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CLASSIFICATION OF KAOLINS EXEMPLIFIED BY THEIR TEXTURES IN SCAN ELECTRON MICROGRAPHS

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Abstract—Varieties of kaolin, a rock, may be classified geologically, mineralogically, crystallographically, genetically, texturally, morphologically, by industrial use, and in other ways which are desired. In this paper, the first-order of classification used is geological, i.e., transported and residual, after which other categories are used as subdivisions.

Scan electron micrographs, SEM, of the textures of kaolin show that distinctive textures characterize the several categories of classification. Varieties in texture of kaolin include similarities to those typical of sedimentary, igneous and metamorphic rocks. Because word descriptions of the textures are inadequate in comparison to pictures of them, the reader is referred to the micrographs.

SEM's illustrate differences between kaolins which were transported, formed, or deposited from solution, a colloidal phase, or as orthodox clastic particles. The parent source of kaolin deposited, or "grown," from solution may be difficult to ascertain. It is suggested that the total role of solution work in kaolin petrology can be more important than has ordinarily been credited.

Key Words—Deposition, Diagenesis, Kaolin, Texture, Transport.

INTRODUCTION

Classifications of rocks traditionally have included factors of texture. It is within good geologic tradition, therefore, that categories of classification of kaolin, likewise a rock though microscopically fine-grained, are also characterized by more or less distinctive textures.

The purpose of this paper is to consider the common classifications of kaolin, and to correlate the textures observed by scan electron micrography (SEM) of kaolins within categories of those classifications. Kaolin has been tentatively defined by the International Committee on Correlation of Age and Genesis of Kaolin as "an earthy rock characterized by a significant content of kaolin minerals."

CLASSIFICATION OF KAOLIN

Geologically, kaolins may be classified as (1) residual, also called primary, or (2) transported, also called sedimentary. Although the phase observed in both groups is solid, both residual and transported clay minerals alternatively may be generated or moved also by a solution phase—a fact scantily mentioned in practice or the literature. Furthermore, some kaolins, such as ball clays and flint clays, may be genetic products of colloidal systems.

Mineralogically classified, kaolins may be monomineralic, or alternatively they may be composed of mechanical mixtures of the several kaolin minerals. These include well-crystallized kaolinite, and varieties of kaolinite in various stages of order–disorder (as "fire-clay mineral"), grading into the vague and blurred nomenclature of halloysite or meta-halloysite (depending on the usage of the person), endellite (always the $4 \cdot H_2O$ variety), imogolite, and allophane.

Morphologically, the kaolin minerals may occur as stacks or "books," straight or curved (vermicular), built of crystal plates or flakes—these are not floccules. In other kaolins, floccules predominate in which the orientation of particles may be face-to-face or edge-to-face. Other morphologies of kaolin minerals include tubules, scrolls, prisms that appear to be solid, stubby (straight or curved), or alternatively long and slender grading into fibers (hollow or solid?), spherical to globular shapes, and irregular forms (as in some allophane).

Genetically, kaolins may be classified as those weathered by vadose or phreatic water, or by artesian water within or adjacent to aquifers, or altered by thermal water in magmatic or solfataric stages, or by resurgent water moving through the parent rocks of the kaolin. Alternatively, kaolin may be deposited on a substrate which is not an aluminum silicate potential parent material. The nutrient solution from which the kaolin was deposited may have been relatively dilute, or conversely may have been relatively concentrated, as in a brine within a sedimentary rock long after deposition of the host rock. Thus the kaolin minerals may be allogenic, authigenic, or diagenetic.

Texturally, kaolin may be euhedral to subhedral in external form, or grade into ragged-edged anhedral flakes; either morphology may be fine to coarse (where coarse is expressed in terms of micrometers to tens of micrometers). The crystals may be relatively uniform in size as when crystallized directly from solution, or exceedingly nonuniform in particle size as observed in some sedimentary kaolins and/or in part of the Cornwall, England, kaolins. The crystals or particles may consist uniformly of one shape or they may be mixtures of radically different shapes, such as stacks of kaolinite mixed with elongates of "halloysite." Kaolin may be a sediment of mineral stacks and particles that are piled together at random, resembling a microconglomerate or microagglomerate, or the kaolin may be built of tight-

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ly interlocked and intergrown crystals of kaolinite as in flint clay. In other words, kaolin may have the texture of a clastic rock of microparticles, or alternatively of a nonclastic rock in which the crystals are intergrown and interlocked (flint clay) and porosity becomes very low, which is in effect a textural microvariety of granite, limestone, or evaporite. Some kaolins show a swirl pattern or fabric of the overlapping face-to-face flakes, as in ball clay, that is reminiscent of slightly contorted schist.

Thus, kaolin may display textures commonly associated with igneous and metamorphic rocks as well as its sedimentary genetic type. Probably no other single variety of rock possesses more or even as many varieties of texture as does kaolin! This fact may surprise petrologists who have heard the ancient cliché of some of their brethren calling kaolin a variety of featureless "rotten rock."

The first order of classification to be used in this report is the geologic one, i.e., residual vs. transported kaolin. Despite its shortcomings, this one has withstood the test of time, is mainly geometrically descriptive and therefore devoid of the complications inherent in one based on mineral genesis, and is the one to which second and third orders of classification can probably be most easily adapted.

SCAN ELECTRON MICROGRAPHS OF RESIDUAL KAOLIN

Residual kaolins are those formed at the places where they occur and thus from which they are collected. They include: (1) kaolin deposited or crystallized from solution on a substrate that is not an aluminum silicate, i.e., not a direct parent rock for the kaolin; (2) kaolin deposited or crystallized from solution on walls of cavities within an aluminum silicate rock, i.e., a potential, but not necessarily an actual, parent for the kaolin; (3) large bodies of solid kaolin formed as a residue resting on parent rock.

Kaolin deposited on a substrate that is not a parent aluminum silicate

Included are kaolinites within quartz geodes in the Keokuk, Iowa, locality (Keller et al., 1966; Hayes, 1963); in vugs in a Mississippian-age dolomitic limestone near Shelbina, Missouri (Keller, 1970); kaolinite and dickite in a Pennsylvanian-age limestone in Kansas (Hayes, 1967); and dickite in the Bonneterre dolomite, southeastern Missouri lead belt. Probably many of the authigenic-diagenetic kaolinite or dickite crystals present in pores of sandstones fall into this category, although some of them may be associated with possible parent material in the sandstones.

In the economy of space, micrographs of only the Keokuk kaolinite, that from the Mississippian limestone, and kaolin from a pore in a sandstone core from the North Sea, will be shown as representatives of this category, Figures 1, 2, and 3.

Kaolin in this category is characterized by euhedral crystals in flat plates, loosely packed, and with not much intergrowth of crystals. Apparently there was a luxury of available space for crystal growth, and presumably crystal growth was slow so as to produce the well-formed crystals.

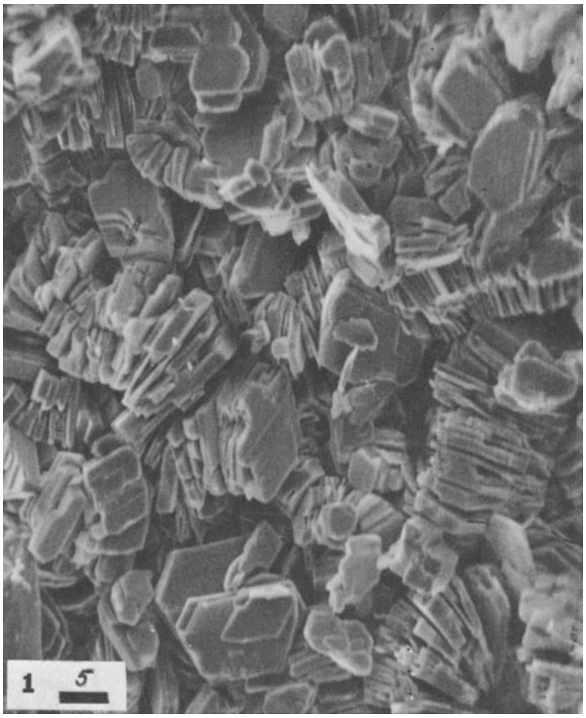
The geochemistry of the transport and deposition of the kaolinite in solution, as that deposited in the geodes and vugs, is not completely understood. For example, at the measured solubility of aluminum in the Keokuk kaolinite, the 15 g of kaolinite in a typical, small quartz geode would have required more than 2 million liters of aqueous solution saturated with Keokuk kaolinite to have moved into the geode (5 cm in diameter), deposit all of its dissolved load, and move out as pure water (Keller, 1970, p. 794)—a geologic improbability—yet the kaolinite is there!

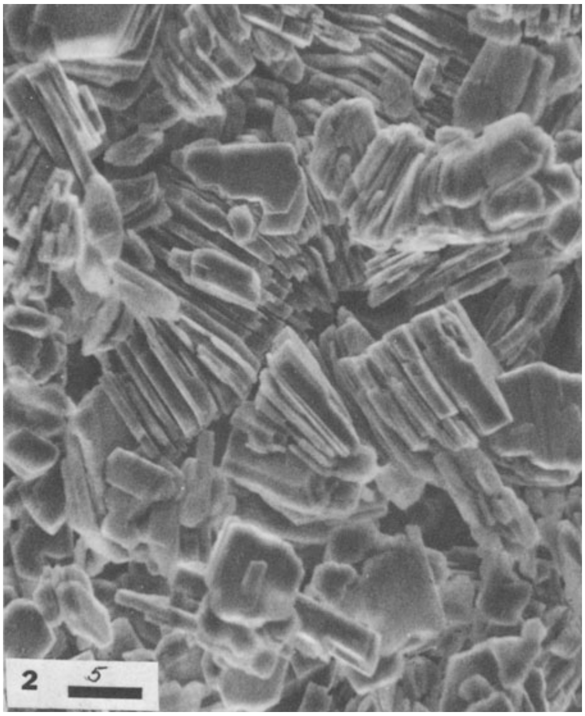
The splendid crystallinity of the Keokuk and Shelbina kaolinites is not only external. Their internal crystallinity is of such high order that a single sample of this clay yields all, or nearly all, of the totality of X-ray reflections reported for kaolinite. The major dehydroxylation peak of these kaolinites is at 690°C, typical of dickite, preceded by a shoulder on the DTA curve at about 600°C (Keller et al., 1966). Whether all of these striking mineral properties are present in all kaolinite deposited from solution on a foreign substrate remains to be determined.

