Clay and Shale
Resources of Indiana

BULLETIN 42-L

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Clay and Shale Resources of Indiana

By GEORGE S. AUSTIN

DEPARTMENT OF NATURAL RESOURCES
GEOLOGICAL SURVEY BULLETIN 42-L

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Introduction

Indiana contains extensive clay[1] and shale units (pl. 1) which are used in manufacturing various products ranging from bricks and ceramic garden ware to ceramic insulators. This ceramic industry has existed since the early part of the 19th century. Although the population of Indiana has increased, the quantity of some ceramic products used in the state has remained nearly constant or has decreased since the beginning of the 20th century. Wood, plastic, and concrete have replaced structural clay products in some segments of the construction industry. Plastics have noticeably cut into the markets for clay draintile, stoneware, and pottery. But many new products, such as pre-formed brick panels, have offset the reduction in demand for more traditional clay products. Because many of the new products require raw materials that meet more exacting standards than existed only a few years ago, known deposits of clay and shale are being reexamined and new sources are constantly being sought.

This report discusses the clay and shale resources of Indiana—their location, quality, mineralogy, and usefulness—and the history and future of the ceramic industry of the state. For more detailed information the reader is urged to consult the selected bibliography at the end of this report. Of special interest is "Clay and Shales of Indiana"

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[1]The term "clay" is ambiguous because it is used as a rock term and as a particle-size term in the analysis of rocks and soils and also has mineralogic connotations. As used in this report, *clay* or *clay material* is defined as a natural fine-grained earthy material composed largely of a group of crystalline compounds known as clay minerals. *Clay-size particles* are those particles with a maximum diameter less than 1/256 mm, or less than 0.00015 inches, regardless of the mineralogy; however, most are clay minerals. Shale also consists largely of clay minerals but in addition occurs in beds in nature and is distinctly laminated or layered.

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(Harrison and Murray, 1964), which summarizes the geologic, chemical, and ceramic data for all the clay-rich units—the data on which much of the material in this report is based.

History of the Clay Industry of Indiana

Little is known of the beginnings of the clay industry of Indiana. The earliest records are from the 1830's and most of them concern potteries. Owen (1839) reported finding a pottery employing 40 potters near Troy in Spencer County when he visited the area in 1837. Esarey (1924) reported that other large potteries had been established near Bloomingdale in Parke County in 1840, at Loogootee in Martin County in 1842, at Clay City in Clay County in 1846, and in many other communities in southwestern Indiana.

In the early 19th century brick structures were common in nearly every town in Indiana (Scott, 1833). These buildings were constructed of bricks made from local clay and burned at the site by traveling craftsmen (Austin and Patton, 1972). By the 1840's and 1850's most itinerant brickmakers were gone and nearly every small community had its own brickyard. Some brickyards in this early period were very large, especially in Clay County, where Esarey (1924) reported that a Dr. Mansur Wright of Brazil produced as many as 40,000 bricks per day in 1869.

The ceramic industry continued to grow and reached its zenith in the number of plants and persons employed in the decade just after the turn of the century. By 1904 there were more than 350 ceramic plants in Indiana (fig. 1). The value of the output of all ceramic plants in Indiana was $6,085,000 and the number of employees was 7,374 (Blatchley, 1905). Indiana's ceramic products were shipped as far away as Montana, Georgia, and Alabama. Ten years later, in 1914, there were 231 factories in Indiana employing only 5,512 persons making ceramic products, but the value of the wares was $8,605,000 (Esarey, 1924). Whitlatch (1933) reported that the number of plants in 1929 had dropped to 87 but that these plants employed 5,746 persons and the value of their products had risen to $18,976,977. In subsequent years the number of plants has continued to shrink; how-

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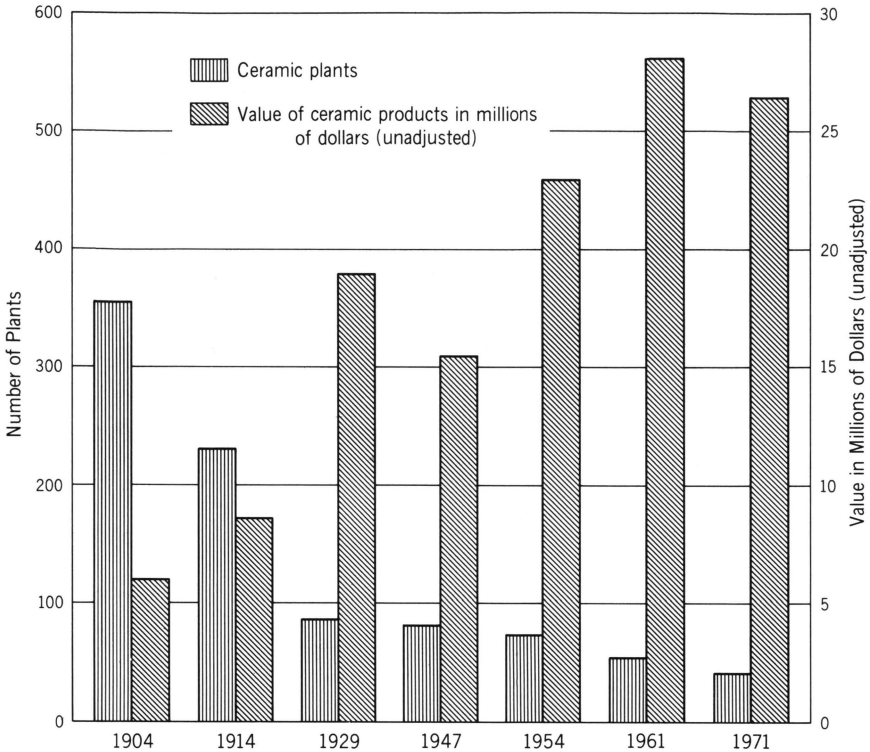
Figure 1. Number of ceramic plants and value of ceramic products in Indiana.

ever, the value of the products has increased, at least until the last decade. The total value of products manufactured from clay and shale in 1961 in Indiana was $28.1 million (Klyce and Fox, 1962). In the last half of the 1960's and early 1970's the total value of clay products in Indiana remained about the same; in 1971 the value was $26.4 million.

The quantity of structural clay products used in Indiana, such as brick, sewer pipe, and draintile, has remained nearly static since the early part of the 20th century. With increasing population, this reflects the increasing use of other materials in place of clay products. Although such products as common brick and paving brick formerly made up a large part of the market of ceramic materials, today the use of common brick, or brick used to add structural strength within walls, has been drastically reduced. The production of face brick has
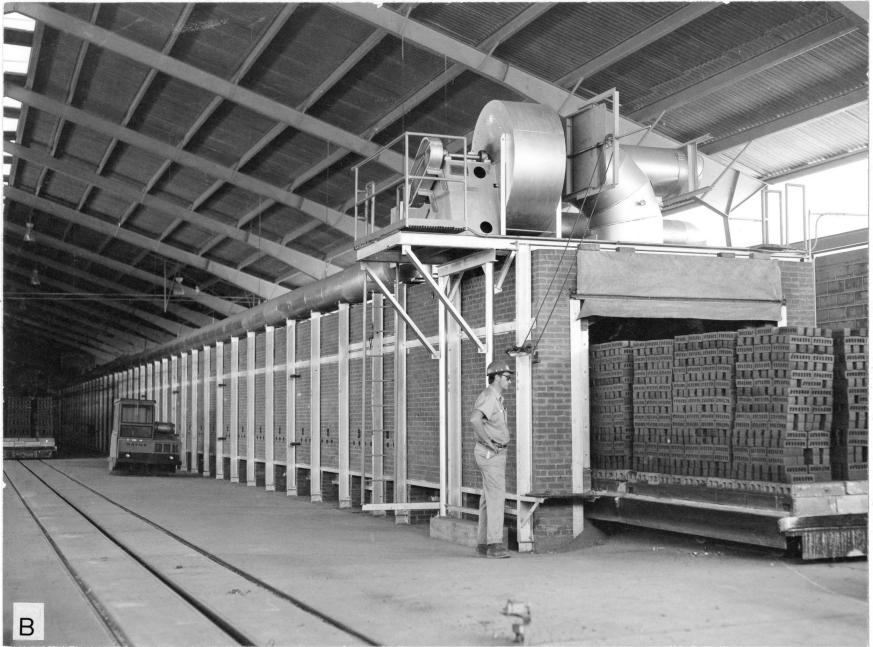
expanded but not enough to offset the reduction in demand for common brick. The use of paving brick has all but disappeared.

The number of ceramic plants in Indiana has decreased partly because of the efficiency of larger plants. Round periodic kilns fired by coal or natural gas are being replaced by continuously fired, large-capacity tunnel kilns (figs. 2A and 2B). Also, improved transportation has aided larger plants in extending their market areas at the expense of smaller plants. For the same reasons, however, plants outside Indiana have been able to expand into the state and replace local industry.

In response to the decline in the use of traditional clay products, the industry has developed new products and new techniques. Two key developments illustrate this point: The use of expanded-shale lightweight aggregate in concrete in the last few decades has created a new use for shale, and the development of pre-formed brick panels which are assembled at the factory and hoisted into place on the job site has revitalized the brick industry by giving it a new way to market a product.

Today fire clay, or clay capable of withstanding a high heat without melting, is produced in five counties in southwestern Indiana and is used in manufacturing heavy clay products and floor and wall tile. Small quantities are used in manufacturing stoneware, refractories, and art pottery. In 1970 about 75,000 tons of fire clay, with a value of $202,000, was produced in this area (Brown, 1972). Miscellaneous clay, which includes all other clays, is mined in 21 counties in Indiana and is used chiefly in manufacturing cement, lightweight aggregate, brick, sewer pipe, and draintile. In 1970 about 1.3 million tons of miscellaneous clay, with a value of $1.94 million, was mined in Indiana (Brown, 1972).

