BASELINE STUDIES OF THE CLAY MINERALS SOCIETY SOURCE CLAYS: GEOLOGICAL ORIGIN

WILLIAM F. MOLL, JR.

7222 Braemar Circle, Crystal Lake, Illinois 60014-6604, USA

INTRODUCTION

History

In any clay deposit, the nature of the mineral assemblage and the composition of individual clay minerals can change radically in a few cm. Consequently, any given locality can contain many subtly different types of clay minerals. Results from different laboratories on ostensibly the same clay material may not always be comparable because the samples may indeed not contain an assembly of identical clay minerals. Such confusion slows the understanding of this important group of minerals. Several attempts were made to provide investigators with reasonably constant clay materials, the first being that of the American Petroleum Institute Project 49 (Kerr, 1949). The Clay Minerals Society Source Clays project proposed to provide investigators with gently homogenized clay materials, carefully collected and processed under the supervision of clay specialists. The collection would include metric ton amounts to ensure a long-lasting collection. The program began in 1972, with the introduction of the materials described in this paper. Later the program expanded to include the Special Clays. These samples are materials not amenable to homogenization, or they are available in very small amounts.

Moll (1979) provided a full description and diagrams of geological occurrences and origins of the clay deposits. He also included details of collection and site maps. This paper updates the original work extensively by incorporating information obtained over the past two decades.

Processing

The Baroid pilot plant in Houston, Texas processed most of the original samples. This processing was minimal, with drying on steam-fired tray driers at ≤100°C. Quartering techniques ensured an even feed into the pilot plant Raymond roller mill used for pulverization. Storage of the pulverized material was in large polyethylene bags in paperboard drums. The Southern Clay Products plant in Gonzales, Texas, processed the Texas white montmorillonite, using a rotary dryer and Raymond roller mill. Exhausted supplies of samples KGa-1 and SWy-1 required replacement. Because the Baroid pilot plant had closed, the A.P. Green Refractories laboratory in Mexico, Missouri, processed these samples.

Drying was in blower-equipped ovens at ≤100°C. Pulverization was in a hammer mill.

KGA-1: KAOLINITE, GEORGIA
KGA-1B: KAOLINITE, GEORGIA
KGA-2: KAOLINITE, GEORGIA

Introduction

Kaolin deposits of unusual purity occur along the contact between the Coastal Plain and Piedmont of the United States in Georgia and South Carolina. Kaolinite minerals typically comprise 50 to 90 wt.% of commercial-grade deposits. The deposits are of two basic types, the 'soft' and the 'hard'. Deposits east of Macon and west of Sandersville are most commonly the soft type. Deposits in east Georgia and South Carolina are of the hard type. Kaolin from Georgia finds extensive use in paper coating, paints, catalysts and other applications.

The soft kaolins (represented by KGa-1 and KGa-1b) associated with Coastal Plain sediments of Cretaceous age, with a few of Eocene age, are often slightly tan or pink and exhibit a characteristic conchoidal fracture. The deposits have few sedimentary features and virtually no fossils, probably because of extensive recrystallization. Iron-rich oxides, principally goethite and hematite, Ti-rich minerals and organic matter cause discolorations. Titanium-rich minerals occur at 1–2 wt.%, and organic matter at 0.1–0.04 wt.%. Kaolinite crystals are in large, euhedral, interlocking plates and vermiform crystals. The crystals have a low Fe content, 0.10–0.45 wt.% Fe_2O_3, and are principally of the low-defect type. Of the particles, 65 wt.% are >2 μm, a critical parameter in industrial applications.

The hard kaolins (represented by KGa-2), associated with Eocene age strata, are often slightly gray, and exhibit a rough, 'hacky' fracture. Iron-rich oxides, principally goethite and hematite, Ti minerals and organic matter cause discoloration. Titanium-rich minerals amount to 1–3 wt.%, and organic matter to 0.06–0.08 wt.%. The kaolinite crystals occur in a face-to-face arrangement. They have more defects than the soft kaolins. The crystals have a greater Fe content, typically 0.70–1.00 wt.%. 80 wt.% of the particles are <2 μm in size.

