4}$ SW $\frac{1}{4}$, Sec. 23, T. 12 N., R. 19 E.

Proceed east on U. S. Highway 64 from Warner City Limits for 1.5 miles. The outcrop is located about 150 feet east of the intersection of U. S. Highway 64 and the section line road.

The Dirty Creek Sandstone member is exposed on both sides of U. S. Highway 64. The exposure of the grayish-buff sandstone is about 10 feet thick.

Sample No. 14

SE $\frac{1}{4}$ SE $\frac{1}{4}$ SE $\frac{1}{4}$, Sec. 5, T. 11 N., R. 19 E.

Proceed south on the section line road from Warner City Limits for 2.5 miles. The outcrop is located near the intersection of the section line roads.

The Blackjack School Sandstone member and A2 Shale are exposed on the west side of the section line road. The 14-foot exposure includes 7 feet of A5 Shale at the bottom and 7 feet of Blackjack School Sandstone above.

Sample No. 15

SW $\frac{1}{4}$ SW $\frac{1}{4}$ SW $\frac{1}{4}$, Sec. 9, T. 11 N., R. 19 E.

Proceed south on the section line road from Warner City Limits for 3.5 miles. The outcrop is located at the intersection of the section line roads.

The A5 Shale is exposed on the bank of the ditch on the northeast corner of the intersection. The exposure of dark gray shale is about 4 feet thick.

Sample No. 16NE $\frac{1}{4}$, T. 5 N., R. 21 E.

Proceed east on U. S. Highway 270 from Bank of Red Oak in town of Red Oak for 2.7 miles. Turn ~~west~~^{south} for 0.9 miles, then turn southeast for 0.2 miles to ridge of hill capped by Hartshorne Sandstone, and then southeast 0.3 miles to bottom of hill.

The Atoka Formation is exposed along the road on the southside of the hill. The rocks here consist of gray shale with thin sandstone layers. Samples were taken from separate sedimentation units about 100 feet below the top of the formation.

Sample No. 17

Samples were taken from a core drilled by Pan American Petroleum Corporation (Well #1. U. S. A., Choctaw Tribe). 35 Samples taken at regular intervals from 6,680 feet to 7,180 feet. The core is located in the Core and Sample Library at the University of Oklahoma (Accession No. 472).

Sample No. 18NW $\frac{1}{4}$, T. 4 N., R. 18 E.

Proceed north for 1 mile on State Highway 2 from Gain Creek Bridge which is located 7.5 miles south of Wilburton.

The gray shale of the Atoka Formation is exposed on both sides of State Highway 2. The 15-foot thick exposure is in the upper part of the Atoka Formation.

Sample No. 19SW $\frac{1}{4}$ SW $\frac{1}{4}$ SE $\frac{1}{4}$, Sec. 23 to NE $\frac{1}{4}$ SE $\frac{1}{4}$ NE $\frac{1}{4}$, Sec. 24, T. 3 N., R. 25 E.

Proceed north on State Highway 103 for 5 miles from intersection with State Highway 63 near Big Cedar. The outcrop was measured along State Highway 63 from the intersection with an unpaved road to the axis of the Spring Mountain Syncline.

The exposure of the Atoka Formation consists mainly of sandstone in the lower one-half and mainly shale in the upper one-half.

Sample No. 20

NW $\frac{1}{4}$, T. 2 N., R. 10 E.

Proceed west on State Highway 7 for 8 miles from the intersection with U. S. Highway 69 and 75.

The exposure of gray shale with thin sandstone layers is about 20 feet thick and is present on both sides of State Highway 7. The exposure is in the lower part of the Atoka Formation.

Sample No. 21

NW $\frac{1}{4}$, T. 2 N., R. 9 E.

Proceed east for 2.9 miles on State Highway 7 from the intersection with State Highway 48.

Exposures of sandstone are located on both sides of the highway. Sample was taken from a 4-foot exposure and is from the lower part of the Atoka Formation.