GEOLOGY OF THE CLAY DEPOSITS IN THE OLIVE HILL DISTRICT, KENTUCKY[1]

by

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ABSTRACT

THE Olive Hill fire clay bed of Crider (1913) is the principal source of the raw material used in the refractory industry of eastern Kentucky. The bed is a discontinuous underclay from 1 to 20 ft above a prominent unconformity which separates Mississippian and Pennsylvanian rocks. Upper Mississippian rocks consist of ten marine limestone and shale units all truncated by the unconformity. Pennsylvanian rocks are chiefly: (a) massive deltaic sandstone ; (b) cut-and-fill deposits of shale, siltstone and sandstone which contain several beds of coal and underclay including the Olive Hill fire clay of Crider (1913) ; and (c) dark-gray shale beds.

The Olive Hill fire clay of Crider consists of approximately one-third flint clay, two-thirds semiflint clay, and minor amounts of plastic clay. The clay mineral content ranges from nearly pure kaolinite to kaolinitic clay containing about 40 percent illite and mixed-layer clay. The kaolinite ranges from highly crystalline to very poorly crystalline " fireclay " kaolinite. The degree of crystallinity of the kaolinite and hardness of the clay vary inversely with the amount of illite and mixed-layer clay present. The nearly pure kaolinite is believed to have formed by removal of silica and alkalies from mixtures of kaolinite, illite and mixed-layer clay by leaching shortly after deposition.

An isopach map shows that Crider's Olive Hill fire clay occurs in irregular, lens-shaped deposits. Fossil plant rootstocks with rootlets attached in the clay clearly indicate it supported plant growth. The overlying coal and presence of some organic material in the clay suggest that the Olive Hill fire clay was deposited under a reducing environment in swamps.

INTRODUCTION

Olive Hill, a town of about 1300 population, is the center of an important refractory clay producing district in eastern Kentucky. The district furnishes nearly all Kentucky's output of refractory clay. The average yearly production was 411,385 tons during the period 1947–1956, when the total value of the clay was $21,581,598 (Reed and McFarlan, 1958, p. 498). All but a very small percentage of the raw material for the refractory brick is mined from a clay bed to which Crider (1913, pp. 594–595) applied the name Olive Hill fire clay. This clay bed is near the base of Pennsylvanian rocks, which underlie an area commonly referred to as the eastern Kentucky Coalfield (Fig. 1). In a general way, the western margin of the eastern Kentucky Coalfield also marks the boundary of the Cumberland Plateau. The topography is characterized by rolling upland surfaces incised by steep-walled valleys having narrow flood plains. Local relief is mostly between 200 and 300 ft. The clay bed crops out intermittently from Portsmouth, Ohio, south-

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southwestward for a distance of more than 60 miles. Owing to a gentle easterly regional dip and the sinuous configuration of the clay outcrop, it is minable within a belt from 5 to 10 miles wide, and at several places inliers to the east widen this belt to about 15 miles. In this report the entire belt is somewhat arbitrarily referred to as the Olive Hill district.

The writer's knowledge of the district has been gained primarily during an investigation by the U.S. Geological Survey of the clay deposits in the Haldeman quadrangle (Fig. 1). This investigation was made in an effort to increase our knowledge of the geology of refractory clay deposits in eastern Kentucky. The work was conducted in cooperation with the Kentucky Geological Survey.

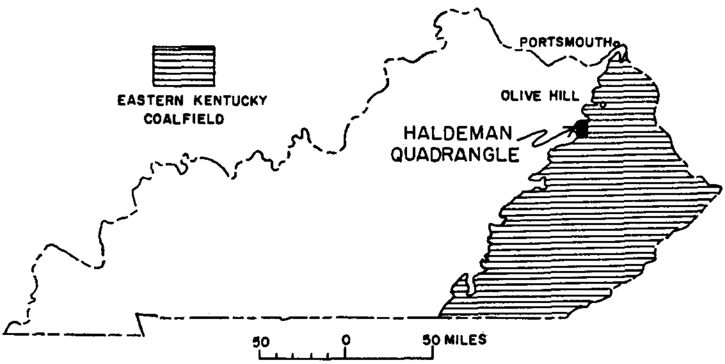

FIGURE 1.—Location of the eastern Kentucky Coalfield and the Haldeman quadrangle, Kentucky.

ACKNOWLEDGMENTS

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GEOLOGY

The Olive Hill district lies in a broad structural downwarp between the Appalachian Mountains and the Cincinnati arch. Regional dips of Pennsylvanian rocks are only 40–50 ft/mile in a south-easterly direction, and the dips of Mississippian beds in general conform closely to this. At a few localities, however, the Mississippian beds dip as much as 150 ft/mile, indicating minor structural warping prior to deposition of Pennsylvanian beds. The Pennsylvanian and Mississippian rocks are separated by an unconformity which truncates all upper Mississippian formations. The regularity of these structures permits rather accurate inferences for location of stratigraphic contacts in a region of sparse outcrops, blanketed by a thick mantle of soil and partly weathered bedrock, and covered by brush and secondary growth of timber.

Mississippian Rocks of Meramec and Chester Age

Mississippian rocks of Meramec and Chester age consist of 10 thin limestone and shale formations. The 3 lower formations, the Warsaw(?), St. Louis, and Ste. Genevieve limestones, are of Meramec age according to the classification by Weller and others (1948, p. 163). Rocks of Chester age, according to McFarlan and Walker (1956), include the Paoli, Beaver Bend, Reelsville, Beech Creek, Haney and Glen Dean limestones, and the Pennington(?) formation. The areal distribution of the 10 formations is very irregular, owing chiefly to their truncation by the large pre-Pennsylvanian unconformity and smaller intra-Mississippian unconformities. The over-all thickness of the 10 formations is about 150 ft, but at most places only 2 to 4 of the formations remain and the total thickness is less than 30 ft.

Of the 10 formations, 9 are dominantly limestone or dolomite: the tenth, the Pennington(?), formation is predominantly sandstone and shale. Limestone breccia zones are common, and all formations contain or are closely associated with thin beds or lenses of green shale. The Ste. Genevieve is the only limestone formation that contains considerable amounts of quartz sand and pebbles. The Haney limestone locally grades laterally from limestone to greenish-gray shale. The Pennington(?) formation is a variable unit of gray and green shale, calcareous sandstone, and dolomite. At scattered localities where the shale beds of the Pennington(?) formation or the shale facies of the Haney formation form the uppermost Mississippian beds there is heavy iron staining, and variegated shades of red and purple replace the characteristic drab shades of green and gray. Presumably these shale beds were weathered during the pre-Pennsylvanian erosional interval.

Lower Pennsylvanian Rocks

The Lee formation of early Pennsylvanian age is composed dominantly of sandstone and shale but also contains some siltstone, thin coal beds and underclays. The formation ranges from 140 ft to nearly 200 ft in thickness. In the northern part of the district it consists chiefly of dark-gray shale with beds and lenses of quartzose sandstone. In the southern part the Lee formation is chiefly a massive cliff-forming sandstone unit overlying thin beds of shale and clay. The shale unit interfingers with and grades into the massive sandstone in a southerly direction. With few exceptions the thin coal beds and underclays are confined to the shale facies.

Sedimentary features of the Lee formation indicate that deposition took place in a coastal lowland characterized by periodic advances and withdrawals of shallow brackish or marine water. Well-developed cross-bedding in the sandstone facies suggests deposition in large coalescing deltas. The principal direction of cross-bed inclination in eastern Kentucky is to the west, indicating that the sand was introduced from the east. This conclusion, in general, conforms with those of students of early Pennsylvanian sediment transport (Potter and Siever, 1956; Siever and Potter, 1956; Fuller, 1955; Wilson and Stearns, 1957). The shale facies of the Lee formation seems to have been formed chiefly by the deposition of fine-grained sediments carried beyond the zones of deltaic sand accumulation. These sediments were deposited in the outer peripheral areas of large deltas, in areas of quiet shallow water (possibly lagoons) and in large coastal swamps that were located between the large deltas. Periodic submergence and emergence of the area are indicated by interbedding of continental deposits with marine or brackish water deposits. Thin coal beds and abundant plant remains, including roots, provide the evidence of continental environment and sparse faunas, chiefly small *Lingula*, indicate marine or more likely brackish water conditions of deposition.