Kaolin deposited from solution on an aluminum-silicate substrate

The large, commercial deposit of so-called primary kaolin in the Spruce Pine, North Carolina, district is primarily the elongate, halloysite variety of kaolin. Probably the great mass of it should be classified in the next suborder, but certainly part of it appears to have been directly crystallized from solution on a feldspar substrate, Figure 4. Note the "spikes" (fibers?, tubes?) that extend into open cavities. A question immediately arises, "Did the kaolin (halloysite) spike 'grow out' from the feldspar as parent material, on which it rests; or were the ions which nourished the kaolin crystal derived elsewhere from the parent material and merely precipitated here?" I favor the latter alternative interpretation for two reasons. First, the pitted feldspar fragment is in its early stages or weathering, i.e., shattering and different pitting or etching has been observed many times by SEM in transition from solid feldspar to kaolin. Second, weathering of feldspar may result in its bodily replacement by an interlacing mat of kaolin elongates (to be shown in a succeeding example). The mat of elongates behind the feldspar fragment represents the fully kaolinized material.

Approximately 325 km (200 miles) south of the preceding example is a thick (at least 10 m) deposit of white





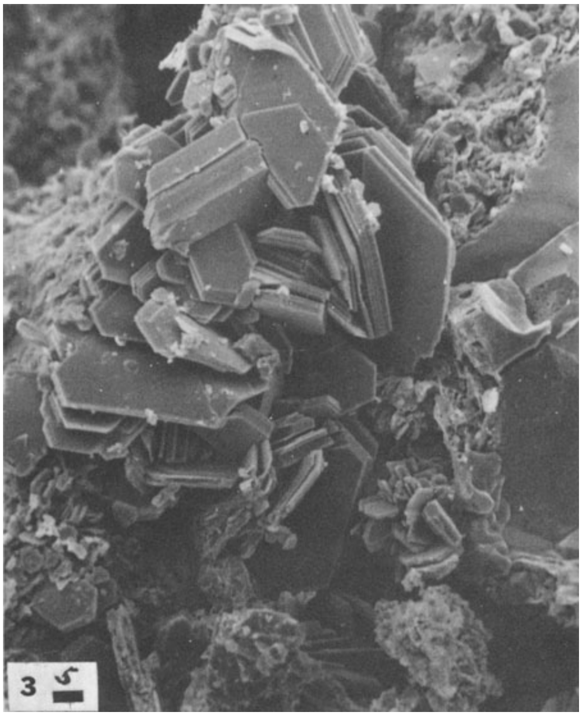


Fig. 1. Kaolinite in quartz geode from Mississippian Warsaw shale, near Keokuk, Iowa, 1500×. Scale is one (1) micrometer unless otherwise designated.

Fig. 2. Kaolinite in vug in Mississippian Chouteau limestone near Shelbina, Mo. 2000×.

Fig. 3. Kaolin in a pore in sandstone from a core, North Sea, courtesy British Petroleum Company, 750×.

Fig. 4. Endellite dehydrated to halloysite on corrosion-pitted feldspar, Spruce Pine, N.C., 4000×.

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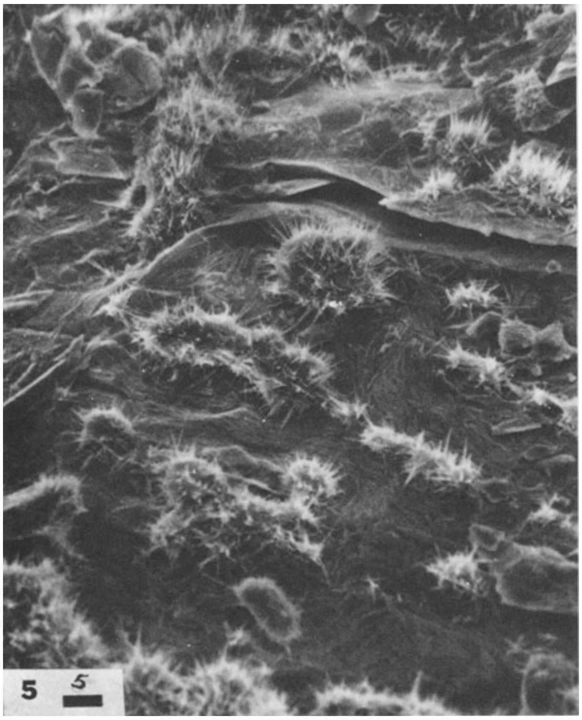

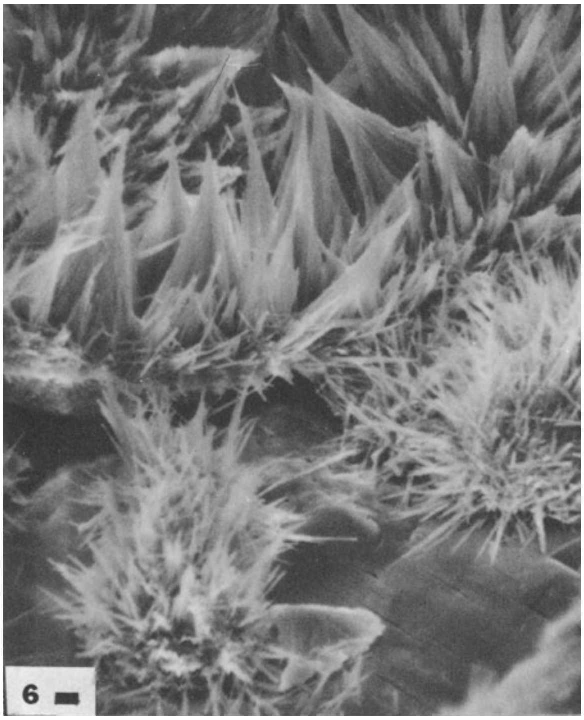

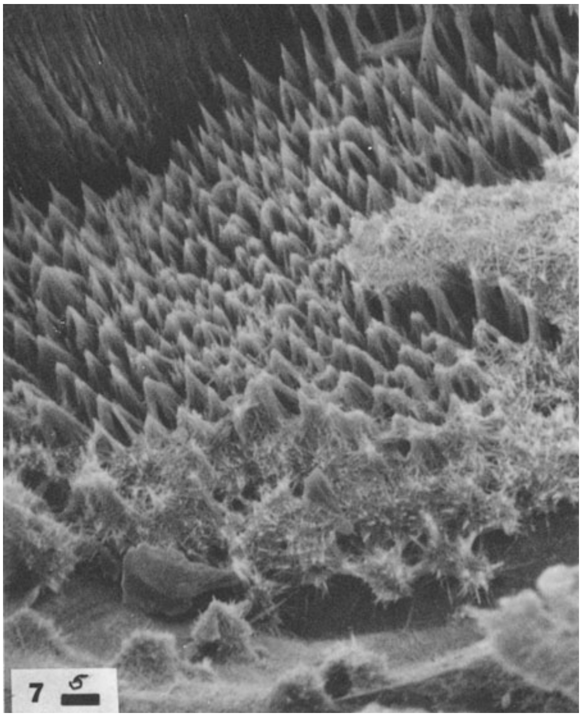

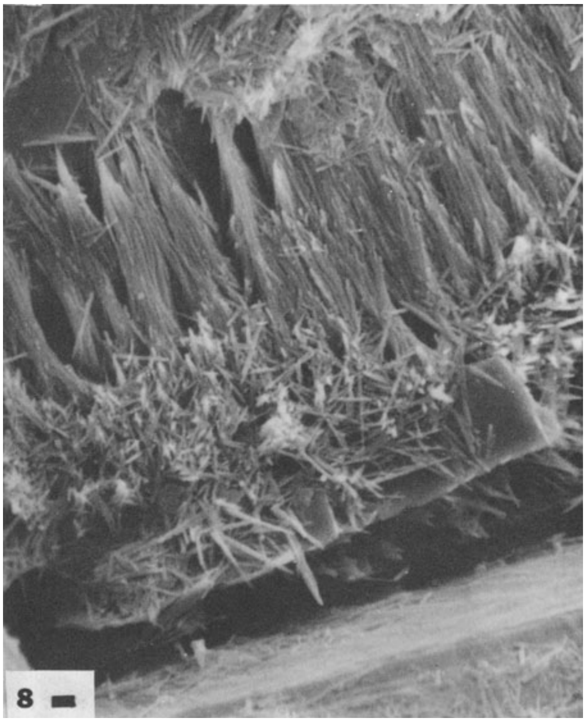

Fig. 5. Tufts of endellite-halloysite along microfractures(?) in kaolinizing Sparta Granite, Martin-Marietta Quarry, Sparta, Ga, 1000×.

Fig. 6. Tufts enlarged to 3000×. Same locality as Figure 5.

Fig. 7. Clustered elongates, same locality as Figures 5 and 6, 1000×.

Fig. 8. A vein filling of endellite-halloysite, same locality as Figure 5, 3000×.

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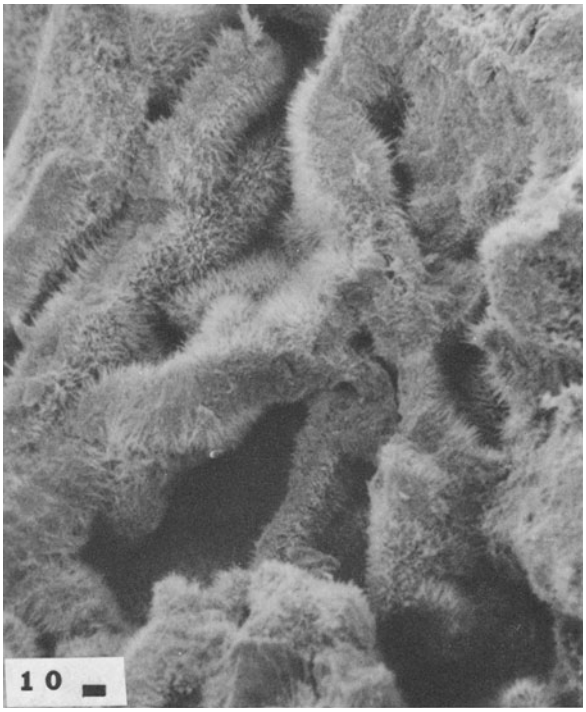

Fig. 9. Kaolin on feldspar in gneiss, 25 km south of Athens, Ga. 4000×.

