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SCAN ELECTRON MICROGRAPHS OF KAOLINS COLLECTED FROM DIVERSE ENVIRONMENTS OF ORIGIN—I

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Abstract—Scan electron micrographs are shown of (1) kaolinite and dickite which crystallized from solution within cavities, (2) kaolinite weathered from clastic primary silicate material, (3) residual kaolinite from primary silicate rock, (4) kaolinite above and below a basal unconformity on granitic rock, and (5) hydrothermally altered kaolinite. The texture of kaolin reflects the environment in which the clay was formed.

Euhedral crystals of kaolin minerals characterize cavity fillings. The weathering environment produces large crystal flakes of kaolinite, expanded books, mats of elongates, high porosity, and low bulk density (less than 2.0). The hydrothermal environment produces smaller crystals, singles, sheaves and packets of crystals, low porosity and high bulk density (2.0 and above).

The interrelationships of genetic environment of kaolin minerals and accompanying texture are discussed in light of available geochemical information.

INTRODUCTION

Kaolin has been defined as a fine-grained, earthy rock which contains a significant amount of the kaolin minerals (Committee on Correlation of Age and Genesis of Kaolins, 1972; Ross and Kerr, 1930). Such kaolin rocks, and other mineral occurrences of kaolin may originate in a variety of diverse environments, including the following;

(1) Crystallization in cavities within other rock,
(2) Replacements,
(3) Alteration of water-laid clastic silicate parent material,
(4) *In situ* alteration of "primary" silicate crystalline rock,
(5) Kaolinization at an unconformity, as below an artesian aquifer,
(6) Hydrothermal argillation (water heated by subsurface sources),
(7) *In situ* alteration of clay parent rock,
(8) Sedimentary deposition of kaolin minerals,
(9) Diagenesis,
(10) Those under controversial geologic interpretation.

Some of these environments may generate a texture within their kaolin products that is distinctive and definitively characteristic of the environment. An example is the two textures or fabrics, found by scan electron micrography to be clearly dissimilar, between kaolins of sedimentary and hydrothermal origin in Mexico (Keller and Hanson, 1975).

Fabric of coarse-grained rocks has long been used to infer their geneses, for example gneiss vs granite. The fabric or texture of clays is not observable, of course, with a hand lens or even a petrographical microscope, but a scan electron microscope (SEM) can magnify the texture of a kaolin (or chert) visibly comparable to that of a phaneritic rock. By breaking a clay in hand, or chipping with a small hammer, a freshly broken surface of a tensile fracture is exposed similar to the fractured surface resulting on a phaneritic broken from an outcrop. In the preparation of kaolin for SEM, no further grinding, etching or other processing which might introduce an artifact is performed on the specimen. The fresh surface is lightly coated with a thin film of sputtered-on gold which carries away excess charge from the electron beam impinged upon it. Magnifications up to about 15,000, but more commonly in the range 1000 to 5000, are used.

The purpose of this report is to show typical textures, by SEM, of kaolins whose origins are known from independent geologic criteria. An attempt will be made to characterize the textures, to discuss them, and to account for their types as products consistent with, and representative of, the environments in which they were generated.

KAOLINITE CRYSTALLIZED IN CAVITIES WITHIN OTHER ROCKS

Kaolinite, dickite, and nacrite have been observed as euhedral crystals partially filling cavities in various rocks. Nacrite, because of its rarity, will not be considered further in this paper. Kaolinite exhibiting near perfection in crystallinity (also dehydroxylates at the same temperature as dickite) and euhedral morphology occurs in small geodes in the Mississippian Warsaw formation (illitic shale and limestone) near Keokuk, Iowa (Keller, Pickett, and Reesman, 1966; Hayes, 1963), Fig. 1.

These well-formed kaolinite crystals occur as loose powder or more snugly packed fillings within quartz geodes a fraction of an inch to serveral inches in diameter. The interior lining of most geodes commonly consists of inward-pointing quartz crystals showing

prismatic and rhombohedral faces. In a few geodes, calcite crystals, and more rarely, sphalerite, galena, or millerite, may occur. Clearly, the other minerals associated with the kaolinite show features that mineralogists regularly interpret as being crystallized from solutions nourishing crystal growth in an otherwise open cavity. Based on this independent mineralogic evidence, it is interpreted that kaolinite was crystallized from solution within a quartz geode.

Although the geologic observation and interpretation are straight forward, the geochemistry of the process of origin is not clearly understood. For example a typical Keokuk geode may contain 15 g of kaolinite. If this kaolinite were deposited from a distilled water solution, the volume of solution, calculated from conventional solubility data on silica and alumina, to bring in the alumina would be impossibly large—over 2,000,000 l if the incoming solution was saturated with Al^{3+} and the outgoing solution was free of aluminum (Keller, 1970). Other mechanisms must be appealed to. Harder (1974) reported that hydroxides of Al, Fe and Mn coprecipitate silica from very dilute solutions. Hem *et al.* (1973) found a colloidal amorphous product having the composition of halloysite to be produced during aging of solutions containing from 10^{-5} to 10^{-2} mols/l of Al and dissolved silica, pH 4–10, at 25°C. Hayes (1963) considered the possibility that concretions, which were precursor to the geodes, dissolved and left material that supplied the lined geodes. The problem of kaolinite genesis, formidable in itself, is compounded because little is known about how goedes (which house the kaolinite) are formed. It has been suggested that diffusion, and/or complexed ions of Al with organic chelators, or with a carbonate-complex, might have provided transport. Obviously the chemistry of kaolinite crystallization and diagenesis is still an inviting area of research.

Not only shale (as the Warsaw shale) but limestone may provide cavities in which kaolinite is crystallized. In the Mississippian Chouteau limestone, near Shelbina, Shelby County, Missouri (O'Laughlin quarry in SE 1/4, sec. 6, T. 57N., R. 9W) kaolinite occurs as loose, euhedral, white, relatively pure flakes as geopetal fillings within vugs and cavities a fraction of inch to inches in diameter, Fig. 2.

The geochemistry of deposition of this kaolinite in carbonate rock is likewise obscure. Despite our lack of realistic geochemical understanding or explanation, one observational fact stands out: kaolinite is mobile in and from solution. An important corollary to this fact likewise should be emphasized, namely, that when other processes are invoked for kaolinization, such as weathering, hydrothermal alteration, diagenesis, etc. the *accompanying role of mobility in solution is ever potentially possible.*

Euhedral, white flakes of kaolinite occur in filled thin veins and partings that cut across shale and other rocks in part of the Joplin lead-zinc district in southwest Missouri (Tarr and Keller, 1937), Fig. 3. Possibly the deposition of this kaolinite is related to the time of mineralization.

Vugs in partially altered volcanic glass that is parent to a kaolin deposit hold elongate clay crystals attached to their walls. Tiny dark centers visible in the original micrograph at the ends of the elongates suggest that the crystals are tubes, Figs. 4 and 5. Dominantly endellite–halloysite comprises the clay in this now-abandoned quarry near Etzatlan, Jalisco, Mexico (Keller, 1963).

Characteristic texture. The characteristic texture of kaolinite which has crystallized from solution within a cavity typically is one of euhedral plates, 5–15 μ dia., which occur as singles, or face to face in packets in loosely expanded books up to 20 μ in thickness. Porosity of the clay mass is high. Elongate-crystals of kaolin in a similar environment of crystallization show relatively unrestricted growth.

Not all non-detrital kaolinite crystals occur in euhedral hexagons, as will be shown later—hence the foregoing texture is definitive of an open crystallizing environment.

DICKITE CRYSTALLIZED FROM SOLUTION

Dickite commonly maintains euhedral hexagons, or even fragmentary hexagons in powder pulverized from massive occurrences of dickite. It was considered by Ross and Kerr (1930) to be primarily a hydrothermal kaolin mineral. Although some occurrences of dickite are hydrothermal in origin, to the contrary, (a) others do not indicate an origin by elevated temperature, and (b) many occurrences of hydrothermal kaolin in Mexico, including those in presently observable, hot-spring and steam kaolinizing-environments do not deposit dickite, but yield kaolinite.

Dickite from the type locality, Isle of Anglesey, N. Wales (courtesy of B. R. Young, British Museum, 1966; Dick, 1888) occurs in euhedral, lustrous, white flakes, books, and packets, Fig. 6.

Much smaller crystals of dickite, though morphologically comparable to the type clay, occur in partly hollow chert nodules at Columbia, Missouri, Fig. 7. The chert is in a Pennsylvanian-age, basal conglomerate above the Mississippian Burlington limestone, from which the chert was derived. Chert nodules which occur in the parent Burlington limestones have not been observed to contain dickite and only some of those redeposited in the conglomerate above have been productive of it. A few chert nodules in both the Burlington limestone and overlying conglomerate contain tiny aggregates of galena, sphalerite, or iron sulphide. Over much of central Missouri this chert conglomerate is overlain by the Cheltenham kaolinitic refractory clay ("fire clay"). Conceivably the geochemical environments, either during weathering and redeposition of the chert or circulating water through the conglomerate, could have emplaced dickite preferentially in the chert of the conglomerate (although the overlying clay is kaolinitic with some illite).

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Dickite occurs in vugs within dolomite of the Cambrian Bonneterre formation in the southeast Missouri lead district (Tarr and Keller, 1936), Fig. 8. Both dickite and kaolinite were found in vugs within the same Pennsylvanian-age-limestone in Kansas (Schroeder and Hayes, 1967). Dickite has repeatedly been observed as an authigenic mineral in porous sandstones, from well-cuttings not associated with observable hydrothermal action, and in rocks ranging from Cambrian to Tertiary in age (e.g. Ferrero and Kublec, 1964; Bayliss, Loughnan, and Standard, 1965). Two occurrences of euhedral dickite, one closely associated with quartz and another with barite, in subsurface Cretaceous sandstone in Mississippi are shown in Figs. 9 and 10. Presumably these crystallized from oil-field brines in a geochemically intriguing environment (courtesy of A. B. Carpenter, Nov. 1975).

Three occurrences of solid-lump dickite, collected from San Juanito, Mexico; Ouray, Colorado (both API Reference Clays); and as a mixture with kaolinite in a commercially quarried, hydrothermal deposit at Guadalupe on the outskirts of Zacatecas, Zac., Mexico are shown in Figs. 11, 12 and 13 respectively. All of these are genetically associated with heavy-metal sulfide minerals.