THE OLIVE HILL FIRE CLAY BED OF CRIDER (1913) AND ASSOCIATED BEDS

The Olive Hill fire clay bed of Crider (1913) occurs 1–8 ft above the base of the Lee formation at most places but locally it is as much as 20 ft above the base. Because the Lee formation rests on the truncated surface of 10 thin Mississippian formations, the Mississippian beds that occur a short distance below the clay vary considerably in lithology from place to place. This relationship together with the variable characteristics of the Pennsylvanian beds below the clay has led to difficulties in prospecting for the clay and differences in opinion regarding its age. However, the position of the clay above the unconformity clearly establishes its age as Pennsylvanian.

Pennsylvanian Rocks Enclosing the Clay

Beds below the clay.—Lee formation beds below the clay consist of dark-gray shale, noncalcareous sandstone, and red, green, and yellow ocherous shale (Fig. 2). These rocks occur as lenses and discontinuous beds, and their aggregate thickness ranges from 1 to 20 ft. The dark-gray shale beds are typical Pennsylvanian shales and contain abundant tiny mica flakes and scattered imprints of plant fragments along bedding planes. The sandstone is essentially pure quartz, and it occurs in lenses ranging in thickness from 0 to 10 ft. Cross-bedding is common in the lower part, but the upper part, where it is in contact with the clay bed, is nonbedded, and *Stigmaria* are common. The varicolored ocherous kaolinitic shale beds ordinarily occur immediately below the clay bed, and in many places they are the only beds between the clay and the Mississippian rocks. Therefore, they could be easily

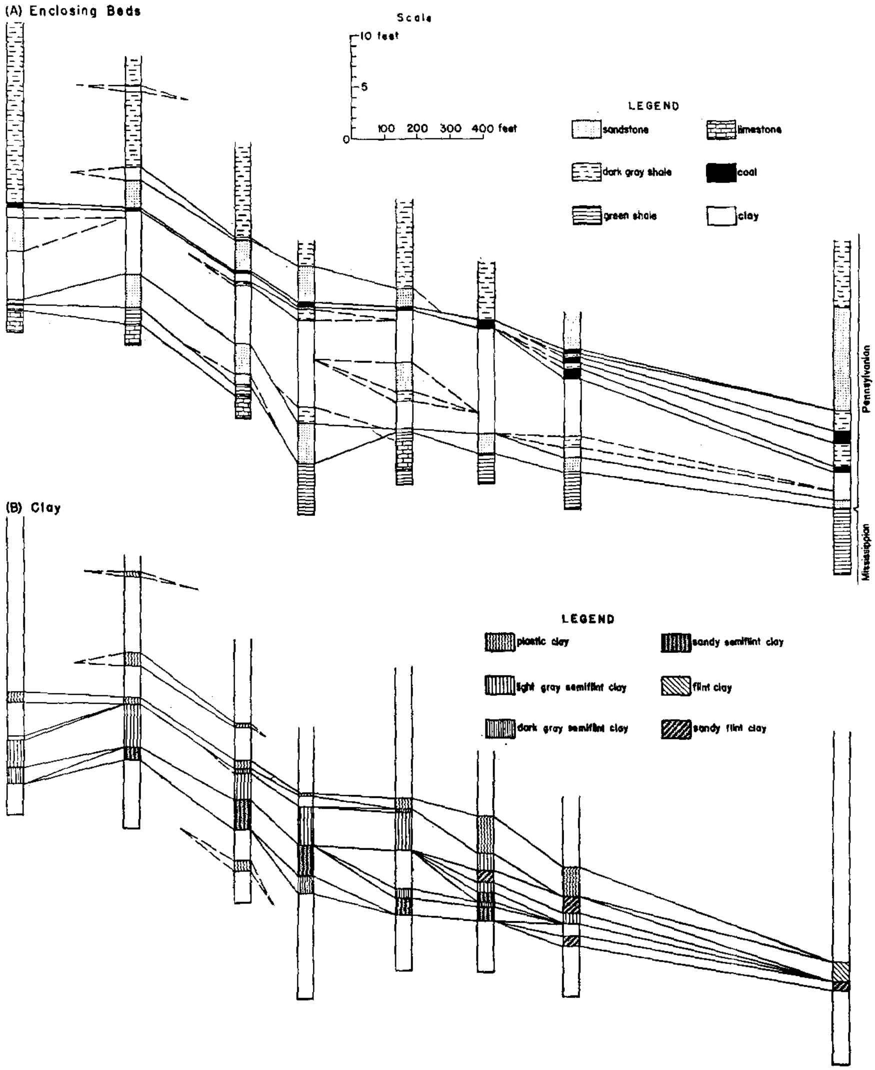

FIGURE 2.—Stratigraphic sections of the Olive Hill fire clay bed of Crider (1913) and enclosing beds at a locality near Haldeman, Kentucky.

misinterpreted as representing the geologic record of an ancient soil which formed on the pre-Pennsylvanian erosional surface. However, the sandstone and the dark-gray shale described above are present below the ocherous shale beds at many places, and they are clearly younger than the unconformity.

The contact between the Pennsylvanian beds below the clay with Mississippian strata is largely covered and can be recognized only at scattered outcrops and in drill core. Where the Pennsylvanian beds are sandstone or ocherous kaolinitic shale, and where the dark-gray shale rests unconformably on limestone, there is little difficulty in recognizing the contact. Exposures are particularly poor where the beds both above and below the contact are shale, but drill core of such strata reveal that the contact is marked in most places by a contrast in color and fossil content. Mississippian shale is green and contains a varied marine fauna, whereas Pennsylvanian shale is dark gray and contains plant remains.

Beds above the clay.—The Olive Hill fire clay bed of Crider (1913) is overlain by an exceedingly variable unit 20–40 ft thick which is composed of discontinuous beds and interfingering lenses of dark-gray shale, siltstone, clayey sandstone, quartzose sandstone, thin coal beds and plastic underclays. The clay bed is a true underclay because it is immediately overlain by a coal bed that averages about 4 in. in thickness but ranges from 0 to 10 in. This coal is in most places overlain by silty plastic underclay over which is another thin coal. In other places the coal is overlain by a dark-gray shale unit locally containing *Lingula*. Thin underclay and coal beds also occur locally higher in the variable unit. Many of the sandstones and siltstones in the upper part of the variable unit occupy basin-shaped depressions in underlying strata, and at a few places lenses of sandstone cut sharply through lower strata including the Olive Hill fire clay bed. These sandstone deposits appear to be channel fills and may represents the shifting distributaries in deltas. Not only are the beds in the variable unit irregular and inconsistent but the lithologies of the beds vary considerably. Some thin sandstone beds are essentially pure quartz. Other quartzose sandstone beds grade laterally into very clayey sandstone within short distances. In a few places oolitic siderite is common in the sandstone. Dark-gray shale units are the most persistent and uniform beds in the variable unit. Most of this shale consists of mixtures of fine-grained quartz and kaolinite, illite and mixed-layer clays.

The Clay Bed

The Olive Hill fire clay bed of Crider (1913) is a discontinuous bed consisting of irregularly shaped lenses (Fig. 3). Neither the lenses nor the areas in which the clay is missing show any regional alignment or preferred orientation. Maximum thicknesses of most lenses are less than 10 ft, but in one old mine, now inaccessible, the bed is reported to be 25 ft thick.