Figure 2 (*on facing page*). *A,* Round periodic kiln, Indiana State Farm, Putnam-ville, Putnam County. *B,* Continuously fired tunnel kiln, General Shale Co., Mooresville, Morgan County.
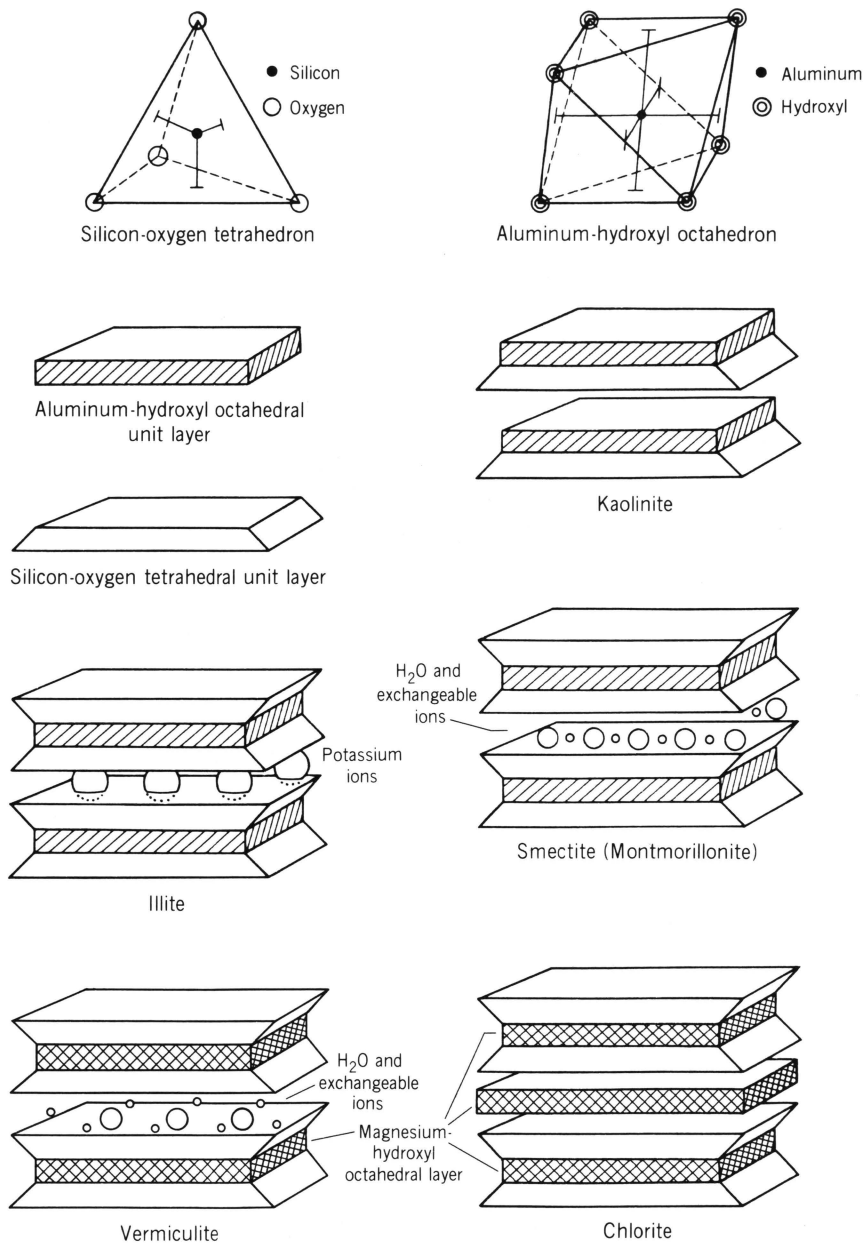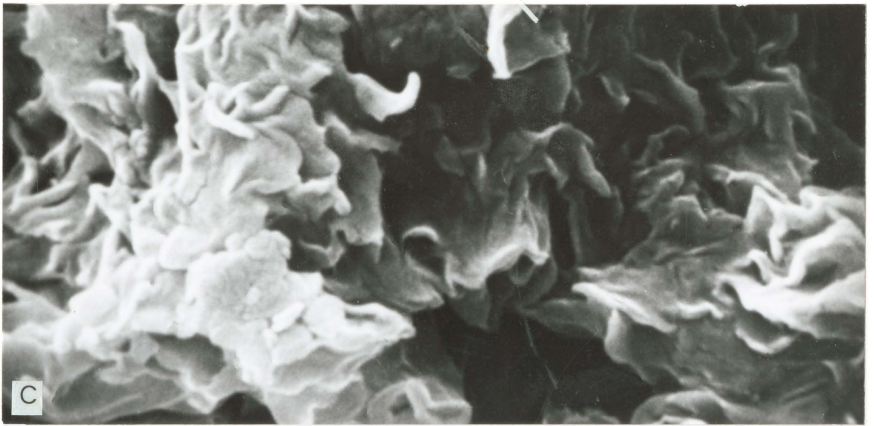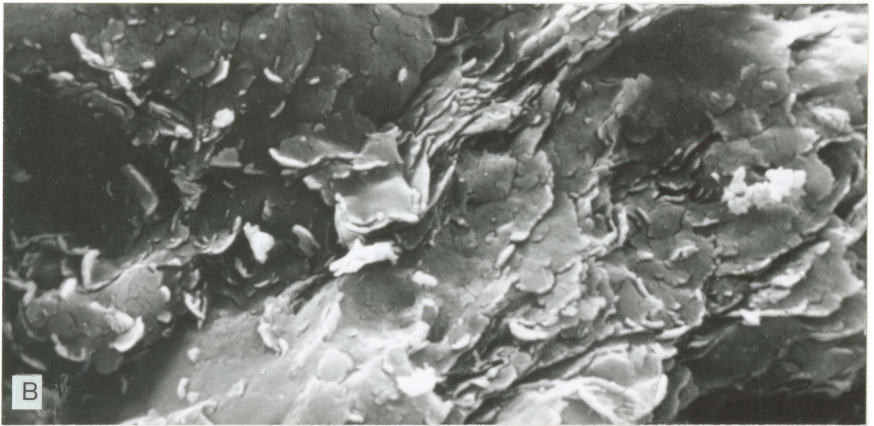
Figure 3. Diagrams of silicon-oxygen tetrahedron and aluminum-hydroxyl octahedron, which are the fundamental building blocks of most clay minerals, and schematic representations of crystal structures of major clay mineral types. Modified from Harrison and Murray, 1964, fig. 1.

Clay Minerals

Clay minerals consist of groups of hydrous aluminum, iron, and magnesium silicates that may contain calcium, sodium, potassium, or other ions. Two types of structure are found in clay minerals: layer and chain. The layered structure is more common. Clay minerals with this type of structure are composed of two fundamental sub-units: the silicon-oxygen or tetrahedral layer and the aluminum-hydroxyl (or magnesium-hydroxyl) octahedral layer (fig. 3). The layers are joined by the substitution of some hydroxyl anions of the octahedral layer for some oxygen anions of the tetrahedral layer, so that the hydroxyl anions are shared between the layers. The resulting layered sheet structure, while bonded relatively firmly within the structure, is weakly bonded to other layered sheets, thereby accounting for the softness, plasticity,[2] and many other special properties of many clay minerals. Clay minerals with chain-type structure are composed of the same kinds of atoms, but these atoms are joined together to form fibers rather than sheets. Clay minerals with this type of structure have properties that are distinctly different from those minerals with sheet structure.

Clay minerals with sheet structure are classified in part by the number of layers. The kaolin group has a simple two-layer structure (fig. 3). The smectite and illite groups are composed of three layers with an octahedral layer between two tetrahedral layers. Some members of these groups have magnesium- (and/or iron-) hydroxyl layers substituting for aluminum-hydroxyl layers. The illites are nonexpand-able; that is, they retain their structural dimensions even when exposed to water or certain organic compounds. Large cations, notably potassium, bond one three-layer sheet to the next. On the other hand, in the smectite group this intersheet position is occupied by zero to two layers of water and (or) certain organic compounds together with some cations and provides little bond strength from sheet to sheet. Members of the smectite group, which are also identi-fied as montmorillonites, therefore swell and contract with relative ease, depending on the presence of these intersheet materials.

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[2]The property of moistened material to be deformed under the application of pressure, with the new shape being retained when the deforming pressure is removed.

| Regular mixed-layer crystallite | Homogeneous | Inhomogeneous |

Random mixed-layer crystallites
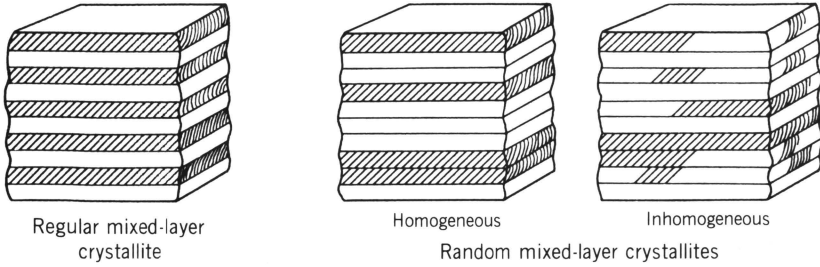
Figure 5. Schematic representations of regular and random types of mixed-layer clay mineral crystallites. Modified from Harrison and Murray, 1964, fig. 2.

Vermiculite is also an expandable clay mineral but consists of a three-layer sheet of two tetrahedral layers and a middle magnesium- (and/or iron-) hydroxyl octahedral layer which alternates with a zero- to two-layer water unit containing adsorbed cations. Members of the chlorite group consist of alternating three-layer sheets of tetrahedral layers and a central magnesium or iron-hydroxyl octahedral layer alternating with magnesium or aluminum-hydroxyl octahedral sheets.

Only very rarely can the sheet structure of most clay minerals be seen with the unaided eye. With the electron microscope, individual clay plates, although thousands of layers thick, can be magnified to the point that the morphology of the different clay minerals becomes relatively distinct. The scanning electron microscope is a further improvement that, through shadowing the subjects, gives pictures of clay minerals an almost three-dimensional effect (fig. 4).