Geological framework

The complex stratigraphy of the kaolin is controversial. Dombrowski (1993) summarized the various theories and provided an excellent historical bibliography, as did Pickering and Murray (1994). Elzea Kegel *et al.* (2000) outlined the current theories in detail, and Hurst and Pickering (1997) presented a theory that is substantially different from the others. In addition to explaining the origins of the soft and hard kaolins, all theories must determine the relative importance of sedimentation and post-depositional alteration in producing the commercial kaolins.

The sedimentary rocks of the Coastal Plain lap upon the crystalline rocks of the Piedmont to the north in a line that strikes northwest across Georgia. The Coastal Plain has seen several profound marine transgressions since the beginning of the Cretaceous. The sedimentary sequence on the crystalline rocks begins with the sandy Pio Nono Formation of late Cretaceous age. Above the Pio Nono lies the Oconee group of latest Cretaceous through early mid Eocene age, consisting of sands with interbedded kaolin lenses. Separating the Oconee group from the overlying late Eocene Jackson or Barnwell group is another profound unconformity. The Barnwell group consists of the Clinchfield Sand Formation and the Twiggs Clay Formation. The Twiggs Clay contains abundant smectite and can effectively seal formations below it from substantial groundwater movement.

All of the commercial kaolin deposits are in the Oconee group. The Buffalo Creek Formation of latest Cretaceous age forms the bottom section, and contains the principal soft kaolin deposits. Separating the Buffalo Creek Formation from the overlying Huber Formation is a profound unconformity. The basal unit of the Huber Formation is the late Paleocene Marion Member, which contains no commercial kaolin. A subtle unconformity separates the Marion Member from the overlying early mid Eocene Jeffersonville Member. The Jefferson Member contains the principal hard kaolin deposits. The Buffalo Creek Formation has fluvial and deltaic characteristics whereas the Huber Formation has marginal marine characteristics. Deposition of both the Buffalo Creek and the Jefferson occurred during highstands of the sea. Highstands allow significant deposition of sediments, whereas transgressions and regressions do not.

The theory currently accepted by most workers follows. Intense weathering, including activity of aerobic bacteria, of the crystalline rocks produced a thick saprolite of impure kaolinite and illite. Muddy rivers brought this material to the Coastal Plain, as they do currently, to form deposits in lagoons and ponds in a deltaic environment. Abundant organic remains ensured a reducing environment, leading to development of pyrite and anaerobic bacterial action. During re-

gressions of the sea, intense weathering and soils-formation cycles commenced, leading to recrystallization of the kaolinite. In the marsh-like environment, burrowing invertebrates ingested the sediment to transform it further. Lateritic leaching led to the destruction of feldspars, removal of alkalies and alkaline earths, and transformation of mica to kaolinite. Other later transgressions deposited the Clinchfield sands and the thick Twiggs smectite. The Twiggs smectite sealed the underlying sediments from groundwater circulation. Later erosion removed the Twiggs clay from some localities, reinstituting groundwater circulation and oxidative conditions. Alteration of muscovite produced vermiform kaolinite crystals and oxidation of pyrite led to hematite and goethite. The Cretaceous as well as some Eocene sediments experienced the most intense alteration and recrystallization. Such intense alteration of the Oconee sediments is not ubiquitous. Of all the kaolin occurrences encountered in exploration in Georgia, only ~1% is of commercial quality.

