

1984 GEORGE W. BRINDLEY LECTURE

At its annual meeting in Buffalo, New York, in October 1983, the Council of The Clay Minerals Society voted to initiate a series of annual lectures in honor of G. W. Brindley, past president and distinguished member of the Society and internationally respected clay scientist. The first George W. Brindley Lecture was presented at the 21st annual meeting of the Society in Baton Rouge, Louisiana, on October 1, 1984, by Walter D. Keller, emeritus professor from the University of Missouri, Columbia, Missouri. A condensed version of Professor Keller's remarks follows.—Editor.

THE NASCENCE OF CLAY MINERALS

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INTRODUCTION

It is a high honor to be invited to give this first Brindley Memorial Lecture. I view it as taking the first step on a ladder, to be followed by succeeding talks that climb higher to the pinnacle that George Brindley erected for us in clay mineralogy. If George were with us, he would be sitting on the front row, as usual, keeping the speakers and audience "honest" in our deliberations. In turn, I would be privileged to ask him personally to enlighten us with his valued opinion on the many questions I will be asking in this talk.

THE PRIMARY QUESTION

How did the first clay mineral to form on Earth "know" or "learn" how to form (by diachronic creation, of course, according to P. H. Gosse quoted in Gould (1984)? The crystallization of clay minerals represents within a framework of fundamental materials a vastly higher stage in organization than was present in the chaotic state of matter at the time of the "Big Bang," or even later in a liquid Earth and/or a primitive basaltic crust. In hierarchical order the most fundamental entities in Nature, applicable to clay mineralogy, may be listed (Keller, 1962) as follows:

- (1) Energy, the Master of Materials and Change;
- (2) Materials, the Slaves of Energy, and
- (3) Information, the Director of Change taking place.

By a deceptively simple answer, the formation of a "first" clay mineral may be thermodynamically described as the production of a well-organized, lowest(?)

energy and low-entropy, relatively stable product located within the environment of the primitive earth. This statement in turn, prompts a new question, "what is a stable product," which is answered, "stability denotes resistance to change within its environment."

But stability, as also resistance to change, may be only a relative term. If allowed enough geologic time, what at first sight appears to be non-changing in the field or laboratory may actually be only slowly changing, i.e., a slow rate of kinetic change. For example, is kaolinite, although persistent for millions of years, actually metastable with respect to dickite, as Lippmann (1981, 1982) has queried? How much does one agent in the environment have to change, or how much do multiple agents working as a team within an environment have to change, in order to actuate the conversion of clay minerals?

Moreover, what constitutes the environment in which clay minerals are stable, or in which they undergo change? Basically, an environment may be defined as a summation of the physical and chemical energies (the Masters) and Materials within the system under consideration. A stable clay mineral, or a clay mineral that appears to be stable, therefore represents the response of its constituent chemical elements to the environmental energies impressed upon it. If, or as, the energies (environment) change, then the clay mineral(s) change accordingly.

The first clay mineral to form on Earth presumably received a definitive thermodynamic message (Information) that directed Materials in the environment to crystallize in a profoundly elegant manner to a phyl-

losilicate by action of the Energies (Environment) that were operative. The result was a 1:1 or 2:1 layer mineral or, as will be seen, possibly a less well-organized precursor of them, such as allophane. External energies drafted the Message that was sent, and clay minerals responded to the messages of these energies by continuing to replicate (Weiss, 1981; Cairns-Smith, 1982) until external energy and materials abated.

Replication also characterizes Life. Indeed, the process of Life has been likened (as was discussed at the Buffalo meeting of The Clay Minerals Society in 1983) to the process of crystallization of clay minerals, in that living cells replicate in response to Energy. A crucial difference between the replication of clay crystals and the life process, however, is that living cells absorb and convert external energy, e.g., solar or other energy, into an internal energy which drives transpiration and the replication processes with a decrease in entropy (or with "negative" entropy, Schrodinger, 1944) in the system over the time interval that the cells are "living." "Living" may be described as experiences and processes of converting certain energies and of selectively directing ambient and available energies toward achieving desired responses from materials and energies. The Message (Information) directing the living process is a function of the internal DNA-RNA component, a distinguishing constituent of life that is lacking in clay minerals and their geneses. Moreover, Information during Life directs not only "go" (grow) but sets a condition to "no go" (stop), e.g., for cells to stop replicating, as in our fingers and teeth, when they have grown to the scheduled number and functional size. Clay minerals, on the other hand, presumably continue to replicate in increasing number, although constrained in size of crystals, as long as nutrient ions are externally available in adequate concentration. The environment, i.e., energy in the environment, apparently dictates the size to which phyllosilicate crystals grow—recall that muscovite in a pegmatite-forming environment grows to large plates of centimeter-size "isinglass," whereas illite, even where well ordered, grows in its environment to micrometer-size crystals during which the number of them increases.

MODERN FIELD OCCURRENCE SIMULATING PRIMITIVE CLAY GENESIS

To obtain information and learn about earth materials and features one may consult the documented scientific literature for background, but for the Truth one goes to the field (Nature) to observe the formation of clay. To discover how clay might have formed on land on the primitive crust of the earth, we may appropriately go to an occurrence of lavas newly erupted from the mantle (devoid of clay-mineral ancestry), as was observed on the field trip of the 1982 Clay Minerals Society Meeting in Hawaii. Alternatively, to search for the first clay mineral formed in a marine environment on earth we might have gone to a black smoker, as off the Hawaiian coast, or elsewhere (Kurnusov *et al.*, 1982). In the soil (land surface) that was weathered *in situ* from the basalt at Stop 2 of the 1982 Hawaii field trip, allophane in which a mesh of imogolite is embedded was observed (Figure 1; mineral identification from Chan, 1972).