Dickite is a common associate of cinnabar in mercury mineral deposits. It is tempting to speculate that the presence of non-ferrous heavy-metal ions may be more strongly contributory to the formation of dickite than hydrothermal temperature alone (see also Chukhrov, 1967). Since doping with Fe^{3+} is apparently necessary to obtain euhedral morphology in synthetic kaolinite (Angel *et al.* 1974, and personal communication) it is conceivable that Hg, Pb, Zn, may contribute to dickite crystallization.

Characteristic texture. Dickite which has crystallized in an open cavity exhibits a texture similar to that shown by kaolinite. Dickite hexagons probably tend to be more nearly equi-dimensional than do kaolinite plates. Dickite maintains euhedrism to a higher degree in packed lumps of clay than does kaolinite, thereby indicating a stronger force of crystallization.

ALTERATION OF WATER-LAID, CLASTIC SILICATE PARENT MATERIAL

Four examples will illustrate kaolin deposits which originated by alteration of water-laid clastic silicate parent material: volcanic detritus at Jacal, or Villa Victoria, Mexico (Keller and Hanson, 1957); arkose at Hirschau-Schnaittenbach, Bavaria (Kramer and Köster, 1974); arkose at Krasny Dvur, Czechoslovakia (Vachtl, 1968); and graywacke at Espenhain near Leipzig, East Germany (Bellman, 1975).

The Jacal kaolin was derived from volcanic detritus deposited in a roughly ellipical interior lake, about 3 km by 1–1.5 km. The commercially usable, white, plastic kaolin is bedded about 4 m thick. It has low bulk density, about 1.27 (Baumann and Keller, 1975–76), which is consistent with the open texture and loose packing of the kaolin, Fig. 14.

The kaolinized Hirschau-Schnaittenbach arkose, located 20 km southwest of Weiden, Germany, is about 75 m thick. It was deposited, and subsequently kaolinized by circulating sub-soil water in Triassic time (Kramer and Köster, 1975), Fig. 15.

At Krasny Dvur, north of Plzen, Czechoslovakia, a large depošit of kaolin has been developed by weathering of Permian–Carboniferous arkose. Opinion is divided as to whether all the argillation occurred when the last weathering crust was developed or whether partial kaolinization has occurred earlier (personal communication from M. Kuzvart). Loosely stacked, relatively coarse flakes of kaolinite, a texture common to kaolinized arkose, typifies this kaolin, Fig. 16.

Kaolin was derived from graywacke in the Espenhain huge, open-pit, lignite mine about 4 km south of Leipzig, East Germany (Bellman, 1975). The "graywacke kaolin", interpreted as Eocene in alteration (and possibly deposition) grades through a definable boundary to the Cretaceous-to-Eocene, "Bunter Gesteinzersatz (three-layer silicate zone)", Fig. 17.

Although not even approaching an economic deposit of kaolin, some of the feldspar in the arkosic lower part of the Cambrian La Motte sandstone in Missouri has been kaolinized. There is no doubt that its genetic process was weathering. The similarity of its open texture to that observed in the previously cited large commercial kaolin deposits in Europe strengthens a genetic correlation between them, Fig. 18.

Texture of kaolin from water-laid, clastic silicate material. Kaolin originating *in situ* from water-laid, clastic, silicate parent material typically possesses a relatively open, porous texture. The kaolin flakes are usually large, although smaller ones (growing? crystals) may cling face-to-face to the larger ones. Large books comprised of loosely stacked flakes typically are abundant. Kaolinite crystals may be subhedral. The bulk density is typically less than 2.0.

IN SITU ALTERATION OF PRIMARY SILICATE CRYSTALLINE ROCK

Granites, gneisses, and other silicate crystalline rocks commonly weather to kaolinitic saprolite or tan or darker-colored gruss. Such products are not termed "kaolin" in a commercial sense. Under appropriate conditions, alteration of the primary silicate rocks leads to deposits of relatively white, commercial kaolin having a low content of iron-oxide minerals. In this report the latter kaolin, rather than the also interesting gruss, is the source of SEM examples.

Prominent among kaolin deposits of central Europe are those formed as a part of the intensely-studied weathering crust which developed to a maximum during Cretaceous–Eocene time. Such an episode of weathering quite probably prevailed also on the

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North American continent (coincident with sea-floor spreading?). It probably played a significant role in the ultimate origin of the Georgia-type kaolin deposits extending from Massachusetts to Texas, and merged with the Eocene weathering in the Pacific northwest.

Representative of *in situ* kaolinized granodiorite is the Caminau deposit near Bautzen, East Germany. It is the largest kaolin deposit of the GDR, according to Storr and Buchwald (1975). Its parent, the West-Lusation granodiorite, is a Variscan intrusion which has been kaolinized to a depth of 15–35 m, and partially altered up to 20 m deeper. The kaolinite is characterized by coarse, loosely packed plates, Fig. 19.

In Czechoslovakia, the Karlovy Vary (Carlsbad) granite massif has weathered to a half-dozen, *in situ* kaolin deposits which include such as Kaolina, Fig. 20, and Sedlec (Zettlitz, a "standard" kaolin) Fig. 21, described by Konta and Koscelnik (1968).

On the island of Belitung, Indonesia, a large granitic area "has been deeply weathered producing a large area of residual kaolin. This is a classic area of true residual weathering without any hydrothermal effects" (Murray, 1975). Kaolinite has been developed in books and flakes, accompanied by lesser amount of elongates, Fig. 22.

The *in situ* Benson deposit near Troy, Idaho, USA, weathered from gneissic granite yields primarily elongates, halloysite and endellite (Ponder and Keller, 1960). The large plates having ragged edges are probably mica altering to clay, Fig. 23. At Spruce Pine, the *in situ*, North Carolina "primary kaolin" is a hydrated halloysite (Sand, 1956). The particular micrographs shown are from a pegmatite in the Gusher Knob locality, Figs. 24 and 25. Note how the elongate crystals have grown into open space outside the micro-pitted feldspar to form a matted mass of clay. The bulk density of this kaolin is low, a typical measurement yielded 1.39 (Baumann and Keller, 1975–76). *In situ* weathering of nepheline syenite in Arkansas produces clay similar in texture (SEM, but not illustrated) to the North Carolina example.

Micro-pitting of feldspar, presumably by incongruent dissolution (Keller, Balgord and Reesman, 1963; Huang and Keller, 1970; Busenberg and Clemency, 1976), is a common pre-, or early-stage, of kaolinization of feldspar. It has been observed in SEM's of altering feldspar also from Georgia, Missouri, France, Czechoslovakia, and Brazil.

Texture characteristic of in situ *kaolin.* The texture of kaolin produced by *in situ* weathering of primary silicate rocks is characteristically coarse, loosely packed books, packets, or mats (of elongates) of kaolin crystals. It signifies an environment in which there was abundant available space for kaolin crystals to grow. Porosity of the clay is high, and bulk density is low, i.e. less than 2.0.

In general, the textures of kaolin formed in the weathering environment of either a primary silicate parent rock, or a secondarily deposited clastic rock (arkose or graywacke), are essentially similar. The causes for the kind of texture developed in these types of kaolin are interpreted in terms of the nature of the conditions present in the physical environment within which these kaolins were developed. In either, or both, cases weathering begins at the surface of the parent clastic rock in contact with the open space of the atmosphere above or the adjacent porosity, providing adequate room into which clay crystals and books can grow, even though they may possess weak crystallizing power. High porosity and permeability of the parent rock likewise permits easy removal of dissolved silica and alkali and alkaline earth metals, thereby increasing the space available to kaolin crystals. Weathering proceeds from the outside surfaces of altering minerals inward. When these conditions prevail over a long time a system of equilibrium, or near-equilibrium, with respect to kaolinite can develop. It is presumed that the kaolinite crystallizes from a rock-soaked solution phase at low molar concentration barely saturated with respect to kaolinite. A loose, open texture results as the SEM's have shown.

KAOLINIZATION AT AN UNCONFORMITY, AS BELOW AN ARTESIAN AQUIFER

Kaolin is commonly developed from the feldspar in a granitic rock below a basal unconformity—likewise in the arkosic sandstone above. A typical example of this situation occurs in southeast Missouri where Proterozoic granite was eroded, and covered with the upper-Cambrian La Motte sandstone. The kaolinite in the sandstone has been shown in Fig. 18. Attention is directed here, however, to the kaolinizing feldspar in the granite beneath.

A micrograph of the contact between parent K-feldspar and daughter kaolinite developed from it is shown in Fig. 26, and other diversified views of the reaction in Figs. 27 and 28.

Several inferences, seemingly of geologic significance, can be drawn from these micrographs. Because an apparently random (not unique) crystallographic orientation exists between the crystals of kaolinite and the crystal of feldspar it appears that the crystal structure of the parent mineral does not necessarily control the crystal orientation of the daughter. Another inference which follows from the random orientation between parent and daughter is that an intermediary solution phase typically intervenes between parent and daughter during kaolinization of feldspar, although the distance of separation between the minerals may be only Angstrom units or micrometers. Furthermore, during crystallization of the kaolinite the geochemical system must have represented near equilibrium or steady state, between kaolinite, liquid and feldspar. Moreover, the chemical system must have persisted over a considerable length of time for the mineralogical alteration and crystallization of the kaolinite to have taken place.