Collection

The sample containing low-defect kaolinite, KGa-1b, is from the Buffalo China Mine, Yates property block D, operated at the time by ECC International 1 (Pruett and Webb, 1993). The mine is in the Buffalo Creek Formation. The sampling location was in the Tabernacle 7.5′ quadrangle, at latitude 32°57′12″N and longitude 82°59′37″W just south of Georgia Highway 24, ~19 km west of Sandersville and ~3 km southwest of the collection site of KGa-1. The sample was from the 69 m elevation, 1–2 m below the top of an 11 m thick kaolin strata of the Buffalo Creek Formation. The overburden at this locality consists of 18 m of cross-bedded kaolinitic sandstone of the Huber Formation and ~7 m of reddish-brown sandstone of the Barnwell Group. R.J. Pruett and H.L. Webb supervised collection on 22 January 1993 from kaolin ore freshly exposed during active mining. ECC International kindly donated the sample.

PFL-1: PALYGORSKITE, FLORIDA

The Meigs-Attapulgus-Quincy Fullers Earth district, in extreme southern Georgia and northern Florida, contains unusually large deposits of clay minerals, including palygorskite of short particle length, sepiolite and smectite. In places these clays are intermingled with diatomite. Local and commercial terminology prefers the term 'attapulgite' for palygorskite, in part to differentiate it from long-length forms. The district has two sections. A southern section centered around Liberty, Gadsden, and Leon Counties in Florida and Decatur County in Georgia, and a northern section centered around Thomas, Grady, and Colquitt Counties in Florida.

The sedimentary history of the district is complex (Patterson, 1974; Patterson and Buie, 1974). More re-

cent developments include that by Huddlestun (1988) who made an important revision to the stratigraphic terminology, and a detailed study by Merkl (1989).

Geological occurrence

The most significant tectonic feature in the district is a graben that developed in the Triassic. The graben, striking northeast across what is now the panhandle of Florida and south Georgia, connected the Gulf of Mexico with the Atlantic Ocean. The graben separated the crystalline rocks of the Piedmont from the carbonate Florida platform. Sediments began to fill the graben in the Jurassic, and had completely filled it by the early Cretaceous. Reactivation in the Paleocene created the Gulf Trough. This strait reconnected the Apalachicola Embayment of the Gulf of Mexico with the Southeast Georgia Embayment of the Atlantic Ocean. Strong currents through the Gulf Trough reduced substantial sediment accumulation, but siliclastic sediments derived from the highlands of the Piedmont began to fill the Gulf Trough in the Eocene. By the early Miocene, the sediments blocked permanent circulation through the Gulf Trough and separated it from the Apalachicola Embayment. Eustatic sea-level rises may have reconnected it periodically but temporarily throughout the lower Miocene, and eventually the Gulf Trough ceased to exist. Huddlestun (1988) considered the Apalachicola Embayment-Gulf Trough as a unit.

The most significant sedimentary section relating to Fullers Earth is the Hawthorne of mid-lower Miocene to mid-middle Miocene age. In Florida the Hawthorne is considered a formation, and in Georgia it is considered a group. The Hawthorne measures ≥ 30 m thick in the Fullers Earth district and lies apparently conformably atop the Tampa limestone. The Miccosukee Formation of upper Pliocene age overlies the Hawthorne unconformably. The Hawthorne consists of fine-to-medium grained quartz sand, silt, calcareous sand and dolomite beds, some phosphate material, opal and clay. The more southerly Fullers Earth deposits occur in the Dogtown Clay Member of the Torreya Formation of the Hawthorne group. The more northerly Fullers Earth deposits are in the slightly younger Meigs Member of the Coosawhatchie Formation of the Hawthorne group.

The Dogtown Clay Member consists mainly of palygorskite interbedded with dolomite. Smectite can also occur associated with the dolomite. Accessory minerals include quartz sand, opal-A, calcareous sand, dolomite, mica, pyrite, K-rich feldspar, phosphates and fossiliferous limestone. At many places, a parting of dolomite and dolomitic clay separates the bed into upper and lower parts. An alteration zone with an irregular border is visible, with the upper zone slightly more tan and the bottom slightly more blue. Above and below the clay are sands. The Sample PF1-1 is from the Dogtown Clay Member.