The irregular Olive Hill fire clay bed of Crider is itself composed of three types of clay in irregular nonbedded lenses of variable thicknesses and shapes (Fig. 2). About one-third of the bed is flint clay and the other two-thirds is chiefly semiflint clay with subordinate amounts of plastic clay, but all variations in hardness from flint to semiflint and from semiflint to plastic clay are present in different parts of the bed. Boundaries between one type of clay and another are ordinarily sharp. Such terms as "semihard, hard soft, semiplastic and number 2 clay," etc., are used by local miners for intermediate clays. Except for the superposition of one type of clay above another,

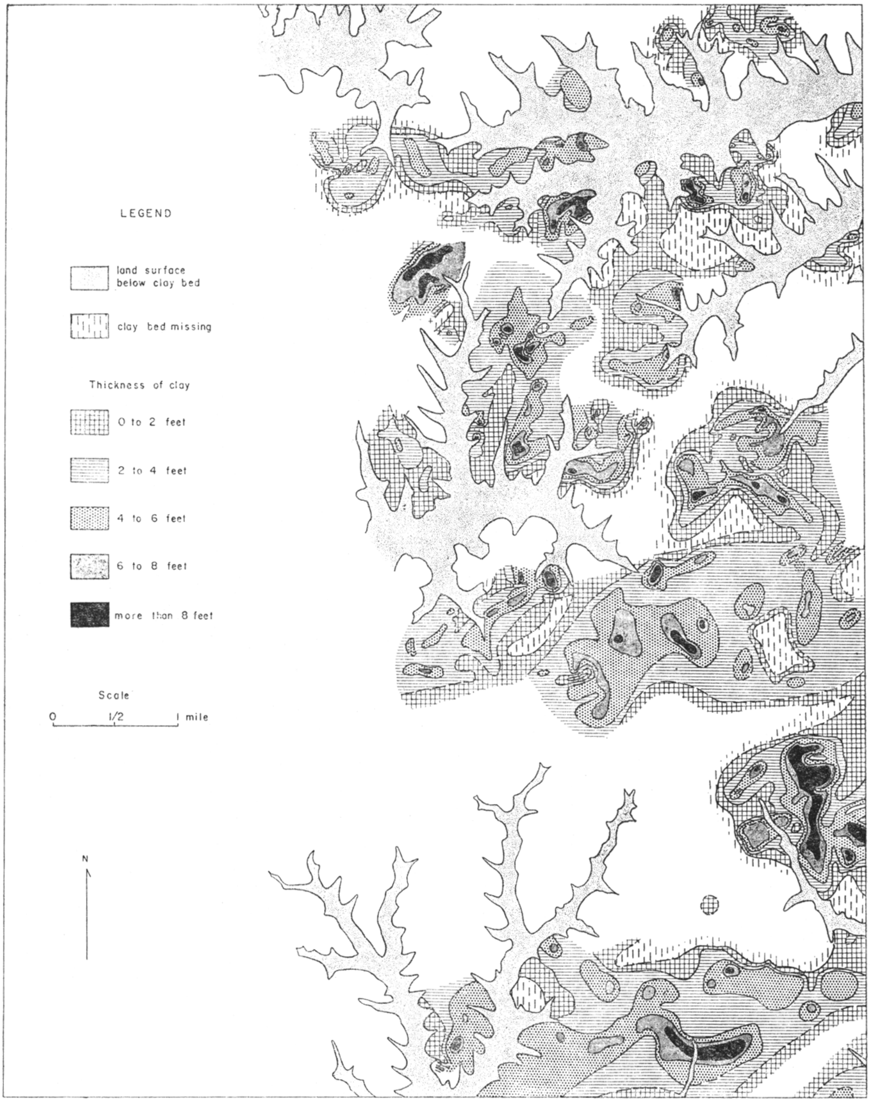

FIGURE 3.—Isopach map of the Olive Hill fire clay bed of Crider (1913), Haldeman quadrangle, Kentucky.

FIGURE 4.—*Stigmaria* from the Olive Hill fire clay bed of Crider (1913), showing main root stock with rootlets attached, pocket knife is 2½ in. long.

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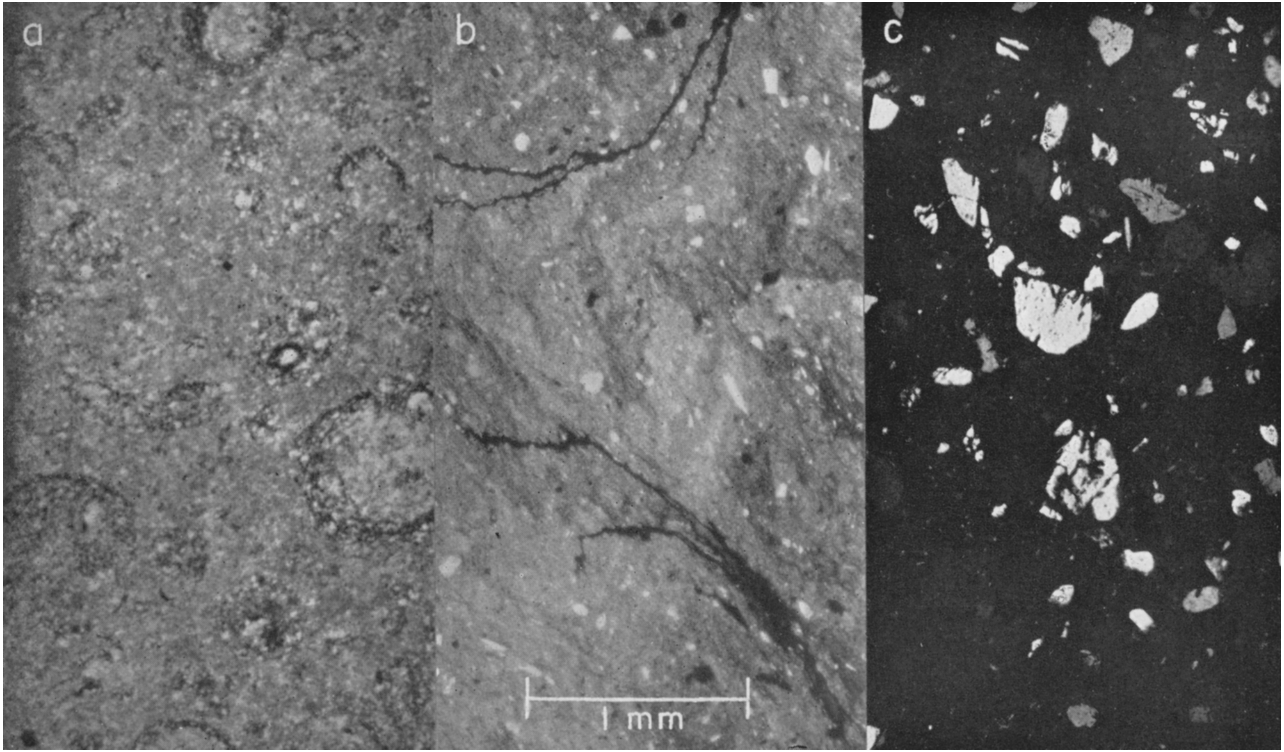

FIGURE 5.— Thin section photomicrographs of (a) oolitic flint clay, (b) silty semiflint clay, and (c) sandy flint clay.