Fig. 10. Kaolin on feldspar shattered during weathering, same locality as Figure 9, 600×.

Fig. 11. Kaolin elongates on pitted feldspar or nepheline, Alcoa bauxite mine, Bauxite, Ark., 5000×.

Fig. 12. Kaolin elongates (endellite) on walls of vug in perlite, Etzatlan, Mexico, 5000×.

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saprolite of the Sparta Granite, Sparta, Georgia. It illustrates one highly probable source of "Georgia kaolin." It has (is) likewise undergone Holocene weathering, as shown by a kaolinizing transition zone above the fresh granite exposed in the Martin-Marietta quarry near Sparta. Kaolinization of the feldspar is observed in SEM as a progressing process via elongate kaolin minerals deposited on a matted-kaolin, substrate-replacement of feldspar (Keller, 1977a), Figures 5, 6, and 7. The linear pattern of "tufts-of-grass" of elongate kaolin minerals probably follows a microfracture pattern. The clay mineral has an Al:Si ratio of 1:1 (analysis by both KEVEX and ORTEC). Deposition of this elongate clay mineral from a solution phase seems confirmed by Figure 8, a vein filling.

Twenty-five km (15 miles) south of Athens, Georgia, on State Highway 15, weathering feldspar from gneiss shows elongates extending outward from feldspar into cavities, Figures 9 and 10. Again, how much of nutrient ions did the substrate contribute to the elongate crystal growth, and how much came from ambient solutions?

A kaolinizing transition zone from fresh nepheline syenite in the Alcoa Bauxite Mine, Bauxite, Ark., likewise shows elongate kaolin mineral upon a substrate of pitted, partially weathered feldspar on nepheline, Figure 11. The similarity in textural patterns is close to that in Georgia.

Another similar morphology of kaolin minerals, but from a different kind of aluminum silicate substrate rock is from vugs in perlite, the country parent rock for a commercial endellite-halloysite deposit in Mexico (Keller, 1963), Figure 12. This kaolin yielded an Al:Si ratio of approximately 1:1 in an ORTEC analysis.

The preceding examples demonstrate that transport and deposition of kaolin from a solution phase is a widespread, common, and usual process in kaolinization. Contrary to the often repeated characterization of kaolin as an immobile mineral, these examples demonstrate that solution work must not be disregarded when interpreting the genesis, and diagenesis, of kaolin deposits even where the only megascopically observable change appears to be solid–solid.

On a microscale, very thin transitional films between parent rock and daughter kaolin, not morphologically differentiable under SEM, may be observed by TEM, electron microprobe, or inferred on chemical grounds. For example, Lahodny-Sarc, et al. (1972) showed intervening, gel-like material to contain mainly alumina. F. Veniale has observed a mineraloid transition phase in silicate alteration (oral communication, 1977). Meunier and Velde (1976) illustrated destabilized and diffusing zones between weathering silicate minerals in a granite. Sand (1956), in a study of residual kaolins, stated that "Remnants of feldspars, partially altered to 'books' of secondary mica and kaolinite likewise were observed." V. Hill, Jamaica, believes that a thin film or phase which predominates in either silica or alumina, depending upon the surrounding microchemical environment, envelops an argillizing aluminum silicate (oral communication, 1977). A similar effect during the hydrolysis of an aluminum silicate was projected by Keller in 1968. Likewise, it was interpreted by Keller (1976) that the random crystallographic orientation of books of kaolinite formed at an interface with parent feldspar must require that a solution phase intervene as a part of the argillation process. Even where a relatively large deposit of kaolin is residual on the source rock, as discussed in the next category, the role of solution work should be carefully scrutinized and evaluated.

Residual kaolin formed by surficial weathering

The huge commercial deposit of kaolin in the Spruce Pine, North Carolina, region is residual on granite and pegmatite. Sand found that "Hydrated halloysite predominated over kaolinite in all these deposits" (1956, p. 33). A micrograph of typical "hydrated halloysite" from this deposit is shown in Figure 13.

At Sparta, Georgia, saprolite 5 to more than 10 meters thick rests on the granite. Several meters above the zone of transitional argillation of the granite, a mixture of elongates and books of kaolin comprise the saprolite, Figure 14. A couple of meters higher, the saprolite typical of the deposit is predominantly books or stacks, although some elongates are present, Figure 15. From the island of Belitung, Indonesia, Murray (1975) described a deposit of kaolin that, "has been deeply weathered producing a large area of residual kaolin," Figure 16. Kaolinization to a depth of 15–35 m from the granodiorite has produced the largest kaolin deposit of East Germany, Caminau, near Bautzen (Störr and Buchwald, 1975), Figure 17. In Australia, residual kaolinite from granite at the Home Rule deposit shows the conventional texture, Figure 18 (Loughnan, 1976). The Dwyka tillite, South Africa, an unusual parent rock for residual kaolin, yields kaolin shown in Figure 19 (courtesy of the Yara Engineering Company).

The texture of residual kaolin produced by weathering typically is replete with open interstices, random in orientation of particle and crystal shape, and porosity is high. It is a pattern that would develop where space for crystal growth was ample, such as would follow leaching of material from the parent rock, and/or relatively low compressive weight or overburden.

Residual kaolin at a sedimentary unconformity

Kaolin present in granite below an unconformity and in the unconformable arkose above is likely to have been produced by the action of artesian water moving through the arkose and along the unconformity. To this point, granites observed on high-energy, wave-washed beaches are typically cleaned down to rounded, smooth, resistant surfaces of relatively fresh rock. Saprolitized granite clearly cannot persist in such an environment, and would not have been buried beneath

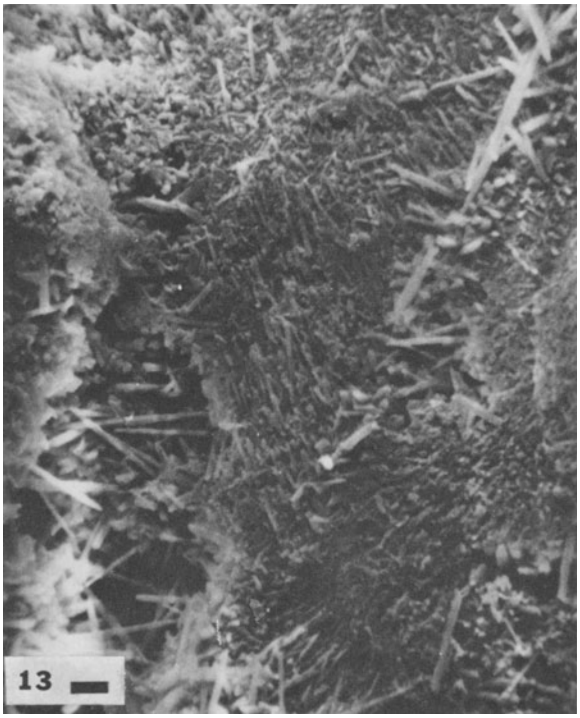

Fig. 13. Mat of "halloysite" elongates representative of the deposit at Spruce Pine, N.C., 5000×.

Fig. 14. Elongates and books of kaolin in the lower part of saprolite over Sparta Granite, Martin-Marietta Quarry, Sparta, Ga, 2000×.

Fig. 15. Books of kaolinite and sparse elongates, middle part of saprolite, same locality as Figure 14, 1000×.

Fig. 16. Books of kaolin with intermixed elongates, Belitung, Indonesia, sample by courtesy of H. H. Murray, 3000×.

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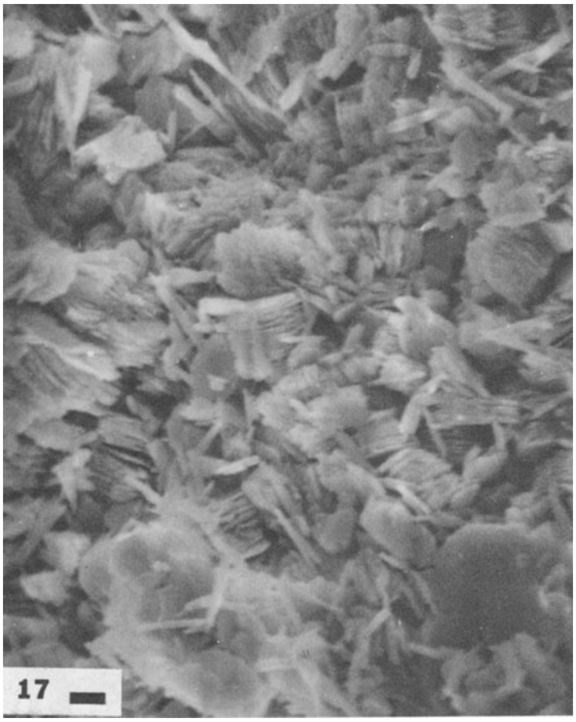


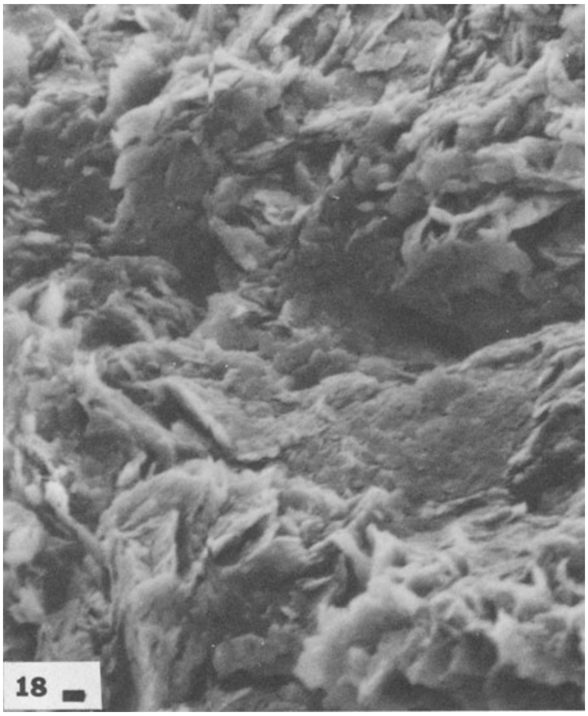
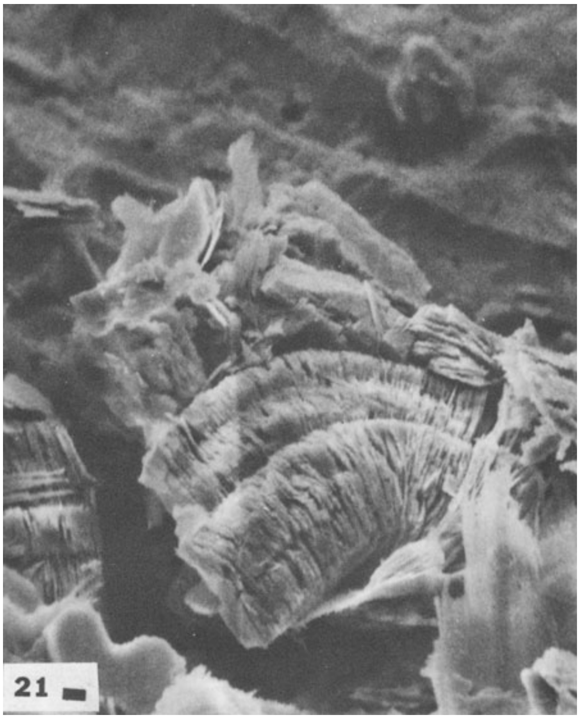


