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# SCAN ELECTRON MICROGRAPHS OF KAOLINS COLLECTED FROM DIVERSE ENVIRONMENTS OF ORIGIN—IV. GEORGIA KAOLIN AND KAOLINIZING SOURCE ROCKS

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**Abstract**—Scan electron micrographs (SEMs), are shown of three representative types of Georgia kaolin: 'soft', Cretaceous-age clay; 'hard', fine-grained clay; and 'flint kaolin'.

Sparta Granite and a thick deposit of its overlying saprolite are taken to serve as examples of probable source rock for Georgia kaolin. SEMs are presented to show sequential argillation of this fresh granite through a transition zone to the saprolite. The saprolite contains abundant books of kaolinite similar to those occurring in Cretaceous kaolin, accompanied by some elongates, whereas in the transition zone elongates are predominant. A morphologic type of fibrous, elongate 1:1 clay mineral, hitherto not illustrated, is shown from kaolinizing Sparta Granite, and from Pre-Cambrian saprolitic gneiss 25 km south of Athens, GA.

Whereas kaolin elongates originated in contact with feldspar in the Sparta transition zone, well-formed books of kaolinite are shown to have been formed in contact with feldspar in the saprolite from a Missouri granite. The arkose above the granite in the Missouri occurrence has altered to loosely packed books of kaolinite. The interpretation is made that book-type kaolinite, where it occurs in large deposits of saprolite or kaolin, was formed under geochemical conditions of relative chemical stability between kaolinite and feldspar, as might prevail in a geological 'weathering crust'. It is interpreted that elongate kaolin morphology may be formed under conditions of limited or lesser geochemical stability.

SEMs show that the established book-morphology of Sparta saprolite is disarranged during secondary Holocene surface weathering and pedogenic processing.

SEMs show that books of kaolinite, although individually fragile, may be protected from destruction or delamination during artificial blunging and transport when moved within naturally coalesced pellets. Possibly original books of weathered kaolinite might similarly survive natural stream transport during sedimentational processes.

Some 'flint kaolin' contains molds of sponge spicules coated with low-cristobalite.

## INTRODUCTION

In parts I, II, III of this series on scan electron micrographs (SEMs) of kaolinite, textures representing modes of origin of kaolin were illustrated without restriction to locality of occurrence or geologic age (Keller, 1976). This report, in contrast, will be confined predominantly to one group, the well-known, so-called 'Georgia kaolins'. That single-name designation, however, is illusorily simple. 'Georgia kaolins' include deposits that occur not only in Georgia but also in South Carolina, Alabama and Florida—indeed, they have kaolin affinities within the entire large arc of Cretaceous–Eocene rocks exposed from Massachusetts southward, turning westward into Texas. Furthermore, 'Georgia kaolins' include kaolins of different geologic ages, probably of different geologic processes of origin, different commercial uses, different mineral compositions and clay–mineral mixtures including high-alumina minerals, and different physical properties and lithologic textures.

The purpose of this report is several-fold. SEMs will be shown of the textures of representative major types of Georgia kaolin deposits. These will be followed by micrographs illustrating sequential stages of kaolinization of the Sparta granite and its saprolite (a probable source rock for Georgia kaolin), likewise of a Missouri granite and its saprolite, and several other possible progenitors of kaolin deposits. While these illustrations are directed initially to the origin of the Georgia kaolin they relate substantially to the problem of origin of endellite–halloysite–kaolin in general. The question of the role of intermediary arkose to the genesis of Georgia kaolin will be considered and illustrated by several SEMs of kaolinized Missouri granite and a counterpart of overlying arkose. A few micrographs will illustrate the durability of booklets of kaolinite in artificial transport during factory processing.

## PROBLEMS OF ORIGIN

Because of their diversity and magnitude, the origin of these 'Georgia kaolin' deposits is still under debate. The more recent views on their genesis include those of Austin (1976), Murray (1976), Patterson and Buie (1974), Patterson and Murray (1975), Grim and Wahl

(1968), and Kesler (1956). The areas of agreement and disagreement between interpretations of origin were well summarized by Patterson and Buie (1974, p. 7) as follows:

> "Strange as it may seem, the kaolin deposits in the extensive belt in Georgia and South Carolina, which have been studied by many geologists and mineralogists and which lead the world as a source of commercial kaolin, are among the kaolins whose origins are least understood. Virtually all who have investigated these deposits agree that either the kaolin or the material from which it formed has been transported. Areas of disagreement center about explanations of how such very large deposits of fine-grained white clay could have formed in environments in which most of the sediments being deposited consisted of sand. Furthermore, an adequate explanation of origin of the deposits must account for the following facts: (1) some deposits of kaolin are finer grained than others; (2) some contain abundant vermicular kaolinite crystals, and some do not; (3) some of the vermicular crystals are very long and slender and must have formed in place; (4) gibbsite is present in some deposits and not in others; (5) lignitic layers or layers rich in organic matter are present in some deposits; and (6) smectite (montmorillonite) is present in some deposits in variable quantities. The deposition of formation of kaolin deposits in Late Cretaceous time and again in at least one interval of Eocene time must also be accounted for."

Murray (1976, p. 123) later wrote to the genesis of Cretaceous and Eocene clays, in part: "The author believes that during Cretaceous time the sands and kaolins were dumped very rapidly into the depositional area along the Cretaceous coastline.... The early Tertiary kaolins, on the other hand, may be reworked Cretaceous kaolins".

Austin (1976) concluded that laterization was significant in the origin of both the Cretaceous and Eocene deposits: "The kaolin and the bauxite in the Cretaceous units were formed by laterization, and are residual deposits derived from former aluminous sediments... the Tertiary units include both lateritic and sedimentary deposits. They were derived largely from the Cretaceous deposits by erosion and were deposited in normal depositional environments. Some were then subjected to even further laterization" (p. 2).

## SAMPLES AND THEIR PREPARATION

Kaolin samples have been generously provided by kaolin-producing companies who likewise kindly invited personal collecting visits to their mines. Also, I am illustrating samples from the original set of kaolins from the API Project 49 Reference Clay Minerals.

For micrography, clay samples were broken from hand-specimens of crude clay, i.e. under tensile fracture by the same mechanism as the hand specimens were broken from an outcrop, exposing the natural texture–fabric of the rock. They were then lightly sputtered with a thin film of gold (to carry away excess charge from the electron beam) without dispersion, etching, or any processing which otherwise might introduce artifacts. In other words, the micrographs are simply photographic views of their lithologic textures observed on the fractured surface of a hand specimen of kaolin under a '1000 × –10,000 × hand lens'. The rationale for the SEM study of kaolin is that eventually the petrology of the clay may be interpreted in part from its texture, or fabric, magnified to visual recognition, after adequate experience is gained from sufficient observations, just as texture has long been used to interpret in part the petrology of diabase, augen-gneiss, or bio-micrite.

The economy of magazine space necessarily permits publication in any single article of only relatively few of the many available, petrologically illustrative SEMs of kaolins.

## MICROGRAPHS OF KAOLIN SAMPLES

The texture, and/or fabric, of commercial Georgia kaolin has been grossly divided into (a) the coarse, soft, 'mealy' type, generally referred to Cretaceous age, and (b) the fine, hard, compact type, some (at least) of which are Eocene in age. The so-called 'flint kaolins' may constitute a third group. Variations within these groups further add to the diversity present within the traditionally single-named ('Georgia') group.

Micrographs to be shown will begin with samples from the Reference Clay Minerals collected by the American Petroleum Institute under its Project 49, centralized under Paul F. Kerr (API 49, 1949). Because these clays are from the original collection, data published on the clays in the eight Preliminary Reports apply unequivocally to these micrographed original kaolin samples.

Kaolin from the No. 6 McNamee Pit (Dixie Clay Co.) near Bath, SC (API 49, Prelim. Rep. 2) is shown at 5000 × in Figure 1 (3558). The horizontal lengths of the white bars represent 1 $\mu$m except where otherwise numbered. The age of the clay was identified as Cretaceous; the use of the clay is reported as a 'paper clay'. Textural features of this kaolin considered to be significant include the following. Books of kaolin plates, and likewise individual flakes of smaller kaolin crystals, are present in random orientation. The books are intermediate in size with respect to the range in sizes observed in Georgia kaolin. The books, although built of expanded plates of medium size, maintain coherent integrity as book-type kaolin crystals—not as face-to-face floccules.

Porosity is notably high, and bulk density is accordingly low. Klinefelter *et al.* (1943), and Baumann and Keller (1975) found the bulk densities of Georgia soft to semi-hard kaolins to fall within a range of 1.32–1.66. Kaolin having the texture illus-

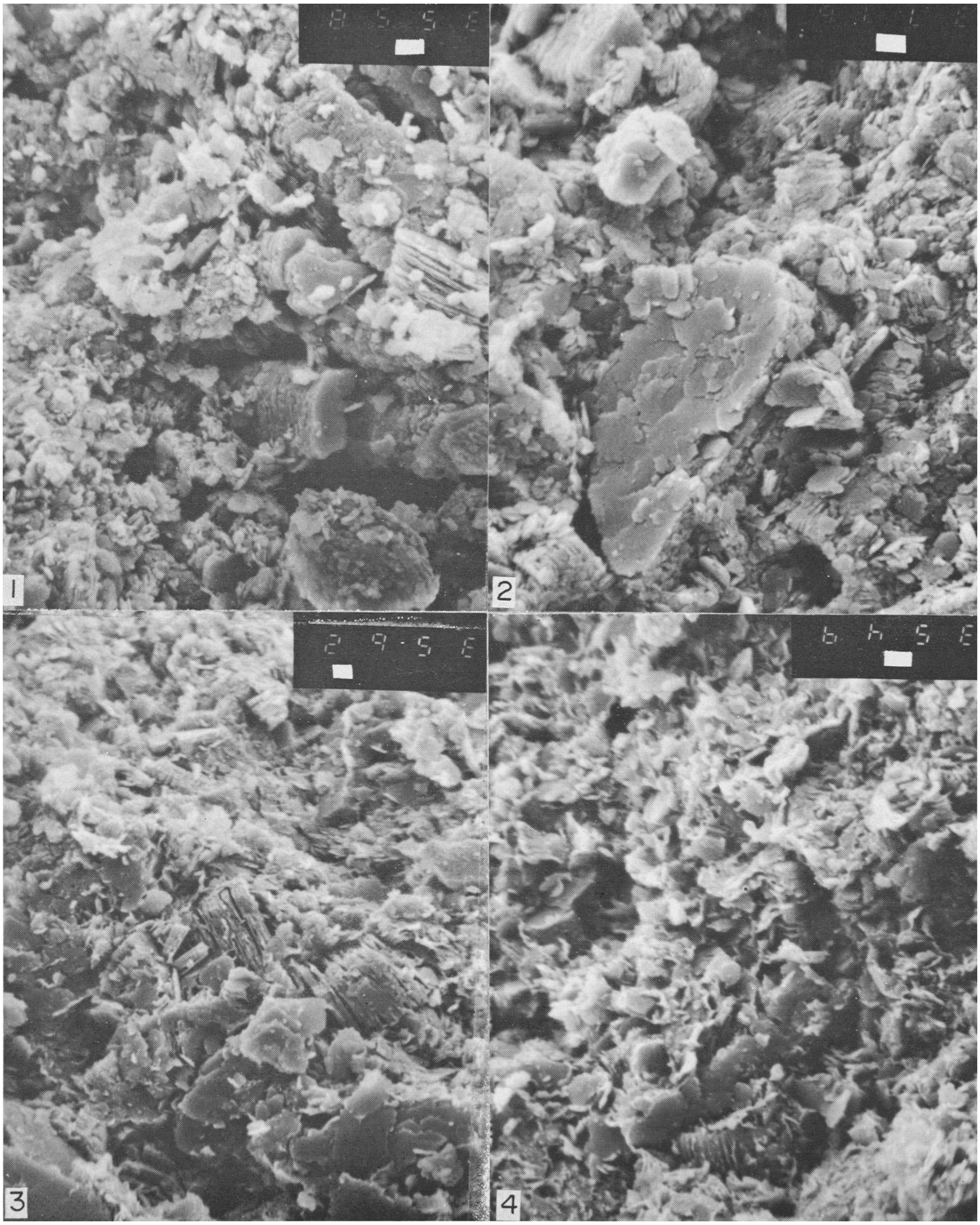



Figure 1. Kaolin, API McNamee Pit, Bath, SC, 5000×, 3558. Horizontal length of white bar represents 1 $\mu$m, except where otherwise numbered.

Figure 2. Kaolin, Huber Co. Pit, Huber, GA, 5000×, 3776.

Figure 3. Kaolin, API O'Neal Pit, Macon, GA, 3000×, 3562.

Figure 4. Kaolin, API Birch Pit, Macon, GA, 5000×, 3549.

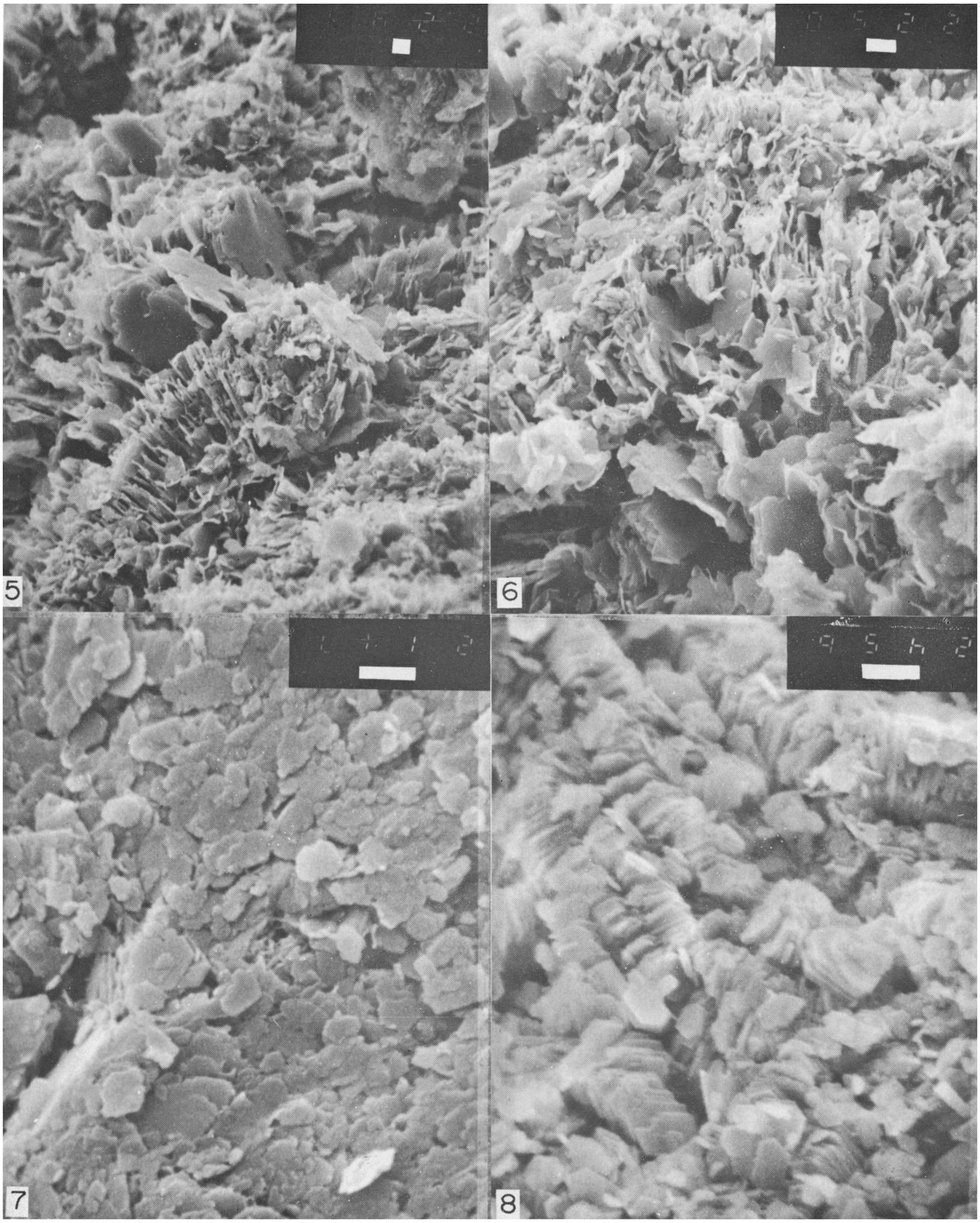



Figure 5. Kaolin, Georgia Kaolin Co., Pit 56, New Haven, GA, 3000×, 2249.
Figure 6. Same as for Figure 5, 5000×, 2250.
Figure 7. Kaolin, A. P. Green Pit, Dry Branch, GA, 10,000×, 2117.
Figure 8. Kaolin, Freeport Pit, Gordon, GA, 10,000×, 2456.