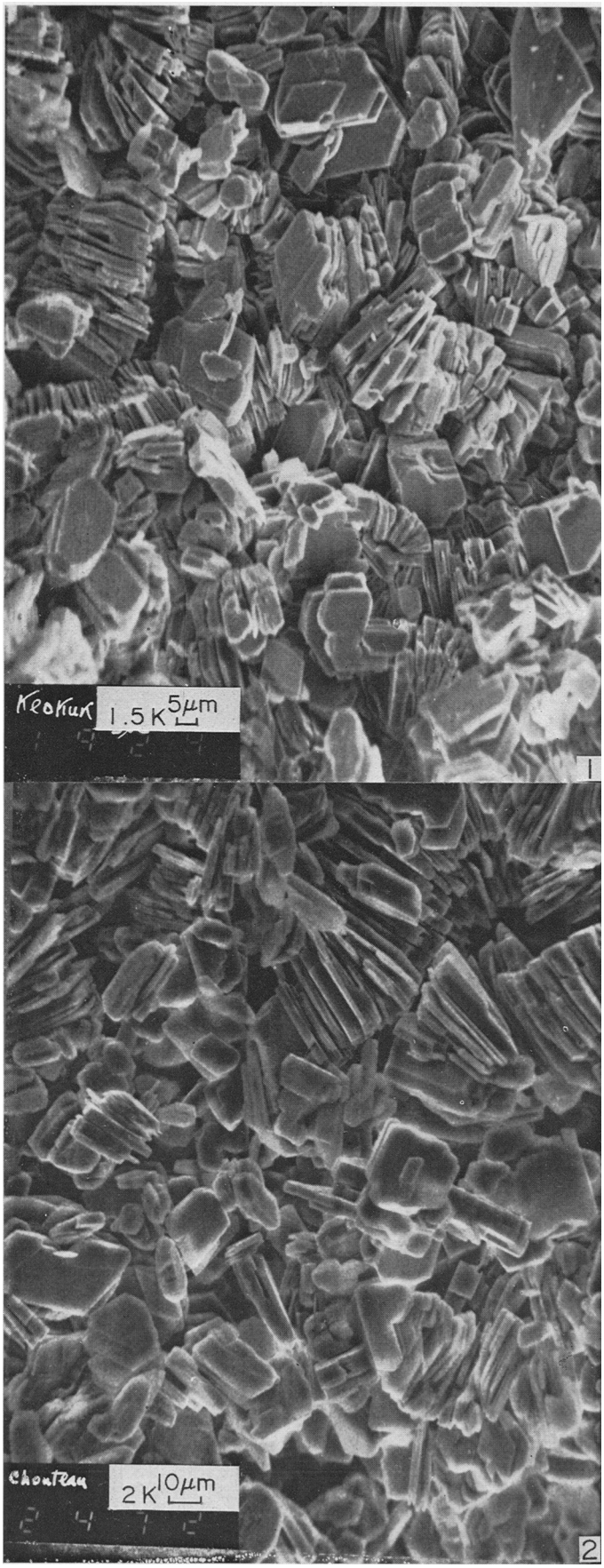

Fig. 1. Kaolinite from a geode, Warsaw Formation, near Keokuk, Iowa, 1500 ×.

Fig. 2. Kaolinite from cavity in Chouteau limestone, near Shelbina, Missouri, 2000 ×.

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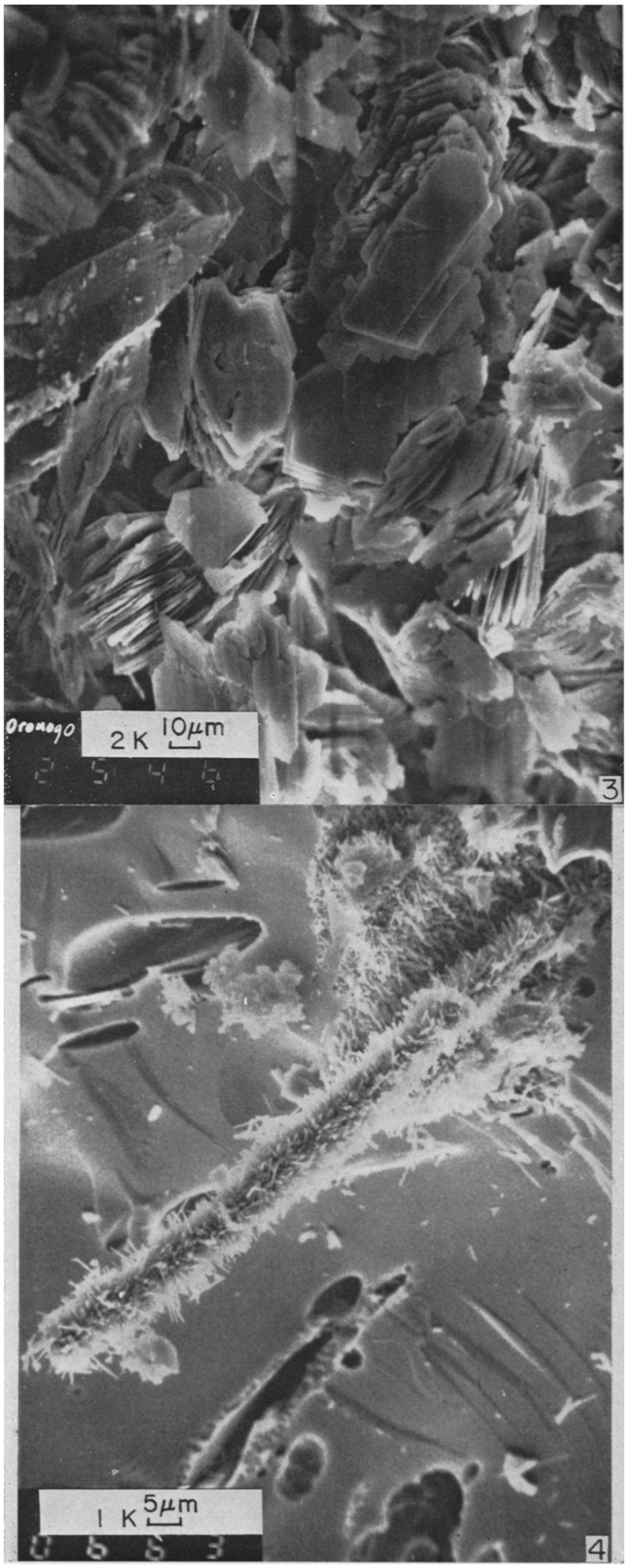

Fig. 3. Kaolinite from veins in shale at Oronogo Mine, Oronogo, Joplin district, Missouri, 2000 ×.
Fig. 4. Endellite in an elongate vug in perlite, near Etzatlan, Jalisco, Mexico, 1000 ×.

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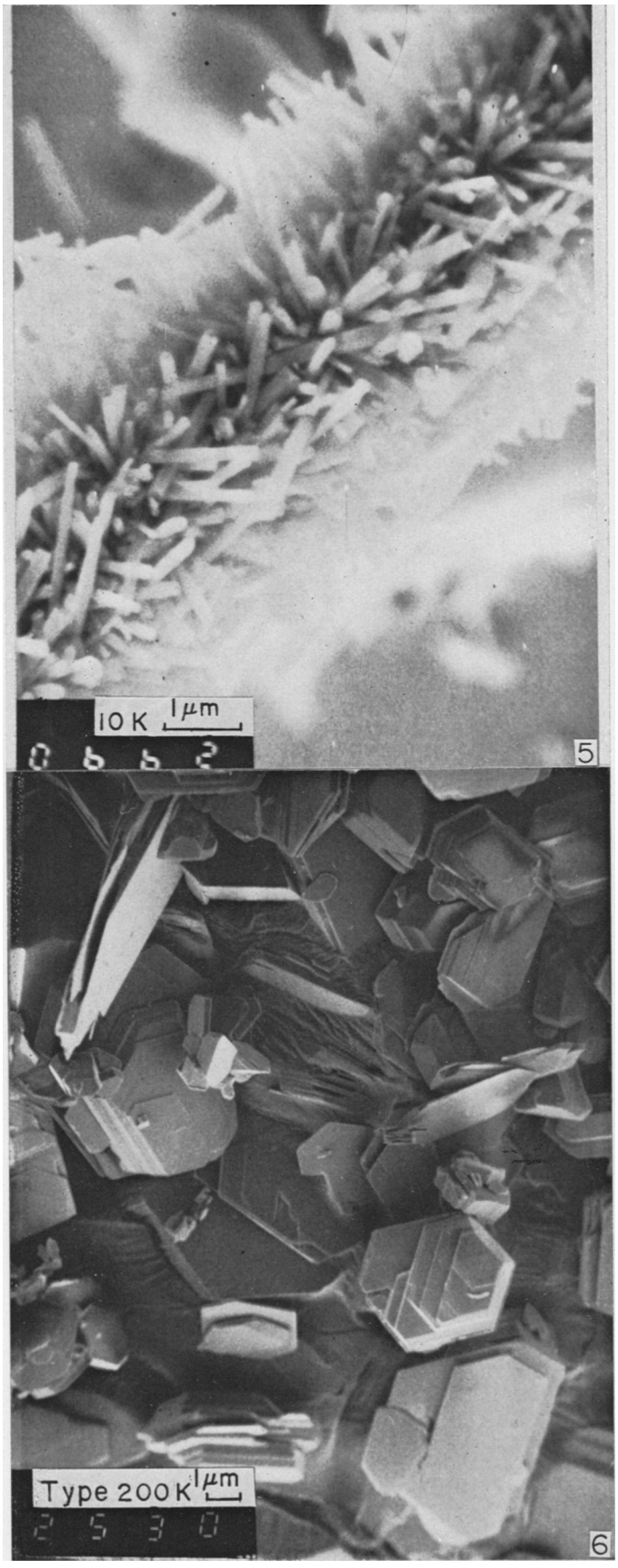

Fig. 5. Portion of vug in Fig. 4 at 10,000 ×.
Fig. 6. Dickite from type locality, Anglesey, Wales, 300 ×.

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Fig. 7. Dickite from cavity in chert nodule, Columbia, Mo., 1000 ×.
Fig. 8. Dickite from cavity in Bonneterre dolomite, near Flat River, Mo., 400 ×.