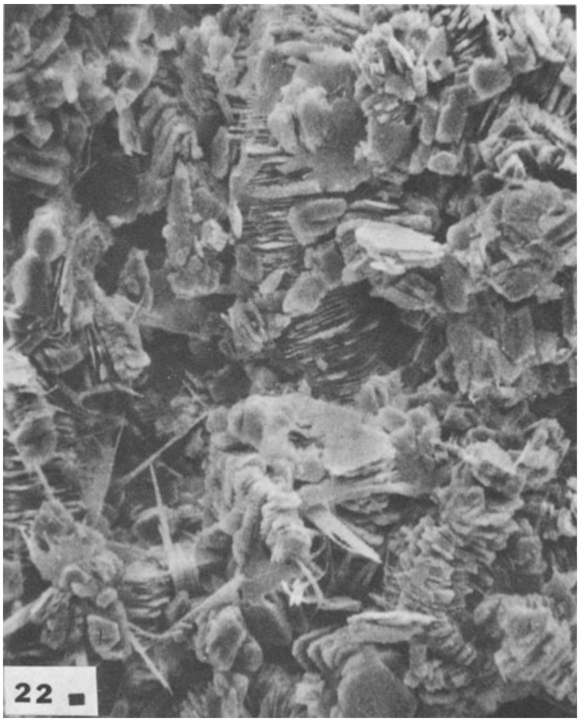
Fig. 17. Kaolin in the residual deposit at Caminau, near Bautzen, East Germany, GDR, 5000×.

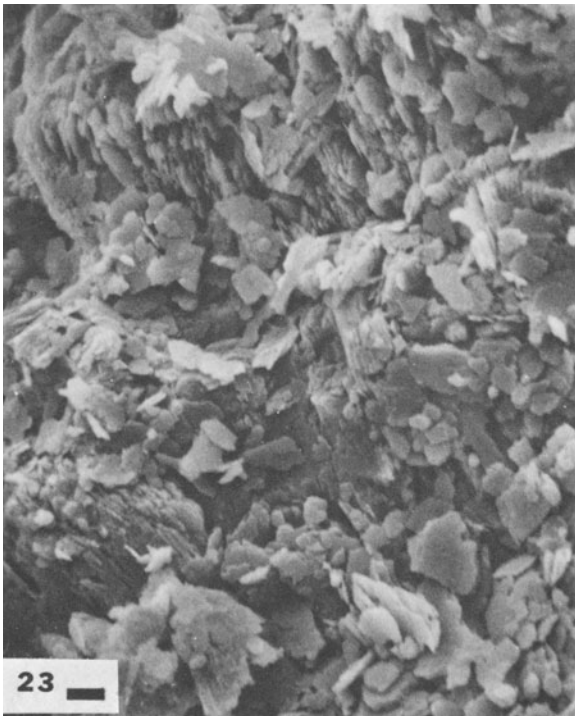
Fig. 18. Residual kaolin from granite, Home Rule deposit, Australia, 3000×.

Fig. 19. Kaolin residual over Dwyka tillite, South Africa, 3000×.

Fig. 20. Kaolinite books from feldspar in granite near Farmington, Mo, 3000×.







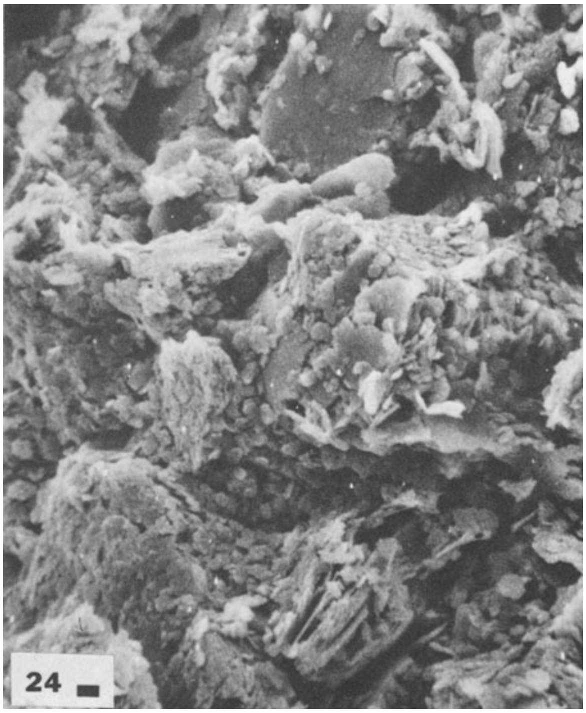


Fig. 21. Curved kaolinite from feldspar, same locality as Figure 20, 3000×.

Fig. 22. Kaolin from feldspar in the arkosic La Motte sandstone unconformably overlying granite, same locality as Figure 21, 2000×.

Fig. 23. Kaolin from feldspar below unconformity, Götzenbüschel Hill, Dohna, Saxony, 5000×.

Fig. 24. Kaolin from production zone, Wheal Remfry Pit, Cornwall District, 3000×.

conglomeratic arkose shifted about on the granite surface. Nonetheless, where such basal conglomeratic arkose and the smooth-surfaced, now-kaolinized subjacent granite have been buried, and later exhumed by erosion, both rocks may be kaolinized. I interpret that this kaolinization has been done by action of artesian water, potentially at any time in the history of the unconformable rocks, including the stage of exhumation.

An example of this geological relationship is illustrated by the Precambrian granite overlain by the Cambrian La Motte sandstone at several localities in southeastern Missouri (Blaxland, 1974; Keller, 1976), Figures 20 and 21. Kaolinized feldspar in the arkose a few centimeters above the unconformity shows stacks of kaolinite loosely expanded into the ample porosity of the sandstone, Figure 22. A second example of kaolinized granite, this one being overlain by Cretaceous sandstone, is at Götzenbüschel Hill, near Dohna, Saxony, East Germany (Störr and Ruchholz, 1975), Figure 23.

Residual clays of controversial origin

The Cornwall, England, kaolins are probably the longest exploited of the largest-ranking kaolin deposits of the world, outclassing in size the original "Kaoling" in China. Nonetheless, their genesis has long been debated whether it was by hydrothermal alteration or weathering. Most recently Bristow (1977) reviewed exhaustively and authoritatively the evidence for both hypotheses and "concluded that acceptable explanation is that a combination of the two must be responsible."

Examples of texture by SEM of these clays include one from the production zone of the Wheal Remfry Pit, Figure 24; two from a drill-core penetrating the transition zone of granite to kaolin at the Blackpool Pit, Figures 25 and 26; and one drill-core sample from the Ruddle Pit, Figure 27. The drill-core samples (furnished by courtesy of C. M. Bristow) are comparable in gross appearance to hand specimens collected at granite–kaolin transitions in quarries exposed at the earth's surface.

The textures of these samples are relatively open, as occur in a weathering environment, or where hydrothermal action has opened up the rocks comparable to the porosity of the pyroclastics at the Itaya deposit, Japan (Keller, 1977a,b). These illustrations of texture accord with Bristow's observation, "We all see that in the hydrothermal phase a 'softening up' process took place which rendered the granite extremely susceptible to later supergene alteration when the actual formation of the kaolinite took place" (Bristow, 1977, p. 15).

Residual, hydrothermally altered kaolins

Field excursions of recent Kaolin Symposia conducted in Mexico, Japan, and Italy, included visits to examples of hydrothermal kaolinization so convincing as to origin to the participants that the criteria for origin need not be argued, only stated here. The field evidence included the presence of hot water springs, H_2S emanations, a silica cap rock, and minerals accessory to kaolin, such as alunite, cristobalite, and possibly metallic sulphides. Textural examples, by SEM, of hydrothermally altered kaolins show both plates and elongates, Figures 28 and 29, Sombrerete, Mexico; Figure 30, Itaya Mine, Japan; and Figure 31, Monte Porcu, Sardinia (Keller et al., 1977).

The texture of hydrothermally altered kaolins is characterized typically by tight packing of clay mineral crystals and relatively low porosity. The crystals tend to be smaller, and to occur in thinner packets or sheaves rather than in books or stacks as in kaolin from the weathering process. Space for kaolinization in massive igneous rock is derived by leaching of silica and metal ions, but in tuffs the space may be ample for slightly larger, or more open crystals of kaolin (as in Itaya, Japan).

SCAN ELECTRON MICROGRAPHS OF TRANSPORTED KAOLIN

Transported kaolins traditionally refer to relatively large, physically transported deposits in contrast to the smaller occurrences of solution-transported examples cited in the first part of this report. These large deposits are conveniently further subdivided into two groups named mainly from their commercial uses, although they may be differentiated also geologically, genetically, and texturally. These two groups are the (1) "kaolins," the nearly white kaolinitic clays whose surface properties make them valuable in industry; and (2) the "refractory" or "fire clays" also of industry.

Transported kaolins having industrially useful surface properties

The first group are exemplified by the Georgia kaolins, and two in the Amazon Basin, namely the Jari River and Rio Capim deposits. Their industrial usefulness results primarily from the surface properties of the fine individual particles into which they may be dispersed. Such properties include color, which is typically a bright white, flatness of the particle sheets, proper size distribution of the particles, and their surface reactivity with both organic and inorganic compounds which fit them to serve as coating material, fillers, carriers, and plasticizers. These morphological characteristics are recognizable in the SEM's of the kaolins.