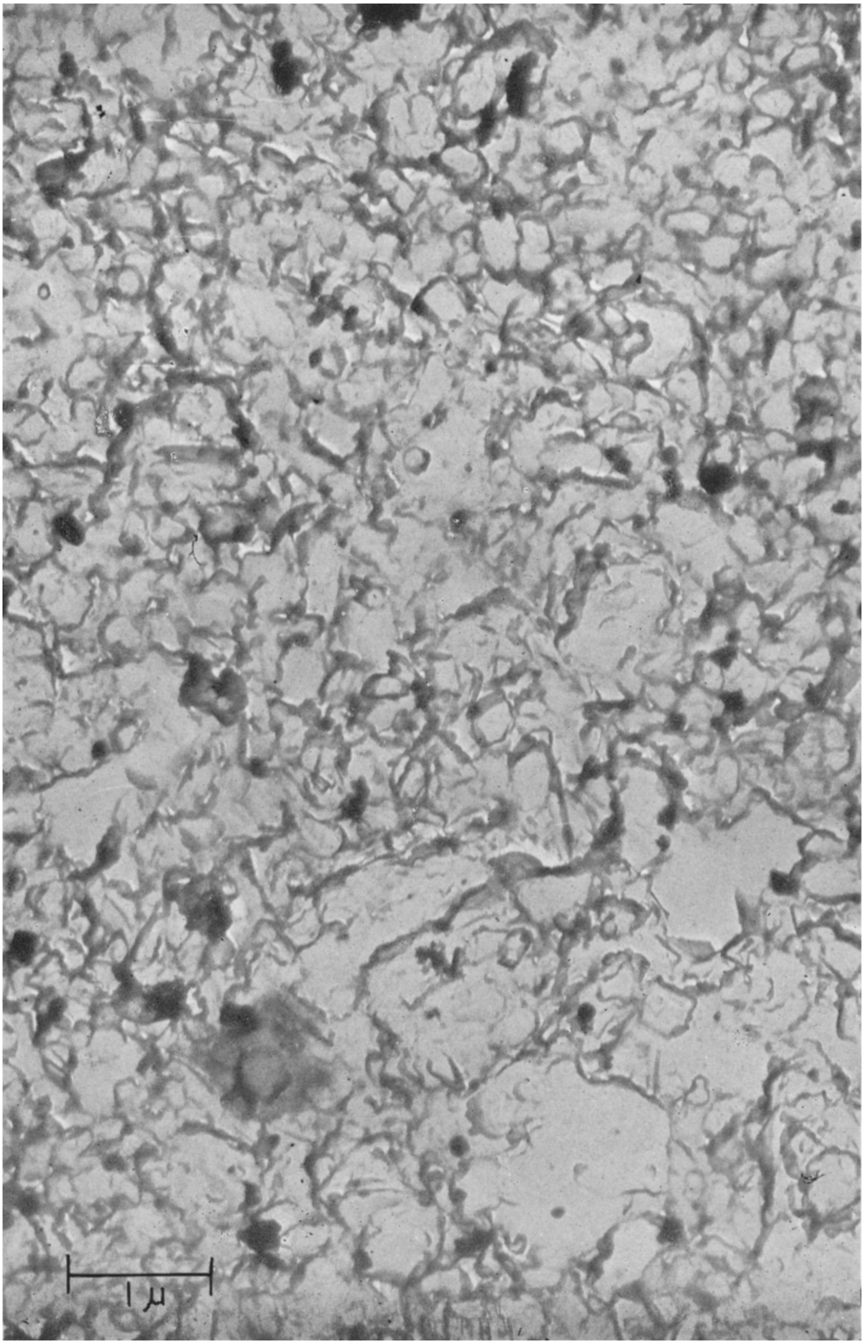

FIGURE 6.—Electron micrograph of carbon replica of flint clay

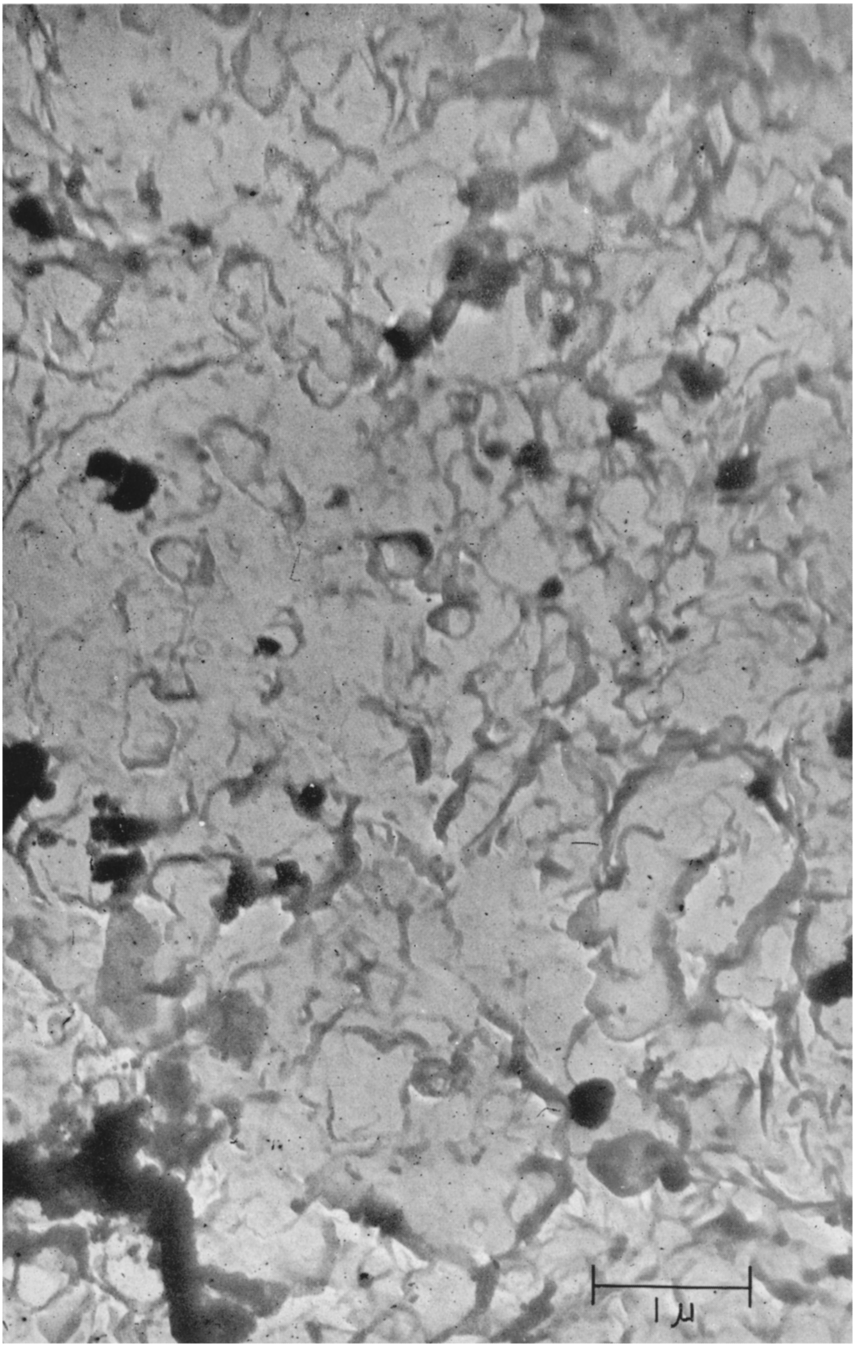

FIGURE 7.—Electron micrograph of carbon replica of semiflint clay.