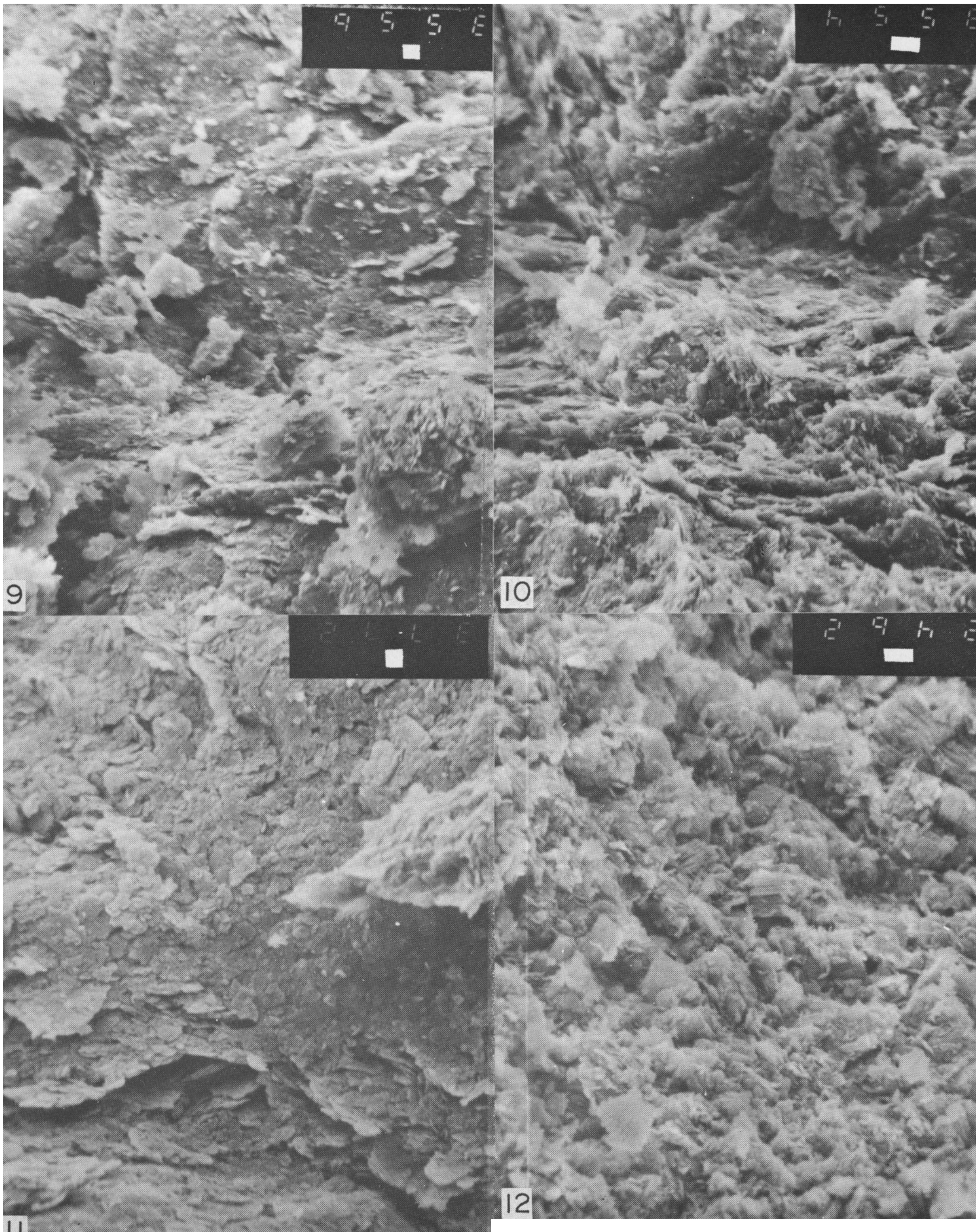
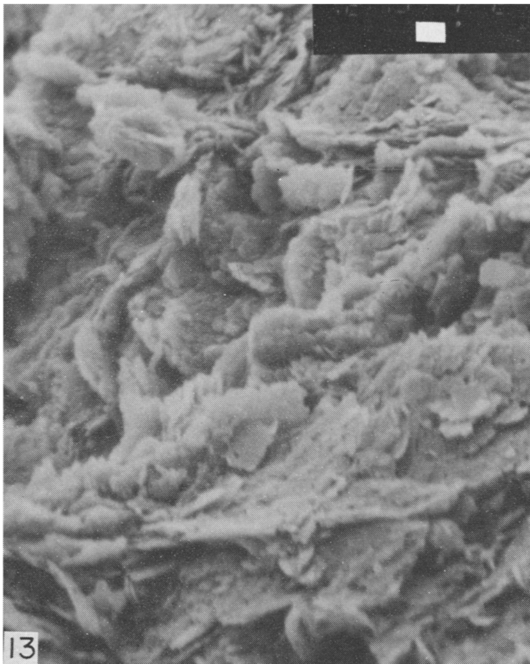



Figure 9. Kaolin, Dixie 'Rubber' Pit, Bath, SC, 3000×, 3556.
Figure 10. Same locality as for Figure 9, 5000×, 3554.
Figure 11. Kaolin, Huber Pit, Wrens, GA, 3000×, 3772.
Figure 12. Same locality as for Figure 11, 5000×, 2462.



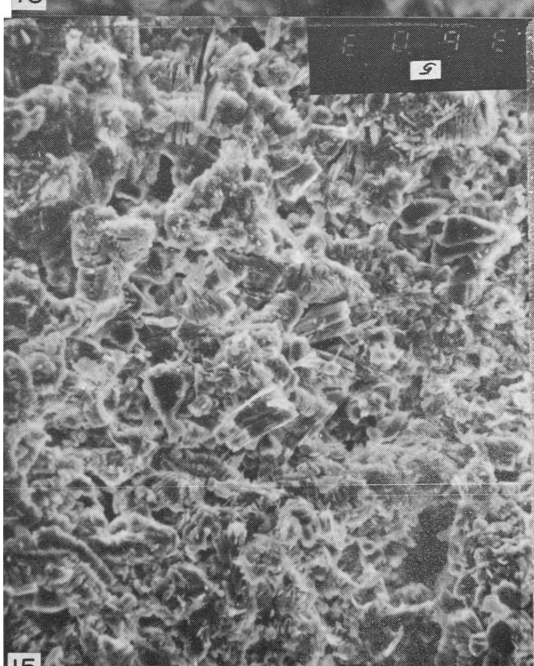


Figure 13. Kaolin, Thiele Pit, Wrens, GA, 5000 ×, 3652.

Figure 14. Kaolin, Purvis Pit, Georgia Kaolin Co., 10,000 ×, 0149.

Figure 15. Massive, white saprolite, above Sparta Granite, Martin Marietta Quarry, Sparta, GA, 1000 ×, 3603. Shows the overall texture and fabric of clay in Sparta saprolite.

Figure 16. Same specimen as in Figure 15, 2000 ×, 3602. Kaolinite books as they occur in random jumble.

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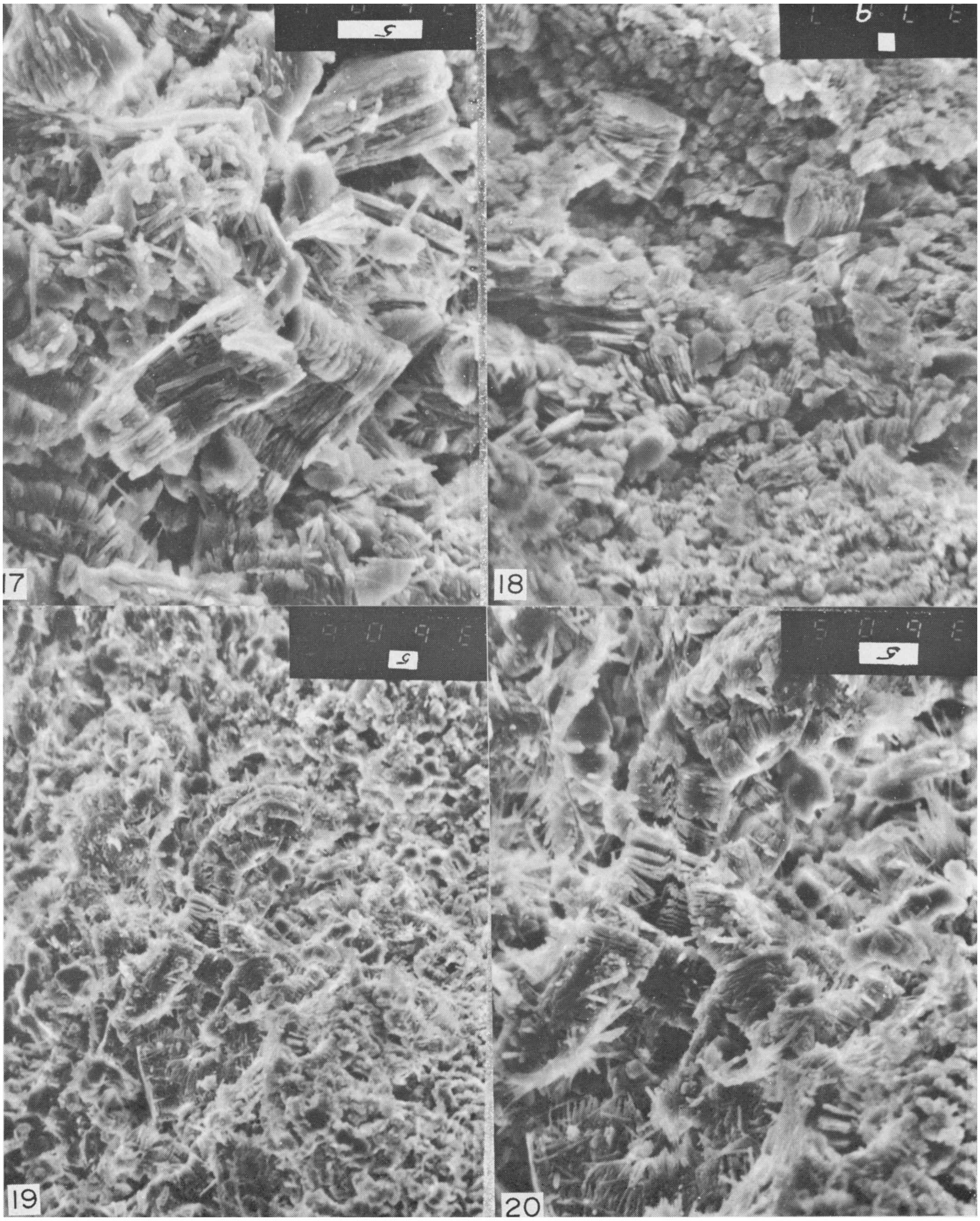


Figure 17. Same specimen as in Figures 15, 16, 3000×, 3601. Apparent re-entrants in kaolinite plates making up books; some elongates interlaced with books.

Figure 18. Saprolite, white, overlying Pre-Cambrian granite, 5 km east of Mitchell, GA, 3000×, 3797. Texture similar to Cretaceous kaolin.

Figure 19. Saprolite from the central part of the deposit, Martin Marietta Quarry, 1000×, 3606. Note large S-shaped book aggregate, probably diagenetic(?).

Figure 20. Same specimen as in Figure 19, 2000×, 3605. Some elongates present with books.

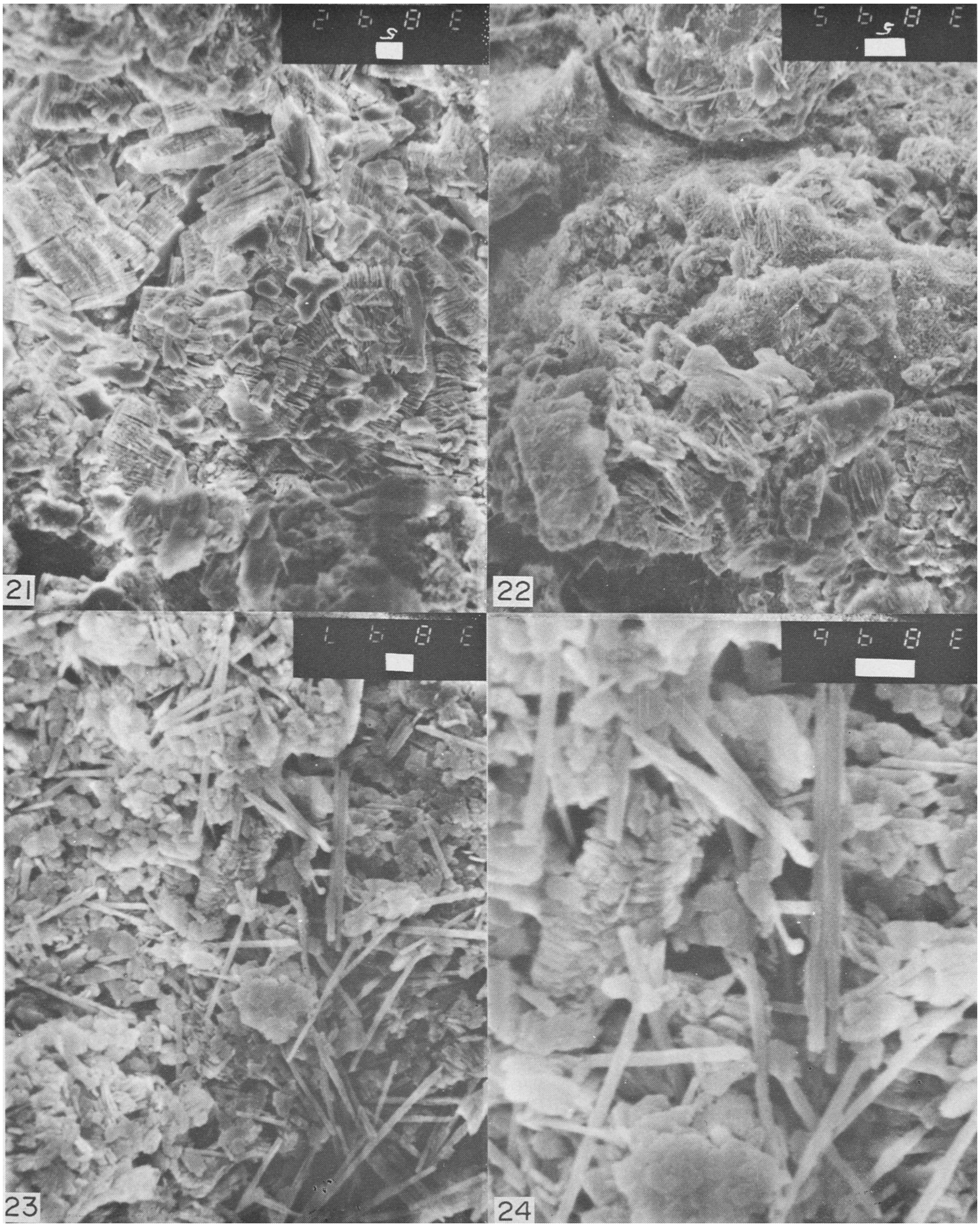

Figure 21. Saprolite, upper part of massive deposit Martin Marietta Quarry, Sparta GA, 1000×, 3892. Note predominance of books.

Figure 22. Same SEM specimen as in Figure 21, 1,500×, 3895. Note abundant elongates with minor amount of books.

Figure 23. Elongates and small plates from the same specimen as in Figures 21 and 22; 5000×, 3897.

Figure 24. A 10,000× view of part of Figure 23, 3896.

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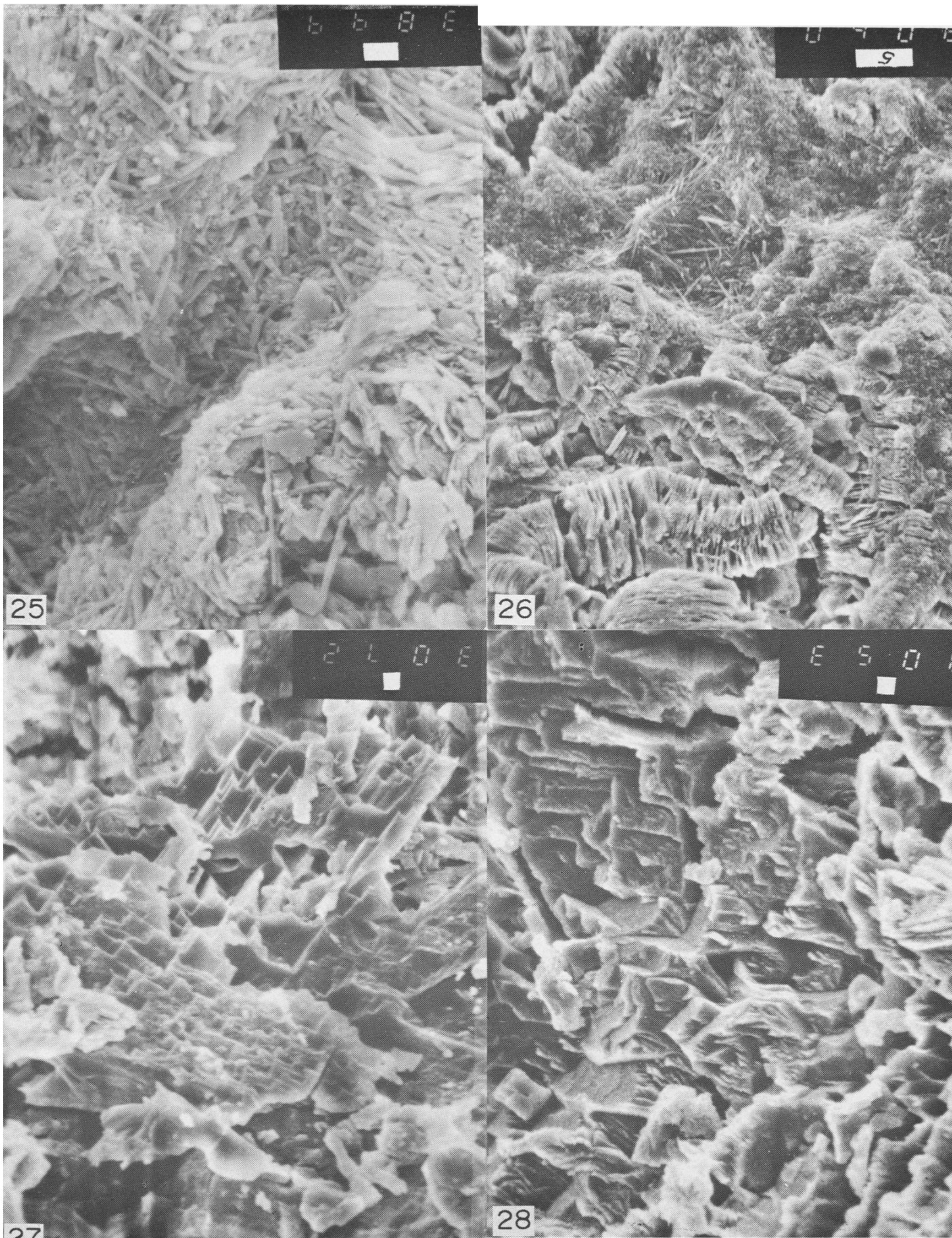


Figure 25. Elongates predominate in this part of the same specimen that produced Figure 21, almost all books, 3899, 6000×.