Texturally, Georgia kaolins may be subdivided into two groups: the "soft," coarse, mealy, porous type found in deposits of Cretaceous-age, Figures 32 and 33; and the "hard," finer-grained type, in further illustration, which typify Eocene-age clays (Murray, 1976).

Although there is a broad concensus that "Georgia kaolins" should be classified as transported and sedi-

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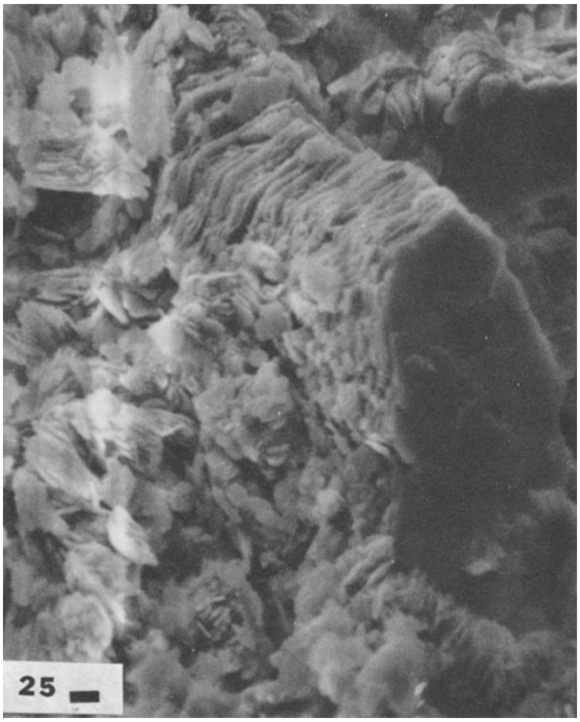

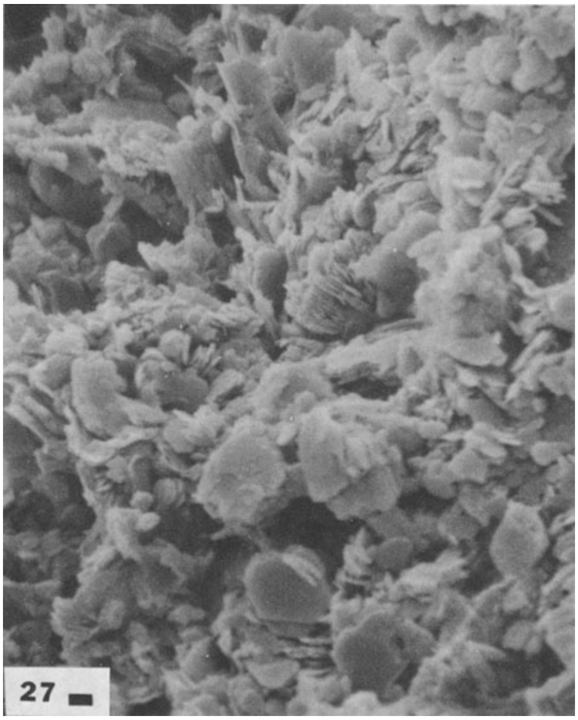

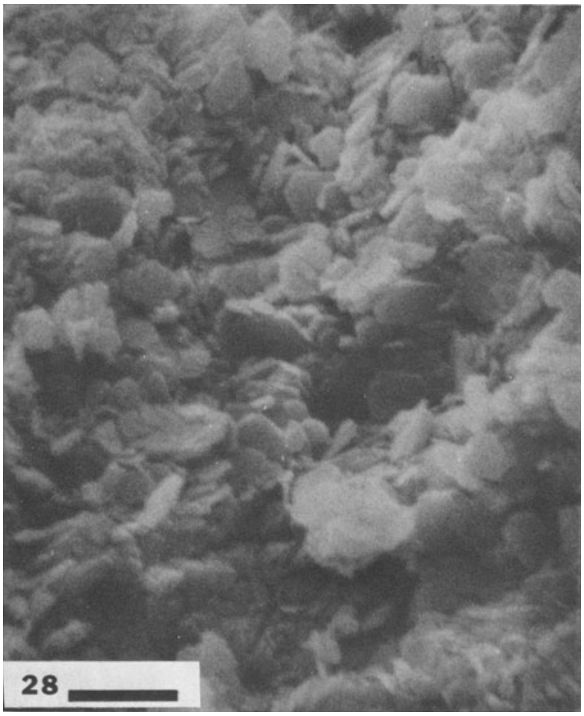

Fig. 25. Kaolin from drill core penetrating alteration zone of granite, Blackpool Pit, Cornwall District, 4000×.

Fig. 26. Kaolin from another sample of drill core, same locality as Figure 25, 5000×.

Fig. 27. Kaolin from drill core penetrating alteration zone of granite, Ruddle Pit, Cornwall District, 3000×.

Fig. 28. Hydrothermal kaolin, crystal plates, near Sombrerete, Zacatecas, Mexico, 15,000×.

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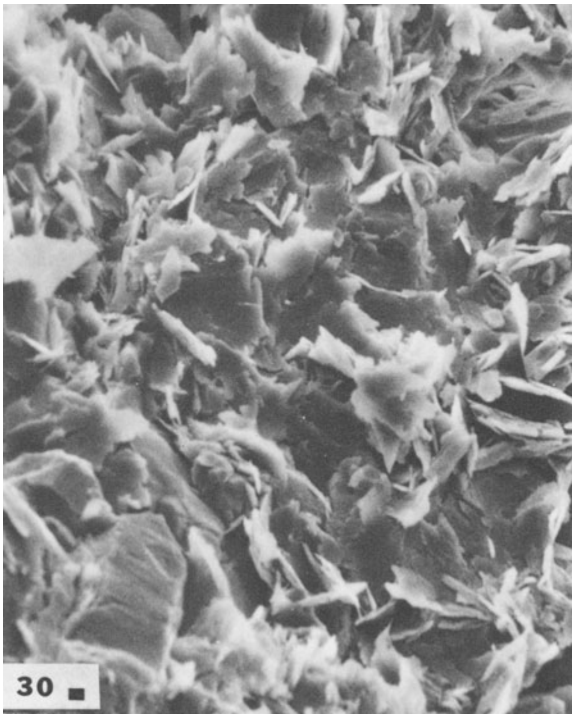
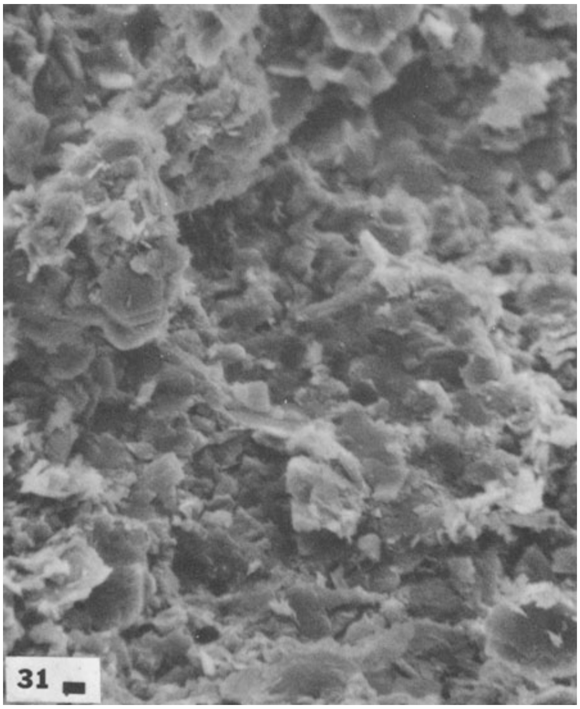




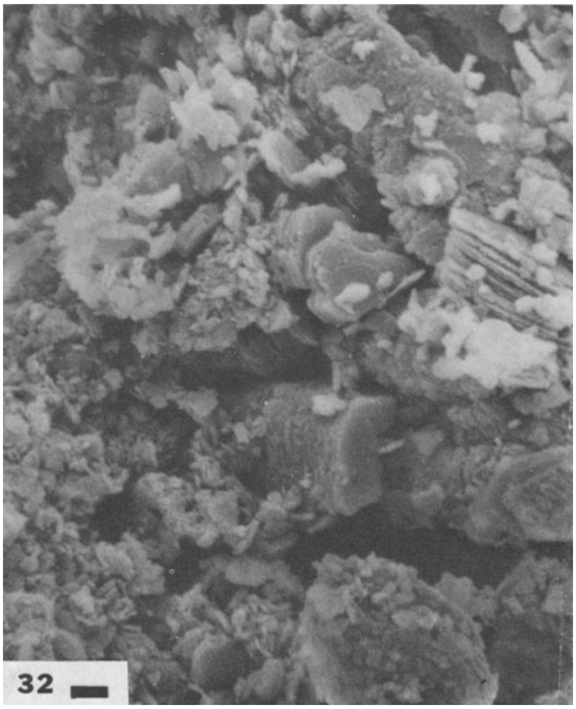
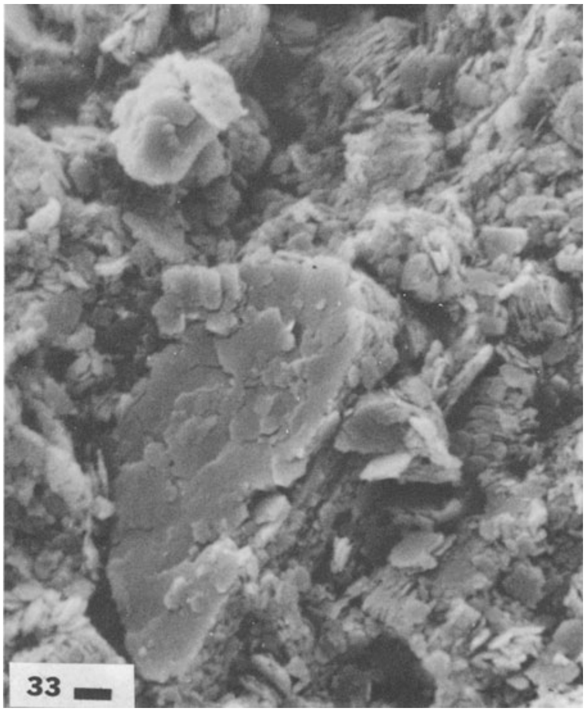


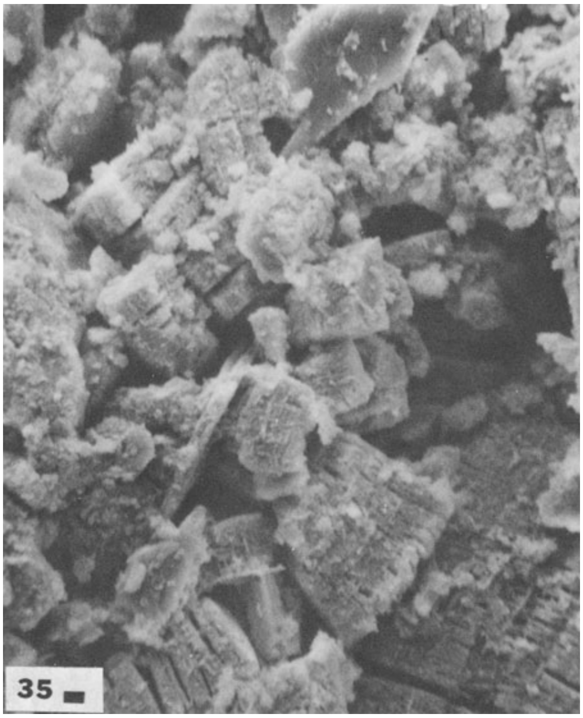
Fig. 29. Hydrothermal kaolin elongates, same mine as Figure 28, 7500×.