This transmission electron micrograph in Figure 1, and the following scanning electron micrographs, are presented for the purpose of geographically illustrating the clay-mineral morphologies produced by various, presumably representative, genetic environments of clay minerals. The micrographs were taken of clean, freshly fractured, unprocessed surfaces (except for a thin gold coating to carry away excess charge from the electron beam) that show the natural morphologies of the clay crystals and cleavages. Original magnifications of the micrographs, before reduction during publication ranged, for example, from 90,000 \times (Figure 1), through 40,000 \times (Figure 3), to 1000 \times (Figure 10). Comparative sizes of the clay crystals may be determined, however, from the scale bars on the micrographs.

Is not the present-day occurrence of the soil over the basalt in Hawaii the best available modern example illustrating the environment and the "Information" or "Message" that may have directed the process by which the first clay mineral was formed on earth? The intergrowth of imogolite and allophane, as in Figure 1, raises other questions, however. Did these two minerals form

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Figure 1. Transmission electron micrograph of soil from Hilo, Hawaii. A mesh of imogolite occurs within a clot of allophane.

Figure 2. Scanning electron micrograph of polygonal tubes of halloysite, from Gardner Ridge, Indiana.

Figure 3. Scanning electron micrograph of circular tubes of halloysite; note one telescoped within the other at the center of the figure; from Spruce Pine, North Carolina.

Figure 4. Scanning electron micrograph of filamentous halloysite. Some filaments consist of multiple strands that are longitudinally joined; others may be hollow; from Piedade, Brazil, courtesy of George Clemency.

Figure 5. Scanning electron micrograph of spherical halloysite, from the Yamaka mine, Nagoya, Japan. (Reproduced from Keller, 1977b.)

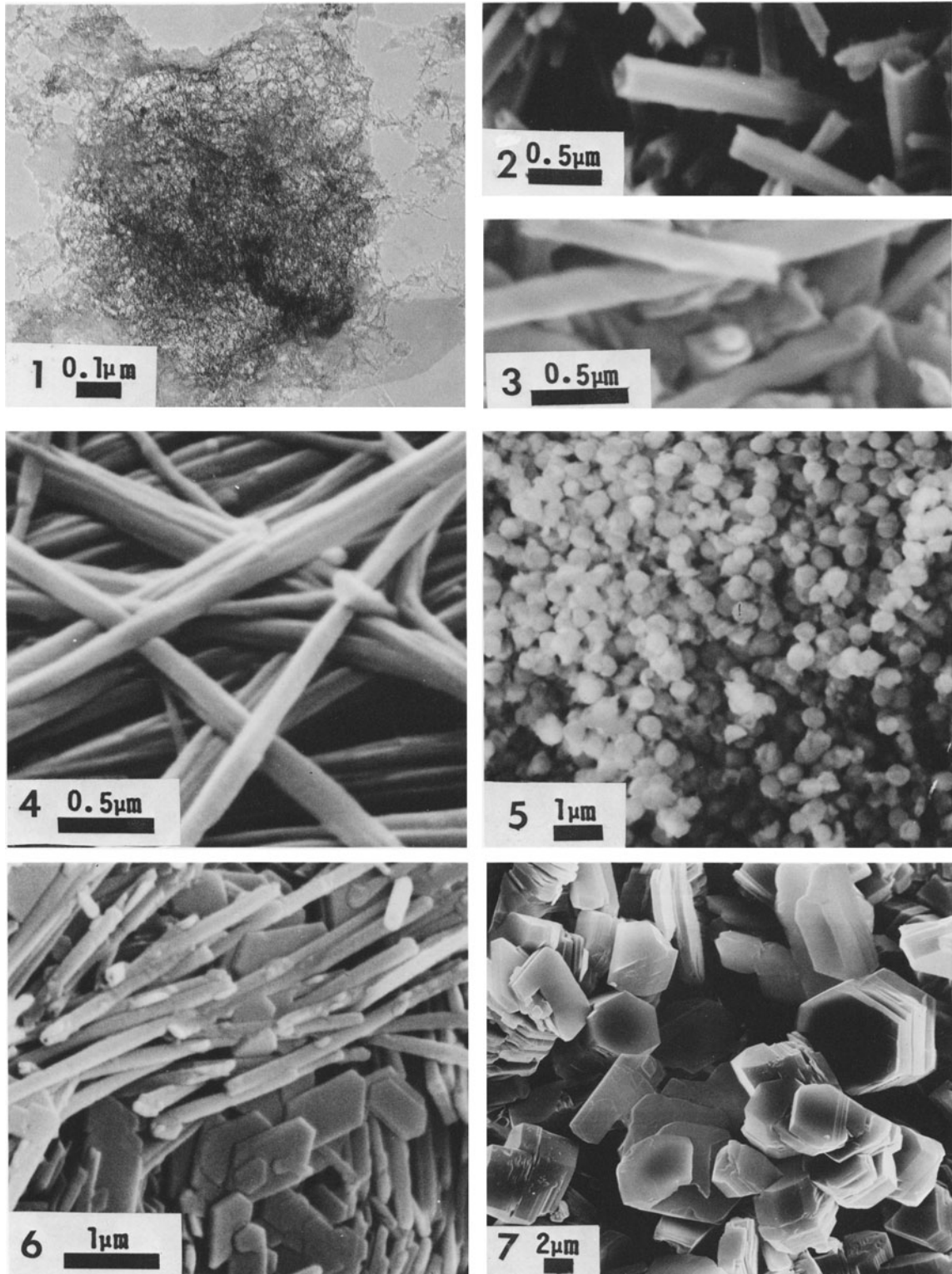


Figure 6. Scanning electron micrograph of elongates and plates of kaolin, from near Kauling Hill, China. (Reproduced from Keller *et al.*, 1980.)

Figure 7. Scanning electron micrograph of euhedral kaolinite crystals, from a geode in the Warsaw shale near Keokuk, Iowa. (Reproduced from Keller, 1981.)