Figure 26. Segregated elongates and books in a single SEM view, Sparta saprolite, Sparta Martin Marietta Quarry, 3060, 2000×.

Figure 27. Feldspar, fresh Sparta Granite, Martin Marietta Quarry, Sparta, GA, 3027, 3000×.

Figure 28. Slightly weathered, dull-luster but hard granite collected 1 m from that in Figure 27, 3053, 3000×.

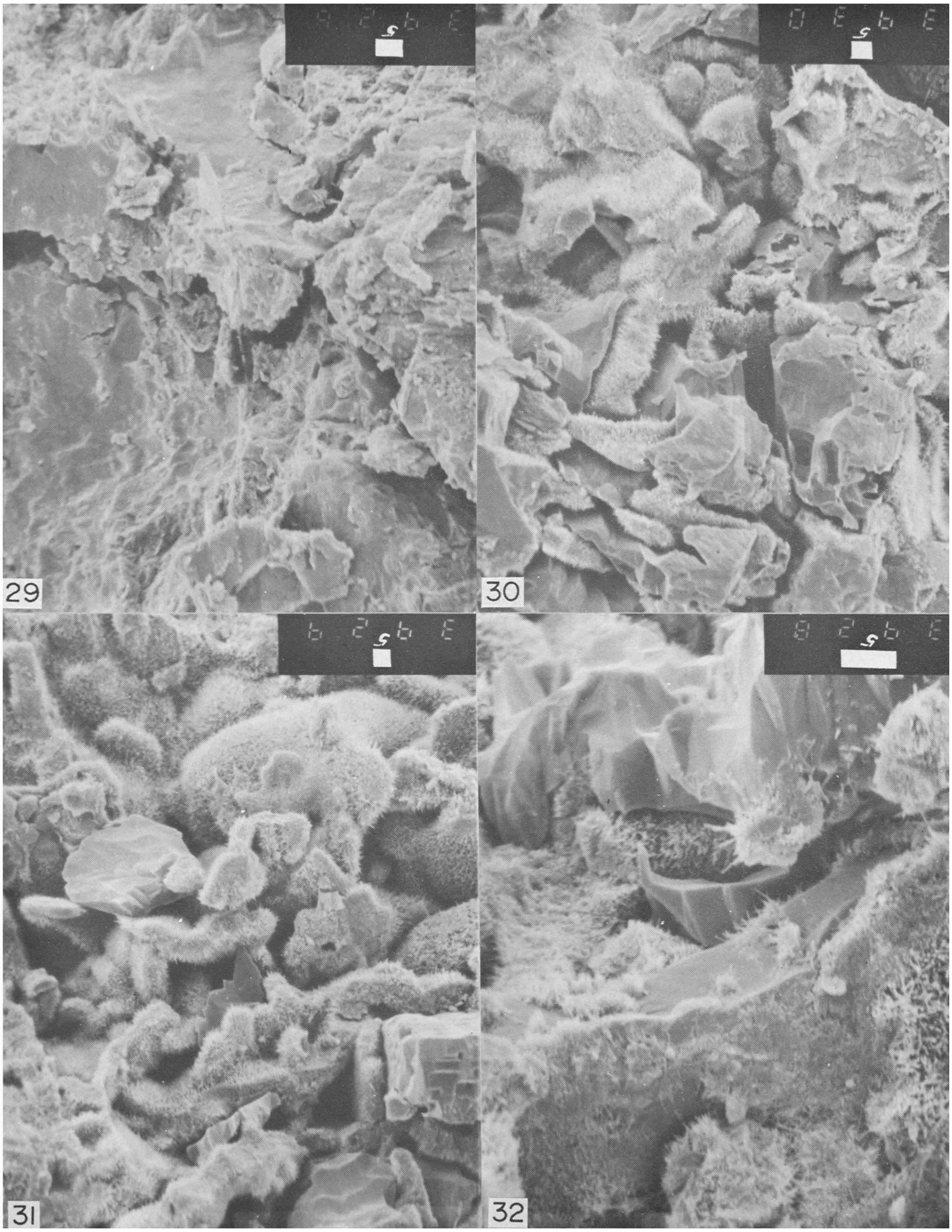


Figure 29. Brown, oxidized granite intervening between fresh and tan, chalky granite, Martin Marietta Sparta Quarry, 3926, 1000 ×.

Figure 30. Incipient argillation on feldspar which manifests first weathering by shattering into micro-fragments. First SEM of a sequential series through Fig. 35, all of Sparta Granite, Martin Marietta Quarry, Sparta, GA, 3930, 750 ×.

Figure 31. More extensive argillation, matting of elongates begins on some feldspar fragments, 3929, 600 ×.

Figure 32. Detail of typical 'growth' of elongate fibers on shattered feldspar, 3928, 2000 ×.

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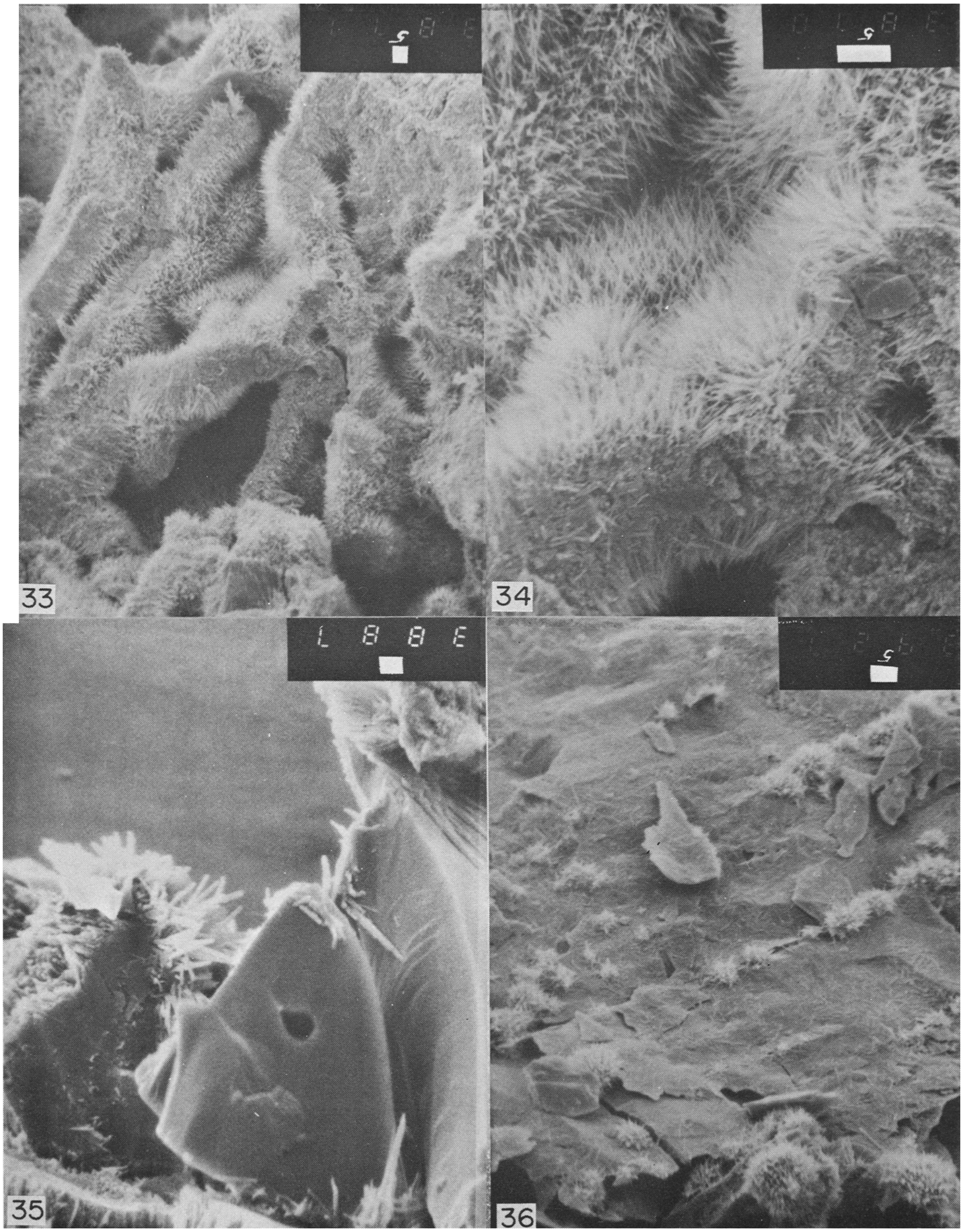

Figure 33. Almost complete coating by elongates of feldspar fragments, 3871, 600×.
Figure 34. Detail of 'clay-whiskered' feldspar, 3870, 2000×.
Figure 35. Detail of beginning of 'growth' of elongate from feldspar, 3887, 4000×.
Figure 36. Argillation beginning along micro-joints in Sparta granite, 3927, 1000×.

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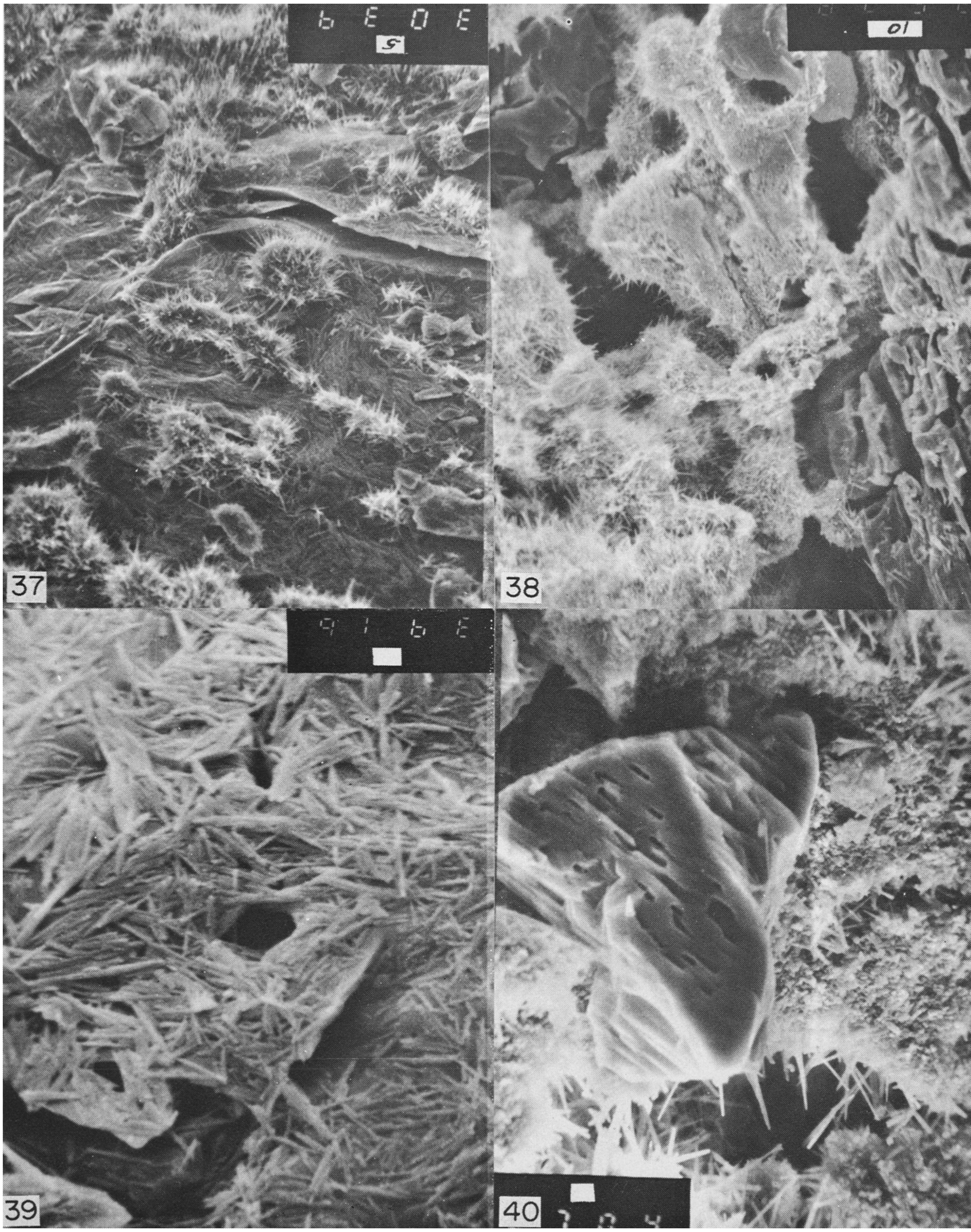


Figure 37. Progressive argillation along micro-joints, plus mat-like argillation of feldspar substrate, 3039, 1000 ×. See also Figure 39.

Figure 38. Parallel micro-jointing accompanied by corrosion-pitting and argillation, 3578, 3000 ×.

Figure 39. Matted clay fibers, flat-lying with respect to surfaces of feldspar, 3916, 5000 ×. Refer to Figure 37.

Figure 40. 'Spikes' of North Carolina 'primary kaolin' (halloysite), Spruce Pine, NC. Note shattering, and corrosion pitting of feldspar followed by argillation to elongates, 0704, 4000 ×. X-ray trace of this clay is No. 5 of Figure 48.

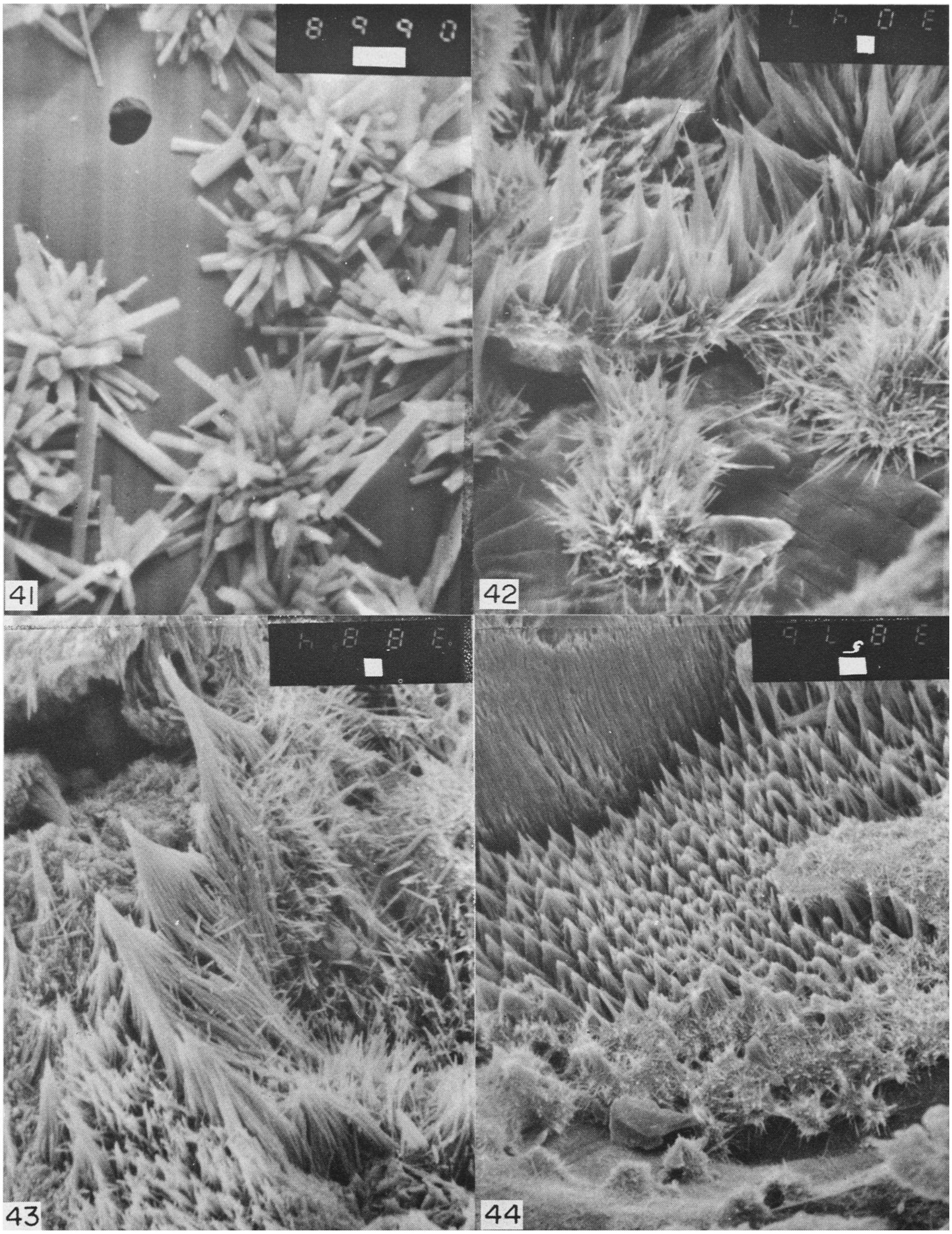


Figure 41. Elongates on the walls of a gas bubble in perlite, Etzatlan, Mexico. The clay deposit commercially produced endellite–halloysite, 0668, 10,000 ×.