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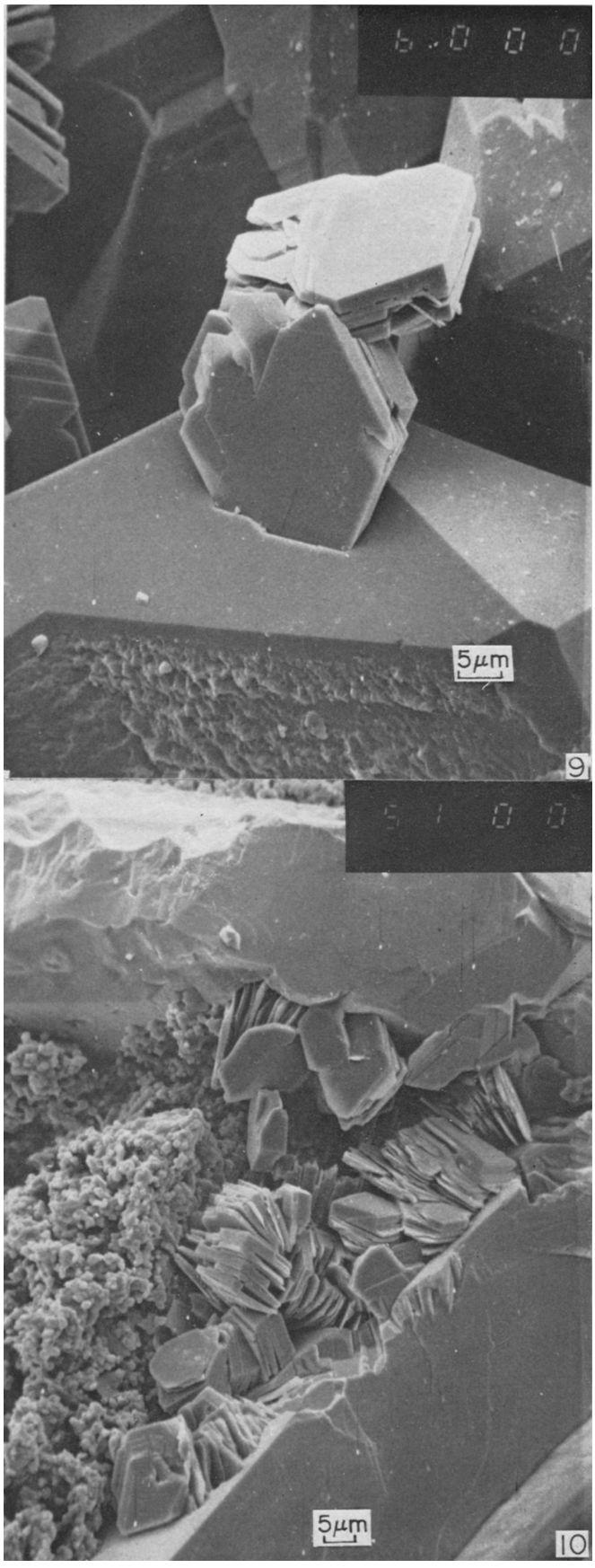

Fig. 9. Dickite intergrown with quartz, from a subsurface Cretaceous sandstone, 1500 ×. Courtesy of Dr. A. B. Carpenter.

Fig. 10. Dickite intergrown with barite, from a subsurface Cretaceous sandstone, 1000 ×. Courtesy of Dr. A. B. Carpenter.

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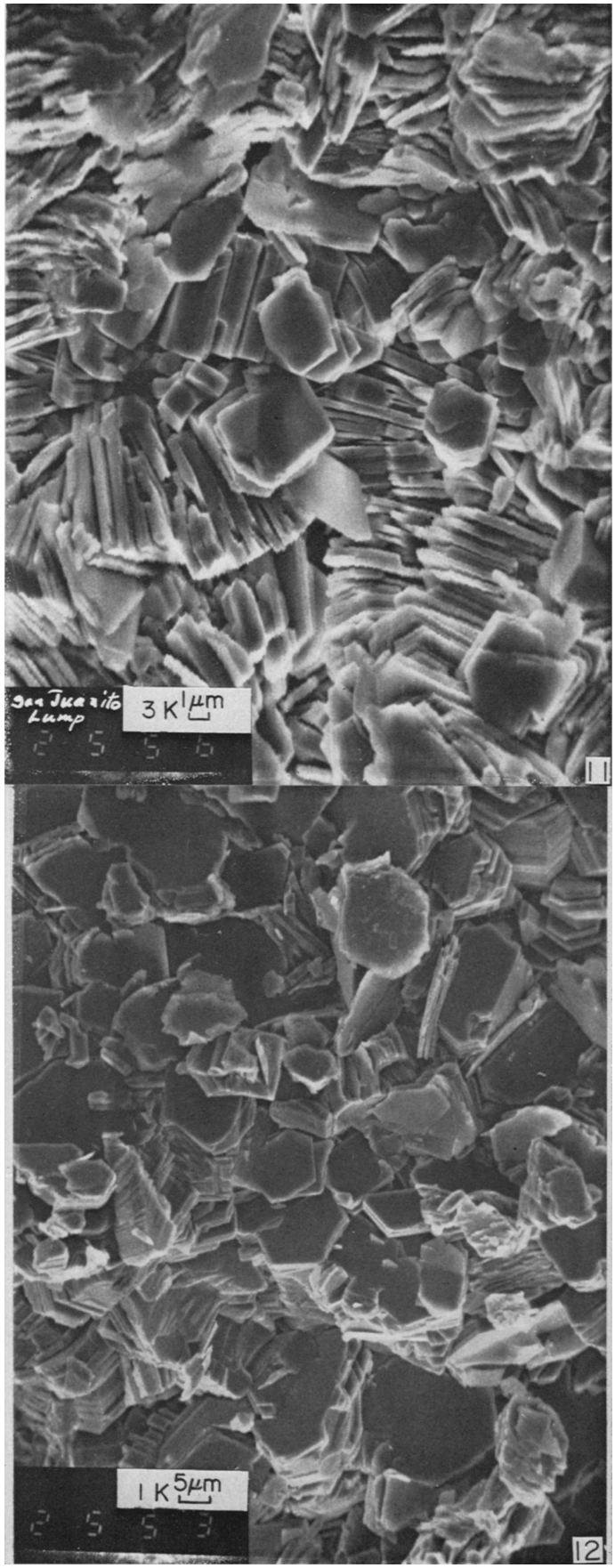

Fig. 11. Dickite from San Juanito, Mexico, API Reference Clay Minerals, 3000 ×.
Fig. 12. Dickite from Ouray Colo., API Reference Clay Minerals, 1000 ×.

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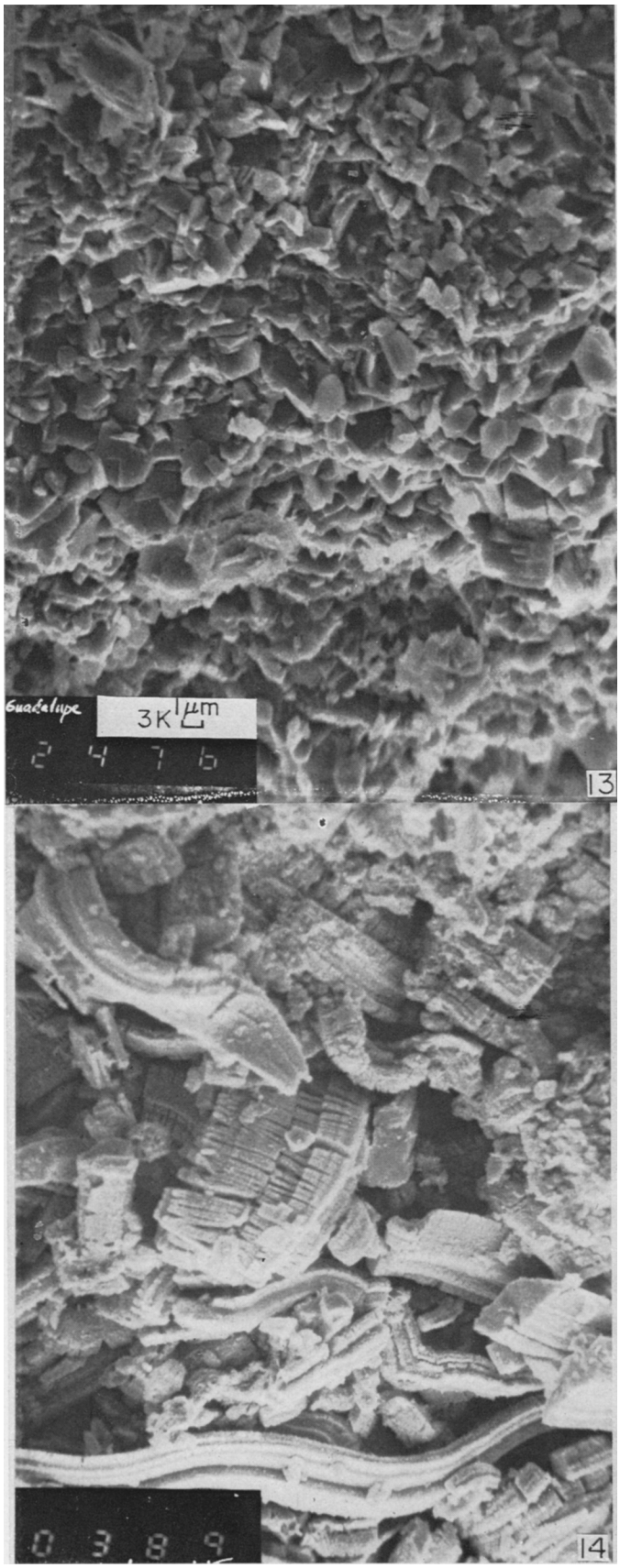

Fig. 13. Dickite–kaolinite mixture (?), near Guadalupe, Zacatecas, Mexico, 3000 ×.
Fig. 14. Kaolinite, Jacal near Villa Victoria, Mexico, 1000 ×.

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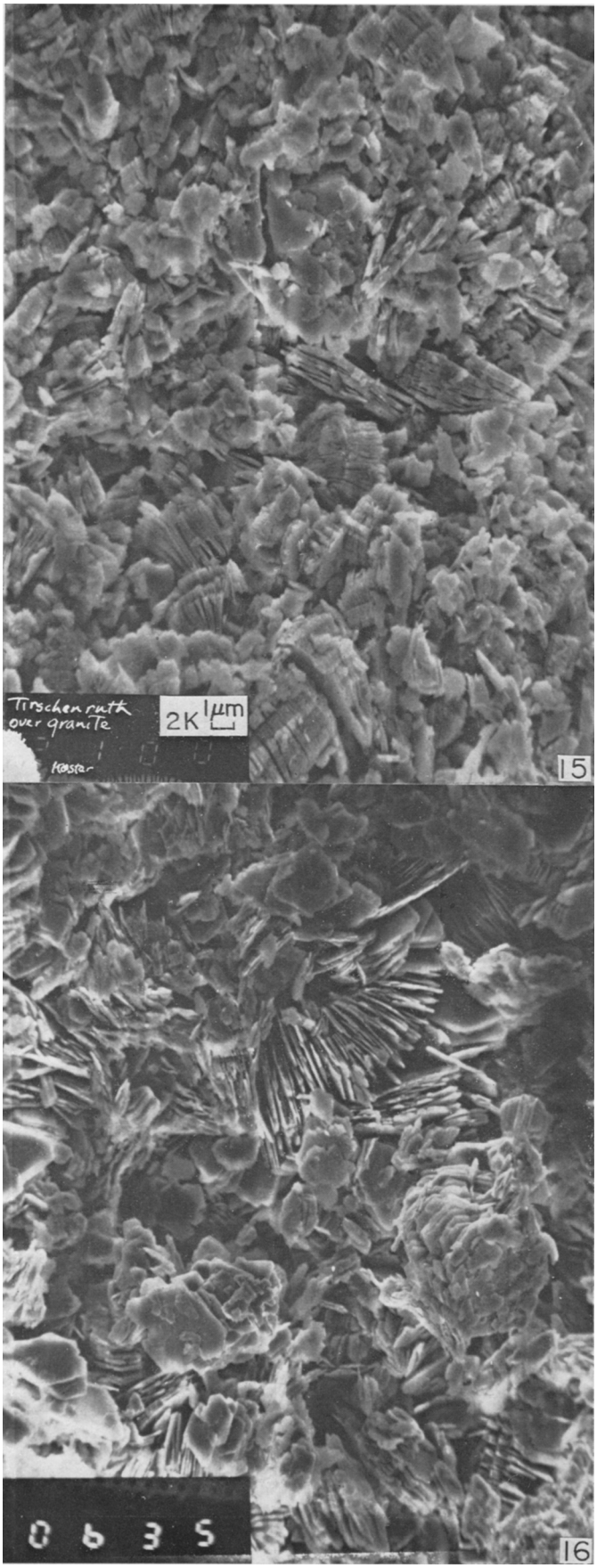