In addition to the well-defined groups of clay minerals described above, many natural clays and shales consist largely or partly of mixed-layer clay minerals (fig. 5). Mixed-layer clay minerals are not mechanical mixtures but consist of two or more mineral species

Figure 4 (*on facing page*). Scanning electron micrographs of clay minerals with layered structure. *A*, Sedimentary kaolinite from the Oneal Pit, Macon, Ga. (X 1940). *B*, Illite associated with fluorite (CaF_2) mineralization in southern Illinois (X 5125). *C*, Smectite (X 8500). Photographs courtesy of Bruce F. Bohor, Illinois Geological Survey.

interlayered within individual crystals or crystallites. The interlayering may be regular in that the layers are present in a constant ratio and stacking pattern, such as 1:1, or it may be irregular with layers present in no particular order. This latter type is called *homogeneous random mixed layering*. If there is a variation in mineral composition laterally within single layers of the structure as well, the structure is said to exhibit *inhomogeneous random mixed layering*. Mixed layering is most common between illite and smectite and between chlorite and smectite.

Chain clay-mineral structure consists of linear silicon-oxygen units rather than sheets linked together by groups of oxygen and hydroxyl anions containing aluminum and magnesium cations. Minerals in this group, which include attapulgite, sepiolite, and palygorskite, are characterized by a fibrous nature. These minerals are uncommon in deposits of Indiana clay and shale and will not be considered further in this report.

Factors Controlling the Properties of Clay Materials

The four principal factors which control the properties of clay materials are clay mineral composition, nonclay mineral composition, organic material, and texture. All four factors help determine the value of a clay deposit.

The clay mineral composition refers to the identity and relative abundance of all clay minerals present. Each clay mineral has individual characteristics determined by its structure and chemical composition. A small amount of some clay minerals, notably smectite, will exert a tremendous influence on the characteristics of the clay. For example, as little as 5 percent smectite will noticeably affect the plasticity and drying shrinkage. Even the size and shape of particles of the clay mineral are important. Some properties, such as plasticity, vary with the crystalline character of component clay minerals. Most clay materials contain a number of clay minerals, each with its own crystallinity and adsorbed ions.

The nonclay mineral composition refers to the identity, particle

size, and relative abundance of nonclay minerals. Calcite ($CaCO_3$), dolomite ($CaMg(CO_3)_2$), and pyrite (FeS_2) have a detrimental effect on clay in a furnace because they act as fluxes and lower the resistance to heat, or refractoriness, of the clay. One group of clay minerals known as kaolins is used as fillers and coatings in high-quality paper. Iron oxides and iron hydroxides are detrimental in the paper industry because they act as pigments and therefore affect the color of the product. Quartz (SiO_2) and other hard minerals are also considered detrimental in a paper clay.

The nonclay mineral composition also includes exchangeable ions and soluble salts. These compounds yield charged particles when ionized and may flocculate clay particles in suspension. It may be necessary to wash these ions and salts out of the clay before it can be used. Such particles could have been washed into the clay at the time of deposition or they may have been developed after deposition by weathering or by the movement of ground water through the clay. Common water-soluble salts include chlorides, sulfates, and carbonates of alkalis, alkaline earths, aluminum, and iron.

The kind and amount of organic material contained in clay material are also highly significant. Besides affecting the color of the clay by acting as a pigment, organic material can absorb a large amount of various ions that may affect the firing properties of the clay material. Organic material may occur as discrete particles of wood, leaves, and spores, as microscopic organic particles absorbed between the clay mineral sheets, or on the surface of clay particles.

The clay minerals and some of the organic material found in clay materials have a significant ion-exchange capacity; that is, wandering ions may move into some clay minerals and substitute for ions loosely held with little or no change in the host structure. Thus it may be necessary to identify the organic material and the exchange capacity for each ion of interest in order to predict completely all properties of the clay.

Texture refers to the size of component particles, the shape of the particles, the orientation of the particles, and the forces binding the

particles together. Only the coarser grains of a clay can be seen with the naked eye or with the optical microscope; however, most of the unique properties of clays are due to clay minerals which are generally less than 0.002 mm across in their longest dimension. If the average size of the clay particles is 0.0005 mm rather than 0.0015 mm, the properties of some kaolinitic clays are significantly different. The mineralogy of these clay particles is commonly determined with X-rays, but the particles can only be viewed with the electron microscope, which can magnify particles millions of times.

The potential relationships between the various clay minerals in a clay or shale are very important. In a suspension of some clays, the particles may orient into a semisolid structure when standing, yet be stirred easily after agitation; such a clay is said to be *thixotropic.* Even in a solid form the positional relationships of clay minerals determine properties. For example, when a drop of water is placed on a bedding surface of most dry shales, or on the surface of clay which has a distinct preferred orientation of the flakelike clay minerals, the water will penetrate the surface rather slowly if at all. However, if the drop is placed on any surface at right angles to the bedding plane, or where the edges of the clay mineral flakes are exposed, the water is quickly absorbed. The permeability[3] of a shale thus depends on the orientation of the clay minerals.

Uses of Clays

The utility of a clay depends on the physical and chemical properties of the material. These properties in turn are determined by the mineralogic and chemical composition of the raw material. Complete analyses are of great importance because one clay may look much like another and yet have quite different properties.

The physical properties of clays related to the manufacture of pottery and other ceramic products are termed *ceramic properties.*

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[3]The property or capacity of a porous rock, sediment, or soil for transmitting a fluid without impairment to the structure or the medium; it is the measure of the relative ease of fluid flow under unequal pressure.

Moist clay can be molded into a form that will hold its shape (plasticity). The resistance of shaped clay to breakage while still moist is called the *green strength*. On drying, it undergoes *air* or *drying shrinkage* and then the *dry strength* can be measured. When the clay body is fired in a kiln, it progressively loses moisture, then volatile organic matter, then water chemically combined in the structure of the minerals, and finally sulfur from any pyrite and carbon dioxide from any carbonate material. On firing, the clay body undergoes reduction in size, which is called *fired shrinkage* and is due to the loss of what are called volatiles.

As the temperature rises, some clay particles begin to fuse, thereby destroying the original texture and binding the mass together. The difference between this temperature and the temperature at which complete melting or *vitrification* occurs is called the *vitrification range*. In making brick at temperatures around 1,000° C (1,832° F) vitrification has barely begun and little glass is produced, but in the making of electrical insulators at temperatures of about 1,300° C (2,372° F) vitrification is almost complete.

CERAMIC USES

About 75 percent of all clay and shale produced is used in manufacturing ceramic products. These products may be divided into two major groups. The first includes various relatively high-cost items, such as pottery, chinaware, chemical stoneware, sanitary ware, high-grade tile, and porcelain. The second includes what commonly are termed *structural clay products,* such as face brick, paving brick, draintile, construction tile, sewer pipe, flue lining, and wall coping (fig. 6).

Ceramic ware other than structural clay products is made from clays containing large proportions of kaolinite. Companies in Indiana producing this ware use clay from outside the state, most commonly from Georgia, South Carolina, Kentucky, and Tennessee. The major source of the Georgia and South Carolina clays is the coastal plain; some 90 percent of the country's supply of kaolin, or impure kaolinite, comes from this area. Many of the Tennessee and Kentucky
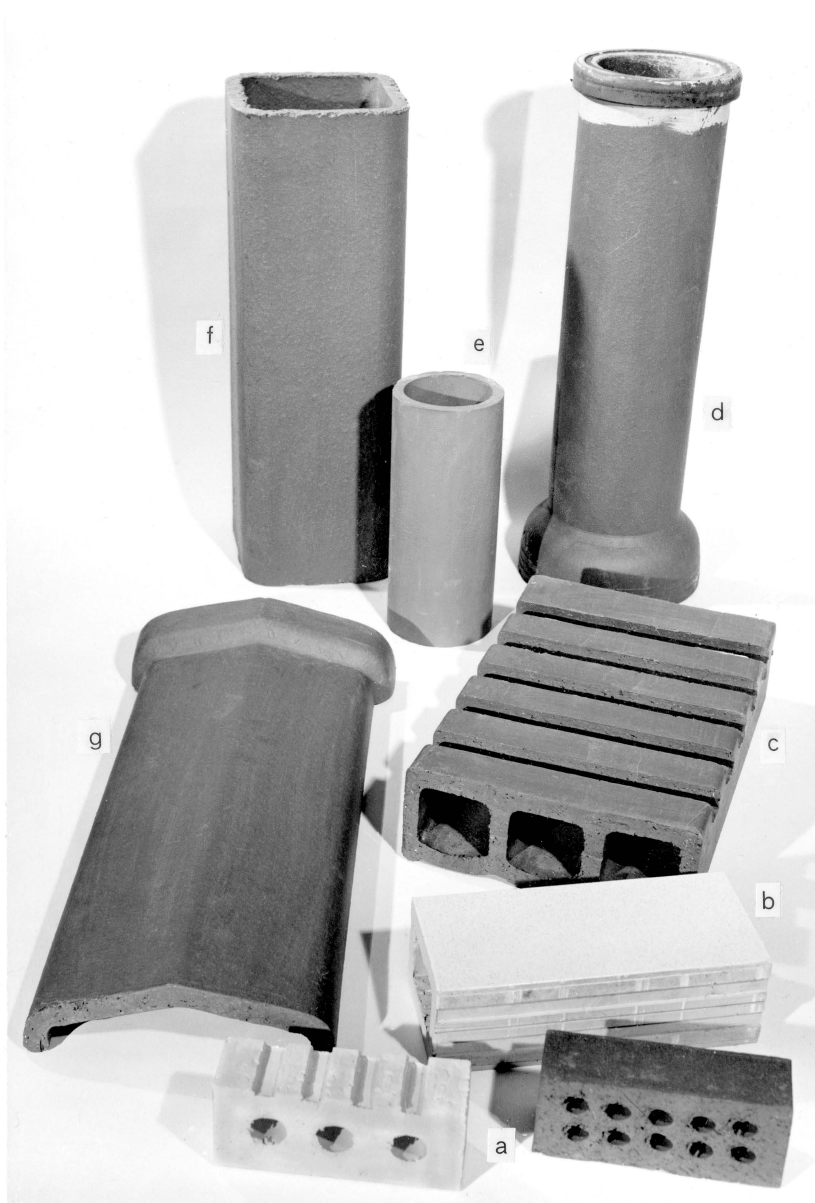
Figure 6. Structural clay products made in Indiana: *a*, face brick; *b*, glazed ceramic tile; *c*, filter block; *d*, sewer pipe; *e*, draintile; *f*, flue lining; and *g*, wall coping.

kaolinitic clays are called *ball clays* because they are removed in ball-like chunks. Ball clay is highly plastic and is used almost exclusively as a ceramic clay in whiteware, chinaware, and pottery. To date, searches for ball clays in Indiana have been unsuccessful. The Tennessee and Kentucky ball clays were formed in environments quite different from those of the rocks now present in Indiana, and the likelihood of discovering any large deposits in the state is remote.