Figure 42. Tufts clumps of 'wet grass' structure of clay elongates, Sparta Granite, Sparta, GA, 3047, 3000 ×.

Figure 43. Cones of coarse filaments of clay elongates, Sparta Granite, 3884, 3000 ×.

Figure 44. Cluster of clay-filament cones, same hand-specimen as Figure 43, 3876, 1000 ×.

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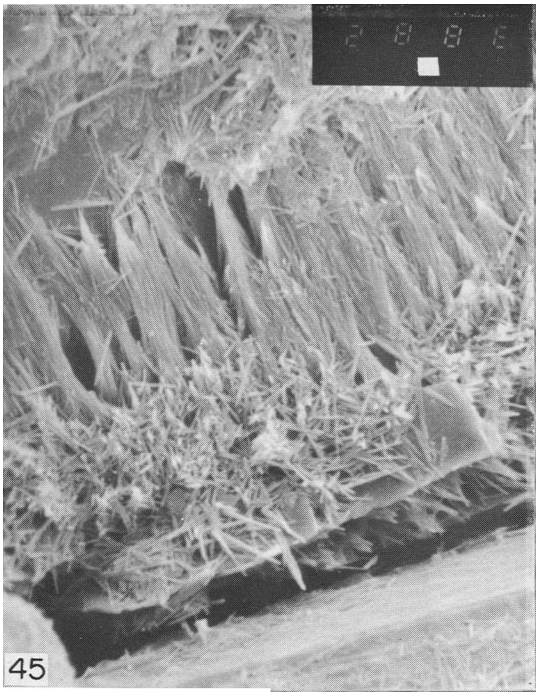

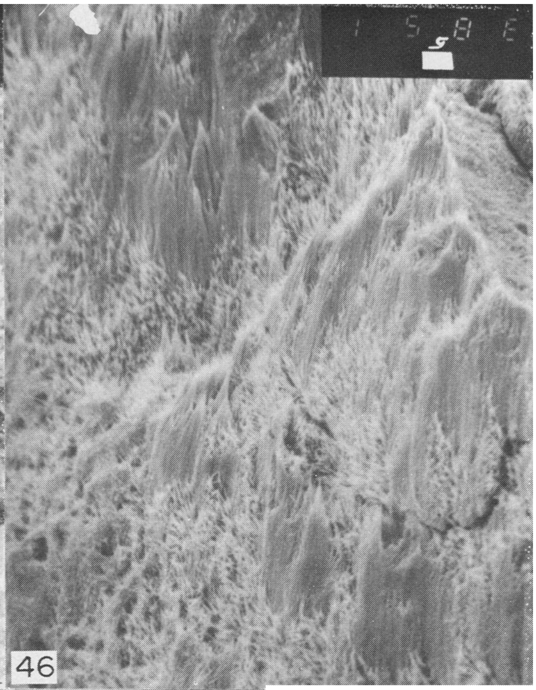

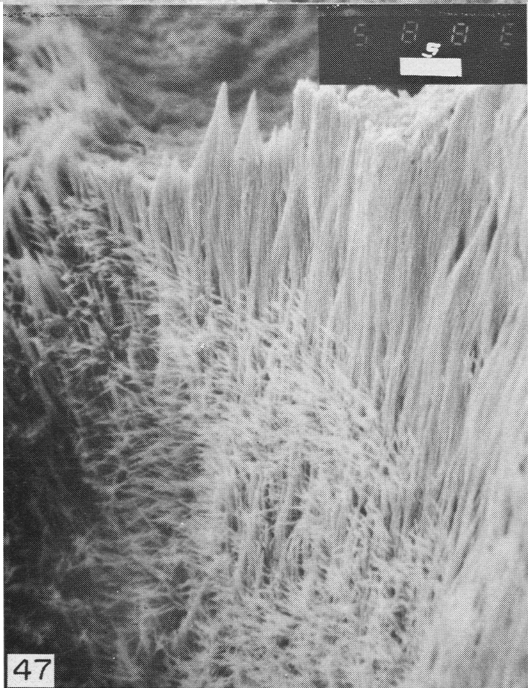

Figure 45. This vein-type filling of 'shredded wheat', cone clusters occupies a micro-crack in the Sparta Granite, 3883, 3000 ×.

Figure 46. Filament masses replace feldspar fragments; filaments parallel fracture surfaces, 3851, 1000 ×.

Figure 47. 'Bent grass' structure of clay-filament elongates, Sparta Granite, 3885, 2000 ×.

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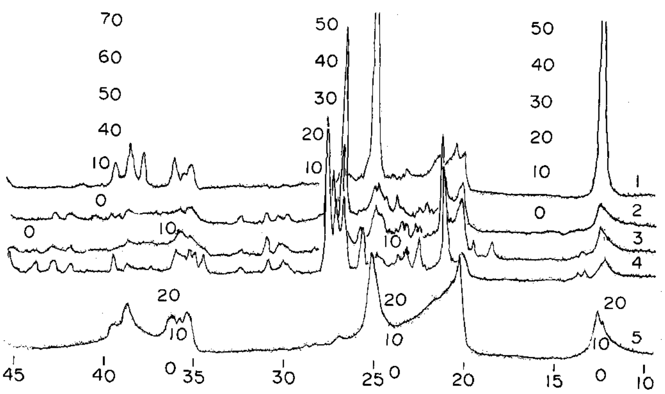


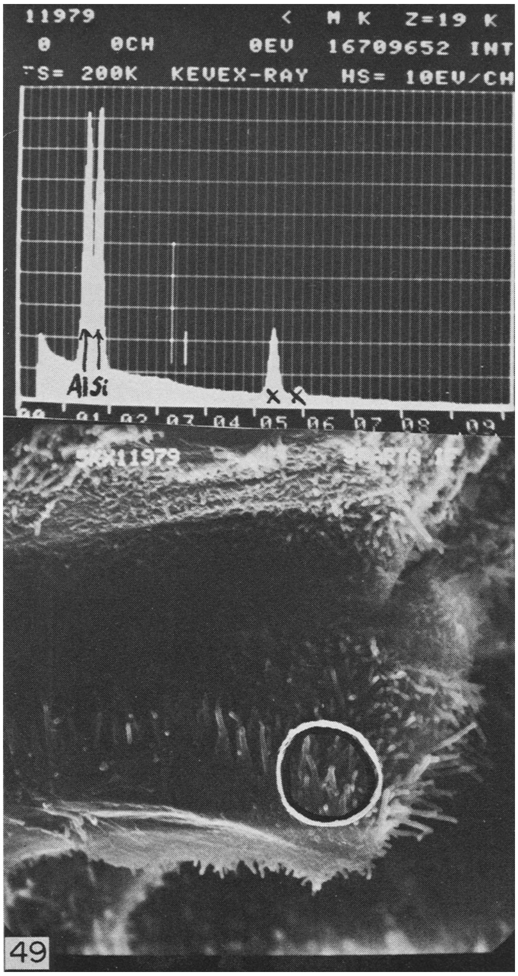


Figure 48. X-ray powder diffractograms of: (1) kaolinite (book morphology) of Sparta saprolite, as in Figure 15; (2,3) clay fraction from lightly mulled, chalky material as in Figures 33 and 34; (4) clay residue from saprolitized gneiss, as in Figure 71; (5) kaolin (elongates from Spruce Pine, NC) such as in Figure 40-type clay. Ni-filtered, Cu radiation, degrees two-theta along base.

Figure 49. KEVEX-Ray analysis of circled area, specimen from same transition zone, that yielded the SEMs of elongates, filaments, 'wet grass'. Peak heights indicate essentially 1:1 molar ratio of Al:Si. Analyses by courtesy of Cities Service Laboratory, Dr. W. Almon.

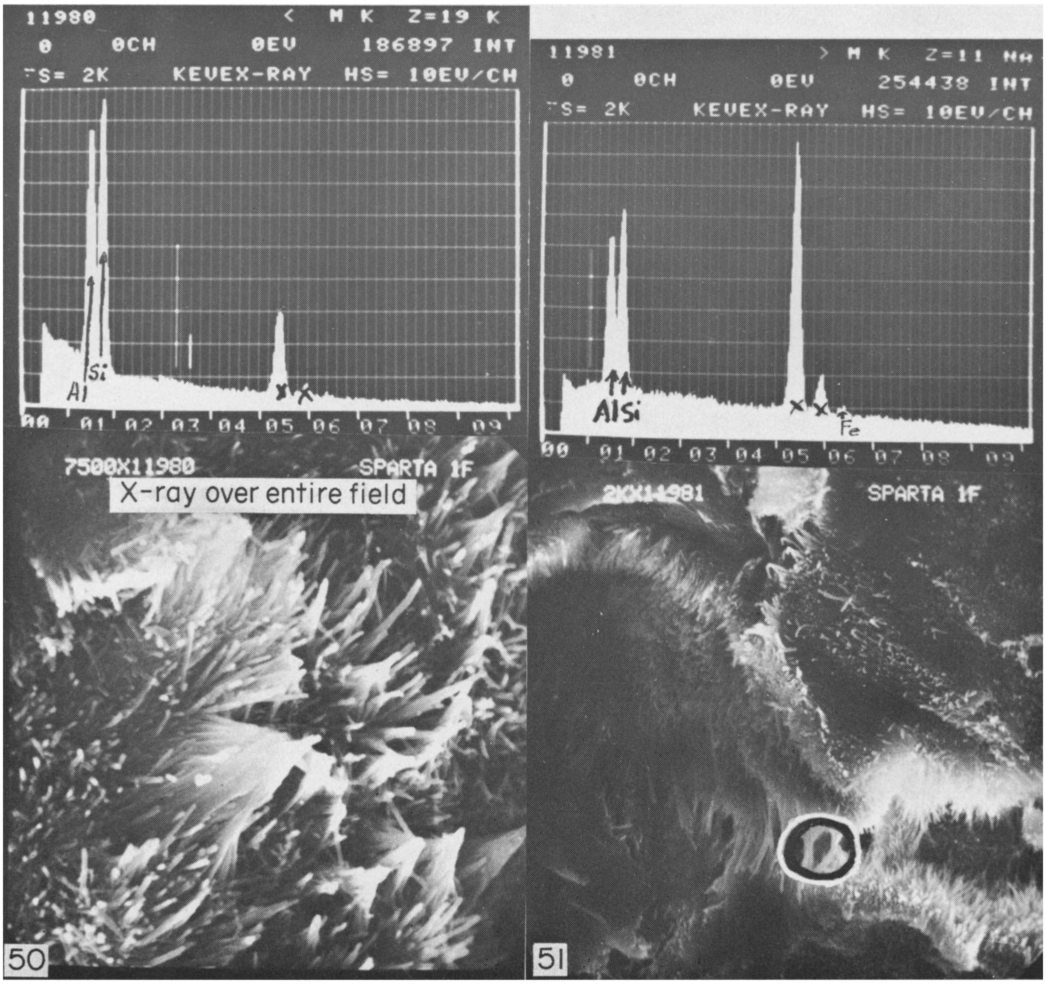


Figure 50. KEVEX-ray analysis over entire field shown.
Figure 51. KEVEX-ray analysis of encircled area.

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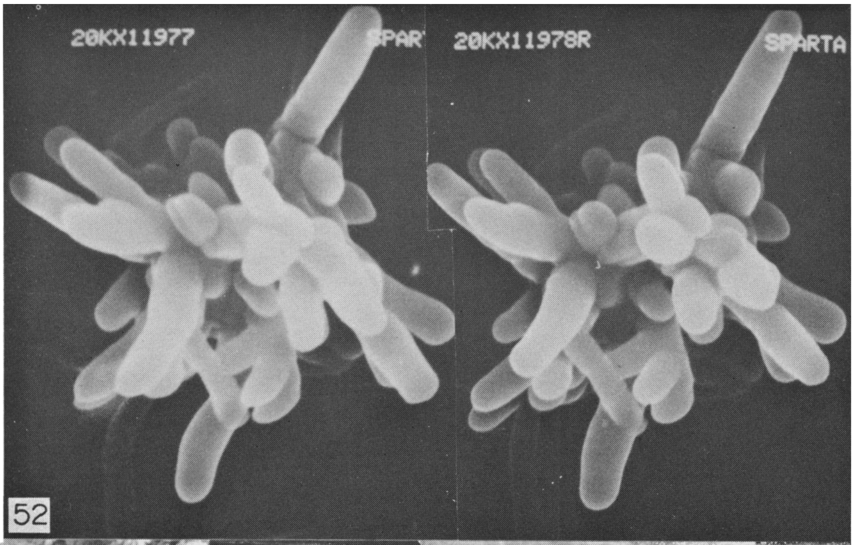


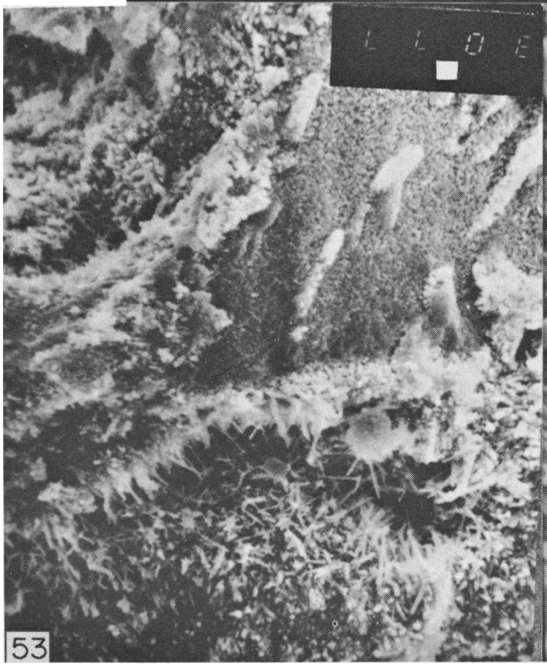


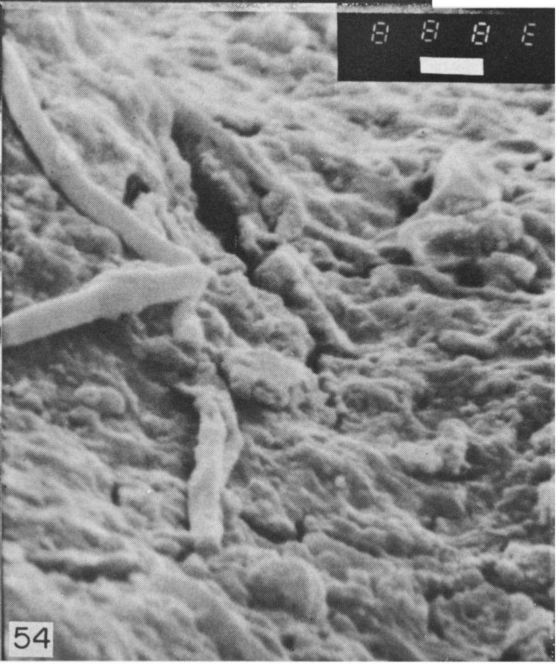


Figure 52. Stereo-pair of elongates from transition zone, Sparta Granite, Martin Marietta Quarry, Sparta, GA, 20,000 ×, Cities Service Laboratory.

Figure 53. Stubby and filamentous elongates in adjacent areas. Sparta transition zone, 3077, 3000 ×.

Figure 54. Surface of feldspar in Sparta Granite mass exposed to open atmosphere, I-20 and GA 15 Highways, 3888, 10,000 ×.