The Meigs Clay Member consists of palygorskite and smectite in approximately equal amounts. Quartz sand, sometimes occurring as distinct partings, is present. Diatoms are locally abundant. Other minerals include sepiolite, phosphate and mica. Opal-CT, perhaps derived from the diatoms, occurs throughout. Shrinkage cracks, filled with clay, are common. The upper tan alteration zone can reach near the bottom of the bed in places. A pebble zone of rounded clay pebbles, often containing significant amounts of sepiolite, occurs midway in the clay bed.

Origin

Sufficient sediment filling the Gulf Trough not only prevented continuous circulation but also set the stage for formation of the clays. The sediment blockage created a southern and a northern section. The southern section, adjacent to the Apalachicola Embayment, had circulation with the Gulf of Mexico, and this section has more marine-like characteristics. The northern section, partially open to the Atlantic Ocean and diatom flora, experienced more freshwater inflow, and this section has fewer marine characteristics.

The sediments, derived from the crystalline rocks, were probably rich in smectite and perhaps kaolinite. Deposition in ponds and lagoons in the saline environment resulted in transformation of these clays to palygorskite, following the model of Millot (1970). The southern section, with greater Mg content, developed abundant Mg-rich palygorskite, whereas the northern section developed palygorskite with lower Mg content. Weathering after deposition has altered some palygorskite to smectite and kaolinite. In the Meigs Clay Member particularly, smectite typically accounts for half of the clay.

SAz-1: MONTMORILLONITE, ARIZONA (CHETO)

Deposits of Ca-bentonite occur in the non-marine Bidahochi Formation of Pliocene age in northeastern Arizona. Upon acid treatment, this bentonite exhibits unusually good bleaching and catalytic properties. It also serves as an effective desiccant. Production began in the Chambers district, northwest of Sanders, in 1924, and having moved to the Cheto district southeast of Sanders, reached a maximum in the 1950s. It continues on a reduced scale today.

Geological occurrence

The Biadhochi Formation possesses a complex depositional history. The portion containing the bleaching clays, on the southwest flank of the Defiance Plateau, lies unconformably upon Triassic beds, principally Chinle, and upon the Permian DeChelly Formations. The lower member is largely of mudstones and argillaceous and fine-grained sandstone with some ash beds. The medial member, existing only outside

the area of interest, consists of lava flows and detritus. The upper member, comprising 60% of the formation, is largely poorly-cemented medium to fine-grained, argillaceous sandstone. At the top, the member coarsens to contain lenses of conglomerate, gravel and coarse sandstone. Beds of calcareous sandstone at the top can form resistant ledges. The bentonite beds occur at the bottom of the upper member.

Kiersch and Keller (1955) suggested the following sequence of events. At the close of lower Bidahochi time, streams cut into the landscape, creating numerous channels and ponds. Then, perhaps contemporaneously with the medial Bidahochi volcanism to the west, a vitric ash fall of quartz-latitic composition blanketed the area, clogging streams and choking ponds. A period of erosion followed, stripping the ash from the landscape, except in the channels and depressions. Some of the ash was redeposited at this time. Deposition, probably subaerially, of the upper Bidahochi followed. In post-Pliocene times, the area saw further erosion. Some stream channels cut entirely through the bentonite beds. Eyde and Eyde (1987) confirmed this scenario.

Origin

Kiersh and Keller (1955) suggested that conversion of the vitric tuff to smectite occurred before deposition of the upper member of the Bidahochi. This transformation proceeded mainly through gain of H_2O and Mg, and loss of silica and the alkalies. They suggested that the Mg originated either from the stream and lake waters or from surrounding rocks.