Structural clay products are made from various common clays and shales, nearly all of which can be mined in Indiana. Illite is the most abundant clay mineral in the shales and some of the clays. Some companies in Indiana mix kaolinitic clay from beds lying immediately below some coals with dominantly illitic shale to improve the quality of their product. This kaolinitic clay, which is called underclay, commonly contains between 30 and 80 percent kaolinite, increases the plasticity of the mix, increases its resistance to heat and decreases the shrinkage of clay in the furnace, and lightens the color of the finished product. In 1971 Indiana had 12 brick plants and in all but two of these plants underclay was added to the mix (Austin, 1972).

REFRACTORIES

Clays suitable for manufacturing firebrick, clay crucibles, pots for molten glass, and other products that must stand very high temperatures for long periods of time are highly refractory, or resistant to heat, and are called *fire clays.* Clays are considered to be refractory only if they melt at temperatures above 1,430° C (2,606° F) at a temperature rise of 20° C per hour (PCE[4] cone 15). Low-duty fire

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[4]PCE (pyrometric cone equivalent) is the standard maintained by the American Society for Testing and Materials (ASTM) for determining temperature maxima of refractories (C24 - 56). Pyrometric cones consist of a series of ceramic mixtures with the correct proportions of fluxes so as to make the mixtures deform at successively higher temperatures. The cones themselves are about 1-inch-tall triangular pyramids which, as the temperature is raised, soften, bend over, and ultimately fuse. Commonly a series of cones is placed in a kiln or oven where the cones can be watched. Because clays are affected not only by the temperature reached but also by the heating rate, the softening point of a given cone varies somewhat, depending on how fast the temperature is raised. In practice today the temperature in ceramic operations is more commonly monitored by more direct means, such as by thermocouples. However, the old rating system is retained by using pyrometric cone equivalents (temperatures).

clays range from 1,430°-1,659° C (2,606°-3,018° F; cone 15 to cone 29), medium-duty from about 1,659°-1,699° C (3,018°-3,092° F; cone 29 to cone 31½), high-duty from 1,699°-1,743° C (3,092°-3,169° F; cone 31½ to cone 33), and super-duty above 1,743° C (3,169° F; cone 33). Fire clays vary greatly in their plasticity. Nonplastic fire clay is called *flint clay*. Intermediate degrees of plasticity give rise to the terms semiflint and semiplastic.

Most fire clays come from underclays and the chief clay minerals in underclays are kaolinite and illite. Generally, the higher the percentage of kaolinite, the more refractory the clay. Indiana's underclays, which underlie the coalbeds of Pennsylvanian age in the southwestern part of the state (pl. 1), have been examined and contain low-duty to medium-duty fire clay (Harrison, 1961).

FILLERS AND COATINGS

More than half of the annual national production of kaolin, or impure kaolinite, is used as filler and coating in high-quality paper. Properties that make kaolin desirable for use as a paper clay include softness, opacity, ink absorption, chemical inertness, dispersability of water, and natural brightness. Kaolin also is used as filler in rubber and with other clays in linoleum and paint. Clays, principally kaolin, are used as extenders or fillers in soaps, toothpaste, chalks, medicines, and plaster and as the carrier in insecticides and fire retardants. Indiana's clays do not contain enough kaolinite to be used as a paper clay; however, they are suitable for any of the other uses where clay mineral purity is not a determining factor.

DRILLING MUDS

A variety of rock composed primarily of sodium-rich smectite called *bentonite* is widely used in the petroleum industry. Bentonites have the property of absorbing proportionally large quantities of water and swelling greatly. In this expanded state the clay particles form a colloid with the water and remain indefinitely dispersed in water. In drilling for oil, bentonite is used in the drilling fluid because it lubricates the bit, lifts rock cuttings from the bottom of the hole,

"plasters" the hole wall to prevent an influx of unwanted water or sediment, and remains gelatinous even when left standing in the hole for long periods without agitation. Indiana, however, does not have deposits of usable bentonite; most of this material is obtained from Wyoming, Montana, North Dakota, and South Dakota.

ADSORBENTS

Adsorbent clays have the useful ability to remove coloring matter from oils, fats, and waxes. This is not a filtering process but rather selective adsorption, because the colored matter will adhere to the clay particles and cannot be easily washed off. Adsorbent clays in the crude state are called *naturally active clay* or *fuller's earth.*[5] Many naturally adsorbent clays are bentonites which contain smectite. Some clays which are not active in the natural state can be made adsorptive by treatment with sulfuric acid.

Adsorbent clays are widely used in the petroleum industry to decolorize and remove gums from gasolines and acid sludge from lubricating oils. Reclaimed oil has been cleaned by being passed through a chemically active clay. Similar clays are used to clean, deodorize, and decolorize raw vegetable oil. Although fuller's earth is not now mined in Indiana, it was reportedly produced from Floyd County in 1934 and 1935 (Adams and Metcalf, 1937).

CEMENT

Cement is made from materials containing lime, silica, alumina, and iron oxides. Because only a few limestones, the principal source of raw material for cement, have the required composition, most cement plants use various additives, which include quartz sand for silica and shale for alumina and silica, to reach the proper proportions. A shale suitable for this purpose would be one with a low concentration of alkalis, such as soda and potash. Consequently, shales high in kaolinite and low in other clay minerals are commonly used. Four of Indiana's five cement plants use clay to supply the

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[5]Fuller's earth has been used since before recorded history in the practice of fulling, or cleansing, wool by removing grease and oil from the fibers.

alumina in at least one of their processes. The plants of the Louis-ville Cement Co. at Speed in Clark County and Logansport in Cass County are able to use local residual soil and glacial till respectively to supply alumina. Plants of the Lehigh Cement Co. at Mitchell, Lawrence County, and Lone Star Industries at Greencastle, Putnam County, use shale from southwestern Indiana as their source of alumina.

LIGHTWEIGHT AGGREGATE

Concrete made with lightweight aggregate is widely used in the con-struction industry. Shale and clay are just two of many raw materials used to make lightweight aggregate, but they are extensively used. When rapidly heated between 1,000° and 1,300° C, some shales and clay will expand or "bloat." Two processes occur simultaneously: evolution of gas and fusion at the surface trapping the gas beneath a liquid surface. The gas may be oxygen, sulfur dioxide, or carbon dioxide; it is produced mainly by the breakdown of the nonclay minerals and therefore is only slightly related to the mineralogy of the clay minerals. On sudden cooling the melt forms a porous, slag-like material. Bloating is usually accomplished in a long, continually rotating kiln into which clay or shale enters at one end. The ex-panded product drops out the other end to be screened to various sizes and shipped. The kiln rotates continuously, so that the raw material is not allowed to fuse into one large mass of slag.

Concrete made with lightweight aggregate weighs as little as two-thirds the weight of conventional concrete made with crushed stone, yet there is small loss of strength. Structures made with lightweight aggregate are slimmer, are more graceful, and cost less.

In 1974 Indiana had one expanded-shale plant, Hydraulic Press Brick, Haydite Div., at Brooklyn in Morgan County (fig. 7). This plant produces lightweight aggregate from a thick shaly unit of the Borden Group, and the aggregate is shipped throughout Indiana and into adjacent states. The potential of the Borden and other rock units in other parts of Indiana as sources of the raw material for lightweight aggregate was explored by Murray and Smith (1958) and Rooney and Sunderman (1964).

Figure 7. Expanded-shale lightweight aggregate plant of Hydraulic Press Brick, Haydite Div., at Brooklyn, Ind., with three rotary kilns in the foreground and piled lightweight aggregate in the background.

CLAYS AS BONDING AGENTS

Clays are used in foundries to bind sand in molds into which metals can be cast. In recent years synthetic mixtures of sand and clay have become popular as bonding sand because physical properties can be varied by controlling the composition of the mix. Properties affected by using varying mixtures are green strength, dry strength, permeability, and plasticity; also affected are the surface characteristics of the finished metal casting.

To give sand a strong bond, only 3 to 4 percent clay composed of smectite from the western United States is needed. Where underclays from the north-central states are used, about two to three times as much clay must be used to give a bond of equal strength (Murray, 1957). Some Pleistocene lake clays in northwestern Indiana are now

used as bonding clays. These clays have a high percentage of mixed-layer clay minerals which, together with illite, produce strong bonds. Murray (1957) suggested that the underclays found in southwestern Indiana are also potential bonding clays and may be used in the future.

Geology of the Clay-Bearing Units

ORDOVICIAN SHALE

The oldest rocks exposed at the surface in Indiana that contain significant quantities of clay minerals are of Ordovician age (pl. 2). These rocks are exposed in extreme southeastern Indiana. The upper Ordovician Maquoketa Group (Gray, 1972) is composed of shale, claystone, and thin, scattered, typically discontinuous layers of limestone and is as much as 1,000 feet thick. The clay minerals consist of illite and lesser amounts of chlorite and mixed-layer clay minerals (Scotford, 1965; Booth and Osborne, 1971). The Maquoketa is not used as a source of clay raw material because of its high proportion of carbonate minerals in thin limestone beds and in carbonate fossil shells scattered throughout the unit.