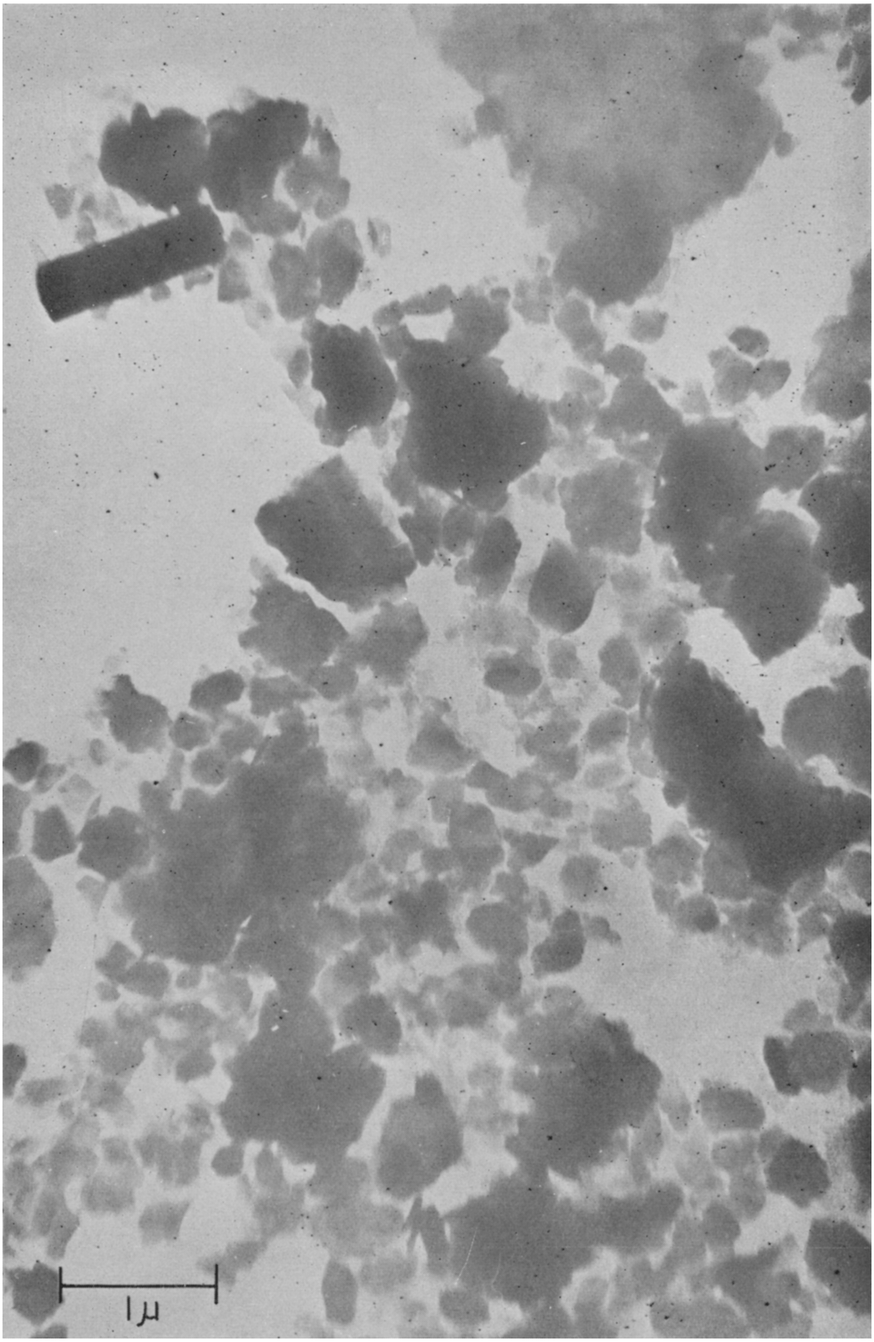

FIGURE 8.—Electron micrograph of flint clay particles.

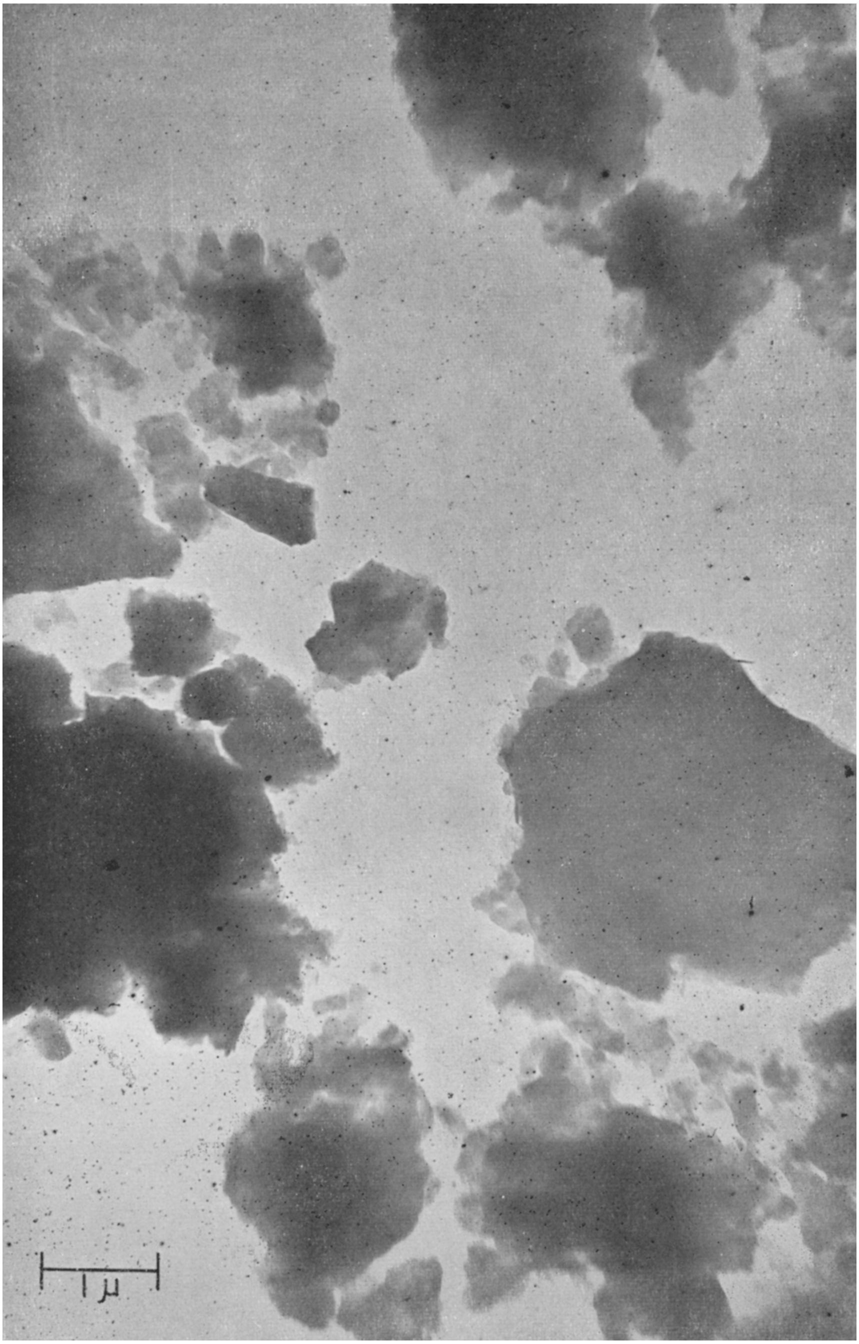

FIGURE 9.—Electron micrograph of semiflint clay particles.

the clay is essentially nonbedded. Typically the flint clay overlies semiflint clay, but at many places the order of superposition is reversed and at a few places the two types of clay occur repeatedly one above the other. Where plastic clay is present it ordinarily occurs in the uppermost part of the bed, but there are many exceptions to this generalization.

Colors, nonclay minerals, soluble salts, organic materials and fossils are similar in all three types of clays; the types of clay differ, however, in the type and crystallinity of the clay minerals and in certain physical properties such as resistance to high temperatures, hardness, plasticity, resistance to erosion and number of slickensides present. Most of the clay is medium gray to brownish gray, but colors range from very light gray to almost black. Rusty iron staining is common along joints and in weathered outcrops. Nonclay mineral contents range from trace amounts to more than 50 percent of very sandy portions of the bed, and lateral gradations from sand-free clay to very sandy clay within a few yards are common. Gypsum is the principal soluble salt present, and most of it is localized in crusts along joints. The plant root fossil *Stigmaria* is commonly preserved in all three types of clay in the form of carbonaceous films. Locally the main root stock with rootlets attached (Fig. 4) is preserved in flint clay but commonly only the detached rootlets remain. The carbonaceous films make up as much as 2 or 3 percent of the clay. The clay minerals in the clay are chiefly kaolinite, illite and mixed-layer clays.