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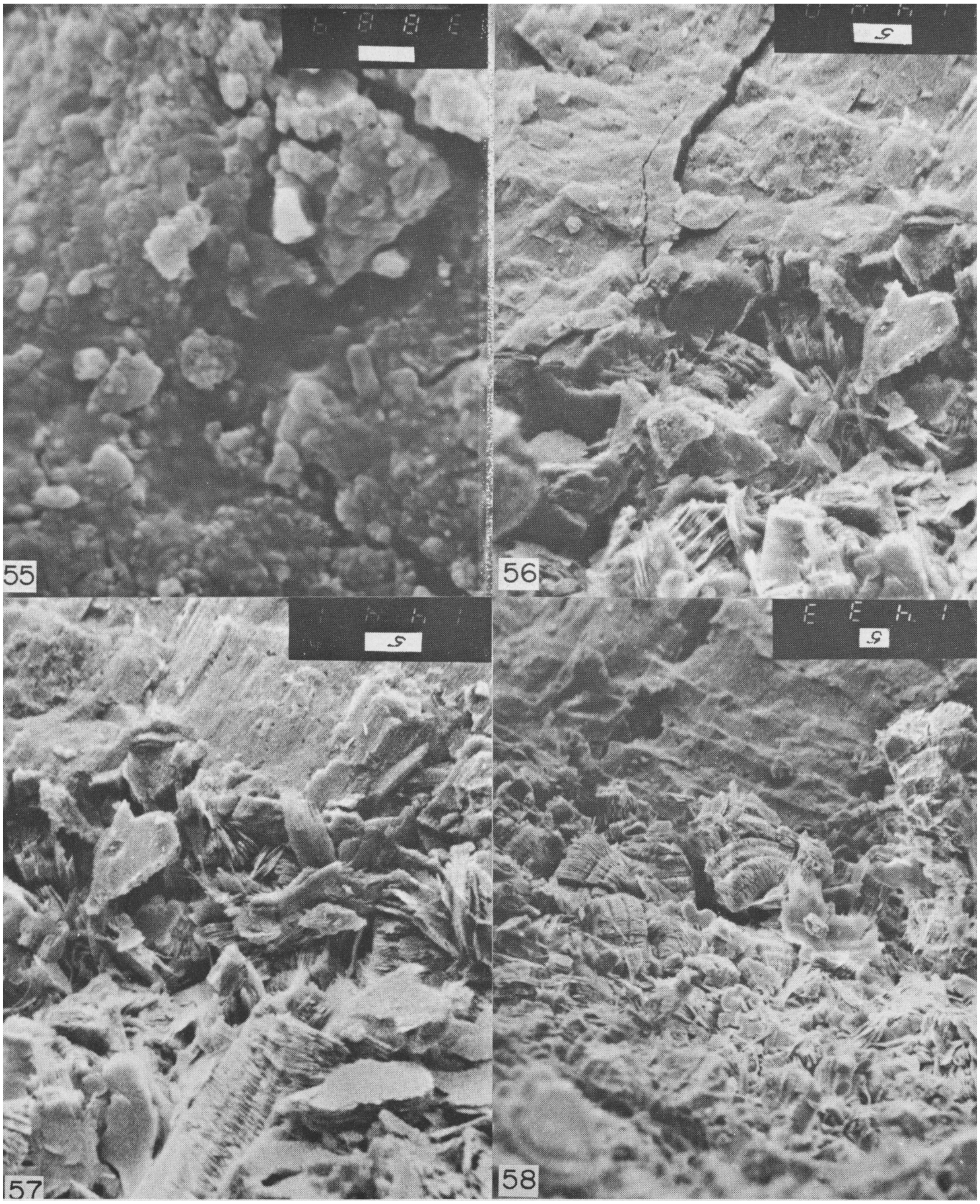

Figure 55. Another view of specimen yielding Figure 54, 3889. 10,000 ×.

Figure 56. Contact relationships of feldspar in Missouri granite altered to kaolinite flakes and books, 1440, 2000 ×.

Figure 57. Adjacent view to Figure 56, 1441, 2000 ×.

Figure 58. Curved, and short linear books of kaolinite in contact with parent feldspar, Missouri granite, 1433, 1000 ×.

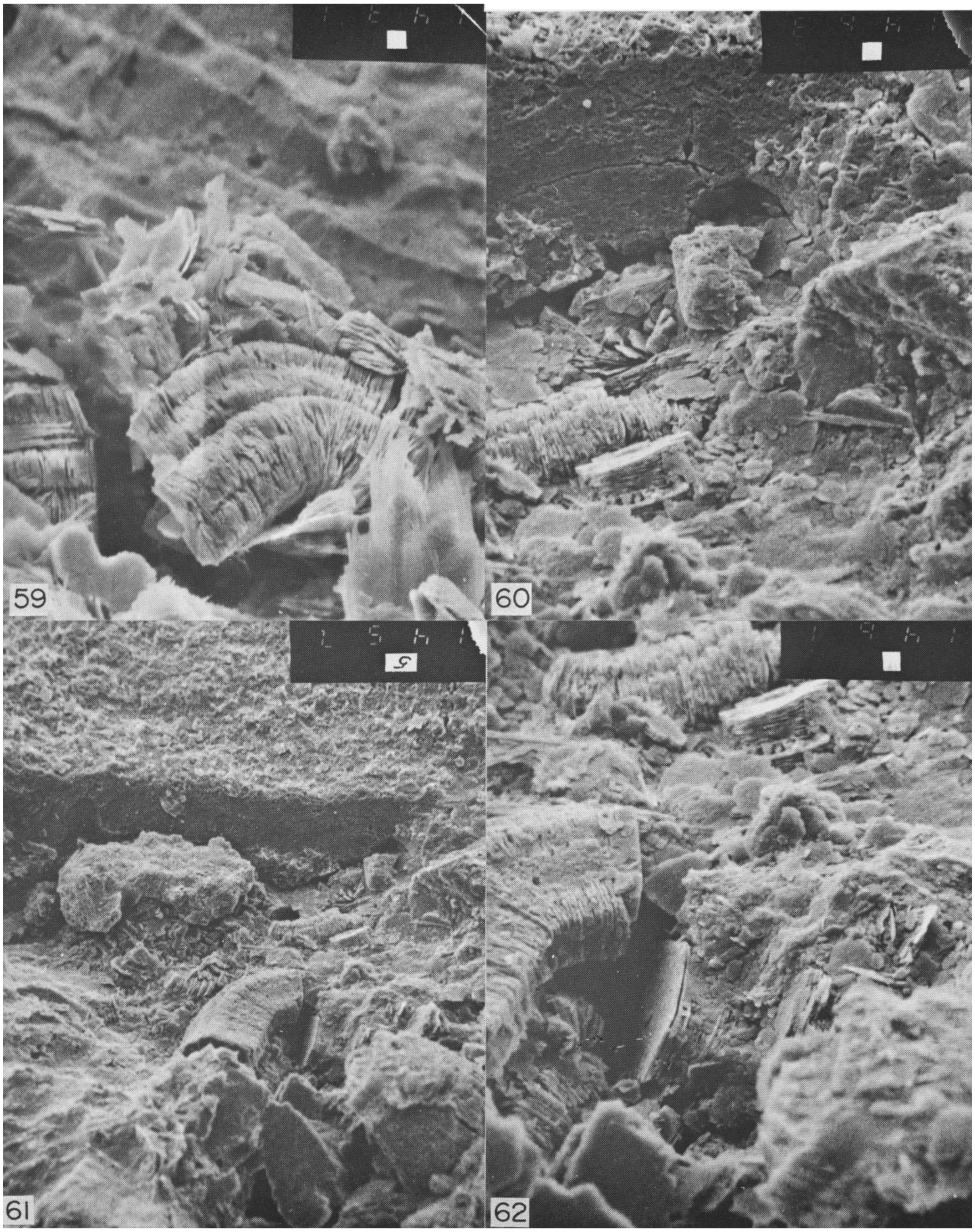


Figure 59. Enlarged view of Figure 58, 1431, 3000 ×.

Figure 60. Feldspar apparently softened and leached, followed by invasive replacement and crystallization of kaolinite, 1463, 3000 ×.

Figure 61. Invading kaolinite, similar mechanism to Figure 60, 1457, 1000 ×.

Figure 62. Enlarged view of Figure 61, Missouri granite, 1441, 3000 ×.

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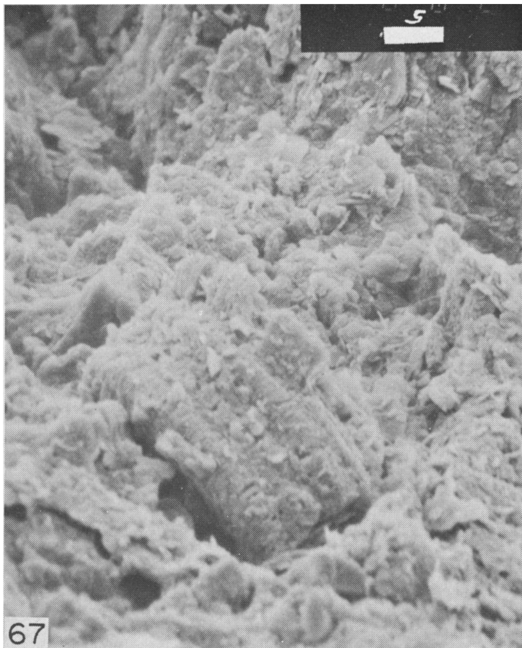
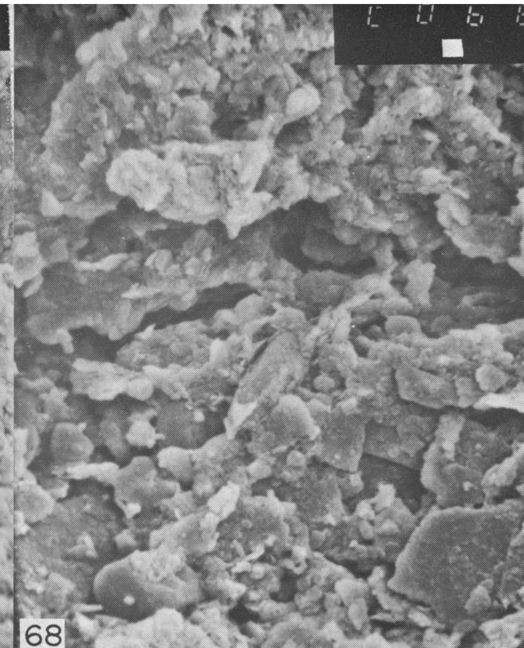
Figure 63. Large S-shaped book (vermiform) of kaolinite, Hodges mine, Georgia Kaolin Co., 0187, 750 ×.

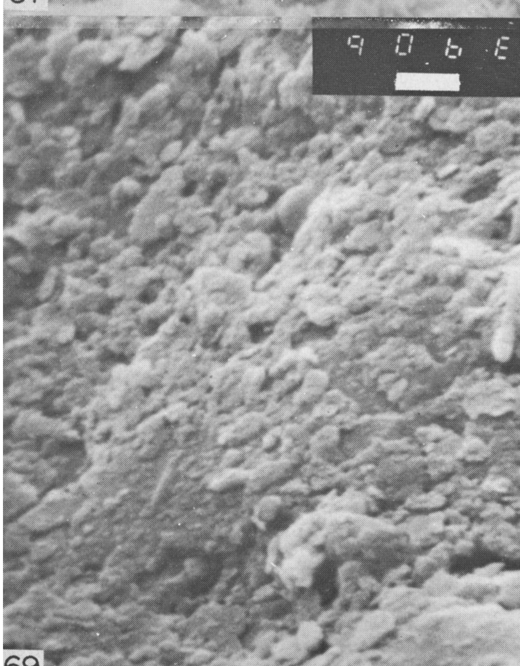
Figure 64. Large, secondarily recrystallized (?) vermiforms and books of kaolinite, Jacal, Mexico, 0389, 1000 ×.

Figure 65. Secondary surface weathering of Sparta saprolite, Martin Marietta Quarry, Sparta, GA, 3900, 3000 ×.

Figure 66. Additional example of surface-weathered Sparta saprolite, 3904, 3000 ×.







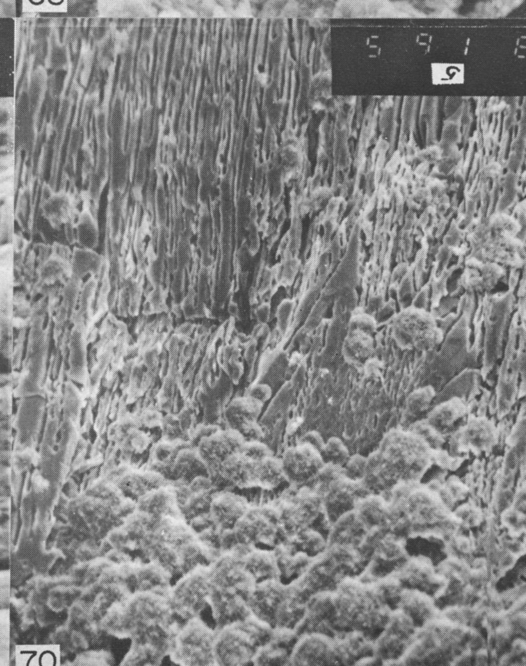


Figure 67. Surface-weathered Sparta saprolite, corroded crystals, 3901, 2000 ×.

Figure 68. Iron-oxide colored, surface-weathered Sparta saprolite, 3907, 3000 ×.

Figure 69. Secondarily transported clay deposited in near-surface cavities within surface-weathered Sparta saprolite, 3906, 10,000 ×.

Figure 70. Saprolitic weathering of feldspar to tufted kaolin elongates, in saprolitic gneiss, GA Highway 15, 25 km south of Athens, GA, 3165, 1000 ×.

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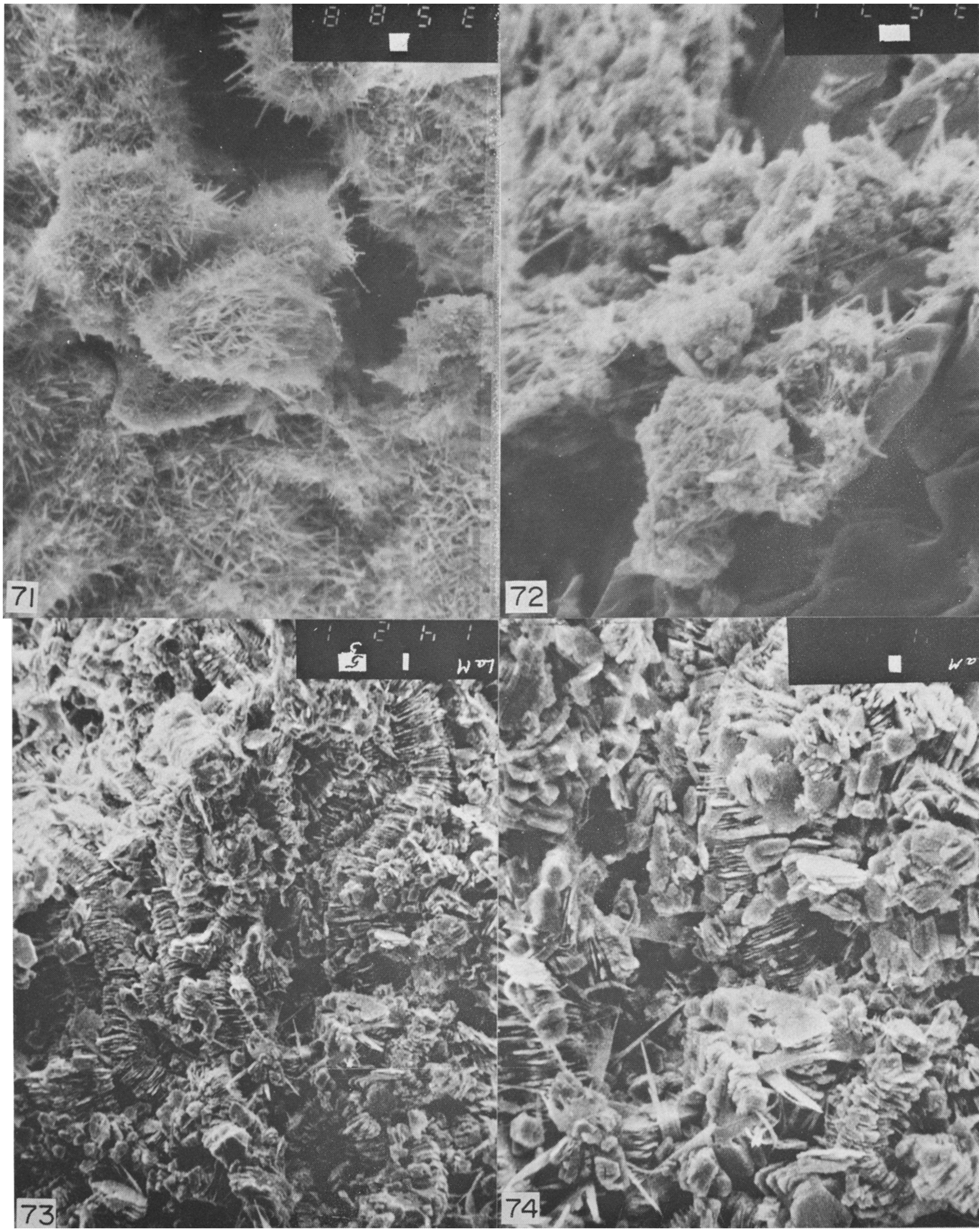


Figure 71. Filament-coated feldspar fragments from gneiss, same locality as for Figure 70, 3588, 3000×.

Figure 72. Intermeshed elongates and roundish particles, same locality as for Figure 70, 5000×.

Figure 73. Kaolinite *in situ* from La Motte arkose above Missouri granite, same locality as for Figure 56, 1421, 1000×.

Figure 74. Enlarged view of part of Figure 73, 1422, 3000×.