SILURIAN AND DEVONIAN SHALES

The Silurian and Devonian Systems are represented in Indiana primarily by a sequence of dolomites and limestones. Some shale beds are present within these carbonate rocks, but they have been used only briefly as a source of clay material.

WALDRON SHALE: The Waldron Shale is Silurian in age; it overlies the Salamonie Dolomite and underlies the Louisville Limestone. It ranges from 0 to as much as 12 feet in thickness along the outcrop in southeastern Indiana. The Waldron is composed dominantly of illite, chlorite, and mixed-layer clay minerals, but there are significant amounts of kaolinite in some exposures. The nonclay fraction consists of quartz, dolomite, and calcite. Because of the large proportion of calcite and dolomite, Waldron shale has a low fusion point and a short vitrification range. For these reasons, little use has been made of the formation as a source for clay material.

OVERSIZED DOCUMENT

Now located at end of publication.

MISSISSINEWA SHALE: The Mississinewa Shale Member of the Wabash Formation (Silurian) overlies the Louisville Limestone and is overlain by the Liston Creek Limestone Member of the Wabash Formation. The thickness ranges from about 200 feet near the northern limit of the member in Fulton and Pulaski Counties to 50 to 75 feet in far western Indiana. The clay mineralogy of the Mississinewa is similar to that of the Waldron: illite and mixed-layer clay minerals and lesser amounts of chlorite; however, no kaolinite has been reported. Quartz, dolomite, feldspar, and calcite comprise the nonclay fraction. Dolomite, the dominant carbonate mineral, in many places constitutes more than 50 percent of the rock.

Like the Waldron, the Mississinewa Shale Member has a low fusion point and a short vitrification range due to the carbonate minerals present. For this reason it is not suitable for ceramic ware, lightweight aggregate, or structural clay products.

NEW ALBANY SHALE: The New Albany Shale (fig. 8) is primarily Devonian in age; however, deposition of the unit extended into the earliest part of Mississippian time. The New Albany is a dark-gray, dark olive-green, dark-brown, or black shale on fresh surfaces but weathers to light gray, brown, or maroon. In Indiana it is commonly a black carbonaceous shale and varies considerably in subsurface thickness. The unit is 104 feet thick in Floyd County where it was first described, thins to 85 feet in Harrison County, and thickens to 307 feet in Posey County (Lineback, 1970). North of the Kankakee and Cincinnati Arches (pl. 1) the strata equivalent to the New Albany, the Antrim, Ellsworth, and Sunbury Shales, are as much as 348 feet thick in Lagrange County.

Clay minerals, which are less abundant than quartz in the New Albany Shale, include chlorite, illite, and mixed-layer clay minerals. Kaolinite has been found in a few samples. In addition to quartz, the nonclay material includes small amounts of feldspar (potassium, sodium, and calcium alumino-silicates), calcite, dolomite, pyrite, and phosphatic minerals.

New Albany shale is not used at present by any ceramic industry

Figure 8. Exposure of the New Albany Shale (Devonian-Mississippian) in Clark
County near the intersection of I-65 and U.S. 31 W west of Sellersburg.

in Indiana; however, it might be suitable for brick or tile and is
definitely a potential raw material for expanded-shale lightweight
aggregate (Rooney and Sunderman, 1964). The amount of hydro-
carbons in the unit also makes it a possible source of petroleum.
These same hydrocarbons have absorbed uranium ions, and thus the
New Albany is a possible source of uranium, although generally its
content is about one-tenth of what today is considered a minimal
ore. The New Albany also has been investigated as a possible ore of
aluminum, but the metal cannot be extracted profitably at present.

MISSISSIPPIAN SHALES

The thick shales of Mississippian age are, from oldest to youngest,
found in the upper 10 to 20 feet of the New Albany Shale, the
Borden Group, and the Chesterian Series. Chesterian clayey rocks

Figure 9. Exposure of shale and siltstone of the Borden Group in Brown County
     along State Road 46 near the west entrance to Brown County State Park.

are represented by the Bethel Formation and thinner overlying
shales.

BORDEN SHALES AND SILTSTONES: Rocks of the Borden Group are
found at or near the surface along a narrow belt from near New
Albany on the Ohio River to Benton County northwest of Lafayette
(pl. 1). The northern part of the outcrop belt, however, has been
mostly covered by glacial drift, and exposures are limited in size and
in number. The Borden (fig. 9), which exceeds 700 feet in thickness
in some parts of west-central Indiana, consists of siltstone with lesser
amounts of shale and sandstone. Quartz, the dominant mineral,
occurs with lesser amounts of clay minerals, feldspar, calcite, siderite,
and iron oxides. Illite, the dominant clay mineral, is present with
chlorite and mixed-layer clay minerals. Shells and hard skeletal parts
of marine organisms consisting of calcium carbonate are scattered

throughout the unit and in local reeflike accumulations. Siderite is present as nodular concretions or as beds of concretions. Iron oxides are present because of the oxidation of iron minerals, notably siderite and perhaps pyrite and chlorite.

Although it is difficult to subdivide this unit into formations, the New Providence Shale at the base of the Borden is generally distinguishable from the overlying rocks. The New Providence commonly is greener than the rest of the grayish-green or tan Borden and contains less sand-size material. It is, however, mineralogically similar to the rest of the group.

Rocks of the Borden Group are extensively used as a raw material in manufacturing brick, draintile, sewer pipe, lightweight aggregate, and inorganic molded plastics. Because of its thickness, lateral extent, uniform mineralogy, and proven value as a raw material, the Borden Group has great potential.

CHESTERIAN SHALES: The Chesterian Series consists of shales, sandstones, and limestones that are exposed at the surface in a belt lying west of Borden rocks from the Ohio River to Putnam County. Chesterian shales are thinner and more diverse in mineralogy and physical properties than the underlying Borden Group. The amount of clay minerals present and their mineralogy vary both vertically and laterally in the shaly units.

The Bethel Formation overlies the Paoli Limestone, the uppermost formation in the Blue River Group. The Bethel consists of dark-gray shale and clayey sandstone and ranges from 5 to 30 feet in thickness. Clay minerals present include illite, chlorite, kaolinite, and mixed-layer clay minerals; however, the proportions of these minerals vary considerably from outcrop to outcrop. At present the Bethel is used only to supply alumina for cement, but tests (Murray and Smith, 1958) suggest that it also may be suitable as a source of raw material for lightweight aggregate.

The younger Chesterian shales have not been used for ceramic purposes but appear to be suitable for brick, tile, and lightweight

aggregate. There are included in the Sample, Elwren, and Hardins-
burg Formations, as well as in the Bethel; are variable in grain size
and mineralogy; and may pass from a shale to a sandstone in less
than a mile. The clay minerals in these formations consist of illite,
kaolinite, chlorite, and mixed-layer clay minerals.

CLAY MINERALS ASSOCIATED WITH THE MISSISSIPPIAN-PENNSYLVANIAN UNCONFORMITY

After the deposition of the youngest Mississippian strata, a long
period of emergence and erosion preceded the deposition of Penn-
sylvanian sediments. The Mississippian strata to the north were more
deeply eroded than those in southern Indiana, and Pennsylvanian
sediments progressively overlie older and older material to the north
(pl. 1). In southern Indiana, Pennsylvanian strata overlie rocks of the
Chesterian Series. To the north these same Pennsylvanian sediments
lie directly on rocks of the Borden Group.

At some localities in southern Indiana allophane and halloysite
have replaced limestone near the Mississippian-Pennsylvanian uncon-
formity (Sunderman, 1963). The ions for these minerals were derived
from the weathering of overlying rocks. The largest deposit known in
Indiana is at the abandoned Gardner Mine, about 30 miles south of
Bloomington.

Halloysite is a kaolin mineral with the same general formula as
kaolinite, but the sheets or layers, instead of being flat, are slightly
curved, so that a typical crystal of halloysite is a tube (figs. 10*A* and
10*B*). In addition, from zero to two layers of water are held between
the sheets.

Allophane is the name applied to "any amorphous substance
which may be present in clay materials as extremely fine material
and which has an indefinite composition" (White, 1953, p. 634) and
is commonly considered to be composed of hydrated oxides of
aluminum, silicon, and some iron. Recent work (Wada, 1967, and
Kitagawa, 1971) suggests that allophane is not amorphous but is
composed of very small particles with a loose association which
makes them transparent to X-rays.

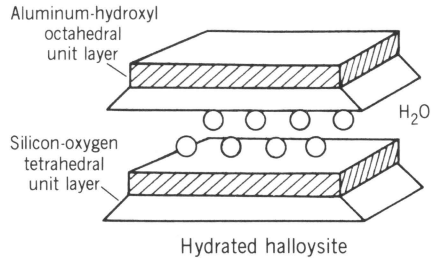Figure 10A. Schematic representation
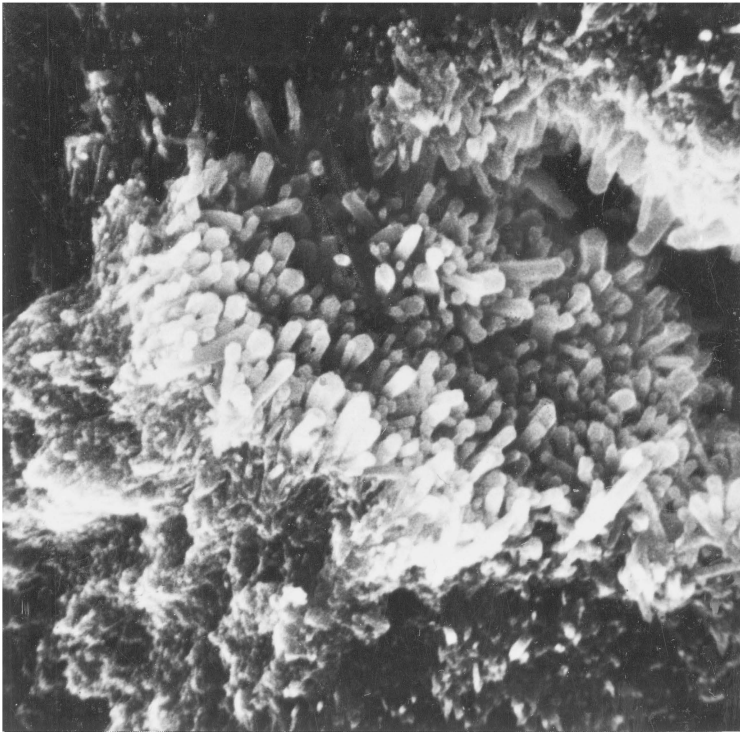of the structure of halloysite. From
Harrison and Murray, 1964, fig. 1.