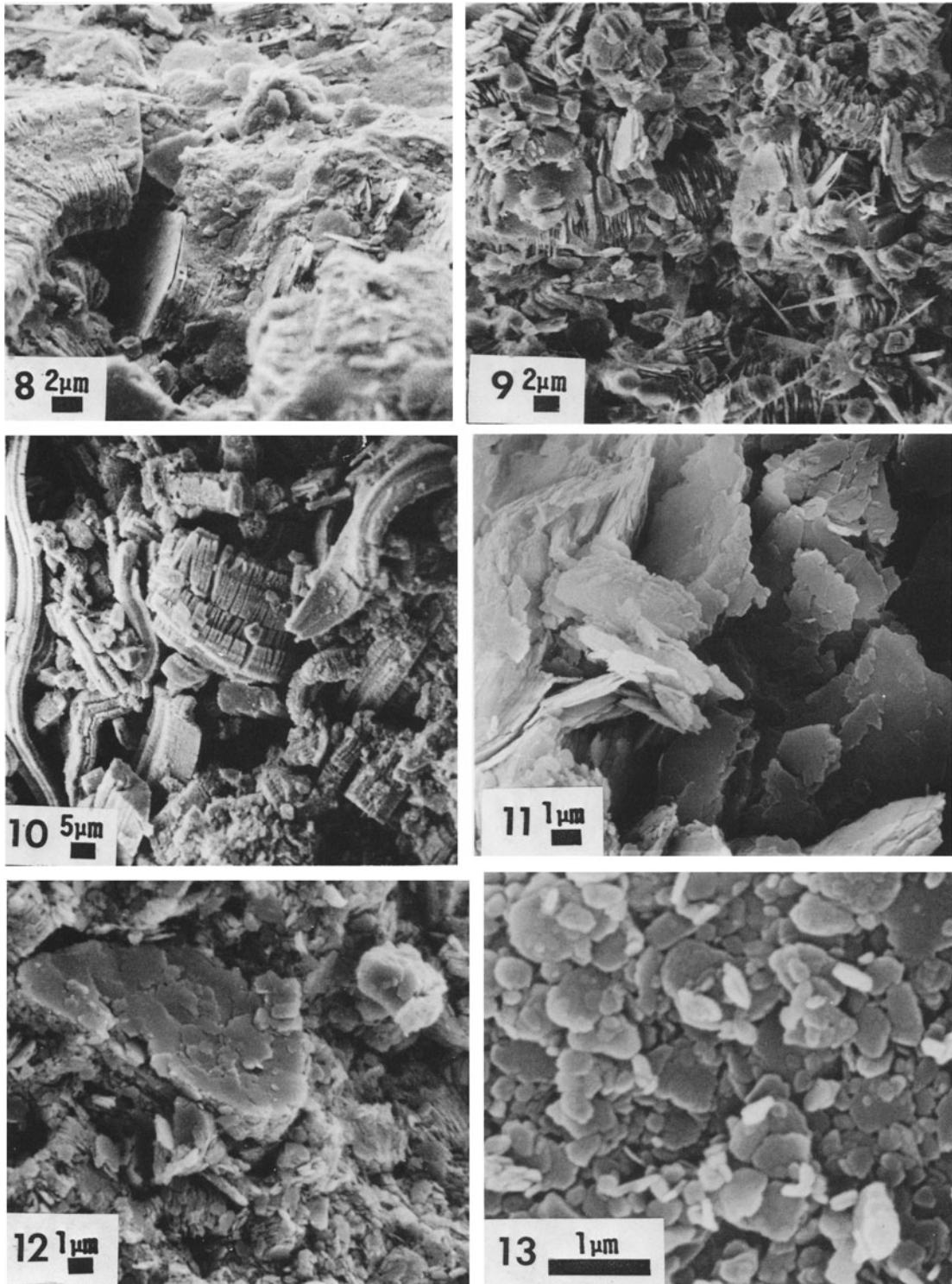


Figure 8. Scanning electron micrograph of kaolinite weathered from feldspar in granite, from near Blaxland, Missouri. (Reproduced from Keller, 1977a.)

Figure 9. Scanning electron micrograph of kaolinite weathered from feldspar in the Cambrian La Motte arkosic sandstone, from about 1 m above the location of the specimen in Figure 8. (Reproduced from Keller, 1977a.)

simultaneously as two separate, direct products of the alteration of basalt, or did the allophane form first, and then by further crystal ordering develop some imogolite? If imogolite was thus formed from allophane, is this an example of clay mineral evolution? Asked in a more general and widely applicable sense, have, or do, clay minerals indeed evolve? To this query, Eswaran (1972) wrote, "Little or no evidence has been observed to support the frequently reported sequence of alteration: allophane to imogolite, to halloysite." An alternative possibility, appearing to me to be more probable, is that environments which contain clay minerals evolve, and then the clay minerals change in accord with the evolution of environments.

Eswaran perceptively included halloysite in the allophane-kaolinite series. Multiple types of morphology, however, may form in halloysite, *per se*, including such variations as polygonal tubular elongates, circular tubes, filamentous elongates, and spheres, as are shown in Figures 2–5. It is intriguing to inquire as to what were the dissimilarities in the thermodynamic Messages that instructed the formation of each specifically different morphology in these halloysites. de Souza Santos *et al.* (1966) tentatively related curvature of crystal plates to the degree of disorder in the kaolin minerals, but direct or close correlation of curvature in crystal plates with the additional different morphologic shapes, such as the spheres that have been observed since the time of that early report, is now not so convincing. Even more conjectural are the thermodynamic messages that instructed disparate, elongate halloysite, in which crystal ordering is poor, and platy kaolinite, in which ordering is good, to develop in essential contact with each other, as is shown in the weathered materials of a pegmatite from near Kauling Hill, China (Figure 6, Keller *et al.*, 1980).

These preliminary observations suggest that three factors in clay-mineral formation are genetically related: (1) normal or typical external morphology of the clay minerals, (2) their internal crystal ordering, and (3) the physical-chemical components of the environment in which the clay mineral crystallized. Further micrographs are shown here of clay minerals from diverse origins, *i.e.*, beginning with visible external morphologies, after which attempts will be made to infer the nature of the other agents that were active in the

genetic systems of the clays. Because convincingly sound interpretations that might elucidate many of those other factors are still lacking, however, such inferences will have to be left with questions which, although unanswered, are hopefully properly directed to eventually find the Truth.