Sloane and Guilbert (1967), in an electron-optical study of the Cheto bentonite, found that argillizaiton developed spontaneously and pervasively throughout the vitric shards. The shards differed in susceptibility to alteration, and produced a range of conversion. Orientation of the smectite crystallites is a reflection of the textures of the original glass. Relic structures are present in even the completely altered material.

SHCA-1: HECTORITE, CALIFORNIA

The type locality of the extremely white, Li-bearing trioctahedral smectite, hectorite, lies in a complex igneous terrain in southeastern California. Its white color and its unusual ability to form strong gels in water at low concentrations of clay are useful in paints and cosmetics. Hectorite is also an excellent clarifier of beverages.

Geological occurrence

Hectorite is associated with volcanic rocks in the Mohave Desert near Hector, California. The Red Mountain andesite series of lower Pliocene age underlies the region. Tuff and agglomerates of angular lava fragments embedded in tuff are interbedded in the lava flows. Over the Red Mountain series lies a bed of andesitic gravels of alluvial fan origin that interfinger with Pliocene and lower Pleistocene lake sediments. Overlying these gravels is a series of brown lacustrine mudstones. Covering these deposits over much of the area is an olivine-basalt flow of Pleistocene or Recent age from nearby Mt. Pisgah and more recent alluvial fans and eolian sands. The actual structure and mineral associations of the hectorite deposit and its genesis, remain controversial.

Foshag and Woodford (1936) suggested that the deposit is associated with a small anticline. In their interpretation, the mine face shows a series of interbedded sands and clays dipping away from the anticline. Whereas the upper part of the series is probably eolian, the lower part is tuffaceous, and a lower bed is a brown, altered dacitic tuff. The tuff contains chalcedony and calcite concretions. The hectorite is a secondary mineral developed at the surface and in cracks in the tuff.

Kerr (1949) concurred that the deposit is associated with an anticline. Bentonite layers alternate with layers of less altered ash, silty clay and limestone. Tight folding at some locations has intensely sheared the hectorite and made the thin layer into a thicker bed which is commercially exploitable.

Ames *et al.* (1958) provided a much different and more complex picture. Instead of an anticline, they proposed a northwest-trending travertine ridge. This ridge is associated with faulting in the Barstow-Bristol trough. Lapping onto the travertine ridge are progressively zeolitic ash, hectorite, brown mud, zeolitic ash and brown mud. Unconformably overlying this series are gravels and the olivine-basalt flow. The travertine, although containing pyroclastic material, contains no dolomite. Hectorite can be interbedded with the travertine. The hectorite bed contains nodules of chalcedony and calcite. The brown mud contains hectorite at its base and grades into analcime tuff.

Origin

Foshag and Woodford (1936) concluded that the hectorite resulted from alteration of dacitic volcanic ash. They proposed no mechanism, but Ross and Hendricks (1945) thought highly Mg-rich solutions were necessary to generate the hectorite. Kerr believed that the hectorite formed from either alteration of volcanic ash or a lava flow. The abundant calcite was derived by recrystallization from the overlying limestome.

Ames *et al.* (1958) postulated a more elaborate origin. They proposed an ancient lake laying across a fault from which hot springs flowed periodically. The hot springs built the travertine ridge. Ash clouds of dacitic composition occasionally blanketed the area. When the springs were inoperative, the ash altered to analcime. If, however, the springs flowed during the ash fall, the ash altered to hectorite. The necessary Li and F were derived from the spring water. Because the

travertine contains no Mg, this element came from the lake water.

W.E. Sweet (pers. comm., 1977), the mine engineer at the time, proposed a variation of the Ames concept. Vitric ash, perhaps from the Fort Cady Mountains, fell into a partially restricted and protected environment of a linear, shallow lake. The deposition of the tuff was contemporaneous with extensive hot-spring activity that provided hot, Li-rich solutions. Crystallization of hectorite apparently occurred only near the on-shore zone. Off shore, in the lake, a brown mud containing a non-hectorite smectite formed. The high B content of the hectorite indicates deep-seated leaching of colemanite from the older, buried evaporite series by the ascending hydrothermal solutions. A basalt flow of recent origin almost completely covers the hectorite deposit.