Fig. 15. Kaolinite, Hirschau-Tirschenuth deposit, Germany, 2000 ×.
Fig. 16. Kaolinite, near Krasny Dvur, Czechoslovakia, 1000 ×.

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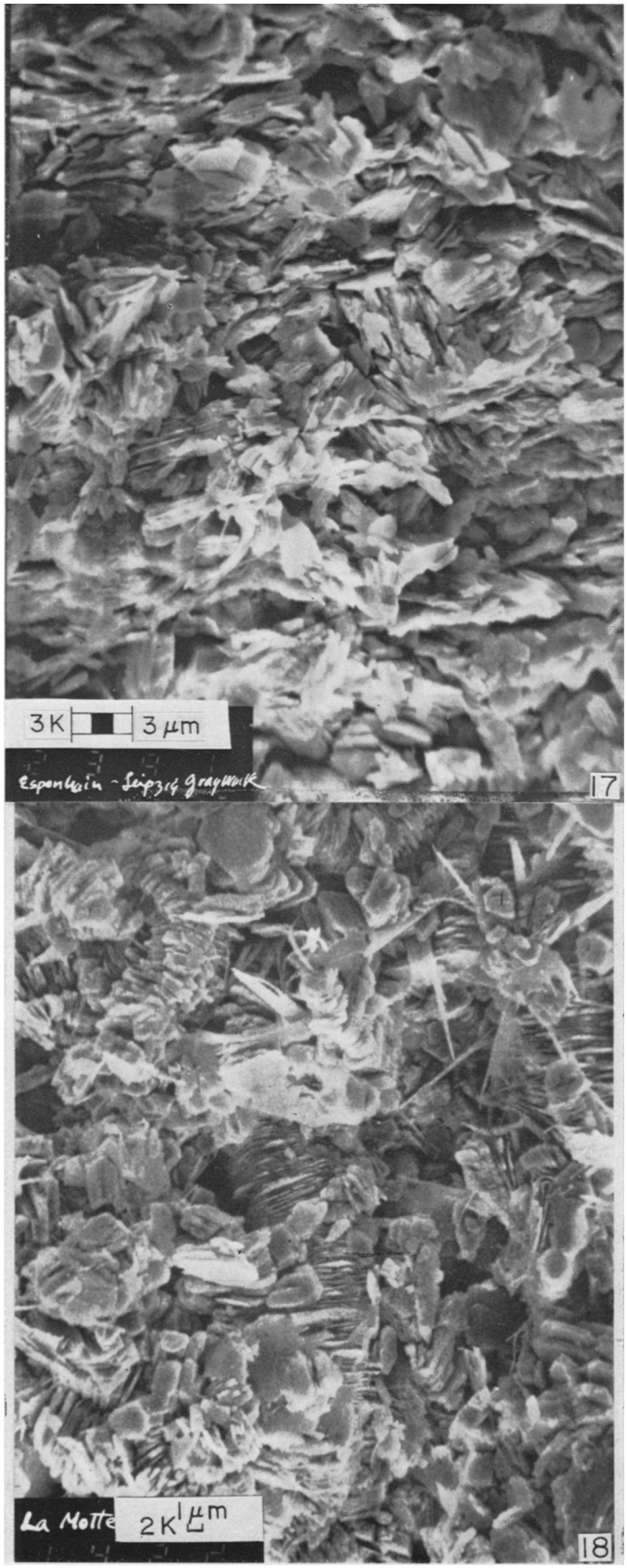

Fig. 17. Kaolinite, Espenhain lignite and clay pit, near Leipzig, East Germany, 3000 ×.
Fig. 18. Kaolinite from La Motte sandstone, near Farmington, Mo., 2000 ×.

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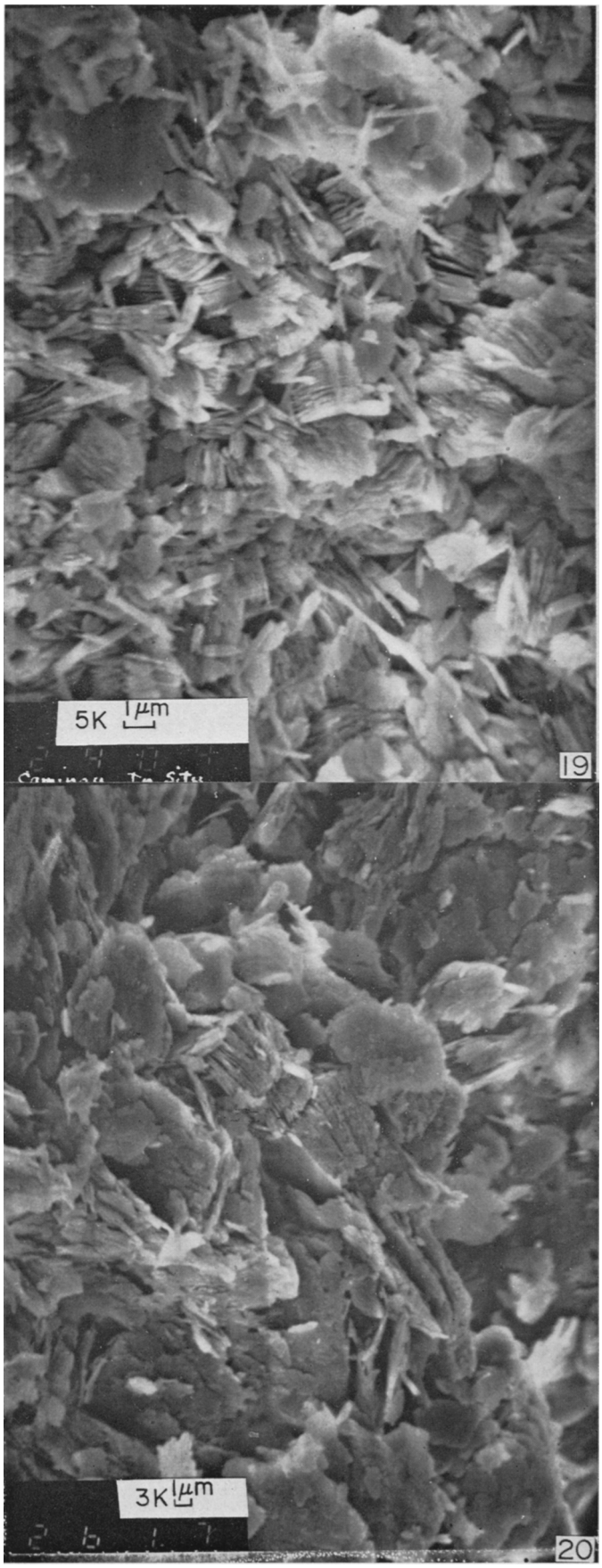

Fig. 19. Kaolinite, Caminau deposit, Caminau, East Germany, 5000 ×.
Fig. 20. Kaolinite, deposit at Kaolina, Czechoslovakia, 3000 ×.

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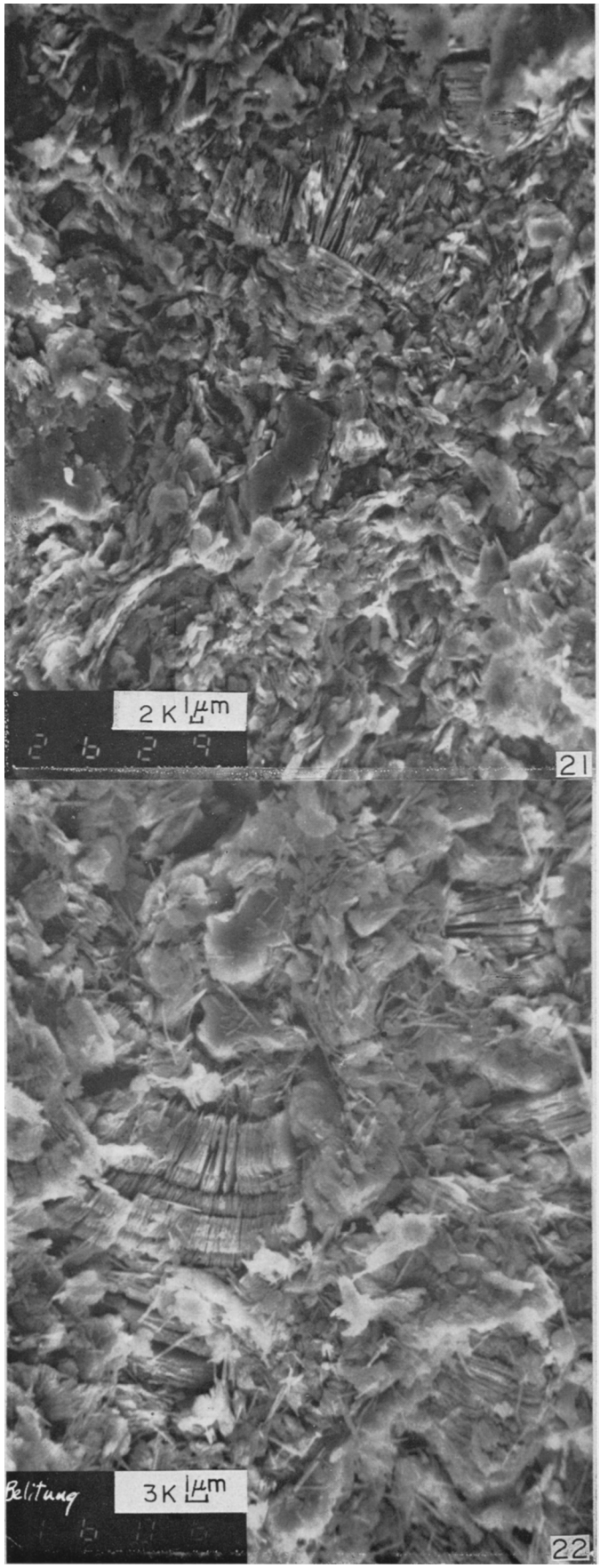

Fig. 21. Kaolinite at Sedlec (Zettlitz) Czechoslovakia, 2000 ×.
Fig. 22. Kaolinite on Belitung Island, Indonesia, 5000 ×.