ILLUSTRATED ENVIRONMENTS OF CLAY MINERAL GENESIS

1:1 clay minerals

Euhedral hexagons of kaolinite that is so well crystallized as to generate all of the X-ray reflections reported for kaolinite occurs in vugs in limestone and in geodes in shale, both of Mississippian age, in the Keokuk, Iowa, region (Figure 7). If the allophane-imogolite pair in Figure 1 represents a primitive stage in the genesis of clay minerals, does it not follow that these platy crystals of kaolinite represent an apparently most advanced or sophisticated degree of crystallization of kaolinite—or alternatively of the environment resulting in a sophisticated genesis?

The origin of this kaolinite has been interpreted as direct crystallization from solution (Keller, 1978), but, recognizing the very low aqueous solubility of kaolinite, would the crystallization of significantly large quantities of kaolinite, as observed, have necessarily been further implemented by especially effective diffusion processes or by enhanced solubility of Al compounds through complexing with organic compounds (Huang and Keller, 1972), or will the slow process of crystallization suffice if continued over very long geologic time?

Other kaolinite growing in contrastingly tight stacks has been observed to have formed from feldspar in confined space within compact, low-porosity Precambrian granite (Figure 8, Keller, 1977a). In a superjacent, open-space porous arkose derived from the same granite, the kaolinite stacks are looser and more open-textured (Figure 9) as they also are in an unconsolidated, open-space, lacustrine deposit of arkosic sand (Figure 10, Keller and Hanson, 1975). Weathering of non-feldspathic, mica-phyllite parent rock yields kaolinite growing with angular, jagged crystal edges (Figure 11, Keller *et al.*, 1981). Does mica when it is the parent mineral direct the genetic pattern toward this type of morphology in daughter kaolinite?

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Figure 10. Scanning electron micrograph of kaolinite stacks weathered from feldspar in an unconsolidated lacustrine sand, from near Villa Victoria, Michoacan, Mexico. (Reproduced from Keller, 1977a.)

Figure 11. Scanning electron micrograph of kaolinite weathered from a non-feldspathic, mica phyllite, from the Znojmo region, Moravia. (Reproduced from Keller *et al.*, 1981.)

Figure 12. Scanning electron micrograph of Cretaceous kaolinite, from the J. M. Huber mine, Huber, Georgia.

Figure 13. Scanning electron micrograph of Tertiary kaolinite, from the J. M. Huber mine, Wrens, Georgia.

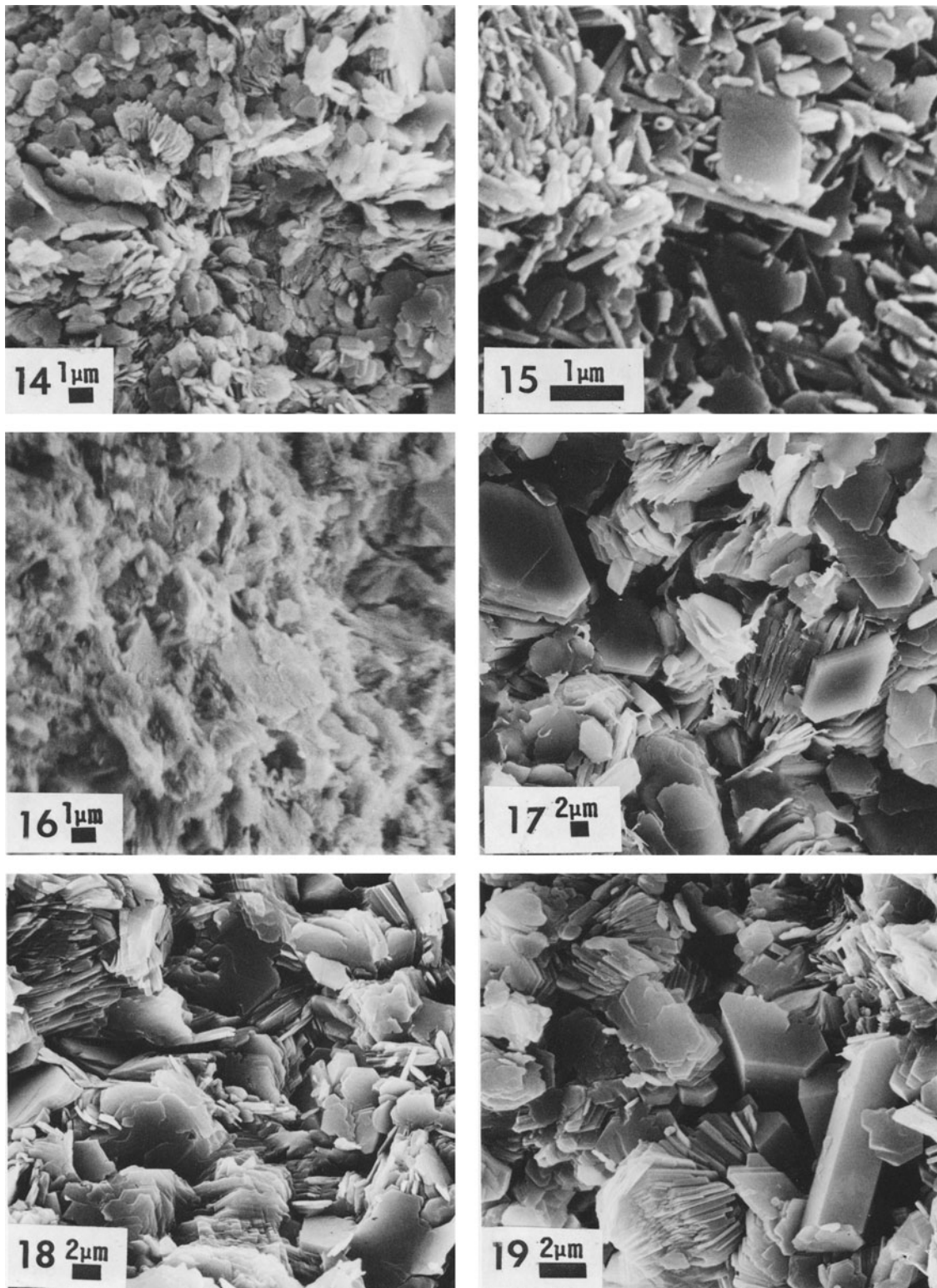


Figure 14. Scanning electron micrograph of kaolinite, Blackwell mine, Cornwall district, United Kingdom.