STx-1: MONTMORILLONITE, TEXAS

The Jackson group of east central Texas contains a rare occurrence of extremely white bentonite. In Gonzales County, the bentonite occurs in commercially mineable amounts. The bentonite finds use in the ceramics industry as a binder owing to its white-firing nature. Through processing, it becomes a very white gellant for aqueous systems, and its oil bleaching and catalytic properties have enjoyed considerable use.

Geological occurrence

A broad band of sedimentary rocks, containing much detrital volcanic material, roughly parallels the Texas Gulf coast ~130 km inland. This sequence was produced by explosive volcanism in Texas during mid-Tertiary time. The abundant bentonitic materials occur in eastern Gonzales County, 100 km east of San Antonio. Here an extremely white Ca-bentonite (Chen, 1968) occurs in the Manning Formation of the upper Eocene Jackson group. Lithological and stratigraphic nomenclature varies among the investigators (Eargle, 1959) with that of Chen (1968) used here.

The bentonite, comprising sample STx-1, occurs at the base of the Manning Formation and rests on a gray friable sandstone that is either the lowest Manning or the uppermost Wellborn. The bed is ~2 m thick and does not appear to be homogeneous. The bed contains several sections characterized by differences in fractures and partings. A brown Fe-rich oxide coats these partings. At the top, the bentonite has numerous Fe-stained fractures. Directly above the clay bed lies a cross-bedded sandstone containing pebbles of white bentonite. Above the sandstone lies ~0.5 m of soil at the surface.

Origin

The general consensus is that this white bentonite resulted from alteration of volcanic ash of rhyolitic composition. The transformation mechanism, however,

is controversial. The source of Mg, which is present in greater amounts in the bentonite than in locally-occurring unaltered ash, remains problematic. Chen (1968) believed that very fine ash fell into restricted coastal bodies of water such as lagoons or abandoned delta distributaries. He believed that sea water in these bodies donated the necessary Mg. E.C. Jonas (pers. comm. 1975) argued, however, that conversion did not take place until after the ash beds were no longer directly in contact with the marine environment. He noted, from aerial photographs, that the ash beds tend to be altered where faults intersect them. He suggested that subterranean brines ascended along fault planes and into the ash. The rich quantities of alkaline earths in the brines would aid in the alteration. After alteration the bentonites were subjected to some erosion as indicated by bentonite pebbles in the overlying sandstone.

SWy-1: MONTMORILLONITE, WYOMING
SWy-2: MONTMORILLONITE, WYOMING

The term 'Wyoming bentonite' includes clay materials from Wyoming, Montana and South Dakota, and consists largely of Na-rich smectite. Typically, this smectite is montmorillonite and possesses mainly Na exchange cations, a high cation exchange capacity, and thin and flexible crystallites. These characteristics produce a rapid dispersion in water, high aqueous viscosities, and exceptional film-forming abilities. Because of these properties, Wyoming bentonite is used in many industrial applications and commonly used for clay mineral investigations, although it represents only a minor fraction of the world's bentonite reserves.

'Wyoming bentonite' does not imply a single occurrence, and involves a number of geological units. In fact, Knechtel and Patterson (1962) listed nine separate bentonite beds. The characteristics of the bentonite in some of the units are significantly different from those described above. Further, commercial processors often blend material from various units to achieve certain desirable commercial properties. Thus, the unwary investigator may detect heterogeneities which may be entirely artificial. The samples SWy-1 and SWy-2 have the properties usually associated with the term, 'Wyoming bentonite'. They are from single sites in the Newcastle Formation.