Figure 10B. Scanning electron micrograph of halloysite from Gard-
ner Mine, Lawrence County (X 25,750). Photograph courtesy of
Sidney Diamond, Purdue University.

Halloysite from the Gardner Mine was used for producing alum,
an ingredient in bone china, and was mixed with underclay for

refractories. Halloysite has also been used in producing white porcelain ware, wallpaper, and writing paper. At present halloysite from other parts of the world is used in chinaware to improve the translucency, in the petroleum industry as a source of raw material for catalysts in the cracking process, and as a bleaching clay. Both halloysite and allophane are possible sources of alumina. The Indiana halloysite- and allophane-bearing deposits have not been exploited since about 1930.

PENNSYLVANIAN CLAYS AND SHALES

Rocks of Pennsylvanian age crop out in southwestern Indiana from the Ohio River to Warren County along the Indiana-Illinois border, with local outliers beyond in southern Newton and Jasper Counties (pl. 1). The northern one-third of the area in which Pennsylvanian rocks constitute the bedrock surface is deeply covered with glacial drift. Pennsylvanian formations were deposited near sea level of the shallow and shifting sea, and consequently the formations may change in rock type in relatively short distances. The oldest four Pennsylvanian formations in Indiana—the Mansfield, Brazil, Staunton, and Linton (pl. 2)—are used for ceramic purposes. Although the overlying Petersburg, Dugger, and Shelburn Formations are not currently being exploited, they have sufficient shales and clays to make them of possible future ceramic importance.

The Pennsylvanian rocks in Indiana that are rich in clay minerals are divided into two main types: shales and underclays (fig. 11). The shales are generally dark gray to black, fine grained, and thin bedded, or they are light gray, are relatively thick bedded, and contain quartz sand. Mineralogically, the Pennsylvanian shales contain illite with significant but varying amounts of kaolinite and mixed-layer clay minerals. Chlorite is absent or is present only in minor amounts. The nonclay fraction consists principally of quartz with lesser amounts of feldspar, iron carbonate, calcite, and other minerals.

In the main, the shales are not suitable as ceramic raw material because of the amount of organic material and iron carbonate present. The most useful are the thick light-gray shales because of their
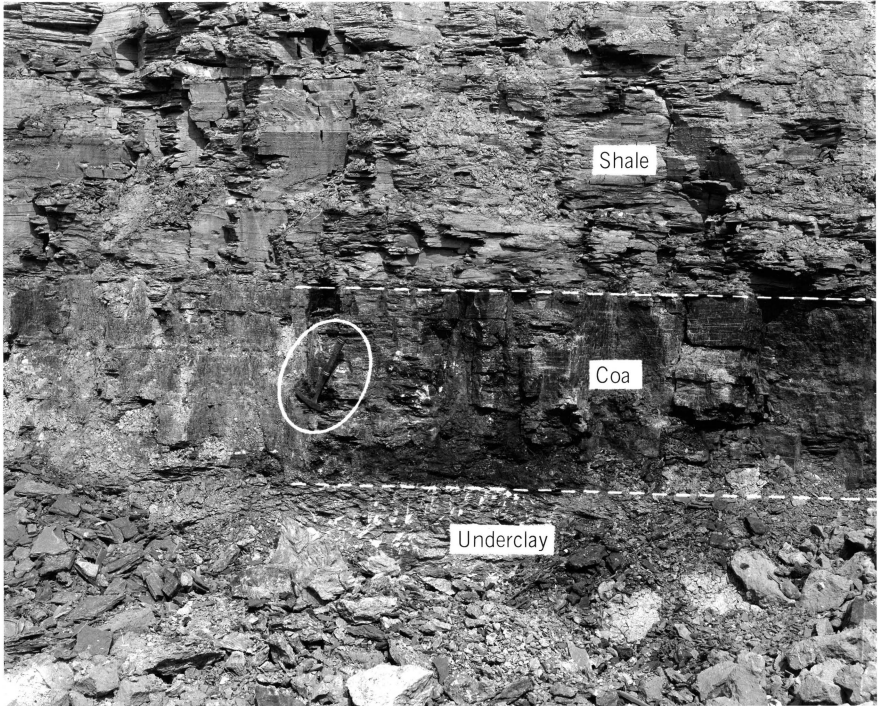
Figure 11. Exposure of Upper Block Coal Member, Brazil Formation (Pennsylvanian), with overlying shale and underlying underclay, near Ashboro, Clay County. Note rock hammer (circled) for scale.

mineralogic consistency and uniform physical properties. At present these shales are used as a source of raw material for bricks, draintile, cement, sewer pipe, and stoneware. Murray and Smith (1958) determined that the shales of the Linton, Dugger, and Shelburn Formations show bloating properties sufficient to be considered as a future source of lightweight aggregate.

The Pennsylvanian underclays are some of the most important clay-bearing units in Indiana because they have the highest proportion of kaolinite of any unit in the state. Although none of the underclays can be classified as high-grade refractory material, large quantities of low- and medium-grade refractory fire clays are available. The underclays commonly lack bedding and most are thin, rarely exceeding a thickness of 6 to 7 feet. They are composed of

kaolinite, illite, and mixed-layer clay minerals with quartz and feldspar as the chief nonclay minerals. Chlorite is a minor constituent or is absent. Iron carbonate occurs in some places as hard nodules.

Indiana underclays may be light gray or dark gray to black, depending on the amount and dispersion of organic material. Because iron in underclays is restricted to minor amounts of chlorite, pyrite, and siderite, underclays generally burn to a much lighter color than do most of the Indiana shales. Most Indiana underclays have high fusion temperatures because they contain only a small amount of fluxes, such as calcium, magnesium, sodium, potassium, and iron compounds.

Indiana underclays are used in manufacturing bricks, sewer pipe, wall coping, and pottery. Many companies mining coal may also sell underclay after removing the overlying coal, thus giving themselves an added source of income for a relatively small cost.

Because the Pennsylvanian shales and underclays are genetically related to coalbeds and are removed the same way in Indiana, they are subject to the same mining restrictions. At present no underground clay operations are being worked in Indiana.

PLEISTOCENE CLAYS

During the Pleistocene Epoch about five-sixths of Indiana was at times covered by thick sheets of glacial ice. These glaciers carried large amounts of rock materials, ranging in size from large boulders to clay-size particles. When the ice melted, thick rock material either remained behind to form *tills* (fig. 12) or was transported away by meltwater streams, in some places into glacial lakes (fig. 13). Because there was little or no sorting of rock particles according to size, tills contain material of many different sizes. They are mineralogically complex because they were derived from many different rock types. Glacial material deposited by meltwater streams or in glacial lakes is also mineralogically complex but has been sorted according to size. Although glacial lake sediments and some tills appear to be composed of very fine-grained material, most contain a far larger quan-
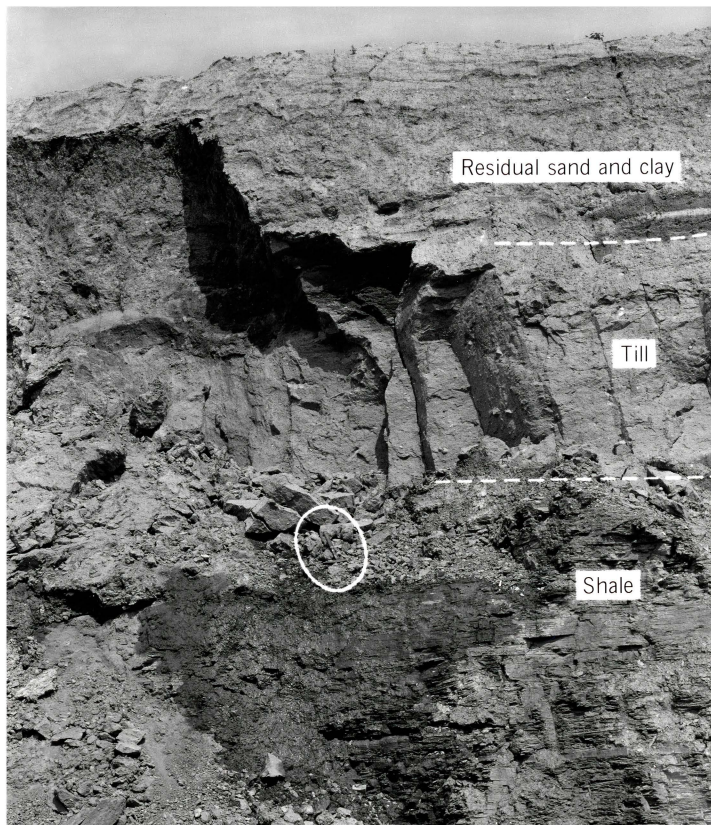
Figure 12. Exposure of Pleistocene till (center) overlying marine
    shale of Pennsylvanian age near Ashboro, Clay County. Blocky
    till is overlain in turn by residual sand and clay. Note rock
    hammer (circled) for scale.

tity of silt than clay-size particles and generally are not good sources
of clay.