Figure 15. Scanning electron micrograph of hydrothermal kaolin altered from volcanic rock, Zaragosa mine, San Luis Potosi, Mexico.

The presence of both large and small stacks of kaolinite flakes in the huge deposits of "soft" Cretaceous kaolin in Georgia might suggest a duality in environment of origin by (1) weathering of feldspar in granite in an environment near the earth's surface where some of the feldspar was relatively unconfined (i.e., abundant available space above it), and (2) from other feldspar which was weathered below in more confined space (Figure 12) as in the Missouri granite. Alternatively, and equally likely, large crystals and stacks of kaolinite also probably grow diagenetically from smaller kaolinite flakes. The "hard" Georgia kaolin in the Wrens area exhibits a different platy morphology (Figure 13). Although these outstandingly large and important deposits have been studied over a long period of time, the message(s) directing their processes of origin have also long been interpreted controversially, e.g., (1) as sedimentary deposition of detrital kaolin plus some later diagenesis, the preferred interpretation, as (2) the *in situ* alteration of an arkose, or (3) as *in situ* alteration of volcanic ash.

Likewise, the origin of the long-worked, large deposits of Cornwall kaolin in Great Britain (Figure 14) continues to be debated. Are those deposits solely magmatic in origin, or were they formed by an early magmatic episode followed by a period of alteration by resurgent meteoric water circulated by thermal energy from radioactivity in the same granite as perceptively envisioned by Bristow (Bristow, 1977; Durrance *et al.*, 1982)? Thus, even for the largest deposits of kaolin, the last word on origin has not been unquestionably documented.

Kaolin in deposits in Mexico, in occurrences where the geologic evidence unequivocally indicates a hydrothermal origin, may be composed of both platy and elongate crystals if derived from volcanic-type parent rock, or platy if the parent rock was hornblende chlorite schist which presumably had a sedimentary precursor (Figures 15 and 16, respectively, Keller and Hanson, 1969). At one locality in the state of Nayarit in Mexico, all three platy kaolin minerals, nacrite, dickite, and kaolinite, occur in a single hydrothermal deposit (Figures 17–19, Hanson *et al.*, 1981). It is baffling to attempt to infer the thermodynamic Message(s) that led to the genesis of these three different minerals in a single deposit—did the diverse products result because of different trace-element compositions, did they form in a sequence resulting from a parallel series of different

time-temperatures (although dickite and nacrite are intergrown), or did they form because of other environmental differences not yet recognized?

Kaolinite that is pseudomorph after smectite (Figure 20), occurring in Oregon, resulted from continued intense weathering of smectite, which was the first weathered product from volcanic ash country rock (Keller, 1976b). Likewise in Australia, kaolin in commercial-size deposits may exhibit both typical kaolin and smectite morphologies, supporting other geologic evidence that the parent rock was volcanic ash.

The origin of kaolinite in flint clay and in some ball clay has been interpreted to have been by dialysis of colloidal clay mud during sedimentation (Keller, 1976a, 1981). In Missouri flint clay, crystals of kaolinite, usually well ordered in crystallinity, are tightly packed in interlocking, randomly oriented stacks that indent each other with mutual boundaries somewhat analogous in texture to that of a monomineralic igneous rock (Figure 21). An interpretation from the texture, accordingly, is that kaolinite crystallized, or recrystallized, from clay mud at low temperature to a flint-clay rock, analogous to feldspar in syenite from a hot magma (Keller, 1981). By diagenetic changes within a paludal environment, smectite underclay was altered through an illite transition to kaolinite flint clay in Illinois (Hughes and White, 1969; Keller, 1982). Ball clay typically exhibits a "swirl" texture in platy crystals suggestive of movement during soft-rock deformation while undergoing consolidation within a paludal depositional setting (Figure 22).

2:1 layer clay minerals

Where primary silicates are hydrolyzed in an environment in which a high activity of H^+ has resulted in the removal of alkali and alkaline-earth metals and their replacement by H^+ , 1:1 layer clay minerals generally form. In contrast, if the activities of the metal ions remain relatively high, 2:1 layer clay minerals tend to form. Such an environment typically represents low-intensity leaching, as in either semiarid weathering or, alternatively, in a water-logged environment where the metal ions remain at high activity in solution but are not removed. Smectite morphology is illustrated by a sample of Na-montmorillonite from Wyoming (Figure 23) which shows the curling "corn flakes or maple- and oak-leaf" texture characteristic of this phase.

An elongate 2:1 clay mineral, palygorskite, illustrat-

Figure 16. Scanning electron micrograph of hydrothermal kaolin altered from hornblende-chlorite schist, San Pedro mine, Guanajuato, Mexico.

Figure 17. Scanning electron micrograph of nacrite, Chon mine, Nayarit, Mexico. (Reproduced from Hanson *et al.*, 1981.)

Figure 18. Scanning electron micrograph of dickite, Chon mine, Nayarit, Mexico. (Reproduced from Hanson *et al.*, 1981.)

Figure 19. Scanning electron micrograph of kaolinite, Chon mine, Nayarit, Mexico. (Reproduced from Hanson *et al.*, 1981.)