Geological occurrence

All commercial bentonites occur in rocks of the Cretaceous system, composed of shales, marls and argillaceous sandstones ≤1300 m thick. All authors agree that the Wyoming bentonites resulted from volcanic ash falling into the sea, or in the possible exception of the Newcastle Formation, a lake. The source of the ash lay to the west. By considering the grain-size distributions of beds in central Wyoming together with the aerodynamics of volcanic explosion

clouds, Slaughter and Earley (1965) mapped the lobes of ash deposited by the clouds and further concluded that the volcanism probably occurred in association with emplacement of the Idaho batholith.

The Newcastle Formation varies over short distances both in thickness and lithological character. Although it is 18 m thick in some areas, it generally thins to the east. The formation consists generally of sandstone, with occasional cross-bedding and interbedded siltstone, sandy shale, carbonaceous shale, bentonite and impure lignite. Terrestrial plant fragments and worm burrows occur. All investigators believe these characteristics indicate a near-shore environment. The volcanic ash fell near the beach and into lagoons. Concentration in lagoons and pene-contemporaneous erosion produced the highly variable thickness of the bentonite. Elzea and Murray (1994) stated that the Newcastle Formation may well be a fresh-water rather than a marine deposit.

Perhaps the most studied Wyoming benonite is from the Clay Spur bed. This material exhibits the best rheological properties. Nevertheless, the Newcastle bentonite has important applications. The organic derivatives show exceptionally good rheological properties in non-aqueous systems.

Origin

The bentonite resulted from a latitic or rhyolitic volcanic ash that fell into the Mowry sea, or possibly in the case of the Newcastle Formation, onto fresh-water lakes, near the shore. Glass shards indicate the volcanic origin, and sedimentary features in the Newcastle Formation denote the depositional environment. Alteration from ash to bentonite probably occurred immediately after deposition. Any proposed mechanism of alteration must explain loss of silica, retention of Mg and the abundance of Na ions. Slaughter and Earley (1965) concluded that the marine environment could account for the Na exchange cation, rather than the higher charge Ca or Mg, which normally supplant Na. They proposed that Na-rich solutions must have passed through the deposit after alteration.

Elzea and Murray (1990) described the characteristics of the depositional environment and their effect on the unusual characteristics of the bentonite mentioned above. The Mowry sea, a western interior seaway, extended from the north. The sea was deeper and more saline to the southeast. Elzea and Murray (1990) noted that varying characteristics result from differences in composition of the ash, depositional environment and weathering reactions, among others. Elzea and Murray (1990) also described a frequent characteristic: the blue, green and yellow colorations. Unweathered bentonite is blue. Upon weathering, it changes from blue through green to yellow. The color change apparently arises from oxidation of octahedrally coordinated Fe in the smectite. Weathering occurs upon exposure of the bentonite to near-surface conditions. During the working life of a bentonite mine, weathering of the bentonite and the concomitant color change often occurs.

Collection

The Wyoming bentonite sample SWy-2 is from a locality, specified by I. E. Odom, adjoining that of SWy-1. Collection was in June 1993 from a stockpile of very recently mined clay. The American Colloid Company kindly donated the sample.

SYN-1: SYNTHETIC MICA-MONTMORILLONITE (BARASYM SSM-100 SYNTHETIC MICA-SMECTITE)

Trioctahedral smectites have proved far easier to produce commercially than dioctahedral smectites. Production of Barasym SSM-100 synthetic mica-smectite, a dioctahedral variety, did prove successful however, although it is no longer in manufacture. Some synthetic clays have been used as catalysts and viscosity-control agents.

Synthesis and nature of Syn-1

Precise techniques of synthesis remain proprietary, but the patent by Granquist (1966) gives an excellent generalized overview. In a typical example, passing an aqueous solution of Na silicate through a hydrogen-ion exchange column produces a silicic acid solution. Stirring aluminum chloride hexahydrate into this solution coprecipitates silica and alumina gels. This gel is filtered, washed and redispersed in water. Next, NaOH is added. The mass is placed in a stirring autoclave, kept at 285°C and 1000 psi for 48 h. After cooling, the material is washed, then redispersed in ammoniacal water, and filtered. The NH_4OH treatment is repeated. The final product can either be tray dried and pulverized or spray dried to microspheroids of ~35 μm size.