In a general way the hardness of the clay varies directly with the amount of recrystallization of the kaolinite. Recrystallization of kaolinite in flint clay is indicated by light colored kaolinite grains sufficiently large to be seen under a petrographic microscope. These grains are scattered throughout an extremely fine-grained groundmass (Fig. 5(a)). A small amount of light-colored kaolinite occurs in vermicular crystals. Some kaolinite grains are inside oolites, but most of them are dispersed throughout the groundmass. Electron micrographs of flint clays (Fig. 6) indicate that the kaolinite grains are interlocking and angular, forming a texture somewhat similar to the texture of certain igneous rocks. No evidence of recrystallization of kaolinite in semiflint clays was observed in thin section (Fig. 5(b)) but in electron micrographs (Fig. 7) kaolinite grains appear much less angular and interlocked than in flint clays. No typical hexagonal kaolinite crystals were observed in either the carbon replicas (Figs. 6 and 7) or the powder electron micrographs (Figs. 8 and 9).

Flint clay.—The flint clay in the Olive Hill fire clay bed of Crider (1913) is a hard, resistant, nonplastic, refractory clay consisting chiefly of kaolinite. It possesses flintlike characteristics of homogeneity and conchoidal fracture, but it is distinctly softer than true flint (SiO_2). Most high-grade flint clay has a Mohs scale hardness slightly greater than 3, which decreases in the clay intermediate between flint and semiflint clay. Flint clay will not slake in water and has no plasticity unless very finely ground, and then plasticity is developed to approximately the same degree as similarly prepared quartz. Flint clay is sufficiently resistant to erosion to form small benches in stream beds. It weathers to angular blocks which, in turn, break down into shard-like fragments having sharply curved knife edges and pointed corners. Slickensides are extremely rare in flint clay. Oolites are very abundant in some of the flint clay but they are not present in all deposits. The best flint clay is composed of more than 90 percent kaolinite, but some illite or mixed-layer clay is always present. This conclusion is based on mineralogical evidence discussed on following pages and on chemical analyses (Table 1).

TABLE 1.—CHEMICAL ANALYSES AND PYROMETRIC CONE EQUIVALENTS OF FIVE SAMPLES FROM THE OLIVE HILL FIRE CLAY BED OF CRIDER (1913) AND THE COMPOSITION OF THEORETICAL KAOLINITE

	Theoretical Kaolinite[1]	Flint Clay	Flint Clay	Semiflint Clay	Semiflint Clay	Plastic Clay
SiO_2	46.54	44.6	45.0	44.7	45.8	46.4
Al_2O_3	39.50	37.8	38.2	37.6	35.1	34.0
Fe_2O_3	—	0.5	0.46	0.59	1.6	1.4
F O	—	0.20	0.19	0.22	0.34	0.41
MgO	—	0.06	0.13	0.16	0.45	0.69
CaO	—	0.04	0.06	0.06	0.06	0.11
Na_2O	—	0.12	0.06	0.09	0.19	0.24
K_2O	—	0.34	0.30	0.41	2.4	3.1
TiO_2	—	2.0	1.9	1.5	1.5	1.4
P_2O_5	—	0.00	0.01	0.03	0.01	0.02
MnO	—	0.00	0.00	0.00	0.01	0.00
H_2O	13.96	14.0	13.8	14.00	12.4	11.6
CO_2	—	0.09	0.05	<0.05	<0.08	0.26
Sum	—	99.00	100.00	99.00	100.00	100.00
SO_3	—	tr.	tr.	tr.	<0.03	tr.
Pyrometric cone equivalent	—	35	34+	34+	32−	32+

[1] Grim, 1953, p. 47.

Chemical analyses by S. D. Botts, M. D. Mack, J. H. Goode under the supervision of W. W. Brannock, U.S. Geological Survey.

Pyrometric cone equivalents by Richard West and Leon B. Coffin, Department of Ceramic Research, Alfred University, Alfred, N.Y.

These analyses show flint clays are very similar in composition to theoretical kaolinite but that some of the alkali constituents of illite and mixed-layer minerals are present. Pyrometric cone equivalents (P.C.E.) of high-grade flint clay range from 34 to 36 (1760°–1810°C).

Semiflint clay.—Semiflint clay is intermediate between flint and plastic clay in physical characteristics and clay mineral composition. It has a Mohs scale hardness between 2 and 3, and it possesses very little natural plasticity except when finely ground. Nearly all semiflint clays contain abundant slickensides at all angles. Parting occurs mostly along the slickensides, and commonly when fresh semiflint clay is subjected to a single rainfall it breaks down into a rubble of irregular polyhedra having a slickenside on each face. Most semiflint clays are rarely seen in natural outcrops, except where they are protected by overlying flint clays or other resistant beds. However, some of the harder semiflint clays, which are gradational into the flint clays, are remarkably resistant to weathering. A good example is the semiflint clay that for many years has supported the footing of the bridge on State Highway 32, $\frac{1}{4}$ mile west of Elliotville, Kentucky.

The semiflint clays consist chiefly of mixtures of kaolinite, illite, and mixed-layer minerals, and the kaolinite present in the clay generally ranges from 60–80 percent or a little more. The P.C.E.'s of semiflint clays are mostly in the range 31–33 (1680°–1745°C) and these clays are distinctly lower in heat-resisting properties than good quality flint clay. In a few places semi-flint clays are very refractory and P.C.E.'s are as high as 34+ (Table 1). The refractory properties of most semiflint clays are lower than those of flint clays chiefly because of higher contents of alkali-bearing clay minerals in the former.

Plastic clay.—Plastic clay consists of mixtures of kaolinite, illite and mixed-layer minerals. Weathered plastic clay readily develops considerable plasticity when wet, but some grinding is required to develop maximum plasticity in the fresh clay. Abundant slickensides are present in the fresh plastic clay, but when it becomes wet the slickensides are sealed and it becomes a homogeneous mass. Natural exposures of plastic clay are exceedingly rare because it is soft and lacks resistance to weathering. Only a small amount of plastic clay is present in the Olive Hill fire clay bed of Crider (1913). The few samples examined were very similar in mineralogical composition to the poorer quality semiflint clays. The content of illite and mixed-layer minerals was high and, accordingly, the alkali content should be high and refractory properties should be relatively low.

Mineralogy of the Clay

Clay minerals.—The mineralogy of the Olive Hill fire clay bed of Crider (1913) was interpreted primarily from x-ray diffraction traces. Investigations of selected samples were also made by differential thermal analysis, electron microscope, and chemical analysis. The diffraction traces of oriented and random specimens for each sample were obtained using Cu K_α radiation. Each oriented specimen was x-rayed in the dry state, after treatment with ethylene glycol, and after heating to 300°C for 30 min.