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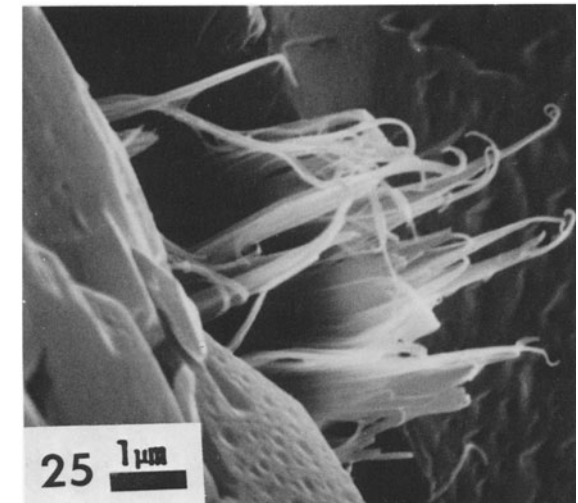
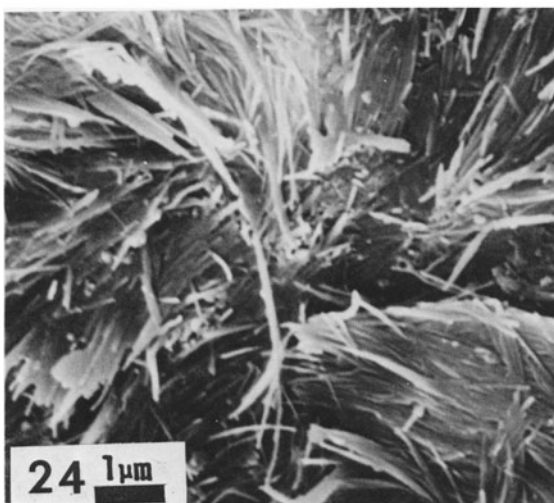
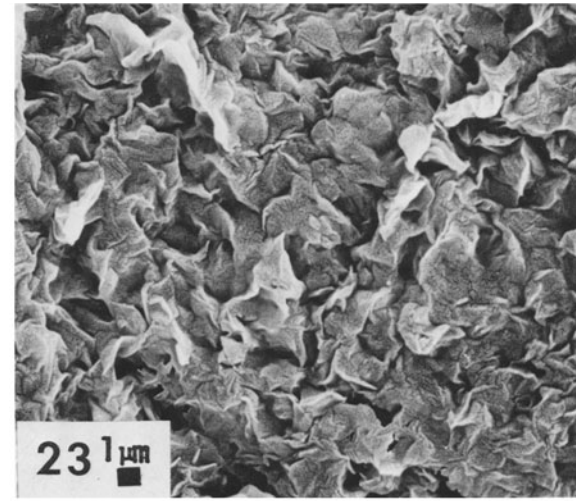
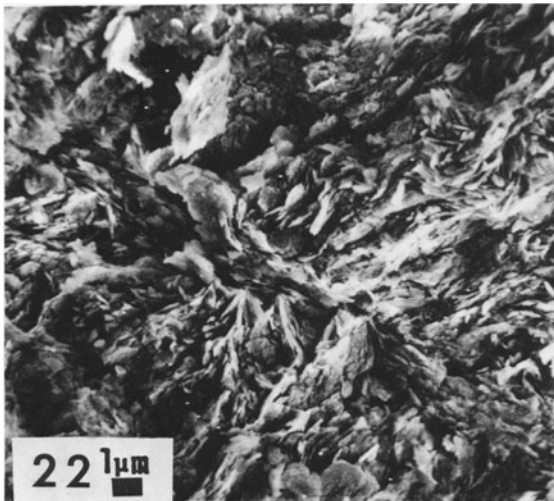
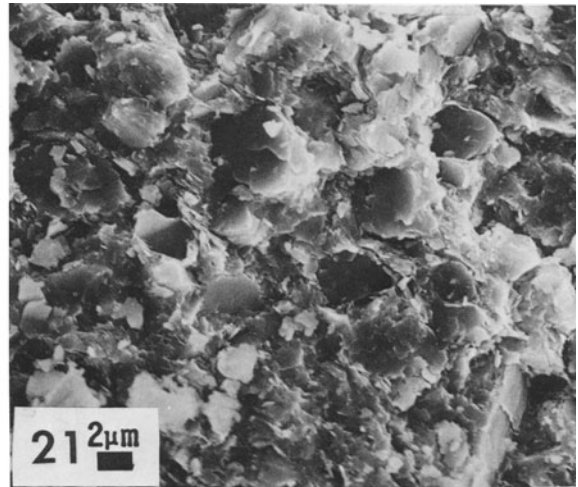
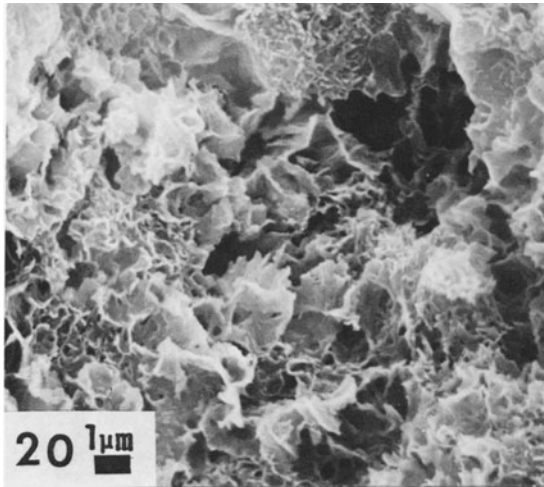


Figure 20. Scanning electron micrograph of kaolinite pseudomorphic after smectite, from near Sublimity, Oregon. (Reproduced from Keller, 1976b.)

Figure 21. Scanning electron micrograph of flint clay, Maher mine, Whitesides, Missouri. (Reproduced from Keller, 1981.)