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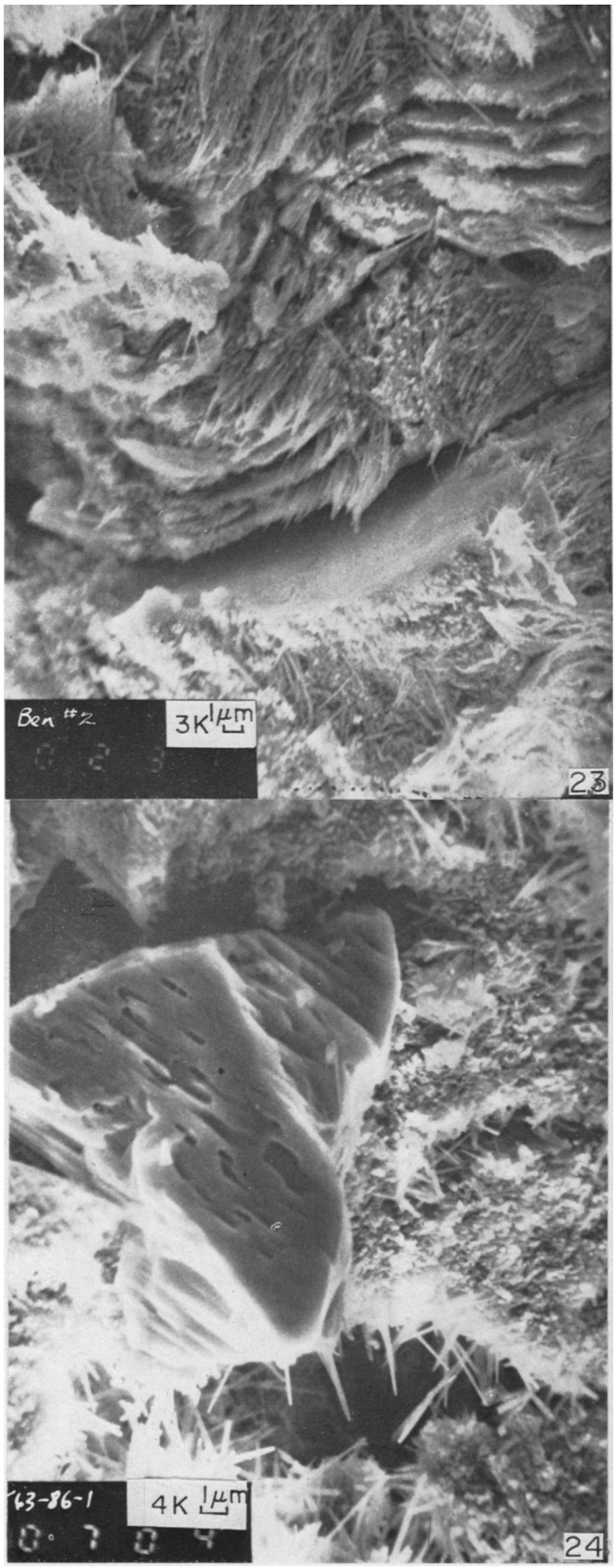

Fig. 23. Kaolinite, Benson clay pit. Latah County, Idaho, 5000 ×.
Fig 24. Halloysite and pitted feldspar, Gusher Knob deposit, Spruce Pine, No. Car. 4000 ×.

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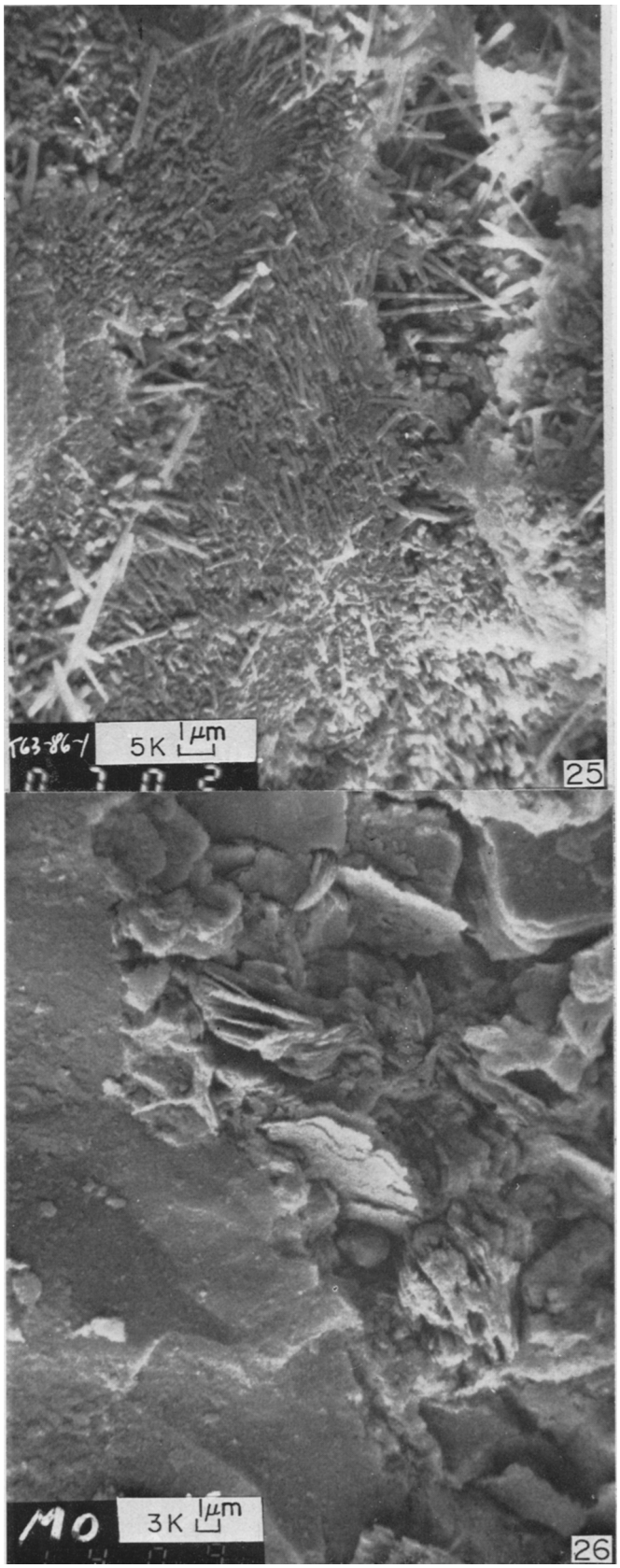

Fig. 25. Matted halloysite, Gusher Knob deposit, Spruce Pine, No. Car. 5000 ×.

Fig. 26. Kaolinite in contact with weathering feldspar in granite, 15 km south of Farmington, Mo., 3000 ×.

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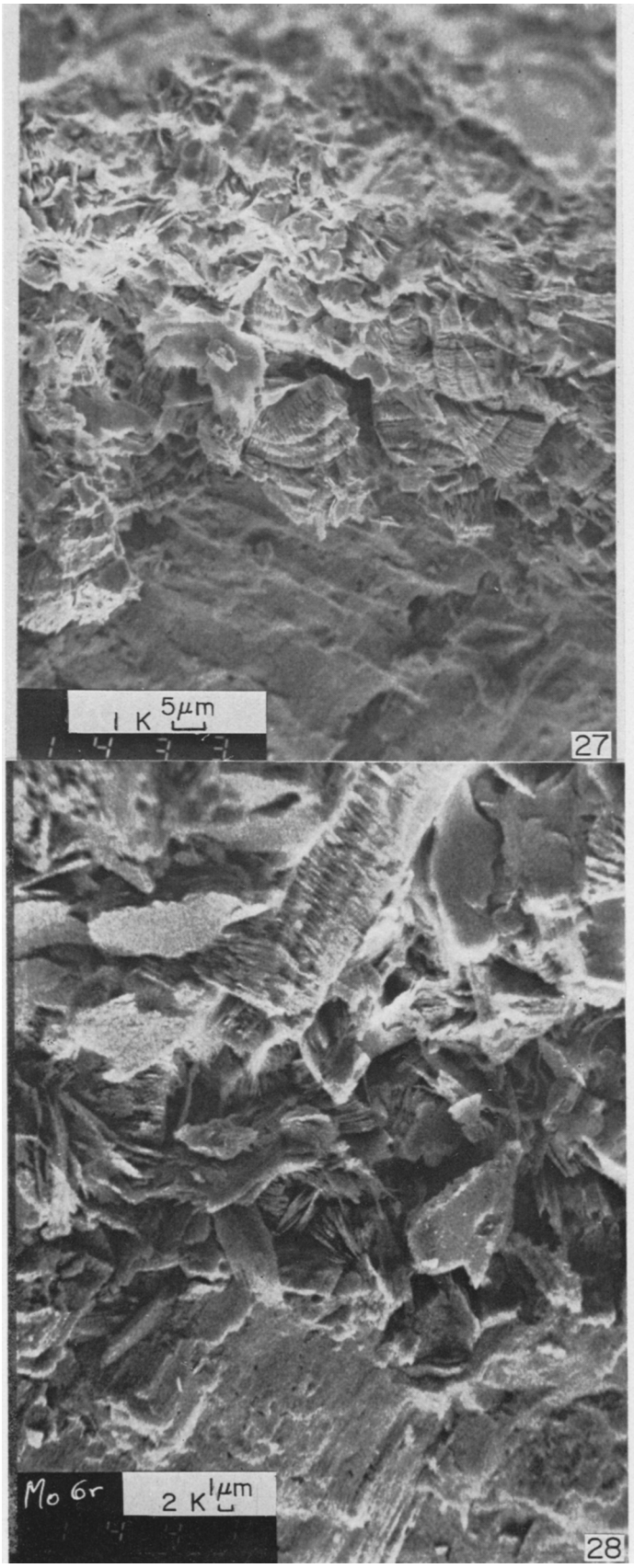

Fig. 27. Kaolinite–feldspar, same locality as Fig. 26.