Kaolinite is by far the dominant clay mineral in the Olive Hill clay bed of Crider (1913), and in places it makes up as much as 90–95 percent of the bed. The kaolinite in the flint clay is predominantly well crystallized. In the plastic and in some semiflint clay, the kaolinite has a poor degree of crystallinity similar to the " fireclay " kaolinite mineral of Brindley and Robinson (1947). Intermediate stages of crystallinity are present in most semiflint clays. Recognition of well-crystallized kaolinite is based on the narrow 001 reflection at 7.1 Å and the sharp resolution of reflections from the pyramidal and prismatic planes (Fig. 10). Poorly crystallized " fireclay " kaolinite gives

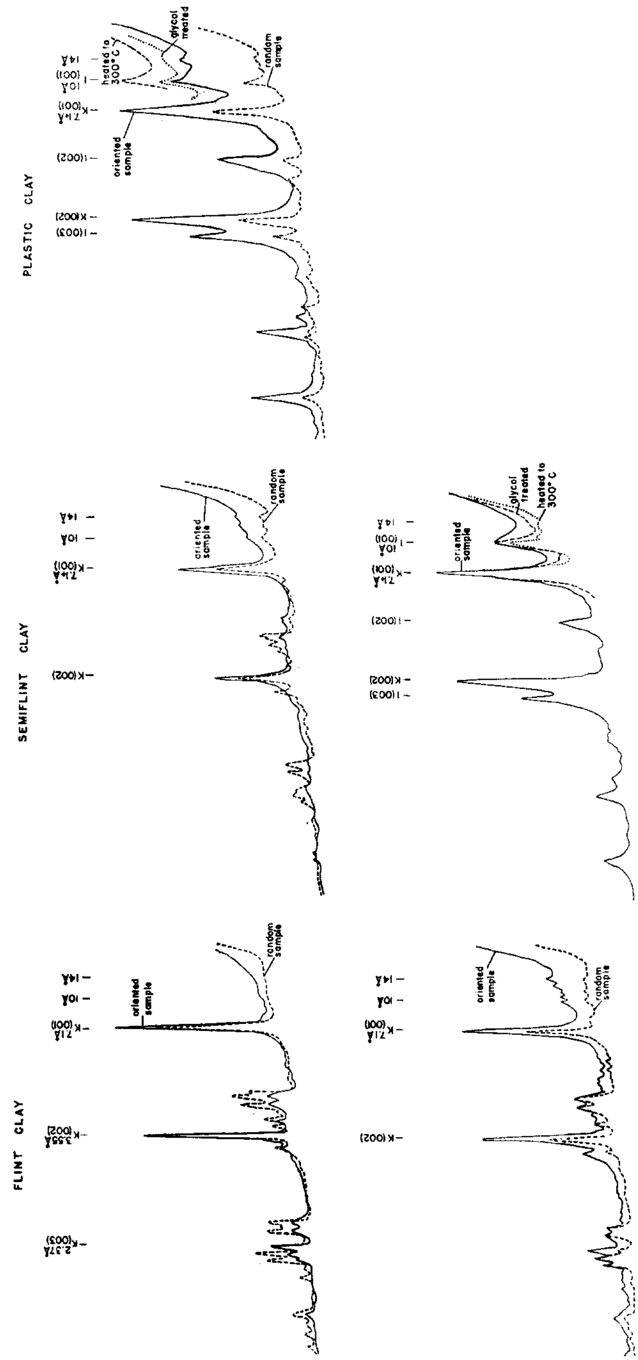

FIGURE 10.— X-ray diffractometer traces (CuKα radiation) of flint, semiflint and plastic clays from the Olive Hill fire clay bed of Crider (1913).

a broad 001 reflection at slightly greater than 7.1 Å and the reflections from the pyramidal and prismatic planes are diffuse. The degree of crystallinity of the kaolinite varies with the proportions of other clay minerals present in the clay. The well-crystallized kaolinite occurs only in clays that contain very small amounts of other clay minerals, and therefore it is restricted to the flint clays. Poorly crystalline "fireclay" kaolinite occurs only where appreciable amounts of illite and mixed-layer clays are also present. Kaolinite having intermediate crystallinity occurs in both the flint and semiflint clays with small amounts of illite and a mixed-layer mineral. Nonclay minerals have no relation to the crystallinity of the clay, and well-crystallized kaolinite occurs in parts of the bed containing as much as 50 percent quartz. The conclusions regarding the crystallinity of the kaolinite are based on the criteria outlined by Brindley (1951, pp. 46, 50–52). Our conclusions closely parallel those of Keller, Westcott and Bledsoe (1954, p. 19) and McConnell, Levinson and de Pablo-Galan (1956, p. 279) who studied similar clays.

Differential thermal analysis curves, not illustrated in this report, support the conclusion of variations in crystallinity deduced from x-ray examinations. The endothermic peak due to loss of hydroxyl is between 610° and 620°C for the well-crystallized kaolinite of the flint clay and between 590° and 600°C for the poorly crystallized kaolinite in plastic clay. The endothermic peak of most of the semiflint clay, which has an intermediate degree of crystallinity, is between the ranges of the flint and plastic clay.

Illite, in this report, is applied to a dioctohedral clay-size mica commonly referred to by some authors as hydrous mica. This clay mineral is the second most common clay mineral in the Olive Hill fire clay bed of Crider (1913). Amounts present range from a trace in the flint clay to about 40 percent in plastic and the softer semiflint clays. Only the material that does not expand when treated with ethylene glycol (Fig. 10) is considered to be illite; if there is some expansion, the material is then considered to be mixed-layer clay.

Complex mixed-layer minerals are closely associated with the illite. Some of these minerals resemble montmorillonite because there is a slight increase in the 14 Å reflection when samples are treated with ethylene glycol. Montmorillonite-like layers are most common in plastic and softer semiflint clays (Fig. 10). Other mixed-layer clays consist of heterogeneous mixtures of minerals resembling chlorite, montmorillonite and probably vermiculite. x-ray traces of these clays have broad irregular bulges in the 10 Å to 14 Å range, and reflections are changed very little by heat or ethylene glycol treatments. Heterogeneous mixed-layer assemblages occur only in small amounts. They are probably present in all types of clay, but they are most abundant in the softer flint and harder semiflint clays.

Nonclay material.—The material other than clay minerals in the Olive Hill fire clay bed of Crider includes allogenic minerals that were introduced during deposition of the clay, authigenic minerals that formed after deposition of the clay, and organic matter. The allogenic minerals—anatase, zircon, tourmaline, garnet, ilmenite and magnetite—occur only in trace amounts, but quartz is present in proportions ranging from traces to 50 percent. Angular and rounded quartz grains range in size from very fine silt to medium sand. The quartz in the plastic clays and semiflint clays occurs as clear and frosted grains, but little evidence of solution or replacement was observed. Many of the quartz grains in flint clays, however, show evidence of leaching inasmuch as their boundaries are serrated and etched, and many grains are partly replaced by clay minerals (Fig. 5(c)). The clay replacements of quartz could not have withstood vigorous transportation, a fact which strongly suggests that the leaching occurred in place. The most abundant authigenic mineral is siderite which occurs, in amounts up to 10 percent, as small euhedral crystals and spherulites. At one locality near Leisure, Kentucky, siderite is in the form of nodular concretions as long as $\frac{1}{2}$ in. Other authigenic minerals that occur in minor amounts are pyrite, iron oxide minerals and soluble salts (of which gypsum and iron sulphates are common). Traces of galena and sphalerite have also been reported from the clay bed. The pyrite occurs as small crystals and films and probably was precipitated along organic films which were formed by the carbonization of *Stigmaria* rootlets. Presumably the reported galena and sphalerite occur in a manner similar to that of the pyrite. The iron oxide minerals include limonite, hematite and lepidocrosite; they occur as films along joints and as very finely disseminated particles causing red, brown and yellow discoloration of the clay.

The nonclay minerals have varying effects on the refractory properties of the clay. Quartz is relatively inert and acts as a diluent, and therefore amounts less than 5 percent have little effect on the refractory properties of the clay. Minerals containing iron, calcium, titanium, sulfur and other metals and alkalies act as fluxes, and very small amounts will greatly decrease the refractory properties of the clay. Organic matter burns off during firing of the brick, and has little or no effect on the refractory properties if the evolving gases are allowed to escape gradually before the exterior of the brick vitrifies.