Figure 22. Scanning electron micrograph of ball clay, from near Mayfield, Kentucky. (Reproduced from Keller, 1976a.)

ed by attapulgite in Figure 24, may be morphologically related to platy smectite as halloysite is related to kaolinite, except in possibly reverse morphologic and genetic sequence. In contrast to elongate halloysite that appears to precede platy kaolinite, palygorskite was reported to form by solid state transformation from preexisting platy montmorillonite, as well as by direct precipitation from solution (Weaver and Beck, 1977, p. 193).

Genetic processes by which illite is crystallized include authigenesis, wherein illite "ribbons" grow in pores in sandstone (Figure 25) and by apparent coalescence of ribbons to platy crystals in shale (Figure 26). Geologically vast quantities of illite have formed in environments in which smectite was converted to illite, as during the deep burial of a shale (Nadeau and Reynolds, 1981). The progress of that conversion can be traced by sequential morphological changes observable in scanning electron micrographs of the shale. Interestingly, a morphologically and mineralogically similar sequence also occurs in hydrothermal alteration products of volcanic rock in Japan (Inoue and Utada, 1983). Two pairs of examples of mixed morphologies, appearing between end-member morphologies of smectite and illite, show 35% non-expandable layers in the Mancos bentonite and 40% non-expandable layers in the Japanese locality (Figures 27 and 28) and contrastingly 70% non-expandable layers in both lithologic series (Figures 29 and 30). A sample containing 88% non-expandable layers, from the Japanese material is shown in Figure 31. The "corn flakes" texture in the high-smectite clay (Figures 27 and 28) gives way to flatter plates with pointed, curled edges typical of illite (Figures 29–31). Crystal morphology in illite/smectite mixed-layer minerals thus correlates with mineral composition, degree of ordering in the illite, and elevated temperature and chemically active K and Al ions in the genetic environment, rather than with the mode of origin, i.e., whether deep burial of shale or hydrothermal alteration. Preliminary observations of illitic shale collected from localities in the Ouachita Mountains known from independent evidence to have been heated to significantly elevated temperatures also show enhanced crystallinity of the illite.

Pyrophyllite, represented by the well-ordered, triclinic variety (crystallography by George Brindley, personal communication) from South Africa (the "African Wonderstone"), is shown in the SEM in Figure 32. Representative morphology of pyrophyllite is clearly

different from those of other 2:1 substituted-type clay minerals.

A question complementary to, "how did the first clay mineral know how to form," is, "where can clay minerals be unequivocally demonstrated as forming at the present time?" In other words, just because a kaolin deposit rests on granite, for example, does not necessarily mean that kaolinization is now going on there. For example, although kaolinite and saprolite gradationally overlie the Sparta, Georgia, granite, thereby showing the kaolinization took place at least in the past, scanning electron micrographs of the bare surfaces of dull-luster feldspar crystals in boulders of that granite now exposed at the earth surface do not show the morphology of kaolinite as is observed in the saprolite. To produce characteristic stack morphology of kaolinite in a weathering environment, burial of the feldspar may be necessary, and/or a diffusion mechanism of alteration may have to be operative.

In my studies, active clay mineral formation today has been documented ("proved") by me at only three localities where the (1) clay mineral, (2) its parent rock, (3) and the ambient groundwater solutions containing dissolved alumina and silica that are chemically compatible with argillation have been related and demonstrated. These environments include the hot spring alteration at Ojo Caliente, Michoacan, Mexico (Keller *et al.*, 1971) and the weathering profiles at Stanford, Kentucky, and on Gardner Ridge, Indiana (Keller *et al.*, 1966). Undoubtedly at innumerable other localities clay mineral genesis is unquestionably going on, but to prove that the process of argillation is operating, and to identify the processes by which the clay is forming, chemical analyses of the aqueous solutions from the argillizing systems are also needed.

FURTHER INVESTIGATIONS ON ENVIRONMENTS OF CLAY-MINERAL GENESIS

The many unanswered questions that have been either openly asked, or implied, in the this overview of clay-mineral geneses suggest that much more remains to be learned in detail about the ways that clay minerals actually originate than is now known. Two apparent avenues of investigation lead to the understanding of clay-mineral genesis, namely, (1) taking the idealistic and more simplistic thermodynamic short cut, and (2) by integrating compatibly the complexity of "hands-on" observations and interpretations of de-

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Figure 23. Scanning electron micrograph of Na-montmorillonite (Wyoming bentonite), Clay Spur, Wyoming.

Figure 24. Scanning electron micrograph of palygorskite (attapulgite), from near Attapulgus, Georgia.

Figure 25. Scanning electron micrograph of ribbon crystals of illite from a pore in the La Motte sandstone, southeast Missouri, courtesy of David Houseknecht.