Fig. 28. Variation of kaolinite–feldspar, same locality as preceding specimens, 2000 ×.

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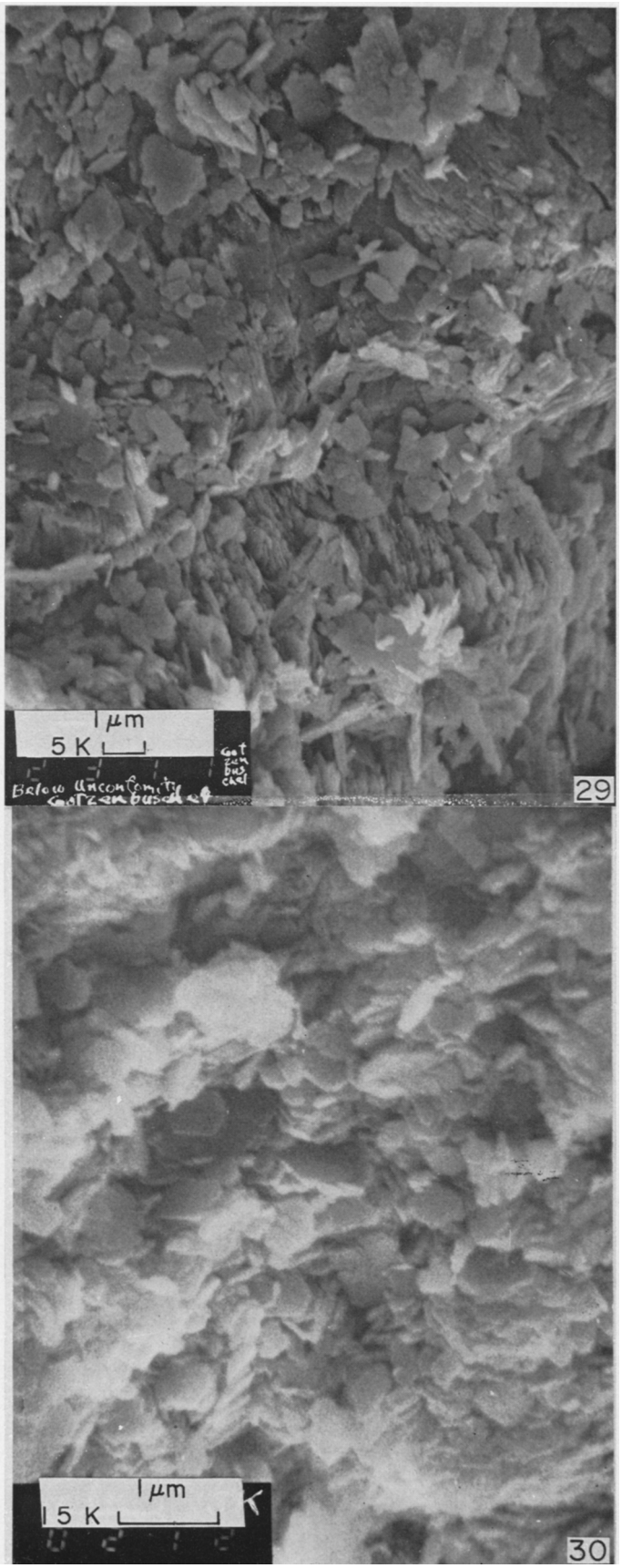

Fig. 29 Kaolinite at Götzenbüschel Hill, near Dohna, Saxony, East Germany, 5000 ×.
Fig. 30. Kaolinite, from near Sombrerete, Zacatecas, Mexico, 15,000 ×.

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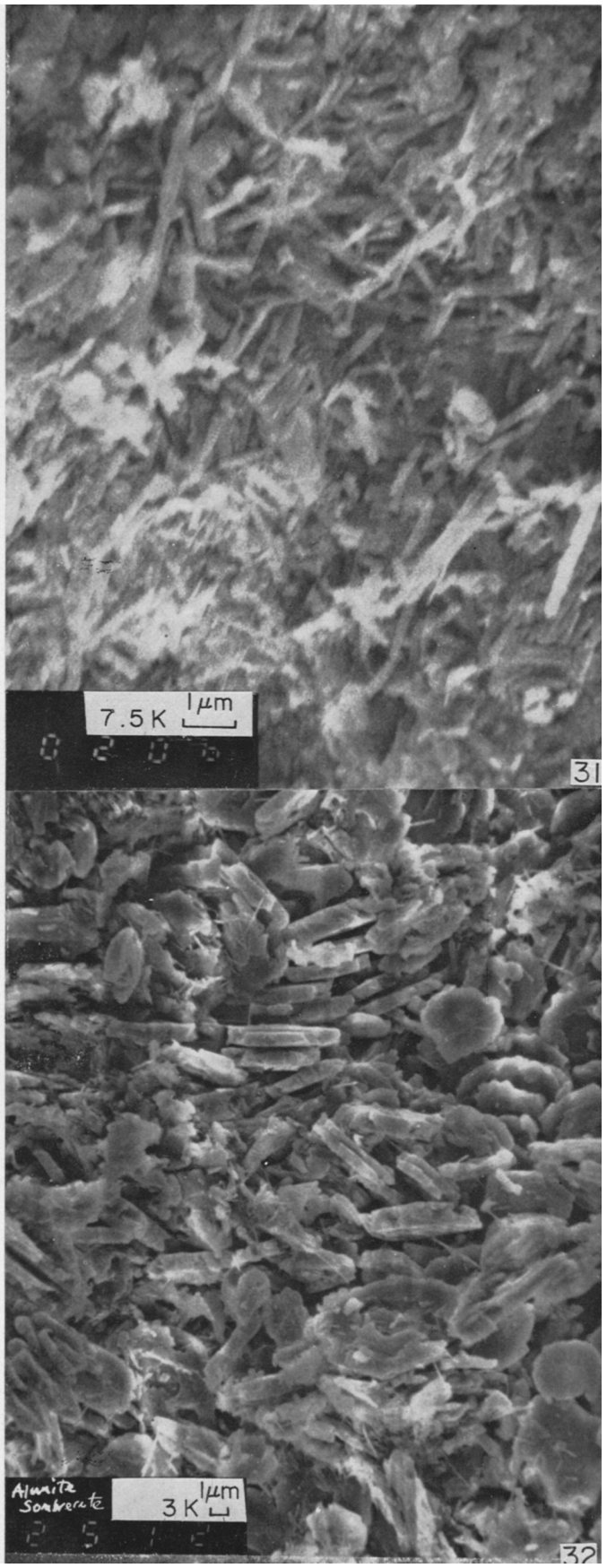

Fig. 31. Halloysite, same locality as Fig. 30, preceding, 7,500 ×.
Fig. 32. Plates of natro-alunite in the Sombrerete clay deposit, 3000 ×.

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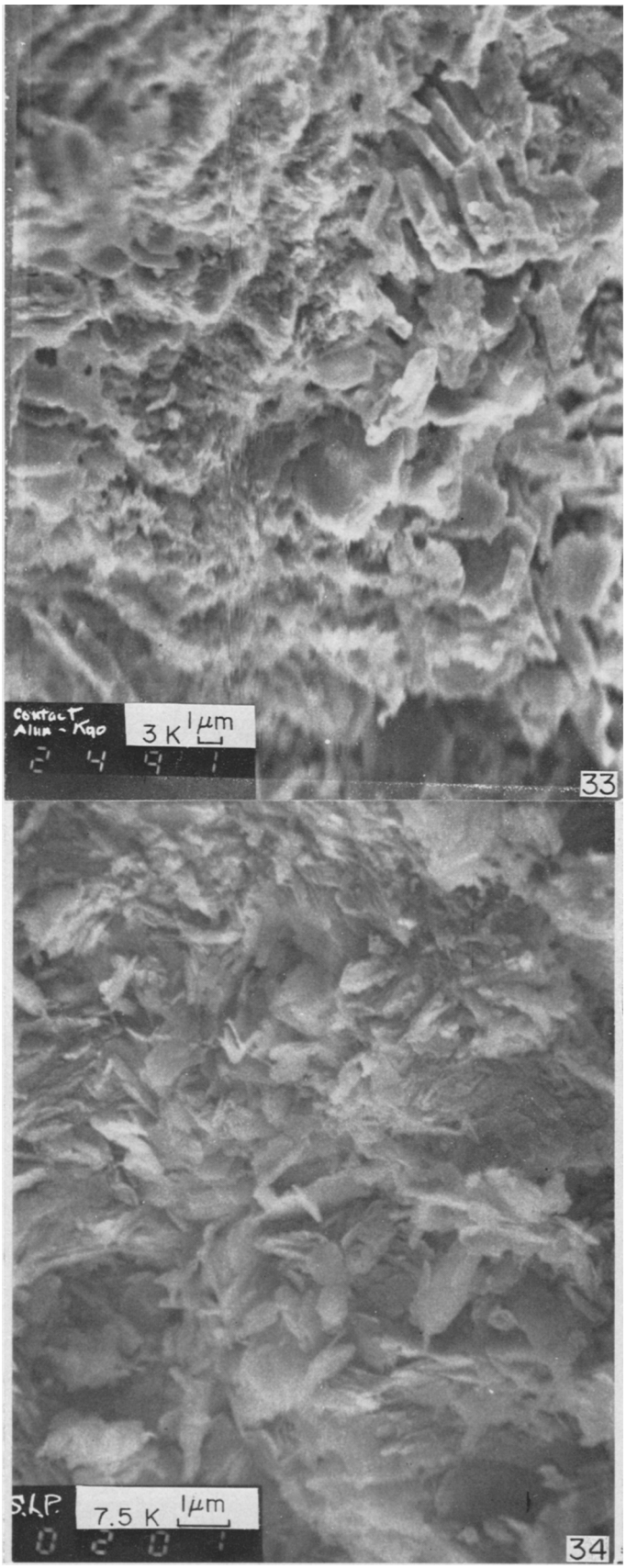

Fig. 33. Contact between coarser crystals of alunite and fine-grained kaolin at Sombrerete, Mexico, 3000 ×.