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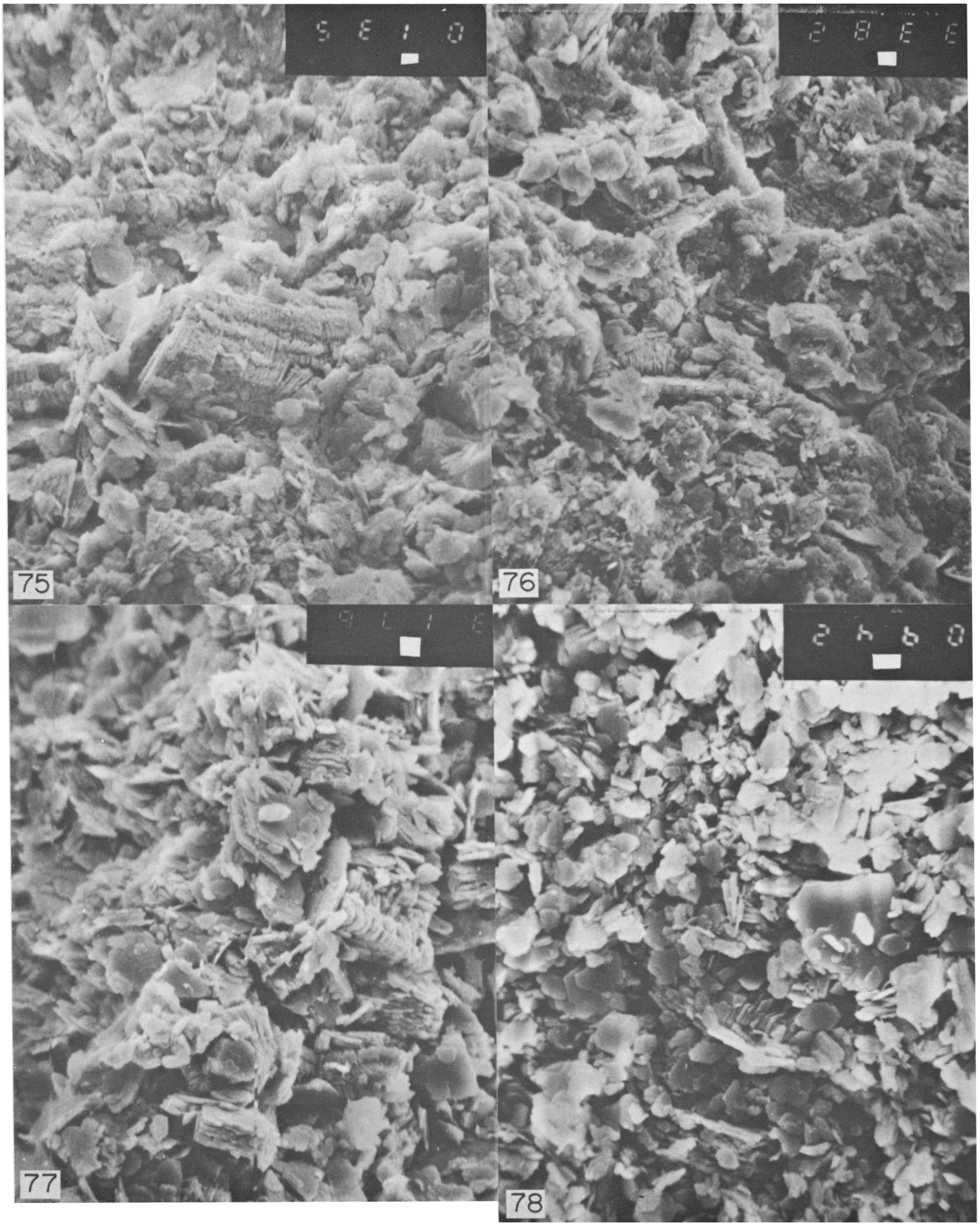


Figure 75. Kaolin collected from the mine face, Chambers Mine, Georgia Kaolin Co., 0135, 3000 ×.

Figure 76. Kaolin collected from the mine face, Hodges Mine, Georgia Kaolin Co., 3382, 3000 ×.

Figure 77. Mixed feed, discharged by Chambers–Hodges blunger and pipe line, entering sand boxes, Georgia Kaolin Co., 3176, 3000 ×.

Figure 78. Kaolin from upper sediment, sedimentation pond, Georgia Kaolin Co., 0942, 5000 ×.

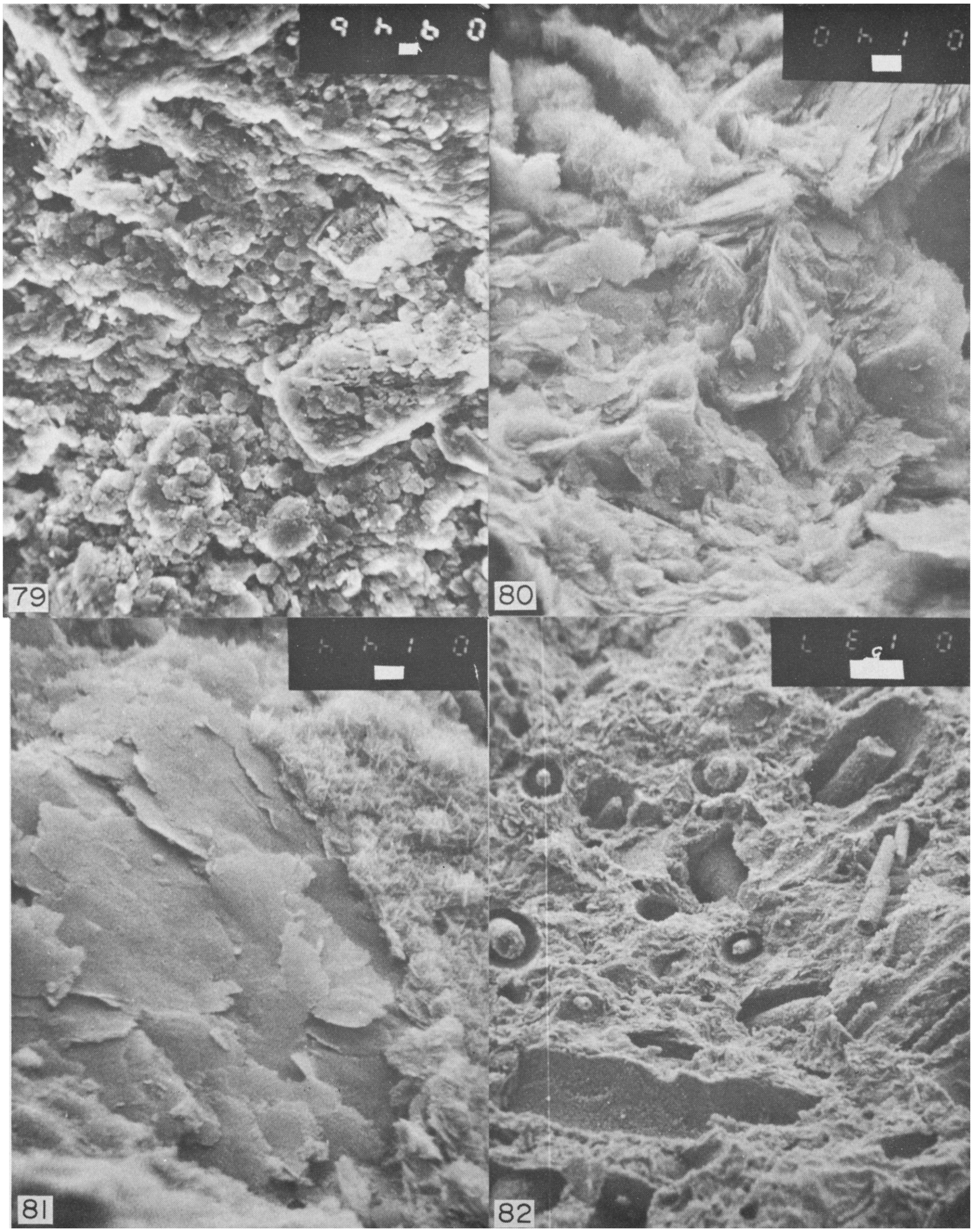


Figure 79. Kaolin from sediment about 15 cm below that of Figure 78, 0946, 3000 ×.

Figure 80. Flint kaolin, about 7 km north of Wrens, GA, 0140, 5000 ×. Note bladed low-cristobalite opposite negative number.

Figure 81. Flint kaolin, partially covered with bladed low-cristobalite, same locality as for Figure 80, 0144, 5000 ×.

Figure 82. Molds of sponge spicules in flint kaolin, same locality as for Figure 80, 0137, 500 ×.

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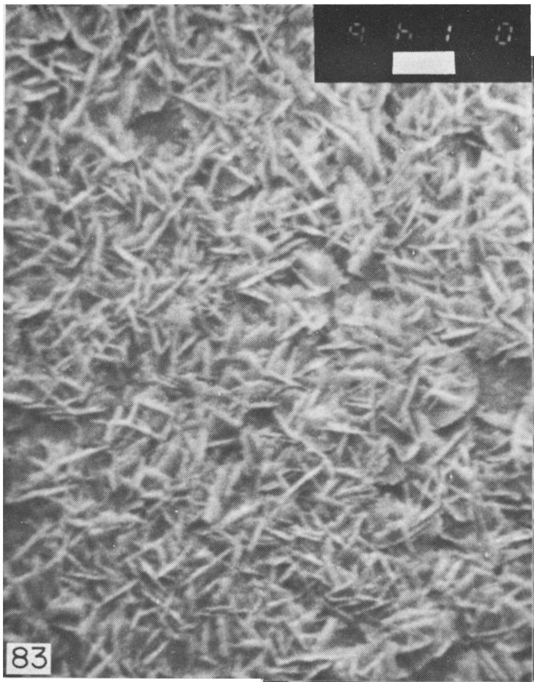


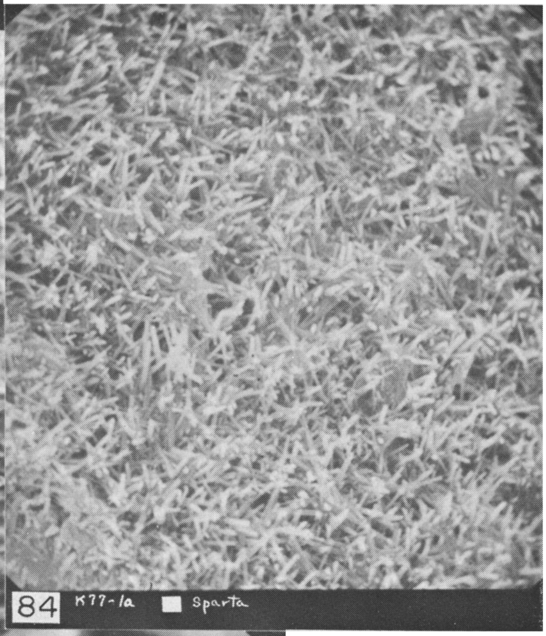


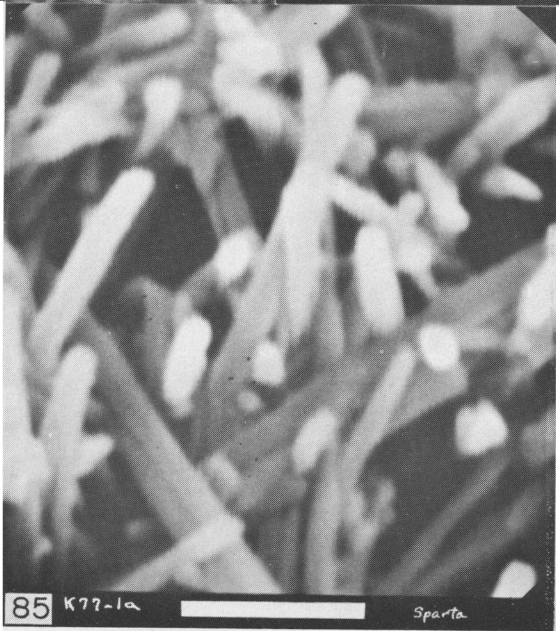


Figure 83. Bladed low-cristobalite lining fossils of sponge spicules in Figure 82, 0146, 10,000 ×.
Figure 84. Elongates analyzed by ORTEC, same SEM mount as for Figures 43–47, 3000 ×.
Figure 85. Enlarged view of part of Figure 84, 30,000 ×. The largest, NE–SW, elongate was analyzed by the ORTEC unit.

trated would probably have a bulk density in the lower half of that range. Note that significant porosity is visible as both inter- and intra-granular open spaces.

Small flakes of kaolin occur on, and as a surrounding matrix to, the kaolin books; the origin of the small flakes is open to alternative interpretations. While they may represent the small-size fraction of a bi-modal size distribution of kaolin flakes resulting from weathering, another viewpoint is that they might have been secondarily deposited from solutions moving through the porous clay after deposition. Easily apparent bi-modal size distribution in kaolin is common, for example, in Figure 2 (3776, 5000 ×) from the Huber Pit, Huber, GA, and in some of the Cornwall, England, kaolin [Figures 20 and 22 of Part II of this series, Keller, (1976) pp. 114–117].

Additional API kaolins are shown from the O'Neal and Birch pits, approximately 0.5 mile apart, near Macon, GA (Georgia Coating Clay Co.). They "... may be on the same stratigraphic horizon..." referred to the Middendorf Formation of Cretaceous age (p. 11, API Prelim. Rep. No. 2). The texture of the O'Neal kaolin [Figure 3 (3562 at 3000 ×)] closely resembles that of the McNamee, SC, clay, although it shows fewer of the small crystals dispersed on the larger books. The Birch clay [Figure 4 (3549, 5000 ×)] contains relatively more single plates than does the O'Neal clay but the two are not greatly dissimilar. More distinctive of the Birch flakes are the micro-scalloped and slightly crinkled edges of clay flakes; these are more clearly displayed in kaolin from Georgia Kaolin Co. Pit 56, near New Haven, GA, as in Figures 5 (2249, 3000 ×) and 6 (2250, 5000 ×). The scalloped kaolin occurs both singly and in books; does such morphology represent uneven original crystallization or later differential dissolution? Angular re-entrants, or projections, on kaolin flakes, as in Figure 7 (2117, 10,000 ×; A. P. Green Refractories Co., Pit, 2 miles southwest of Dry Branch, GA) suggest original recrystallization effects. More nearly perfect or complete, although small, hexagons were crystallized in clay from a Freeport Kaolin Pit about 4 miles south of Gordon, GA [Figure 8 (2456, 10,000 ×)]. I do not know the geologic age of the last two clay samples. Additional book-containing, relatively porous, 'Cretaceous-type' kaolins similar to the McNamee and Birch clays will be shown within other categories.

The second major textural type of Georgia kaolin, the fine-grained, or finely crystalline harder variety, is illustrated by another API sample from the Bath, SC, region, and others from the Wrens, GA, area. The API sample was taken from the 'Rubber Pit' (so named from the use of the clay; Dixie Clay Co.), 2 air-miles northeast of the McNamee Pit. The beds in the two pits were not connected, as the Rubber Pit clay was 50 ft stratigraphically higher than the McNamee clay.

In hand specimen viewed by the unaided eye, the Rubber Pit clay shows a continuous 'slick' surface, presumably because individual particles or crystals are too small for individual reflections to be resolved. The clay is compact, relatively tough and 'hard' (low friability, but not high Moh's number), and fractures irregularly, almost suggesting micro-pelletal clumping.

In SEM, basal planes of compacted kaolin crystals on a 'slick' surface are shown in Figure 9 (3556, 3000 ×), and edges of flakes, as might be molded about a micro-pellet or clump, in Figure 10 (3554, 5000 ×). Transmission electron micrographs made in the original API study illustrated the Rubber Pit kaolin to be "Irregular, poorly sorted kaolinite associated with halloysite as an impurity" (Figure 1, plate 8, API Rep. 8), whereas the McNamee clay was described as "Euhedral, six-sided kaolinite showing overlapping plates..." (Figure 2, Plate 1, API Rep. 8).

In Georgia, the Wrens district produces 'hard', fine-grained kaolin of Eocene age. Typical examples are from 2 Huber Co. clays [Figures 11 (3772, 3000 ×) and 12 (2462, 5000 ×)], a Thiele Co. pit [Figure 13 (3652, 5000 ×)] and Georgia Kaolin Co. pit [Figure 14 (0149, 10,000 ×)].

The micro-texture of these hard, Eocene-age clays is as different from that of the softer Cretaceous clays, as are the gross physical properties. Note the smallness of the plates which commonly are singles or small flakes in face-to-face contact. They overlap either on flat surfaces or in curved and contorted figures (due to soft rock deformation?). They are compacted relatively tightly. Among the examples illustrated, the clay in Figure 12 (2462), collected by S. H. Patterson from Huber Mine 32, "above Paleocene pollen", is finely crystalline, but the overall fabric bears some resemblance to that of Cretaceous kaolins.

Eocene age clays have been interpreted by Murray (1976) as being reworked Cretaceous clay redeposited during Eocene time. He interprets the face-to-face orientation as an effect of flocculation in marine water. Austin (1976, p. 2) wrote also that, "... Tertiary units... were derived largely from the Cretaceous deposits by erosion and were deposited in normal depositional environments. Some were then subjected to even further laterization".

Illustrations of 'flint kaolins', another textural group, will be deferred until a later section in this report in order not to break the discussion on genesis.

### MICROGRAPHS OF SAPROLITE FROM SPARTA GRANITE

Scan electron micrographs may be used to shed further light on the problem of origin of Georgia kaolin by photovisually observing the stages during argillation (kaolinization) of primary silicate rocks which most likely served as parent materials for the kaolin. In the same way, such observations may likewise be applicable to the investigation of kaolinization in general.

One of the most debated aspects of the origin of Georgia kaolin, despite concurrence of virtually all investigators that the kaolin was ultimately derived from crystalline rocks of the Piedmont Plateau, is the time that the major kaolinization took place. One viewpoint is that clastic feldspar was deposited in sedimentary basins during Cretaceous time and that the process of dominant kaolinization occurred after deposition. For example, Grim and Wahl (1968) state (p. 17), "The present authors are in general agreement with the Kesler concept... Kesler (1963) has questioned the extent of kaolinization that occurred through weathering at the source and showed quite conclusively that most of the kaolin has been derived from feldspar which was first deposited as clastic particles" (Grim and Wahl, p. 16). Jonas, after a detailed petrographic study, wrote in 1964, "These observations lead to the conclusion that these Georgia kaolin deposits were not sedimented in still-standing waters as the mineral kaolinite. Major mineral constituents of the original sediment were muscovite and feldspar". Buie (1964) considered the possibility that volcanic ash was the source material for the kaolinite, the ash weathering first to montmorillonite and then to kaolinite.