Texture of the Clay

The textures of the three types of clays were examined by petrographic and electron microscope, and also by x-ray diffraction from slices of clays. Electron micrographs were taken of powder samples of plastic, semiflint and flint clays and of carbon replicas of flint and impregnated semiflint clays. The carbon replicas were prepared according to the procedure outlined by Bates and Comer (1955). The slices for the x-ray investigations were cut from samples on which the orientation had been recorded in the field. Slices of flint clays were cut horizontal and vertical east–west and north–south. Slickenside surfaces of the semiflint clay and slices cut at angles to slickensides were also examined. Interpretation was based on the assumption that orientation of the clay minerals would give intense basal and subdued prism reflections similar to those from mounts prepared by settling, and intense prism and subdued basal reflections would be indicative of random distribution of clay minerals.

The kaolinite grains in flint clay lack preferred orientation; some of the kaolinite grains in semiflint clays are aligned parallel to slickenside surfaces, and much of the illite and mixed-layer clays in semiflint and plastic clay is partially oriented. The evidence for lack of kaolinite orientation in flint clay is based on the x-ray diffraction traces of oriented slices. In the traces, the basal reflections from kaolinite are no higher in slices from one direction than any other and the prism reflections are resolved equally well in traces of slices in all directions. Lack of orientation is also shown in the electron micrograph of flint clay (Fig. 6). x-Ray diffraction traces of semiflint clay slices cut at angles to slickensides are similar to those from flint clay showing general haphazard orientation. Also, no evidence of kaolinite orientation is present in the electron micrograph of semiflint clay (Fig. 7). However, basal reflections from kaolinite are more intense in traces from slickenside surfaces from semiflint clay than from slices cut at angles to the slickenside. Apparently some of the kaolinite grains are oriented parallel to slickensides.

Some of the illite and mixed-layer clay in thin sections of semiflint clays appear to be partly oriented into wavy distorted bands (Fig. 5(b)). Some of these partly oriented illite and mixed-layer clay bands extend along slickensides, and others are enclosed in clay showing no evidence of parting or movement. Apparently some slickensides form along zones of weakness caused by partial orientation of clay grains and very little force or movement is required to form a parting that has a shiny surface. Little geologic evidence pertaining to the origin of the bands is available, but they may represent mineral orientation by pressures related to the churning action of roots or plastic flowage.

Origin of the Clay

Stratigraphic, paleontologic, mineralogic and chemical evidence all support the conclusion that the clay deposits in the Olive Hill fire clay bed of Crider formed by the alteration of ordinary fine-grained Pennsylvanian sediments in acid swamps. Some of the facts and observations pertaining to the origin of the clay are as follows:

(1) The clay is a true underclay as indicated by (a) the thin overlying coal bed, (b) abundant fossil plant roots, *Stigmaria* (Fig. 4), in the clay, including main root stocks with rootlets attached, (c) lack of bedding in the clay, (d) abundant slickensides in semiflint and plastic clays.

(2) Root fossils indicate that the clay supported plant growth and therefore served as a soil; however, evidence for a soil profile in the clay is lacking.

(3) The clay bed is discontinuous and consists of irregularly shaped lenses having no preferred orientation.

(4) Essentially all the clay is acid according to pH measurements of 40 samples by Patterson and Hosterman. Of these samples 2 were neutral and 38 were acid ranging down to pH 3.9.

(5) The kaolinite, illite and mixed-layer clay minerals in plastic clays are similar to clay mineral assemblages in Pennsylvanian shales enclosing the

clay bed. Schultz (1958, pp. 363, 377, 378) also observed close mineralogic relationships between several plastic underclay beds and enclosing shales.

(6) Proportion of kaolinite increases gradually from plastic to flint clay, and this increase is accompanied by a corresponding decrease in the amounts of illite and mixed-layer clays present.

(7) Recrystallization of the kaolinite in flint clay is indicated by interlocking grains and by comparatively light-colored large kaolinite grains in a dark-colored very fine-grained groundmass. Semiflint and plastic clays show little evidence of recrystallization.

(8) Some of the quartz grains in sandy flint clays are fresh but others show evidence of solution and replacement by clay (Fig. 5(c)).

(9) The clay bed contains essentially no feldspar.

(10) The titania contents of most flint clays are about 2 percent, semiflint about 1.5 percent and plastic clay from 1 to 1.5 percent.

The shapes of the irregular lenses of clay, relations of lithologic units within the bed, fossil roots, absence of soil profiles, lack of bedding, overlying coal and marine or brackish water fossils in the dark shale above the clay all point toward origin of the clay in coastal swamps. Clearly the irregularly shaped lenses of clay lack the orientation, continuity and bedding that would be expected if they (a) formed by dissection of a blanket of sediment, (b) accumulated in channels, as in certain kaolin deposits of Tertiary age in Mississippi (L. C. Conant, written communication, 1958), or (c) formed in cut-off stream meanders as has been suggested for the kaolin deposits in Georgia by Kesler (1956, p. 553). The irregular shapes and lack of orientation of the clay lenses, however, would be expected if the deposits accumulated in swamps in which bodies of water were irregular in shape and depth. Further evidence that the clay deposits formed in swamps lies in the root fossils in the clay and the overlying coal, remarkably in accord with the invasion of modern swamps by plants and the accumulation of peat in modern swamps described by Twenhofel (1939, p. 79). The best explanation for the absence of a soil profile seems to be that none developed because the clay was waterlogged at the time it served as a soil. The lack of bedding in the clay is probably due to the churning action of roots and plastic flowage. The lateral gradation from essentially pure clay to very sandy clay appears to be similar to the decrease in grain size away from shore in sediments in modern swamps diagrammed by Twenhofel. A sparse fauna, chiefly small *Lingula*, in the shale a short distance above the clay, with no unconformity between, suggests that only slight subsidence was required to lower the clay below sea-level. This, in turn, suggests that the swamps were located along coastal lowlands, a possibility that seems in accord with the evidence for deltaic deposition in the sandstone facies of the Lee formation.

The clay appears to have formed by the leaching and alteration of ordinary fine-grained Pennsylvanian sediments in acid swamps, a theory similar in some respects to those proposed by Keller, Westcott and Bledsoe (1954) and McMillan (1956). Inasmuch as the clay minerals in plastic clay do not differ greatly from those in the Pennsylvanian shales enclosing the clay bed, there is no reason to assume that special sedimentary sorting processes were involved. The three types of clay, of which plastic clay is the least and flint clay the most altered, can be explained by progressive stages of leaching. According to this theory kaolinite formed after the removal of alkalies and silica from illite and mixed-layer clays and certain nonclay minerals. Leaching of the clay is indicated by both direct and indirect evidence, but unfortunately there is little evidence to support the idea that kaolinite formed from other clay minerals, and nothing to reveal what happened to the dissolved materials. The etched quartz grains and their replacement by clay minerals are convincing evidence that leaching took place. Also, the absence of feldspar, which is common in many underclay beds, is suggestive of leaching. The increase in titania from plastic clay to flint clay seems to represent an expected increase in resistates with leaching. The root fossils provide still another line of indirect evidence for they clearly indicate that the clay supported plants, and alkalies and perhaps silica would be removed from any material which served as a soil. Perhaps most of the leaching took place by an attack of acid swamp waters on sediments lying on the floors of swamps. The materials removed by the leaching process were flushed away by sluggish movement of water through the swamps. The acidity of the swamps is indicated by the present acid characteristics of the clay, the overlying coal, and by organic materials scattered throughout the clay. A weak suggestion that kaolinite formed from other clay minerals lies in the relationship of crystallinity of the kaolinite and its proportions to other clay minerals in the three types of clay. In plastic clay, the kaolinite is a poorly crystallized " fireclay " variety, and its proportions to other clay minerals are low. The flint clay is essentially pure kaolinite that is well crystallized. In the semiflint clay, the perfection of the kaolinite structure as well as the proportions present are intermediate between plastic and flint clay. This progressive increase in the perfection of the kaolinite structure accompanying a decrease in the amount of other clay minerals seems more than a coincidence.

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