Fig. 30. Hydrothermal kaolin, Itaya Mine, Japan. Note individual flakes or sheaves, but not stacks or books, 2000×.

Fig. 31. Hydrothermal kaolin, Monte Procu, Sardinia, 3000×. Note tight packing of small flakes and sheaves.

Fig. 32. Kaolin, API Reference Clay, McNamee Pit, Bath, S.C., 5000×.





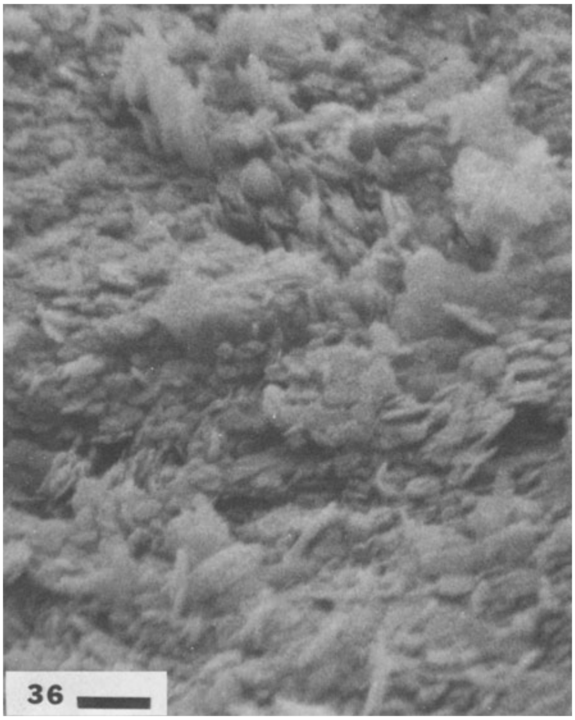


Fig. 33. Kaolin, Huber Pit, Huber, Ga, 5000×.

Fig. 34. Kaolin, Jacal (Villa Victoria) Mexico, 1000×.

Fig. 35. Kaolin, orientation parallel to bedding plane, same locality as Figure 34, 2500×.

Fig. 36. ''Hard'' kaolin, Purvis Pit, Wrens, Ga. 10,000×.

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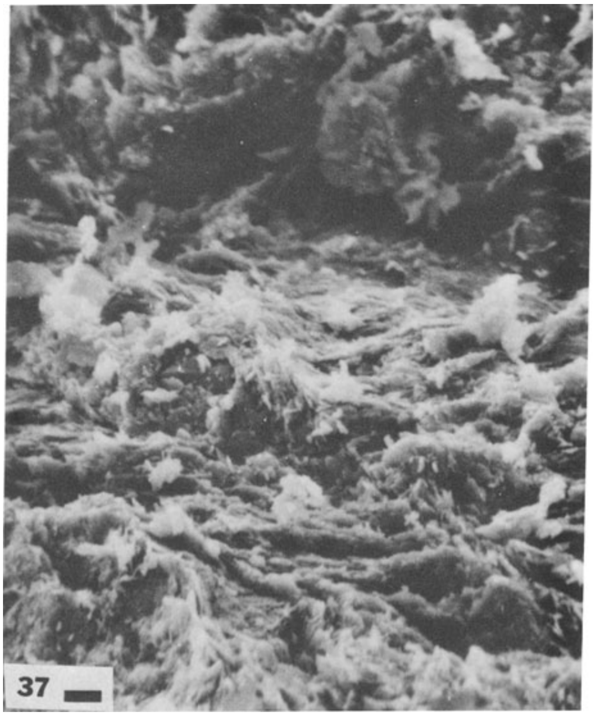

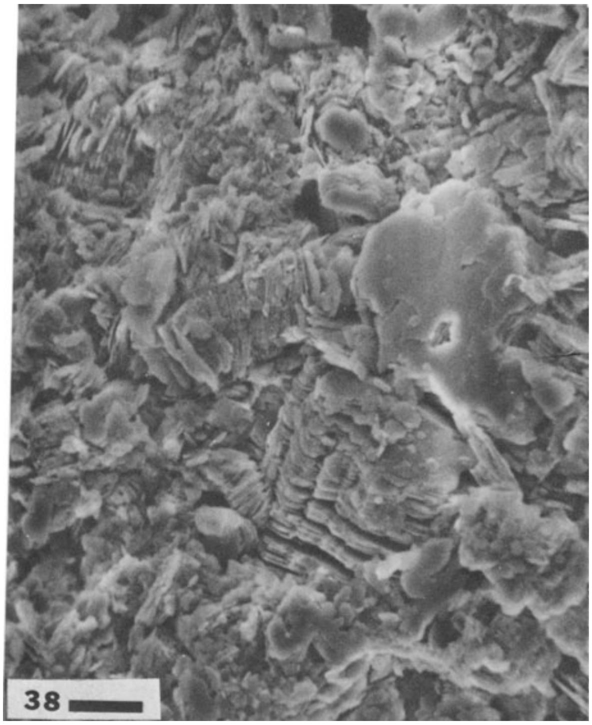

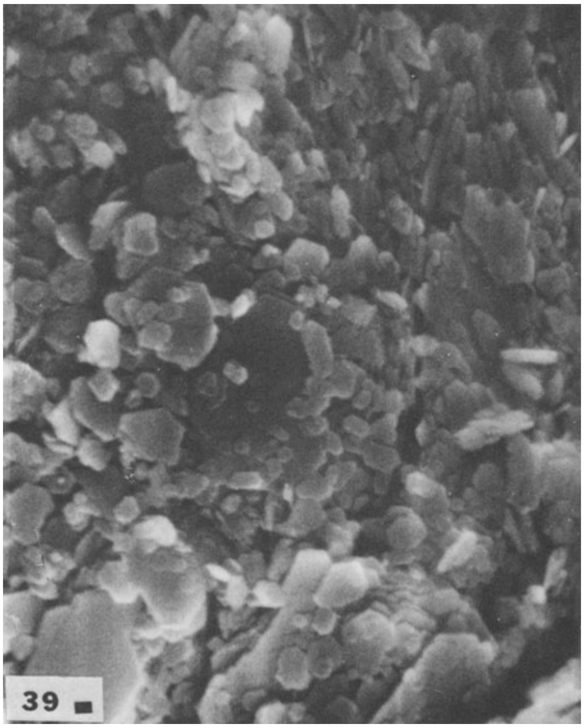

Fig. 37. "Hard" kaolin, API Reference Clay, Dixie Pit, Bath, S.C., 5000×.

Fig. 38. Kaolin, Jari River, Brazil, 10,000×.

Fig. 39. Kaolin, Rio Capim, Brazil, 2000×.

Fig. 40. Ball clay from near Mayfield, Ky, note the "swirl" pattern, 5000×.

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mentary, not all have agreed as to whether the kaolinization process occurred before deposition or after deposition (of arkosic feldspar). These points of view, which were summarized by Patterson and Buie (1974), and Keller (1977a), need not be repeated here.

Several investigators have believed that during first-stage kaolinization the kaolin would be red with iron oxide. Thus, a subsequent stage of deferritization would be necessary to decolorize it to its present whiteness. Whitening by more than one stage of alteration is not necessary, however. Thick, large deposits of white saprolite, derived directly from granite, as at Sparta, Georgia, described by Keller (1977a), could serve as adequate source material for white kaolin. Such saprolitic kaolin could be washed by streams and winnowed by waves into depositional basins as postulated by Murray (1976). High durability during aqueous transport of books and stacks of kaolinite flakes as pellets was reported by Keller (1977a, p. 343). Such observations strongly favor the hypothesis of predepositional kaolinization.

Near Jacal, or Villa Victoria, about 125 km west and north of Mexico City, on National Highway 15, is a stratified, sedimentary deposit of white kaolin in an intermontane basin, or old lake (?). The basin is rimmed with partially kaolinized gravel, sand, and volcanic detritus. Field evidence, therefore, is inconclusive as to whether the main kaolinization process in this transported deposit was pre- or postdeposition. The texture of the kaolin is coarse, replete in books, and has very high porosity, Figures 34 and 35 (Keller and Hanson, 1975).

SEM's of "hard" Georgia kaolin are in Figures 36 and 37. The kaolin plates are relatively fine-grained, and are oriented face-to-face. Murray (1976) interpreted these deposits as retransported and redeposited kaolins.

Kaolins from the huge deposits on the Jari River, north of Belem, and from the Rio Capim, south of Belem, in Brazil are shown respectively in Figures 38 and 39. Eisenlohr (1975, oral communication) interpreted their origin as sediments of kaolin deposited in a large interior lake within the Amazon Basin during late Tertiary to Pleistocene time. The kaolin was derived by residual weathering, under a tropical climate, of crystalline silicate rocks in a region draining into the lake. The texture of these samples is similar to that of other sedimentary kaolins. Although the micrographs show the Rio Capim clay to be coarser than that on the Jari River, I had only a half-dozen samples for comparison—these may be too few to be representative of the size distribution.