The second viewpoint, expressed by the previous quotation from Murray (1976), is that the kaolin, already weathered before deposition, was dumped along with sand into the depositional area along the Cretaceous coast line. Murray further believed that the Cretaceous, transported kaolins were deposited in fresh to slightly brackish water, whereupon they were flocculated in edge-to-face orientation, thereby yielding clay having relatively low density. The early Tertiary kaolins, however, deposited under marine conditions, "settled out in a face to face relationship which accounts for their high density..." (Murray, 1976, p. 123). The flocculation differences were originally reported by Hinckley (1961).

One of the almost certain parent sources of Georgia kaolin near the large deposits is the Pre-Cambrian Sparta Granite, widely exposed near Sparta, GA. Resistant, rounded boulders and masses of Sparta granite occur in fields and road cuts in a band paralleling the fall line, and an excellent exposure of fresh granite with overlying thick saprolite may be studied in the Martin Marietta quarry (not operating in early 1977) about 4 km northeast of Sparta. I was guided there by Doral Mills, Georgia Kaolin Co., after which samples were collected of representative material for SEM (courtesy of A. Clyde Marsh, Manager, Martin Marietta Co.).

The fresh gray granite at the top of the north wall of the quarry has been exposed by stripping of saprolite overburden. The exposed alteration zone above the fresh granite, which is a zone of transition to saprolite, must represent at least in its major part an episode of weathering prior to any possible further slight weathering which may have followed the stripping of overburden. The weathering of the transition zone, however, in my opinion, took place between the interval of saprolitization and exposure by stripping. Typically, the fresh granite passes upward into a brownish, oxidized, but hard granite zone a few centimeters thick. This oxidized zone merges gradually upward into tan to chalky, whitish, progressively more decomposed granite, and thence into relatively soft saprolite. This transition zone from fresh granite to very soft, friable saprolite is typically not more than 10–25 cm thick.

The soft saprolite above, in which the kaolin is essentially white, is some 10 m thick at maximum, thinning by erosion in east and west directions. The upper part of the saprolite zone becomes mottled (by weathering) in a zone a couple of meters thick, containing rounded to ovoid, reddish blotches in oxidizing saprolitic material, and this in turn merges upward into reddish subsoil and soil generated by pedological processes. Micrographs were taken of kaolin samples from the (a) white saprolite, (b) the mottled red and white zone, and of (c) fine-grained, transported gray clay deposited in small pockets and cavities within the mottled zone. These samples, plus those from the transition zone above the granite, can indicate potentially (1) how the granite alters to saprolite which probably formed below the groundwater table, and (2) how the uppermost saprolite has further weathered more recently above the groundwater table.

The first SEMs from this regolith are of the kaolin in the white saprolite [Figures 15, 16, 17 (3603, 3602, 3601, at 1000, 2000 and 3000 ×, respectively]. They show the overall natural texture and fabric of the undisturbed kaolin, the relationships of clay flakes and books, and details in individual crystals. Note that the saprolite–kaolin is composed of books, sheaves and lesser amounts of individual flakes in random arrangement. They are loosely packed and porous in structure. The books are medium to coarse in size and loosely expanded, and the kaolin plates are subhedral in shape. The texture and composition of this saprolite so closely resembles that of the Cretaceous deposits that they might be taken as counterparts. A proponent of the genetic interpretation that the Cretaceous deposits were derived from already weathered kaolin (Murray, 1976) can find strong graphic support herein that the kaolin which was weathered before transport was ready-made by weathering for the deposit. Alternatively, a proponent of the interpretation (Kesler's, 1963) that feldspar was transported and deposited as arkose might claim that weathering of clastic feldspar would yield the same kaolin texture as from granite. In a later section, SEMs will be shown of kaolinized arkose above saprolitized granite.

Elsewhere, approximately 5 km east of Mitchell, GA, a white saprolite furnished by Walter A. Payne shows the same general texture, though in smaller crystals, as that from the Sparta quarry [Figure 18 (3797, 3000 ×)].

Another sample of saprolite kaolin from the Sparta quarry contains not only large vermicular to S-shaped accordion-books of kaolinite [Figures 19 and 20 (3606, 1000 × and 3605, 2000 ×)], but shows at close scrutiny, especially in the higher magnified 3605 (Figure 19) definite elongate crystals, commonly referred to as halloysite morphology, interlaced with, or between, the books of plates. The relative abundance of elongates varies from sample to sample of kaolin in Sparta (and other) saprolite. Even in one small hand specimen, elongates may mutually interpopulate with books from none to all, as shown in the next series of SEMs. One part of a hand-specimen from the upper zone of the massive saprolite shows well-formed, closely packed, large books [Figure 21 (3892, 1000 ×)]. In another part of the same SEM specimen, books and elongates are intimately intermingled [Figure 22 (3895, 1500 ×)]. Progressively in the same hand specimen, the elongates increase in prominence, as seen in Figure 23 (3897, 5000 ×), enlarged to 10,000 × in Figure 24 (3896). Note in these the small flakes making up face-to-face aggregates, in pseudo-book forms. In Figure 25 of the same specimen, elongates greatly predominate over books (3899, 6000 ×). A separate sample collected 5 m distance across the exposed face of saprolite shows nearly segregated groups of plates and elongates [Figure 26 (3060, 2000 ×)].

## MICROGRAPHS OF ARGILLIZING SPARTA GRANITE TRANSITIONAL TO SAPROLITE

Quarry-blasted, fresh Sparta granite is shown in Figure 27 (3027, 3000 ×), and dull-luster but otherwise hard granite in Figure 28 (3053, 3000 ×). Brown, oxidized granite preceding argillic alteration is in Figure 29 (3926, 1000 ×).

No farther than 5 cm outward (or upward) in the same original block broken from the transition zone, the granite has weathered by (a) mechanical shattering, and (b) clay crystal growth, as shown in Figures 30, 31, 32, 33, 34 and 35 (3930, 750 × ; 3929, 600 × ; 3928, 2000 × ; 3871, 2000 × ; 3887, 4000 ×). Evidence will be presented later for identification of this clay morphology as a 1:1 (Si:Al) clay mineral Mechanical, micro-shattering, and/or corrosion pitting of feldspar, which I have observed as a common prelude to argillation in specimens from North and South America, Europe, Australia and Japan, may be accompanied by micro-jointing and growth of clay crystals along the micro-joints. Such as these are seen in Sparta samples from three different locations along the transitional white zone above the granite, as in Figures 36, 37 and 38 (3927, 1000 × ; 3039, 1000 × ; 3578, 2000 ×). Parham (1969) likewise illustrated corrosion pitting of feldspar, and similar early alteration along crystal dislocation and/or micro-joints resulting from both natural and artificial weathering.

It is not unequivocally clear from SEMs whether the tiny clusters of erect clay fibers spring directly from feldspar that is otherwise relatively fresh, or if their growth accompanies more profound and complete argillation of their massive substrate. Close examination of some of the original micrographic prints, as in Figure 37, show an interlacing texture of fibers in the substrate. Certain of these are well resolved in Figure 39 (3916, 5000 ×). Photo-similarity between these fibers and those photomicrographed from gel (imogolite?) is high (micrographs by Wada, Henmi, Yoshinaga and Patterson, 1972). One wonders if the fibers of clay at Sparta are genetically related to imogolite, and/or if they retain a relic imogolite structure.

On the other hand, at Spruce Pine, NC, 'spikes' of kaolin-elongate, the long-established, commercially produced, 'primary kaolins (halloysite)' occur on feldspar as in Figure 40 (0704, 4000 ×). Parham's (1969) replica of 'tapered projections' from his sample DWB-3 shows similarities to 'spikes'. Elongates occur on the walls of essentially fresh glass in perlite [Figure 41 (0668, 10,000 ×)] from near Etzatlan in Mexico (Keller, 1963). The actual mineral cluster in the last example has been identified as kaolin by microprobe, and the deposit of which this is an external part produced endellite in commerical quantity. Transmission electron micrographs of the commercial clay showed elongates similar to the laths (?) in this SEM. Hence, although elongates develop, or 'grow', on an aluminum-containing rock base, it is unclear whether they acquire crystal nutrients directly from the solid base, or from saturated nutrient solutions which may fill the pore space into which the crystals extend. My predilection is toward crystal growth from solution, although the solutions most probably derive nutrients from the substrate. This view appears to be supported by Parham's (1969) study of natural and artificially produced halloysite.

The practice of describing or naming the morphology of elongate kaolin minerals has been to use familiar geometric forms, such as tubes, scrolls, spikes, laths and flame-shape in artificial weathering. Should the envelope of filaments on the feldspar particles in preceding SEMs be called filaments, 'whiskers', or 'porcupine quill' fragments? Should the clusters of filaments 'growing' out of micro-fractures be called 'grass tufts', or 'wet grass'? From a small tuft of disperse needles, as in Figure 37, a larger group may become matted or clumped at the free ends to produce 'wet grass' cones, as in Figure 42 (3047, 3000 ×) and Figure 43 (3884, 3000 ×). Groups of multiple cones are developed in Figure 44 (3876, 1000 ×), or as a 'shredded wheat' vein-type filling, in Figure 45 (3882, 3000 ×).

Masses of parallel filaments are pseudomorphous after feldspar anhedrons or fragments, as in Figure 46 (3851, 1000 ×). Bending of filaments, as in a pack of fibers ('sedimentary nematoblastic' fabric), or bent-over grass, is seen in Figure 47 (3884, 2000 ×). Did these fibers have imogolite precursors?

### IDENTIFICATION OF THE ELONGATES

Direct identification by X-ray powder diffraction of the microscopic filamentous envelopes is not easy. Several small lumps of grains broken from the transition zone were lightly mulled with water in a mortar, to dislodge gently the 'whiskers' as clay fraction which was then separated by sedimentation, and the clay-size fraction was X-rayed, yielding traces Nos. 2, 3 and 4 in Figure 48. For comparison, trace No. 1 is of the book-containing saprolite (above the transition zone) at the Sparta quarry, and No. 5 is of mine-run, Spruce Pine, NC, 'primary kaolin' possessing spike and elongate morphology. Traces 2, 3 and 4 show a 7A, kaolin (?) reflection characteristically tailing off toward the higher *d*-spacings. The other reflections are higher order spacings of clay plus some from feldspar.

Such indirect identification (?) for the filaments as a kaolin mineral is not wholly convincing because it is possible that some kaolinic substrate may have been carried along with the 'whiskers'. More convincing, however, are several KEVEX-RAY analyses made by the Cities Service Laboratory through the courtesy of Dr. William Almon. In Figures 49, 50 and 51 (11979, 11980, 11981), the areas analyzed are outlined, except for 11980 in which the entire field was covered. The Al and Si peaks, and minor Fe are so marked; the Cr coating is marked 'X'. The molar ratio of Al to Si, almost directly represented by the peaks, is nearly 1:1, with Si in slight excess. Considering that kaolinization of feldspar includes the dissolution of silica, it is not anomalous that Si may slightly exceed Al in the precipitate. My interpretation, as was that of Dr. Almon, is that the elongate, tufted filamentous mineral is a 1:1 kaolin mineral, presumably endellite–halloysite. A stereo-pair from the Cities Service Laboratory depicts the 3-D geometry and further detail in the filaments (Figure 52, 20,000 ×).

A second set of samples, collected from the Sparta transition zone 8 months after the time of the first collection, were independently analyzed by a non-dispersive energy ORTEC unit at the Materials Research Laboratory, University of Missouri–Rolla, courtesy of Leonard Levenson and Harlan Rice. The same SEM mount that yielded Figures 43–47 inclusive was analyzed over a large field of elongates (Figure 84, 3000 ×), and on one fiber of it (Figure 85, 30,000 ×), for Al:Si ratio. Using energy counts in the range 491–776, the Al:Si ratios determined for Figures 84 and 85 were 0.79:1 and 0.78:1, respectively. These are in accord, within experimental error, with the KEVEX data.

For comparison, as a part of the same continuous instrumental run, the particular SEM mount that produced the 'known' (Figure 75) book-type, Cretaceous-age kaolinite from the Chambers Mine, yielded an Al:Si ratio 0.77:1. Similarly, the SEM mount from which Figure 2, Huber Mine clay, was micrographed, yielded an Al:Si ratio 0.88:1. Thus, in independent confirmation, the elongate mineral occurring in the transition zone is identified to be a member of the kaolin family as close to the 1:1 compositional type as is the unquestioned, book-type Georgia kaolinite.

As a relevant digression, ORTEC analyses that were made across the edges of kaolinite books, from Figures 75 and 2, rather than from the randomly oriented crystals in the general field, yielded Al:Si ratios of 0.97:1 and 1.07:1, respectively. These are slightly higher in Al than are the ratios from the whole field. My interpretation of this higher Al ratio is that the exposed edges of kaolinite crystals (broken edges of the books) presented relatively more Al atoms, located in the octahedra, to the impinging electron beam than did the basal cleavage surfaces which are characterized by sheets of silica tetrahedra. They come closer to the ideal 1:1 ratio than do jumbled kaolinite crystals.

The spike-like and tufted filaments of the Sparta transition zone may also be accompanied by shorter, stubbier elongate crystals, as in Figure 53 (3077, 3000 ×). It is intriguing to speculate whether there is a genetic and/or chronologic sequence between these two types. Do the filaments form first, and these recrystallize to the stubby elongates? Alternatively, does the stubby variety form first, as in Figure 53 (3077), with the matted substrate [Figure 39 (3916)], and do these enrich solutions from which the filaments crystallize within open space; or third, do the two morphologic types form under slightly different geochemical environments? I find no unequivocal evidence to resolve these alternatives, although from numerous observations I am inclined to favor the last one, slightly different geochemical environments.

### WEATHERING ON RECENTLY-EXPOSED SURFACE OF SPARTA GRANITE

Boulders and masses of Sparta granite stand out as exposed, resistant (to weathering) knobs in cleared fields and pastures above the fall line. The feldspar and quartz exposed on their surfaces are wetted during rain, and then dry out until the time of next dew or precipitation. The environment of weathering is therefore ephemeral, intermittent, and alternating with dehydration. Dried salts will be concentrated in the surface layer from completely evaporated solutions. The weathering environment is utterly unlike geochemical equilibrium between clay mineral and feldspar as during saprolitization. It more nearly resembles the conditions in the short-term artificial weathering experiment as conducted by Parham (1969).

A sample of such exposed granite was collected from a knob in a pasture near the exit from Interstate-20 of Georgia Highway 15 to Siloam and Sparta. SEMs of the altering feldspar surfaces are shown in Figures 54 and 55 (3888, 3889, 10,000 ×). A subdued surface coating, and nondescript morphology characterize these surfaces. They are similar in indistinctness to those I have observed in present-day weathering of rhyolite in Missouri, gneiss in Brazil, and aphanitic porphyry in Czechoslovakia. I believe a monotonous coating effect such as this characterizes weathering of feldspar exposed to the open atmosphere. The elongate forms in 3888 may be clay or they may be organic (algal remains?).

### BOOKS OF KAOLINITE AS PRODUCTS OF WEATHERING

Although elongates of kaolin apparently were formed in the transition zone at the Sparta quarry, the dominant volume of kaolin in the large deposit of massive saprolite occurs in books, as was shown in Figures 16 and 20 (3602, 3605). Is there a genetic and chronologic relationship between kaolin elongates as are present in the transition zone and the books in the saprolite? Do elongates form first, and then these recrystallize to books? If so, why have not the Spruce Pine elongates recrystallized to books?

Alternately to the genetic sequence of elongates to books, is the possibility that the environments producing each morphologic type were geochemically different. Do elongates from under one environment of weathering, e.g. intermittent leaching above the ground-water table, whereas books of kaolinite form under very long-duration, 'equilibrium' or steady-state, argillation as under conditions of a 'weathering crust' (the term much used in Europe?).

Apparently, the last episode of kaolinization from feldspar at the Sparta quarry, and at Spruce Pine, produced elongates, not books. I have micrographed the same morphology (elongates) also from granodiorite at the Yamaka open-pit in Japan (Part V of this series, in press). Nonetheless, books can and do apparently form *directly* from feldspar, as will be shown in several micrographs from a Missouri occurrence.

About 9 km south of the junction of MO Highway W with U.S. Highway 67, near Farmington, MO, the Pre-Cambrian Butler Hill granite is exposed in a road cut (Blaxland, 1974). Unconformably overlying it is the Cambrian La Motte arkose and sandstone. The granite is saprolitized for a meter, more or less, below the unconformity. Feldspar in this granite was clearly kaolinized directly to books, as is shown in Figures 56 and 57 (1440, 1441, slightly overlapping, both at 2000 ×).