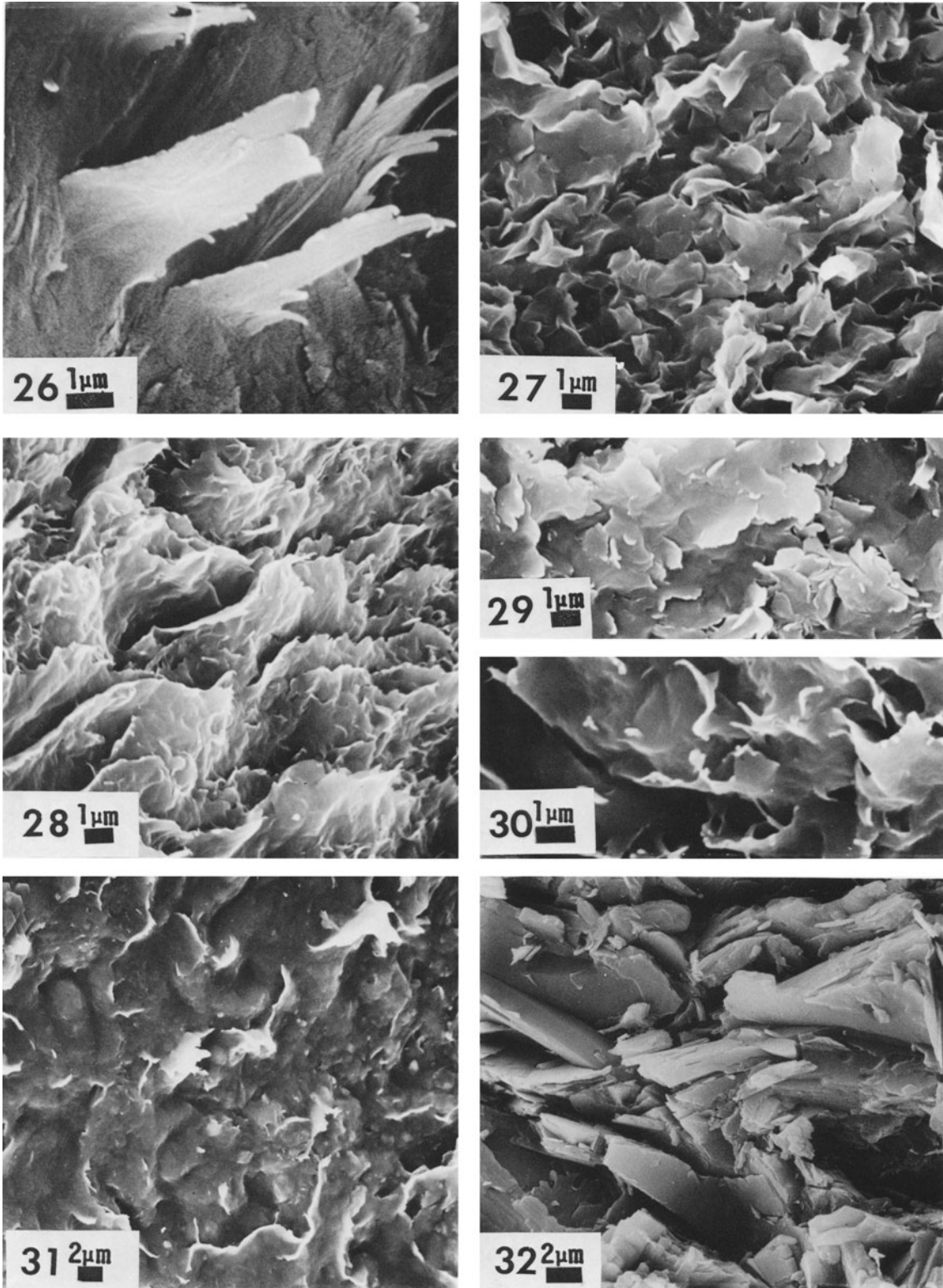


Figure 26. Scanning electron micrograph of illite, Imt-1, Silver Hill, Montana, Source Clays Repository, The Clay Minerals Society.

Figure 27. Scanning electron micrograph of bentonite, Mancos Shale, I/S conversion series, 35% illite.

tailed examinations made on the actual outcrops and occurrences in the field with the analytical data from the laboratory. The shape, form, size, and gross mineral compositions of clay deposits as they occur in the field are preliminary, but necessary fundamental observations. Keeness of observation is imperative because "direct observation is the first step in research" (Ross and Shannon, 1926), and more waggishly stated, "did you see what you looked at"? Beginning with megascopic observation, micro-examination must follow by using light microscopy, scanning and transmission electron microscopies, X-ray and neutron diffraction, infrared and Raman spectroscopy, isotope ratios, chemical analyses, calculations of bond energies, and other techniques not yet discovered, so that basic elements of observation can be increasingly resolved in order to see more of "what is looked at." Likewise, laboratory syntheses of clay minerals made under known and controllable conditions of materials and energies will help to bridge the gaps between models derived from thermodynamic calculations and observed occurrences in the field.

Rational interpretation of genesis that is consistent with all field and laboratory data and observations is the next conceptual step ("do you understand all that you know") to elucidate how clay minerals truly form. It would appear that investigation of clay-mineral genesis is currently at the stage where basic searching questions more likely can be asked, rather than giving final "correct" answers in the spirit that, "science progresses toward Truth by the process of reducing error."

State-of-the-art attitudes in thinking and learning about clay minerals also continue to undergo periodic evolution as episodically as environments change in clay-mineral genesis. Four decades ago, a clay mineralogist was respectably professional if he or she could look at a trace of a differential thermal analysis or an X-ray powder diffractogram and call the fine-grained specimen a kaolin, montmorillonite, or illite mineral. "Chlorite(?),—never(!)—chlorite is a metamorphic mineral, not a clay mineral," said one professor of high-temperature petrography along about that time. Also, mixed-layer clay minerals were then only one stage above the category of rubbish minerals. Now, a sharp-shooting clay mineralogist is expected to locate quantitatively the clay as a mixed-layer mineral within the

space of a three-phase diagram in which end-members of clay mineral families are located at the corners.

We find humility to be equally in vogue with confidence in knowledge in clay mineralogy—an attitude that prevails now also in the study of plate tectonics, origin of mineral deposits, paleo-life extinctions, sedimentology, and the origin of the earth. If this summary is handed out by teachers to classes in order to challenge students with fertile and imaginative minds, these remarks obviously "will not fill a vessel," but they may "light a flame" in those students so that they will discover the principles by which the genetic environment of a clay mineral is expressed by its crystallinity and morphology.

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Figure 28. Scanning electron micrograph of hydrothermally altered volcanic rock, I/S, 40% illite, Shinzan, Japan, area.

Figure 29. Scanning electron micrograph of bentonite, Mancos Shale, I/S conversion series, 70% illite.

Figure 30. Scanning electron micrograph of hydrothermally altered volcanic rock, I/S, 70% illite, Shinzan, Japan, area.

Figure 31. Scanning electron micrograph of hydrothermally altered volcanic rock, I/S, 88% illite, Shinzan, Japan, area.

Figure 32. Scanning electron micrograph of triclinic pyrophyllite, South African "Wonderstone." Sample, courtesy of George W. Brindley.

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