Refractory clays, fire clays

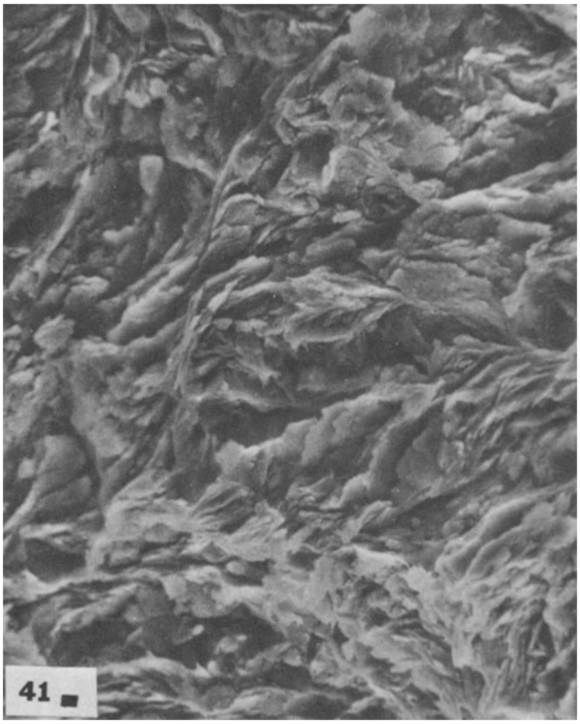
These clays are characterized by other classification names from industry such as ball clays, plastic fire clay, semi-plastic, semi-flint, and flint fire clay. No sharp petrologic or scientific line can be semantically drawn between the clays of the preceding category and this one, because Georgia-type kaolin is used for refractory purpose, and ball clays are used in ceramic mixes that are not refractory in function. On the other hand, differentiation between the two types is valid because a boulder or lump of flint clay, or ball clay, is easily differentiated visually, without slightest doubt, from a lump of "Georgia kaolin." Probably texture by SEM provides the best way of demonstrating documentable differences between the two types of clay.

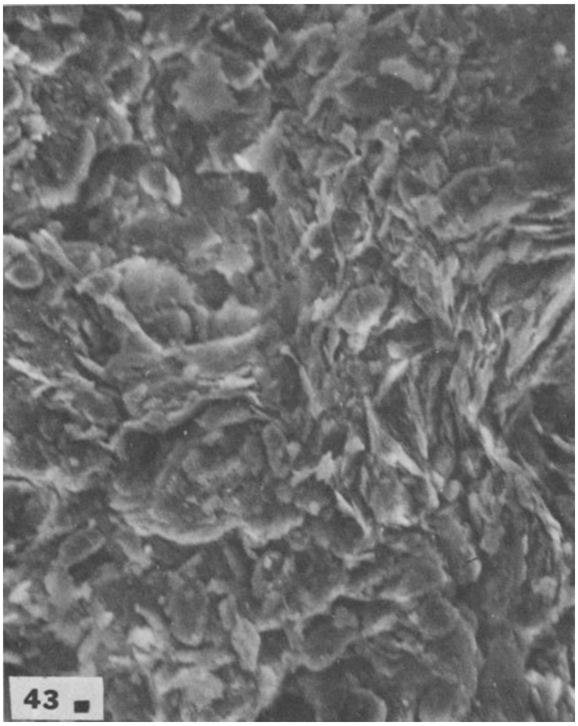
Ball clay is shown in Figures 40 and 41, from Kentucky-Tennessee, U.S.A. and Devon Basin, U.K., respectively. Ball clays must be exceedingly plastic in order to qualify for that classification. Texturally, they consist of platy aggregates of tiny flakes of kaolin, and possibly some illite and/or smectite, tightly compacted in face-to-face orientation. These aggregates may be floccules of colloidal clay particles (?). Typically they show a "swirl" pattern, probably resulting from movement during packing, settling, dewatering, or other soft-rock deformation.

All ball clay deposits, so far as I have been able to determine from my experience and that of colleagues questioned, represent detritus from a previous weathering regime. It seems genetically important that typically the source clay, or a significant part of it, has been through a previous sedimentational cycle. Organic matter present in the clay attests to significant vegetation associated with the basin in which the ball clay was deposited. No doubt the organic colloids contribute to the highly plastic properties of ball clay.

With respect to geologic age, ball clay deposits, as such, are not older than the Tertiary. Does this mean that a geologic environment in which ball clays could form did not exist before Tertiary time? Certainly not! Textural patterns found in Miocene plastic fire clay, as at Breitscheid, Germany, Figure 42, and thence to Pennsylvanian-age, plastic fire clay in Maryland, Figure 43, demonstrate they are sequential in genesis and time. Other "plastic fire clay," though probably lower in plasticity than the Maryland example, grades sequentially through semi-plastic to semi-flint clays as occur in Maryland, Pennsylvania, Kentucky, and Missouri. Representative textures of such clays are shown in Figure 44, a semi-plastic fire clay; and Figure 45, a semi-flint fire clay.

That plastic and semi-flint refractory clays grade directly into flint clay can be shown from two geologic observations. A few refractory clay deposits, or commercially mined, open "pits," contain typical flint clay in the bottom of the pit which grades directly upward, within the same pit, into more plastic varieties (Keller, 1978, in press). On a larger, or wider scale, areas of dominantly plastic refractory clay grade into areas of dominantly flint clay—the flint-clay facies (Keller, 1968). Textures of representative flint clay from Mis-





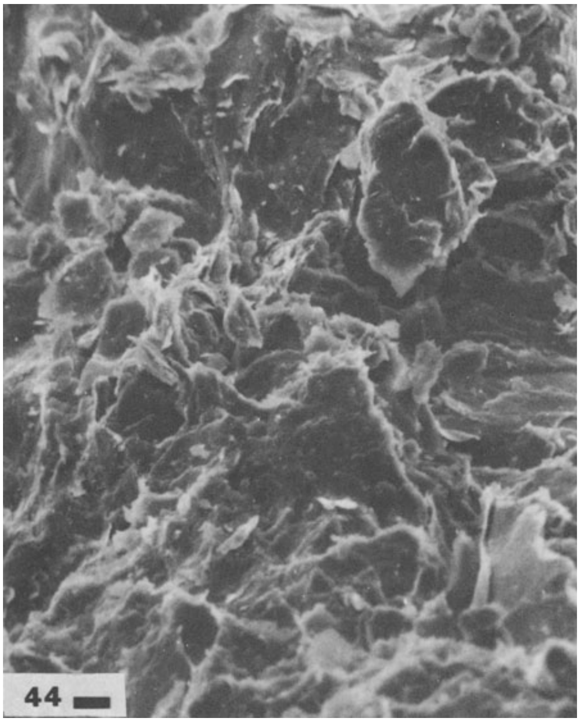


Fig. 41. Ball clay, Devon Basin, U.K. As in Figure 40, flakes are in face-to-face orientation, 2000×.

Fig. 42. Plastic fire clay of Miocene Age, API Reference Clay 129-A, Breitsheid, Germany. Note similarity in texture to the ball clay, 3000×.

Fig. 43. Plastic fire clay, Pennsylvanian Age, Frostburg, Md. Although much older than the fire clay in Figure 43, the texture is similar, 2000×.

Fig. 44. Semi-plastic (less plastic) fire clay, Clearfield County, Pa, 1000×.

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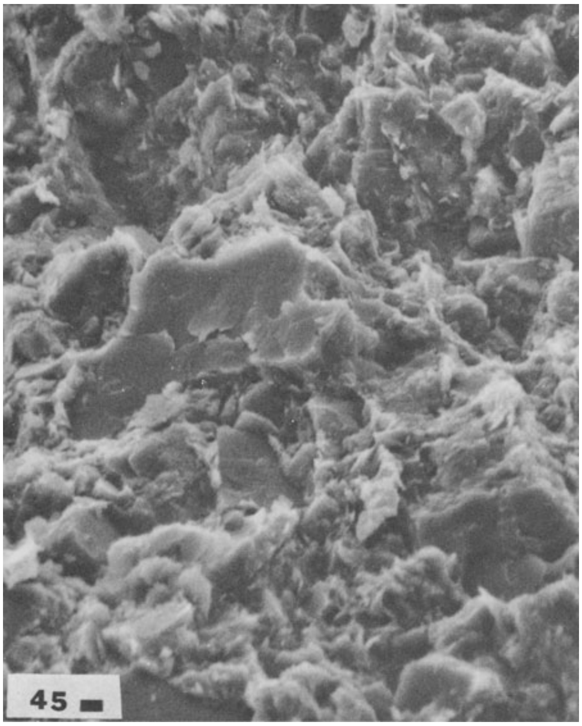