Kaolinite flakes and sheaves 'grew', in random orientation, from their contact with feldspar which is slightly corrosion pitted. Farther inward toward the kaolin, books of kaolinite were well developed. One might first interpret, dubiously, from these views that the large books were later-stage growths from small, single flakes developed at the contact. That such a relationship is not mandatory is shown in Figures 58 and 59 (1433 at 1000 ×, 1431 at 3000 ×, of the same view), where a curving veriform shape, and flat books, were developed close to the contact, but where more random kaolinite is present inward toward the kaolinite. The next three SEMs (same locality) leave the impression that the first process in kaolinization was destructive dissolution (pore-producing) and decomposition of the feldspar, which was then followed (or carried on almost simultaneously) by constructive crystallization of the kaolinite replacing the feldspar [Figures 60, 61 and 62 (1463, 3000 ×, 1457, 1000 ×, 1461, 3000 ×)]. It should be noted that, in the Missouri examples, no unique crystallographic orientation of kaolinite crystals prevailed with respect to feldspar crystals. Crystals of kaolinite grew in random directions, which is interpreted that clay crystals grew from an intermediary solution phase, incongruent in composition with respect to the parent feldspar. Parham's (1969) studies support the interpretation of a solution intermediary. No evidence was observed of mineral reactions or phases at feldspar–kaolin contacts such as was described by Meunier and Velde (1976), where illite was formed. Possibly I did not observe in sufficiently fine detail to find them, or alternatively they may not have developed in this particular system or environment where kaolinite, not illite, was the clay product.

In the Missouri saprolite, the kaolin is present as books (kaolinite), and apparently originated as books; in the massive, thick saprolite at Sparta, the kaolin also occurs dominantly in books; but in the transition zone at Sparta the kaolin is dominantly as elongates. Why the differences? In an effort to explain the difference in geneses, let us ask what is the common denominator in origin of the two saprolites that contain the kaolinite books?

In the Missouri saprolite, it is almost certain that the kaolinite was formed under a very long time interval of kaolinization, presumably by action of either artesian water and/or below the ground-water table. Likewise, the thick saprolite containing books of kaolinite at Sparta was formed also under a geologically long regime of weathering, possibly during as long as half of the Mesozoic Era. A long interval of geologic stability during which weathering is a dominant process gives rise to a regolith defineable as a 'weathering crust'. As I visualize the geochemical environment prevailing under such geologic conditions, the interstitial solutions in the feldspar–clay system would become essentially chemically stable, and approach or come as closely as possible to equilibrium between kaolinite and decomposing feldspar. Presumably, the conditions of the weathering system (feldspar, kaolinite and liquid) could express for a long time the graphic stability diagrams mapped and calculated from chemical constants of the constituent oxides. During such a long time of essential equilibrium (uniform geochemistry), kaolin could form, also precipitate as crystals including thick books of large plates, and likewise redissolve, or recrystallize as intricate S-shaped, platy veriforms, and/or as a second ($n + 1$) generation of tiny euhedral kaolinite crystals plated on to older larger ones. Adequate time, under uniform, geochemical stability, would also permit large books of first-generation (neoformation) kaolinite to grow in place, as in the Missouri micrographs and the large books in Sparta (or other) saprolite of Cretaceous accumulations. It would permit secondary or diagenetic growth of large crystals, as in Figure 63 [(0187), 750 ×], or an example from an intermontane lake basin near Jacal in Mexico [Figure 64 (0389, 1000 ×)], reported by Keller and Hanson (1975).

However, after Sparta saprolite was exposed to surficial weathering processes, as above the ground-water table, ostensibly the kaolin in it underwent morphological change. In the mottled zone of the upper part of the saprolite, where surface oxidation and infiltration partly colored the kaolin, the white material (associated with the colored) has been transformed, as shown in Figures 65, 66 and 67 (3900, 3000 × ; 3904, 3000 × ; 3901, 2000 × ). In the first two micrographs, the kaolin plates are smaller, are separated from books, and are arranged typically in small packets or overlapping face-to-face orientation, something like overlapping shingles. They slightly suggest a resemblance to the texture of the Wrens fine-grained clay. The large, remaining book in Figure 67 (3901) appears to be etched, corroded, and lightly coated with clay substance (not fuzzy focussing). The red-colored clay is further modified by an iron oxide coating [Figure 68 (3907, 3000 × )]. Elsewhere in the mottled zone occurred tiny pockets of slate-gray, more compact, fine-grained (to unaided eye), apparently secondarily transported clay. This, in SEM also, is fine textured, even at 10,000 × [Figure 69 (3906)]. The grains are not as smoothly flat as is the white clay from the mottled zone. May they be analogous to, or a textural criterion of, secondarily reworked and transported large commercial deposits of Geogia kaolin?

Two conclusions are to be drawn from the examples of secondary weathering (mottling) of Sparta saprolite. Recent, surficial weathering destroys the original texture of typical saprolite; therefore, the environment of surface weathering is different from the weathering environment that produced white-kaolin saprolite. Second, the thick deposit of original saprolite must have been formed, not by Holocene surficial processes of weathering above the ground water table, but in a way, permissively at least, as within a weathering crust.

If the book-type kaolin deposits in large size signify a common denominator of a long-term, uniform, geochemical system essentially at equilibrium, what are the environmental conditions under which the elongates were formed in the transitional zone at the Sparta quarry? Two alternative interpretations may be offered. One hypothesis is that feldspar regularly or always weathers first to low-stability elongates, and these subsequently recrystallize to a more stable book-form of kaolinite. Although this may be a logical hypothesis, the lack of elongates in the Missouri examples casts strong doubt on the explanation—indeed it invalidates the 'always' part of the statement.

A second hypothesis is that elongates become the kaolin that weathering produces under conditions where (1) land stands high, as during the Holocene, (2) where movement of ground water is rapid, and (3) possibly where the chemical activity of the compound HOH is relatively higher, as in ground water which is renewed more often than under conditions of a 'weathering crust' formed on a denuded and low-lying terrain. Higher activity of HOH might produce endellite ($4H_2O$), the typically elongate kaolin, which is found in so many examples of high-land weathering and high-land hydrothermal alteration. As a statistical test of the validity of this hypothesis, it is supported by the 27 examples of halloysite in 'recent rock weathering' cited by Parham (1969, p. 15), and by SEMs shown or quoted in this paper. The latter include the filaments and elongates in the transition at Sparta, the spikes at the Spruce Pine mountain area, tubular elongates at Bauxite, AR, the laths in mountainous volcanic flows at Etzatlan, Mexico, and tubular endellite at Laguna Larga, Michoacan, Mexico (Keller *et al.*, 1971). These were indeed formed under present high-land conditions—not a weathering crust.

That environmental conditions, rather than specific, geologic rock formations were the control for argillation to elongates in the Georgia kaolin area is shown by similar alteration in rocks other than the Sparta granite. Incompletely weathered feldspar in saprolite forming from gneiss collected at an outcrop on GA Highway 15, about 25 km south of Athens, GA (guided by R. E. Carver) yields SEMs in Figures 70, 71 and 72 (3165, 1000 × ; 3588, 3000 × ; 3571, 5000 × ). Figures 70 and 71 are typical also of Sparta alteration. In Figure 72, the elongates interlace tiny rounded forms; speculatively are these spheres of halloysite as have been reported from altered pumice at the Yamata open-pit mine in Japan (micrograph in Part V, in press). At any rate, elongates occur widespread without apparent restriction to geographic locality or type of parent rock.

## TEXTURE OF KAOLINITE FROM ARKOSE

Arkose containing 20–30% of chalky feldspar has been kaolinized in the base of the Cambrian La Motte Sandstone at the outcrop where it unconformably overlies the MO granite previously shown to produce books of kaolinte. Because the arkose was collected across the unconformity only a few cm above the kaolinizing granite, the surrounding geochemical environment of kaolinization must have been the same for the two rocks. The books of kaolinite from the arkose are long and curving, in which the plates are loosely stacked or expanded [Figures 73 and 74 (1421, 1000 × ; 1422, 3000 × )], in comparison to the kaolinite books from the feldspar in the granite (Figures 56–62). The looseness of stacking is possible, and most probably reflects the abundance of free, open space in the pores of the sandstone. The poorly aligned margins of the plates leave ragged, somewhat saw-tooth faces along the longitudinal edges of the books. These books from the arkose are probably longer and more of them parallel to one another than in the typical book fabric of the Cretaceous kaolins. Whether one example, such as this, is sufficient to invalidate, or even weaken the hypothesis that Georgia kaolin originated from intermediary arkose is vulnerable to question by proponents of intermediary arkose.

## DURABILITY OF KAOLIN BOOKS

Books of kaolin, whether viewed under either light or electron microscopes, appear weak, delicate and fragile. Intuitively, it has been believed that the books would be shattered to essentially single plates, or delaminated (the term used in industry), during stream transport from a site of weathering to a place of deposition. This interpretation has been cited as an argument to be convincing that strong feldspar or other strong primary mineral was necessary to withstand the rigors of transportation from parent-rock source on the Appalachian Plateau to the site of kaolin deposit.

To test this concept, SEMs were taken of kaolin which had gone through the regular industrial process (courtesy of the Georgia Kaolin Co.). After mining, the clay was mechanically blunged with a deflocculant at the mine, the slurry was then pumped through a pipeline several miles to the treatment plant, passed through the size-classifier 'sand boxes', and the reject material allowed to settle out in sedimentation ponds. This processing constitutes rather drastic treatment which may, or may not, be equivalent to ordinary stream transport (without a deflocculant). At any rate, comparison SEMs indicate that books of kaolin are indeed more durable than intuition may lead one to believe. In Figures 75 and 76 (0135 at 3000 ×, 3382 at 3000 ×) are shown crude, mine-kaolin collected from outcrops at the Chambers and Hodges Mines, respectively, of the Georgia Kaolin Co. After blunging and pumping to the plant, clay was recovered as routine mixed-feed entering sand boxes, as shown in Figure 77 (3176 at 3000 ×). It has not been significantly disrupted. Two samples collected from the sedimentation pond show the range in texture of kaolin which went through this industrially simulated cycle of transport and deposition. A mixture of coarse and fine kaolin flakes is shown in Figure 78 (942 at 5000 ×) and a view down on cleavage faces and packets in Figure 79 (946 at 3000 ×).

These SEMs are convincing to me that books of kaolin can, and do, resist considerable disruption or delamination during rigorous transportation by water (including a deflocculant). Visual inspection of the clay slurry finds in it abundant, tiny, naturally packed, well-preserved aggregates or pellet-like particles of clay and clay–sand within which the clay morphology remains intact, despite the presence of a chemical dispersant. Presumably, in natural stream transportation, similar pelletal aggregation could protect books and vermiforms, thereby explaining how structures produced by weathering could be preserved in the transported and deposited sediment. This observation therefore lends support to Murray's (1976) interpretation of the origin of Georgia kaolin, i.e. pre-Cretaceous kaolinization followed by transportation and deposition of the already formed clay.

## FLINT KAOLIN

The term 'flint kaolin' was used by Smith (1929) to refer to certain 'rock hard' types of Georgia kaolin which broke with a conchoidal fracture, were commonly higher in silica content than the kaolinite formula, and contained sporadic small cavities containing silica gel and/or opaline silica. A separate report is planned for this atypical clay but, since it is in the Georgia kaolin district, several micrographs will be included in this paper to show some of its general textural features.

One type occurs in thin plates or scales which may be several micro-meters in diameter. The plates may lie flat, face-to-face, or may be bent and twisted much as occurs in some ball clays [Figures 80 and 81 (0140, 5000 × ; 0144, 5000 × )]. Whereas the more conventional Georgia kaolin is scantily fossiliferous, some parts of the flint kaolin contain abundant molds of sponge spicules [Figures 82 and 83 (0137, 500 × ; 0146, 10,000 × )]. Tiny bladed crystals coating the surfaces of the fossils were recognized by S. H. Patterson to be similar to low cristobalite-opal reported from Miocene siliceous shales (Murata and Larson, 1975).

## GEORGIA KAOLIN AS A NON-REFERENCE KAOLINITE MINERAL

Georgia kaolin, because of its vast reserves, high quality and value as an 'industrial or non-metallic mineral', and distinctive geologic and scientific characteristics, has commonly been regarded as a reliable source for specimens of the mineral kaolinite. Most of us accepted a lump of first-quality commercial Georgia kaolin as a dependable source of valid monomineralic kaolinite. Such an attitude or practice is now seen to be suspect. In several of the SEMs presented herein, at least two distinct kaolin minerals have been intimately mixed in samples so tiny as to serve for electron-micrographic mounts. These are not monomineralic even within the kaolin group, and many of them are known by commercial producers of kaolin to contain also smectite. Such multi-mineral mixtures can lead to scientific pitfalls if used as reference material for the single mineral kaolinite.

One example where different speciments of Georgia kaolin yielded a range of experimental values is that of free energies of formation for kaolinite, even when using a single method of measurement (Reesman, 1966; Reesman and Keller, 1968). Other examples include non-uniform dehydroxylation temperatures, infrared absorption, excitation by electron beam, and probably other properties.

While Georgia kaolin is an unsurpassed example of kaolin as a rock, where defined as, "an earthy rock characterized by a significant content of kaolin minerals" (tentative definition of kaolin by the International Committee of Correlation of Age and Genesis of Kaolin, Milos Kuzvart, Exec. Secretary, Prague, Czechoslovakia), an indiscriminate use of it as monomineralic kaolinite is unsound.

## ADDITIONAL UNSOLVED PROBLEMS OF GEORGIA KAOLIN

A quotation from Patterson and Buie (1974) listed a large number of questions on the origin of Georgia kaolin yet to be answered. The preceding SEMs reaffirm the presence of books (kaolinite), and stubs, filaments, spikes and fibers of elongates, presumably endellite–halloysite in close juxtaposition. What are the geochemical or mineralogical micro-environments within which each, or all, are crystallized? What are the geological mega-environments which include those micro-environments? Are there chronologic–genetic relationships between the several clay minerals? Have post-depositional, artesian-drainage conditions altered the original clay deposits? Probably the question longest unanswered is: how can low solubilities of kaolin reported by geochemical measurements permit recrystallization and/or deposition of kaolin indubitably observed in geological occurrences?

## CONCLUSIONS

Conclusions in a report of this type in which the evidence is largely photomicrographic can be stated only in context of that which the pictures show. Interpretations and inferences may also be usefully extrapolated provided they do not go too far from observation.

Georgia kaolin of Cretaceous age shows a relatively open, porous, permeable texture in which expanded books of kaolinite accompanied by many smaller crystals and packets of kaolinite crystals predominate; many of them are in random orientation.

Tertiary-type Georgia kaolin characteristically is relatively fine-grained and compact. The flakes are in face-to-face orientation in planar to bent and contorted arrangement.

Thick, white, kaolinitic saprolite, presumably formed during Mesozoic time, overlying the Sparta granite, Sparta, GA, is viewed as a prototype of source kaolin for deposits of Georgia kaolin. Book-type kaolinite is abundant, presumably predominant in this saprolite, but elongates are also significantly present.

A transition zone of partly argillized granite intervenes between fresh granite and saprolite at the Sparta quarry. Kaolin elongates predominate in the clay in this zone. They include the common stubby type, but those produced from earliest-stage weathering from feldspar feature filaments (imogolite-type?), fibers and tufts, and 'wet-grass' clumps, and packs ('nematoblastic') of fibers.

In buried, saprolitic granite occurring in Missouri, presumably formed analogously to that at Sparta, books of kaolinite occur directly in contact with feldspar from which they were derived. Elongates were not observed in intermediary position at the magnifications used. Random crystallographic orientation of kaolinite with respect to feldspar crystallography bespeaks a solution-phase intermediary between feldspar and kaolinite.

Kaolinite developed from feldspar in arkose derived from, and located immediately above its unconformity with, the Missouri granite shows long, loosely expanded and ragged-edge books. The morphology of these books is consistent with a luxury of open space available for expanded crystallization of kaolinite in the abundant, large pores in the arkose.

The formation of book-type kaolinite from weathered feldspar is interpreted as being a product influenced by environment of formation. This is visualized as having been of long duration, in relative stability geochemically (approaching or achieving equilibrium between feldspar, kaolinite, and associated solutions). It is interpreted as taking place presumably in low-lying terrain, and below the ground-water table where movement of ambient solutions was slow—an environment characterized as a 'weathering crust'. Diagenesis and recrystallization of kaolinite could and did take place in this environment. Possibly, previously formed endellite ('halloysite') would recrystallize to book-type kaolinite (greater stability) in this long-time environment.

The formation of elongates (halloysite morphology) is interpreted as occurring under a Holocene-type, 'high-land' environment of weathering, possibly above or within the fluctuations of ground-water table. Unequivocal evidence is lacking whether feldspar typically weathers to endellite, which then recrystallizes to kaolinite, or whether it always so weathers unless the geologic and geochemical environment is that of a 'weathering crust'. The Missouri examples of both granite and arkose preclude interpretation that feldspar and granite *always* weather directly to elongates.

Holocene surface weathering of Sparta saprolite disarranges its previously long-established original texture. Such kaolin where secondarily transported by descending water into open spaces is fine-grained, and tends to pack in face-to-face orientation. Possibly this effect may be correlated with fine-grained Tertiary-age Georgia kaolin.

Books of Georgia kaolin may be transported during artificial aqueous suspension within protective tiny pellets of clay which offer strong resistance to shattering or delamination of leaves in the books. Possibly a similar mechanism could protect them during natural transport and sedimentary deposition.

A single, tiny, micrographic-size specimen of 'Georgia kaolin' may easily contain at least three clay minerals, book-kaolinite, elongate 'halloysite' (whatever that means), and smectite. Therefore, 'Georgia kaolin', as a group, must be considered as a rock, not as a single mineral nor as a dependable reference for monomineralic kaolinite.

Much remains to be learned about the geochemical microenvironments and geological mega-environments which determine specifically which of the several kaolin minerals will be formed or deposited.

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