In Indiana the most common types of minerals found in Pleisto-
cene glacial deposits are quartz, calcite, dolomite, and clay minerals
consisting of illite, chlorite, and mixed-layer clay minerals. Kaolinite
is rarely found. Weathering of glacial materials tends to remove the
more soluble components in the upper few feet of glacial deposits;
limestone and dolomite are normally removed, as are potassium and
magnesium ions from clays. Some amorphous material is developed

Figure 13. Exposure of bedded glacial lake sediments near Francesville, Pulaski County. These sediments were formerly used at Francesville in manufacturing draintile.

and Fe++ is oxidized to Fe+++. Such clay minerals as illite tend to lose their potassium ions to form illite-smectite mixed-layer clays; chlorite loses its magnesium ions and perhaps iron ions to form chlorite-smectite mixed-layer clay minerals.

Clay deposits of Pleistocene age in Indiana, containing only small amounts of such fluxes as limestone, are used in manufacturing such ceramic products as brick, pottery, and draintile. Glacial lake clays near Gary are used in molding sand for nearby foundries. Leached till is used by one cement plant to supply the necessary alumina to its mix.

RESIDUAL CLAYS

Residual clays developed on bedrock and on glacial drift in south-

eastern and south-central Indiana have been used occasionally in manufacturing ceramic products. These clays are developed chiefly on limestones of Ordovician, Silurian, and Devonian ages in southeastern Indiana and of Mississippian age in south-central Indiana. They consist of various oxides of iron and aluminum, calcite, dolomite, quartz, illite, and mixed-layer clay minerals. Most of the clays, however, are too iron rich or calcareous to be used commercially. Residual clay is used at only one plant in Indiana at present—the Louisville Cement Co. at Speed in Clark County—where it supplies alumina in manufacturing cement.

Evaluation of Clay Deposits

A few simple tests can help in determining the value of a deposit. Of course, complete mineralogic and chemical analysis can be performed only in a properly equipped laboratory, but an individual can run some experiments that will save himself both time and money.

AMOUNT OF CLAY IN A SAMPLE

Simply looking at or feeling a clayey sample is not enough to give a good approximation of the amount of clay-size material present. A relatively small amount of smectite or mixed-layer clay minerals can give a sample a very clayey or sticky feeling. The easiest test is to gently grind a small amount between your teeth. Clay-size particles are about as fine as face powder and will feel smooth. A sample with an appreciable amount of silt-size particles (1/16 to 1/256 mm) will be abrasive but not particularly gritty. Sand and larger particles can be seen in most samples without a microscope, but in some samples fine sand will be obscured by the finer size particles; between the teeth, sand particles are noticeably gritty.

Determination of the weight percent of sand in a clay is important. To determine the proportion of sand, the clay and silt must be removed and the coarser fraction of the sample examined. If possible, first weigh the sample; however, this involves the use of accurate scales, which are usually not available in the home or on the farm. A small amount of the sample, about a handful, is placed in a glass

container. Add water, distilled water if possible, to the container along with a small amount of dispersant; any common detergent will do. Cover and shake the container for about 30 seconds; set it down, and allow the mixture to settle for about 10 seconds. The sand and larger particles will have settled to the bottom, and the clay- and silt-size material will probably be in suspension. Very carefully pour off the suspension, being careful not to pour off material that has settled to the bottom. Repeat the process several times with fresh water but without the dispersant until the water after shaking is relatively clear. You are now ready to examine the coarser fraction of the original sample. If you are able to weigh the residual material accurately, you can get a fair idea of the percentage of sand and larger material in the sample. As a rule of thumb, the sample should contain less than 50 percent sand-size material to be considered a good prospect. A good clay for premium whiteware should contain about 5 percent or less sand-size material.

Some clayey rock units in Indiana will not break down with this procedure. Many of these can be induced to disperse by grinding in water with some blunt instrument, but some will not break down even with this procedure and home determination of the percentage of sand-size material in them is best abandoned.

The residual or coarser material from the preceding test should be examined, under magnification if possible. If the material contains quartz sand, which looks like clear or frosted rounded bits of glass, and feldspar, which appears as pink or milky, usually angular sand, then that residual fraction will be relatively inert in low temperature furnaces or kilns. If, on the other hand, the residual fraction contains small fossil shells or bits of limestone or dolomite, the residual fraction will produce deleterious effects in firing. Calcite and dolomite can be identified by effervescence, or bubbling, when a small amount of acid is put on the particles. Household vinegar will usually react with calcite, but a reaction with dolomite is less likely. A 25-percent hydrochloric (commercial muriatic) acid solution usually produces good results. Another mineral producing poor results in a kiln is pyrite, or fool's gold. It may appear in the residual fraction as bits of

yellow metal or as a dirty black powder associated with organic material.

ANALYZING THE CLAY IN A SAMPLE

Colors of the original sample can lead to some conclusions as to the percentage of iron in a clay material. Yellow and red indicate undesirable oxidized iron. Only a very small percentage of oxidized iron can color a clay, and this small amount is too much for expensive whiteware or a paper clay. For structural clay products the iron content is only important in clay and shale if it occurs as pyrite. When this mineral oxidizes in the kiln, it causes *checking,* or small eruptions, on the surfaces of the product. A green color in the original sample is usually caused by reduced iron ($Fe++$) in the sample. This color usually eliminates the deposit as a source for high-cost whiteware because the clay will turn red when fired, but the clay may still be used in manufacturing pottery or structural clay products. The more valuable low-iron clays are generally white to light gray.

The fired color of a clay may be determined by preparing a small brick of the clay with water, letting it air dry for several hours, and then placing it in a kitchen oven. The oven should be set as high as possible; even 600° F is far below the usual firing temperature in a kiln. But clay with an appreciable amount of reduced iron will turn red after only an hour at 600° F (315° C). You will also be able to examine the brick for excessive shrinkage cracks. This too may eliminate the clay material as a possible source of ceramic clay.

A black or gray color is usually due to included organic material. If only a small amount is present and the organic material does not contain adsorbed cations which can cause deleterious effects to the product, the firing destroys the organic material and the color is not seriously affected. On the other hand, the heating of organic-rich clays can produce a surge in temperature in the kiln as the organic material ignites and the gases produced may cause checking in the product. Both results are considered undesirable.

Chemical, mineralogic, and particle-size analyses from a source for

a clay material can be compared with the following data. Sample A is an average of three analyses made of an underclay from Greene County now being used to improve the refractoriness of clay mix in a brick plant. Sample B is the average analysis of two samples of a shale now being used in manufacturing bricks and lightweight aggregate.

	Sample A	Sample B
Chemical analyses (in percent)		
SiO_2	60.70	57.75
Al_2O_3	23.20	17.75
Fe_2O_3	0.78	1.16
FeO	1.63	4.74
TiO_2	1.20	0.86
CaO	0.10	2.28
MgO	0.50	2.01
Na_2O	0.13	0.98
K_2O	2.32	4.16
MnO	0.02	0.06
P_2O_5	0.04	0.10
CO_2	0.79	1.06
C	—	1.21
S	0.05	0.80
Total H_2O	7.89	5.10
	99.35	100.02
Mineralogic analyses (semiquantitative analysis of clay-size fraction in parts of 10)		
Illite	2	6
Chlorite	0	2
Kaolinite	7	0
Mixed-layer clay minerals	1	2
	10	10
Particle size analyses (in percent)		
Clay (less than 0.002 mm)	38	24
Silt (0.0625 to 0.002 mm)	48	51
Sand (greater than 0.0625 mm)	14	25
	100	100

A comparison of these analyses reveals several interesting points. The first impression is that there is an overall similarity in the chemi-

cal analyses. On closer inspection, however, one observes that the alumina in A is proportionately about one-fourth greater than in B and that the iron, calcium, magnesium, potassium, and sodium oxides are considerably higher in B than in A. The mineralogic analyses reflect these chemical differences. Underclays (sample A) commonly consist of a large amount of kaolinite which is composed of silica, alumina, and water. Clayey material composed of other clay minerals contain other ions in addition to Al, Si, H, and O.

TRANSPORTATION

Most of the structural clay products produced in Indiana are sold within a few hundred miles of the factory; the extent of the market area is dictated by the production, the sales of the company, and the competition. Because structural clay products have a low unit value, the cost of transportation constitutes a large part of the price of the product. Truck transportation is the easiest, quickest, and least expensive method for moving structural clay products in small lots to points in the market area near the plant. Rail transportation rivals trucks in delivering clay products to the Chicago area, which is one of the principal market areas in the north-central United States. Chicago receives bricks from as far away as Kentucky. Barge transportation offers the least expensive method of long-haul transportation of bulk material. The access to barge transport has enabled the Can-Tex Industries plant at Cannelton, Perry County, on the Ohio River to move and sell its sewer pipe to points as far away as Florida.

Relatively high-cost clay products, such as sanitary pottery, art clay, and other special clay products made in Indiana but from raw materials shipped into the state, are shipped throughout a much wider market area. Sanitary pottery and glazed bathroom fixtures from Indiana are shipped mainly to outlets in the north-central United States. Art clay and other special ceramic products, which include ceramic insulators and pre-formed ceramic cores for high temperature equipment, enjoy a nationwide market area and are sometimes shipped to Canada as well.

ESTIMATING THE VALUE OF THE DEPOSIT

The owner of a clay deposit must remember that clay generally is a very low-cost material and that any necessary processing other than simple grinding decreases the value of the deposit. Similarly, if a large amount of material has to be removed to get at the clay, the value of the deposit is less. If the deposit varies a great deal in thickness or in composition and extensive drilling is necessary to find out its shape and character, the value of the deposit is decreased. The more potentially usable clay deposits are those that offer large quantities of clay with uniform character and that require little additional processing.

In addition to the mineralogic and chemical composition of the clay, companies want to know about the size of property, the thickness of the prospective deposit, the thickness of material to be stripped, any variability of the deposit, accessibility to roads, and the location of the property. All these aspects must be considered before spending a great deal of money developing a deposit.