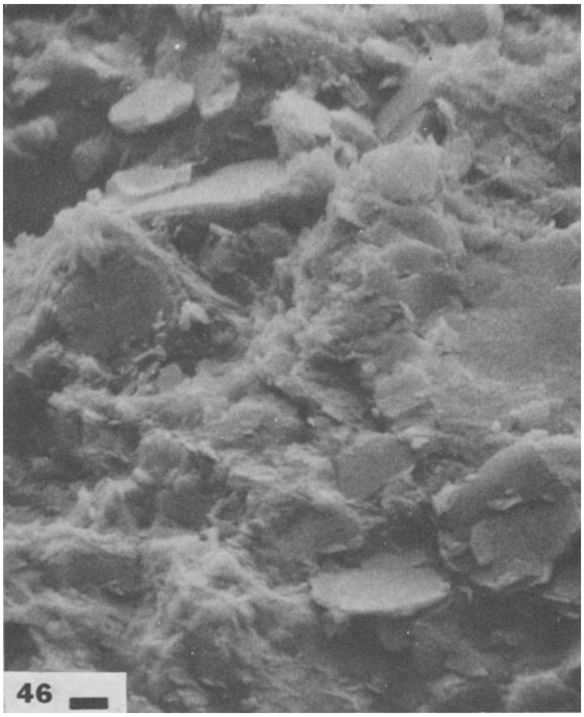

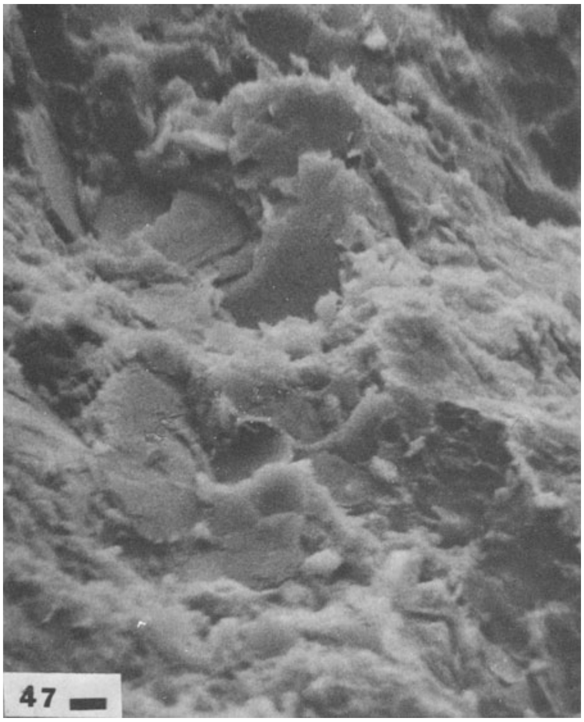

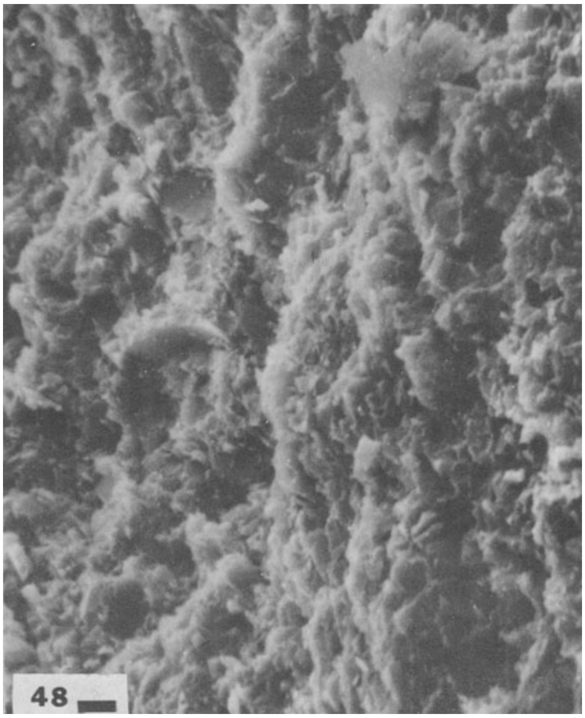

Fig. 45. Semi-flint fire clay (typically self-bonding but having some flint-clay refractory properties), Mexico, Mo, 3000×.

Fig. 46. Hard flint clay, Whitesides, Mo. Kaolin packets and flakes are tightly intergrown, porosity is low, 5000×.

Fig. 47. Hard flint clay, Vereeniging, South Arica; similar in characteristics to American flint clay, 5000×.

Fig. 48. Flint clay, Permian Illawarra Coal Measures, Cambewarra Mountain, Sydney Basin, Australia. Subdued relic ''cornflakes'' texture inherited from smectite derived from volcanic ash, 5000×.

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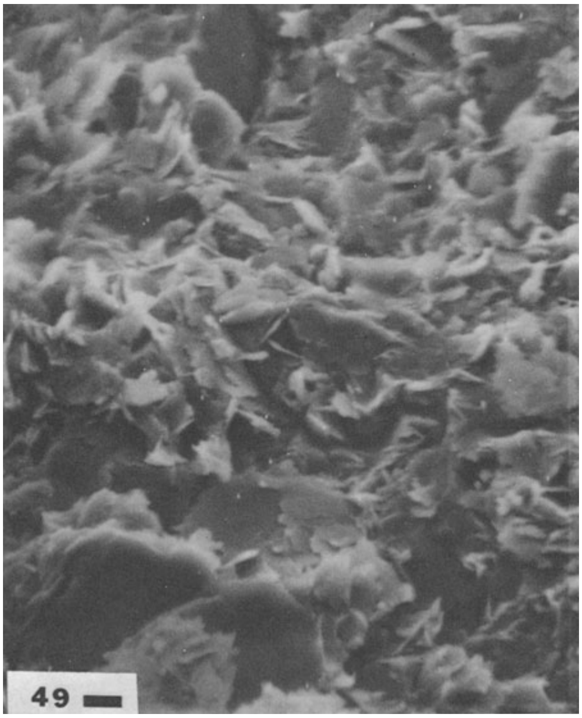

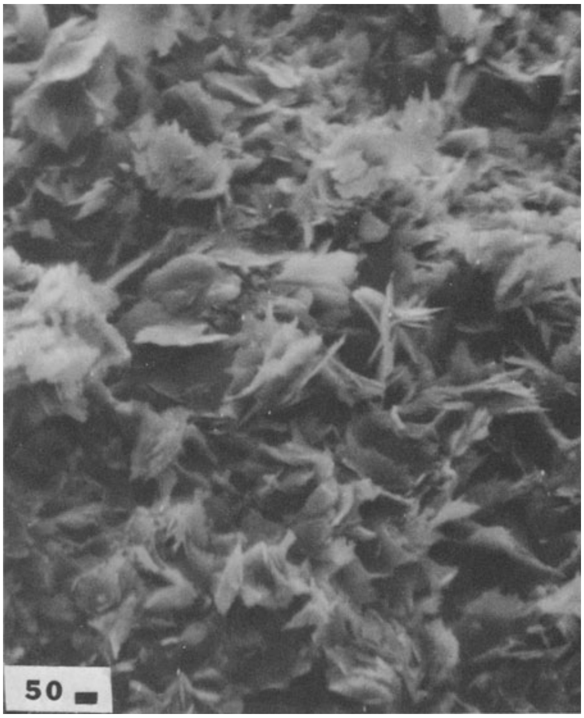

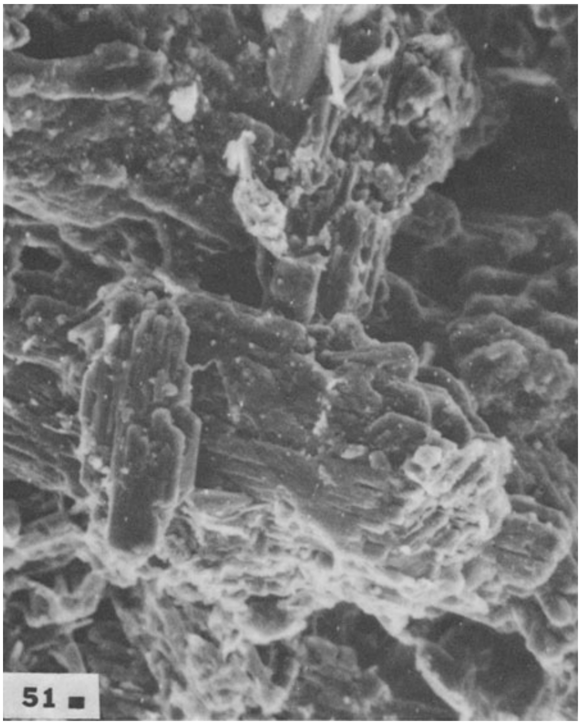

Fig. 49. Burley clay (kaolinitic flint clay containing oolites or disseminated diaspore); the Al_2O_3 content of this specimen is about 50%. Schaefferkoetter Pit, near Owensville, Mo, 5000×.

Fig. 50. First grade diaspore; this specimen contains 70–72% Al_2O_3, same pit as Figure 48, 3000×.

Fig. 51. "Surface-boulder" diaspore, recrystallized at surface temperature and pressure, Gaume Pit, near Aud, Mo, 2000×.

souri, Africa, and Australia are shown in Figures 46, 47 and 48. Flint clay is composed of tightly interlocked, small packets of kaolinite, which makes it compact and low in porosity (typical bulk density of unfired flint clay is in the range of 2.2 to 2.6, Baumann and Keller, 1975). The texture of the Australian sample, Figure 48, shows small packets of kaolin, typical of flint clay, interspersed in a modified "cornflakes" texture, a relic of progenitor smectite. The parent rock of this flint clay was volcanic ash (Loughnan, 1976; Keller, 1977b) which presumably weathered to smectite, followed by conversion of smectite to kaolinite (and flint clay) during the second-stage, and final alteration in a paludal environment to flint clay.

In a few localities, such as Missouri, Pennsylvania, Israel, and France, and some bauxite-producing areas, flint clay or flintlike clay may grade into high-alumina minerals (Keller, 1968; Keller et al., 1954). In Missouri, the gradational rock phase between flint clay and diaspore is called "burley" clay, shown in Figure 49. First-grade diaspore, Al_2O_3 content of 68% and higher, is shown in Figure 50. Such diaspore, when exposed in boulders to the weather at the top of a deposit, probably since late "Tertiary" and/or Pleistocene time, oxidizes and recrystallizes at surface temperatures to porous, harsh, tan-colored "surface boulders" of diaspore. The recrystallized, tabular diaspore is shown in Figure 51 (Keller, 1977c; 1978 in press, American Mineralogist).

CONCLUSIONS

Scan electron micrographs may be used to illustrate textures of kaolins that are representative of different categories in a geological classification of kaolin. They may also be used for alternative classifications of kaolin.

SEM's demonstrate that solution work is exceedingly important in the transport, deposition, and diagenesis of kaolin. Solution work may significantly accompany other processes which form kaolin deposits, including those in which the materials are dominantly clastic.

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Резюме- Разновидности каолина,горной породы,могут быть классифицированы по геологическим,минералогическим,кристаллографическим,генетическим,структурным и морфологическим признакам,по промышленному использованию и другим показателям.В этой статье геологическая классификация используется в качестве основной,т.е.разновидности каолина подразделяются на привнесенные и остаточные,в то время как другие категории используются в качестве более мелких подразделений.

Микроснимки структур каолина,сделанные с помощью развертывающего электронного микроскопа,показывают,что четкие структуры определяют несколько классификационных категорий.Разновидности структур каолина подобны типичным структурам осадочных,изверженных и метаморфических пород.Поскольку словесные описания стрктур не адекватны визуальным наблюдениям,в статье приводятся микроснимки.

Микроснимки иллюстрируют различия между каолинами,которые были привнесены, сформированы или отложились из коллоидальной фазы раствора или в виде обычных обломочных частиц.Первоисточник каолина,отложенного,или "рожденного" раствором,вероятно,установить трудно.Предполагается,что в целом роль деятельности раствора в петрологии каолина более важна,чем обычно принято думать.

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