Fig. 34. Kaolin plates and elongates, General Zaragosa mine, San Luis Potosi, Mexico, 7500 ×.

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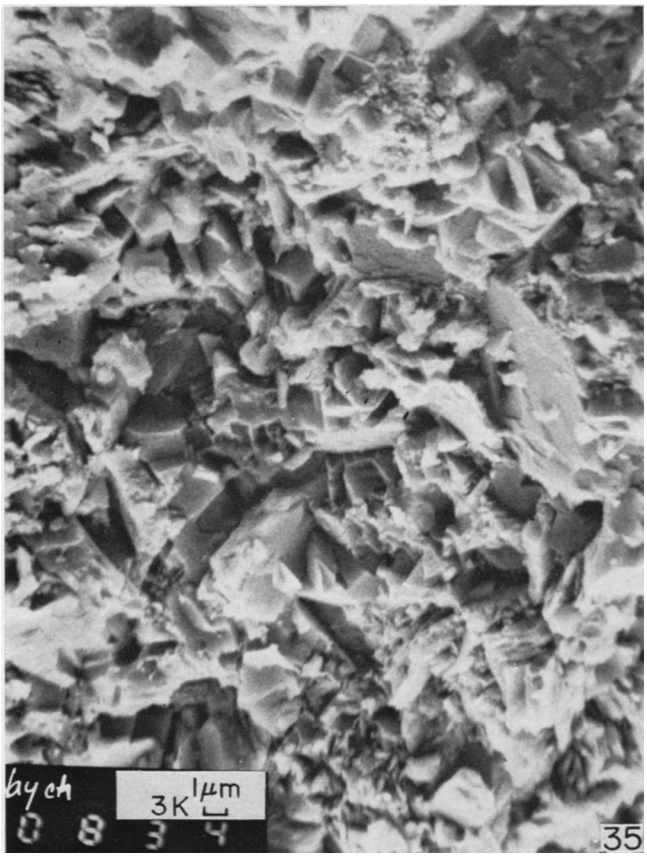

Fig. 35. Kaolinite, "Duropact" variety, Nayarit, Mexico, 3000 ×.

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Considerable significance, it is believed, should be attached to these inferences of genetic processes. It is probable that these processes may apply as principles to the genesis of most deposits of white kaolin.

Another geologic question may be raised as to the time that the process of kaolinization of the granite beneath the unconformity took place. Statistically alternative times include (a) pre-unconformity, (b) the time after deposition of sandstone while the rocks were buried and artesian water circulated through the permeable sandstone, and (c) by weathering during the erosion cycle in which the now-exposed, ancient rocks were dissected and bared.

A strong case can be made that the kaolinization had not preceded the deposition of the sandstone above the unconformity. The sandstone was deposited in a high-energy wave environment in which soft kaolin as now exists below the unconformity could not survive the abrasion of shifting sand. Undoubted observation of granite along present-day sand-swept beaches finds the granite surface to be clean, hard and fresh.

Where an artesian-water system prevailed, and many liters of water, both connate and fresh, migrated through the sandstone, the conditions for kaolinization must well have been satisfied. The water may have been oxidizing or reducing—hence, it might have developed either iron-oxide colors in the kaolin, or it may have reduced and removed iron in solution, leaving white kaolin. Certainly the process and/or stage of removal of iron-oxide pigments from argillation products so as to yield a large deposit of nearly white kaolin is always a question that must be answered if the genesis of the kaolin is explained. Since artesian water apparently can bleach the kaolin that it hydrates, the concept that artesian water can kaolinize feldspathic rocks must not be rejected without compelling evidence.

Alternatively, kaolinization may have occurred in part, or wholly, while geologically recent weathering and erosion cut down through the sandstone and granite beneath, exposing them to present-day view. Would the kaolinizing system have been sufficiently strongly oxidizing to have generated colored kaolinite? Or alternatively, would humic acid solutions from plants growing on eroding slopes have removed iron compounds? No unequivocal criteria observable from a single outcrop are known to the writer to determine if the kaolinization took place by ancient artesian water or by recent erosion. More extensive observations such as bore-hole cores back from recent-weathering effects would determine if the granite was kaolinized independently from the recent weathering and erosion.

A second example of kaolinization of a feldspathic rock below sandstone that unconformably overlies it is at Götzenbüschel Hill south of Dresden in Saxony, GDR (Störr and Ruchholz, 1975). At this locality, Cenomanian sandstone unconformably overlies Proterozoic paragneiss. Bleached kaolin is present about 0.2 m thick, grading downward into mottled red kaolin and altered gneiss at Götzenbüschel Hill, Fig. 29. In terms of the argument against kaolin persisting on a sand-swept beach, the interpretation of this being Pre-Cenomanian weathering is unconvincing.

Texture of kaolin formed at an unconformity included within a potential artesian system. The texture of the kaolin altered from feldspar in a granitic rock below a basal unconformity is closely similar to that of kaolin produced during *in situ* weathering.

HYDROTHERMAL ARGILLATION (KAOLINIZATION)

The materials and the genetic processes of kaolins claimed to be hydrothermally altered have been debated for some time from two different aspects. Some "purists" insist that the hydrothermal-type water which reacts with the primary silicates must all be magmatic or juvenile. Others, including the writer, interpret hydrothermal literally as "thermal water", i.e. water whose temperature is higher than that indigenous to the local surface of the earth—much or all of it can be resurgent.

More serious controversy arises as to whether independent geologic evidence convincingly demonstrates to all observers that a given deposit was truly hydrothermal. An example of such disagreement under the most favorable of observational conditions is the interpretation of origin of the kaolin of the mammoth Cornwall district of England. During the field visit to those pits, following the Exeter Kaolin Conference in 1974, many of the most experienced kaolin geologists of Europe (and indeed, the World) saw together the same outcrops and deposits, yet their interpretations and conclusions regarding the genetic process ranged across a 180-degree spectrum. To cite as an example, therefore, a kaolin deposit as unequivocally hydrothermal in origin demands clear-cut compelling, positive, evidence of an independent nature. This appears to be unequivocally demonstrable for several kaolin deposits in Mexico, e.g. in the Los Azufres hot-spring area in the state of Michoacan (Kesler, 1970; Keller, Hanson, Huang and Cervantes, 1971) where kaolin minerals are currently being formed by active, visible, reproducible fumarolic action and hot springs. Moreover, at the active vents and in the clays, both cristobalite and alunite are intimately mixed with the kaolin minerals. Otherwise skeptical observers regularly find here the evidence for hydrothermal alteration to be overwhelmingly convincing.

Elsewhere in Mexico, an ancient body of kaolin, irregular pipe-like in shape, altered from a rhyo-latitic rock intruded into Cretaceous limestone, occurs near Sombrerete, state of Zacatecas, Mexico (Keller and Hanson, 1969a). It has been partially dissected and exposed by streams and has been opened by mine and quarry workings during current exploitation. Its white kaolin is "contaminated" (as a refractory clay) here and there by natro-alunite and cristobalite. Visiting geologists commonly concur that the geologic occurrence, shape, and mineral composition of the

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deposit are convincing evidence that it is hydrothermal in origin.

Likewise in San Luis Potosi, a huge, long-time mined, kaolin deposit developed from rhyolite and rhyolitic flow breccia exhibits geologic relationships compatible only with hydrothermal alteration. Briefly, it grades upward, not into a weathered zone but into a silica cap more resistant to weathering than is the parent rhyolite, and fresher rock above. The clay contains widespread disseminated alunite and cristobalite and numerous concentrated masses of those minerals which are left behind during mining for refractory clay (Keller and Hanson, 1968).

Clay and alunite typical of hydrothermal kaolin deposits in Mexico are illustrated by SEM's from Sombrerete: kaolin plates in Fig. 30, elongates in Fig. 31, alunite in Fig. 32, and a sharp contact between fine-grained clay and alunite in Fig. 33. Another typical hydrothermal kaolin, a mixture of plates and elongates, is Fig. 34, from San Luis Potosi. The most compact example of hydrothermal kaolin known to the writer occurs in the state of Nayarit, Mexico, Fig. 35. Additional SEM's of hydrothermal kaolins from Mexico have been published elsewhere (Keller and Hanson, 1975).

Texture of hydrothermal kaolins. Hydrothermal kaolins exhibit a characteristic texture of relatively small flakes and/or elongates that are tightly packed and interlocked. Rather than as expansive books, the plates occur as singles, sheaves, or thin packets. Porosity is low and bulk density is high—more than 2.0 (Baumann and Keller, 1975–76).

The tight texture and high bulk density are interpreted as being effects resulting from the genetic environment. Hydrothermal kaolinization occurs subsurface, at depth beneath a thick, heavy cover of rocks, i.e. high rock pressure that would compact the clay during formation. Furthermore, at the outset, space for the growth of the kaolin is restricted in all directions, including vertically and laterally. Indeed, the only space available for clay-crystal growth may be that generated by removal in solution of silica, and alkali and alkaline earth metals during the incongruent dissolution of feldspars.

Simultaneously the bulk volume of the space-demanding kaolinite is increased because of the necessary addition of about 14 per cent by weight of water combining with the reacting silica and alumina. Moreover, the direction of alteration of feldspars is primarily from the interior of solid grains outward. In contrast during weathering, it is recalled, the kaolinization proceeds inward from the outside of mineral grains where adequate space is available. In hydrothermal action the water reactant has, in contrast to supergene water during weathering, high vapor pressure, low viscosity, high penetrating power, and an accelerated rate of reaction because of the higher temperature. Many centers of reaction, i.e. centers of crystallization of kaolin, are set up during pervasive hydrothermal alteration at depth.

The net result of this process is to produce characteristically small, tightly packed crystals of kaolin—as the micrographs show.

TEXTURES OF OTHER VARIETIES OF KAOLIN

Textures, by SEM, of other kaolins, such as ball clays, flint clays, Georgia-type, and controversial Cornwall kaolins, will be illustrated in the following paper.

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