Future Prospects

The Borden Group, the Bethel Formation, the Mansfield Formation, and Pennsylvanian underclays and shales offer the best sources of clay in Indiana. Pleistocene clay deposits in northern Indiana are used in manufacturing low-cost clay products primarily because of their accessibility at the surface and nearness to large markets. The New Albany Shale and other clay-bearing units from other formations may have promise.

There is an increasing need for raw clay material as shown by the increased volume of ceramic products for both industrial and home use manufactured in Indiana from local and out-of-state sources. To locate good clay prospects and to eliminate poorer ones, only a general knowledge of the mineralogy and chemistry of clays and their areal and geologic location and an understanding of what to look for and how to test a clay are necessary for many clays. Indiana's raw clay material is of sufficient quality and quantity to supply a larger economic industry than it is supplying at present.

Future clay and shale operations will supply more of their products to producers of less traditional products, such as cement plants, than they did in the past. The total value of the output of the ceramic industry in Indiana in the next 30 years will grow at about the same rate as the rest of the economy. The segment of the industry manufacturing structural clay products, however, will grow but at a low rate as plastic, wood, concrete, and metal substitutes take a larger share of the market. The development and expansion of this industry in Indiana is, however, more of an economic problem than a geologic one.

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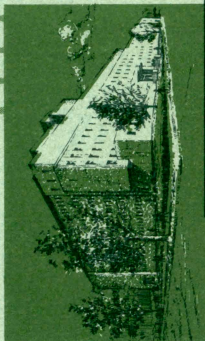   1953 - Allophane from Lawrence County, Indiana: Am. Mineralogist, v. 38, p. 634-642.

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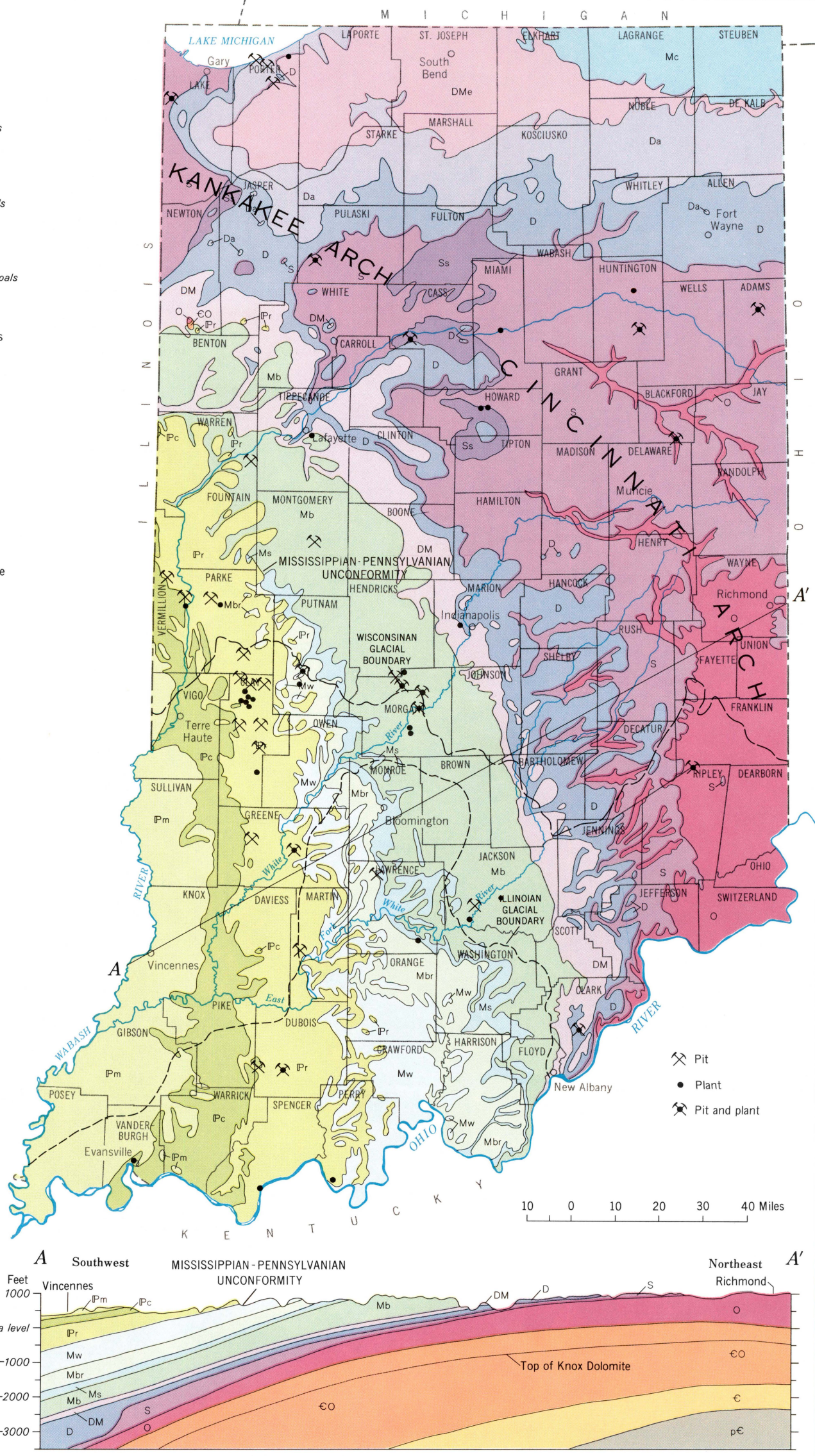
OVERSIZED DOCUMENT

The following pages are oversized and
need to be printed in correct format.

EXPLANATION

PENNSYLVANIAN

Pm — McLeansboro Group
Shale, sandstone, limestone, thin coals

Pc — Carbondale Group
Shale, sandstone, limestone, thick coals

Pr — Raccoon Creek Group
Sandstone, shale, clay, limestone, thin coals

MISSISSIPPIAN

Mw — West Baden and Stephensport Groups and upper Chesterian rocks
Shale, sandstone, limestone

Mbr — Blue River Group
Limestone, dolomite

Ms — Sanders Group
Limestone

Mb — Borden Group and Rockford Limestone
Shale, siltstone, limestone

Mc — Coldwater Shale
Gray shale

DEVONIAN AND MISSISSIPPIAN

DMe — Ellsworth and Sunbury Shales
Gray, green, and black shales

DM — New Albany Shale
Black shale

DEVONIAN

Da — Antrim Shale
Black shale

D — Middle Devonian rocks
Limestone, dolomite

SILURIAN

Ss — Salina Formation
Limestone, dolomite

S — Lower and middle Silurian rocks
Limestone, dolomite, siltstone, shale

ORDOVICIAN

O — Upper Ordovician rocks
Shale, limestone

CAMBRIAN

€O — Uppermost Cambrian and lower and middle Ordovician rocks
Dolomite, limestone, sandstone

€ — Upper Cambrian rocks
Sandstone, shale, dolomite
Shown on cross section only

PRECAMBRIAN

p€ — Granitic, basaltic, and metasedimentary rocks
Shown on cross section only

Pit

Plant

Pit and plant

10 0 10 20 30 40 Miles

A Southwest   MISSISSIPPIAN - PENNSYLVANIAN UNCONFORMITY   Northeast A'

Feet Vincennes   Richmond
1000
Sea level
-1000   Top of Knox Dolomite
-2000
-3000

Modified from Indiana Geological Survey Miscellaneous Maps 11 and 16, November 1974.

MAP OF INDIANA SHOWING BEDROCK GEOLOGY, KANKAKEE AND CINCINNATI ARCHES, AND LOCATION OF ACTIVE CLAY AND SHALE OPERATIONS

System	Bedrock map unit	Map symbol		Group, formation, or member	Thickness (ft)
QUATERNARY	Recent / Pleistocene			(Residual clays*)	
PENNSYLVANIAN	McLeansboro Group	Pm			
				Shelburn Formation*	50 - 250
	Carbondale Group	Pc		Dugger Formation*	73 - 185
				Petersburg Formation*	70 - 193
				Linton Formation*	43 - 162
	Raccoon Creek Group	Pr		Staunton Formation*	75 - 125
				Brazil Formation*	40 - 90
				Mansfield Formation*	50 - 300
MISSISSIPPIAN	Upper Chesterian rocks and Stephensport and West Baden Groups	Mw			
				Hardinsburg Formation*	20 - 62
	Blue River Group	Mbr			
	Sanders Group	Ms		Elwren Formation*	20 - 60
				Sample Formation*	24 - 42
	(N. Ind.) / (S. Ind.)	(N. Ind.) / (S. Ind.)		Bethel Formation*	10 - 42
				Paoli Limestone	
	Coldwater Shale (N. Ind.) / Borden Group and Rockford Limestone (S. Ind.)	Mc / Mb		BORDEN GROUP*	485 - 700+
				New Providence Shale*	30 - 290
DEVONIAN AND MISSISSIPPIAN	Sunbury and Ellsworth Shales / New Albany Shale	DMe / DM		New Albany Shale*	85 - 307
DEVONIAN	Antrim Shale	Da			
	Muscatatuck Group	D			
SILURIAN	Salina Formation (middle to upper Silurian)	Ss		Liston Creek Limestone Member	
				Wabash Formation — Mississinewa Shale Member*	50 - 200
				Louisville Limestone	
	Lower to upper Silurian rocks	S		Waldron Shale*	10 - 30
				Salamonie Dolomite	
ORDOVICIAN	Upper Ordovician rocks	O		MAQUOKETA GROUP*	70 - 1000+
	Middle Ordovician rocks / Lower Ordovician rocks / Uppermost Cambrian rocks	€O			
CAMBRIAN	Upper Cambrian rocks	€			
PRECAMBRIAN	Granite, basalt, and metasedimentary rocks	p€			

*Clay-bearing units discussed in this report.

GEOLOGIC COLUMN SHOWING STRATIGRAPHIC POSITION AND GEOLOGIC AGE OF UNITS CONTAINING SHALES AND UNDERCLAYS DISCUSSED IN THIS REPORT