The resulting material, Syn-1, has the general formula:

$$[^{VI}Al_4{}^{IV}(Si_{8-x}Al_x)O_{20}(OH,F)_4][wNH_4{}^+ + yAl(OH)_{z+3}{}^{-z}]$$

where x, y, z, and w relate to compositional and charge parameters.

Barasym SSM-100 synthetic mica-smectite (Syn-1) is an interstratified 10–12.5 Å phase. The ratio of mica to beidellite units is 2 to 1. Wright *et al.* (1972) described the material in detail. Note that Syn-1 is not calcined. The material is an irregular, mixed layering of 10.4 Å and 12.5 Å units. The MacEwan transform (MacEwan *et al.,* 1961) indicates that the layers are randomly stacked, with perhaps a small amount of ordering. Electron-optical studies show that the material crystallizes into irregular platelets, ~1000 Å across. The platelets average 50 Å in thickness.

Manufacture

The Wallisville, Texas, synthetic minerals plant of NL Industries produced this sample in 1972. NL Industries kindly donated it.

ACKNOWLEDGMENTS

REFERENCES

Ames, L.L., Jr., Sand L.B. and Goldich, S.S. (1958) A contribution on the Hector, California, bentonite deposit. *Economic Geology,* **53,** 22–37.

Chen, Pei-Yuan (1968) Geology and mineralogy of the white bentonite beds of Gonzales County, Texas. Ph.D. thesis, University of Texas, Austin, Texas.

Drombrowski, T. (1993) Theories for origin of the Georgia kaolin. Pp. 75–98 in: *Kaolin Genesis and Utilization* (H. Murray, W. Bundy, and C. Harvey, editors). Clay Minerals Society, Boulder Colorado.

Eargle, D.H. (1959) Stratigraphy of the Jackson Group (Eocene) South Central Texas. *American Association of Petroleum Geologists Bulletin,* **43,** 2623–2635.

Elzea, J.M. and Murray, H.H. (1990) Variations in the mineralogical, chemical and physical properties of the Cretaceous Clay Spur bentonite in Wyoming and Montana (USA). *Applied Clay Science,* **5,** 229–248.

Elzea, J. and Murray, H.H. (1994) Bentonite. Pp. 233–246 in: *Industrial Minerals and Rocks* (D.D. Carr, editor). Society for Mining, Metallurgy, and Exploration, Littleton, Colorado.

Elzea Kogel, J., Pickering, S.M., Jr., Shelobolina, E., Yuan, J., Chowns, T.M. and Avant, D.M., Jr. (2000) *Geology of the Commercial Kaolin Mining District of Central and Eastern Georgia.* Georgia Geological Society Guidebooks, **20,** number 1, Atlanta, 92 pp.

Eyde, T.H. and Eyde, D.T. (1987) Bentonite and specialty sand deposits in the Bidahochi Formation, Apache County, Arizona. Pp. 123–127 in: *Proceedings of the 21st Forum on the Geology of Industrial Minerals* (H.W. Pierce, editor). Arizona Bureau of Geology and Mineral Technology.

Foshag, W.R. and Woodford, A.O. (1936) Bentonite magnesium clay-mineral from California. *American Mineralogist,* **21,** 238–244.

Granquist, W.T. (1966) Synthetic Silicate Minerals. *U.S. Patent 3,252,757.*

Huddlestun, P. (1988) The Miocene through the Holocene, a revision of the lithostratigraphic units in the coastal plain of Georgia. *Georgia Geological Survey Bulletin,* **104,** 162 pp.

Kerr, P.F. (1949) *Reference Clay Minerals, A.P.I. Project 49.* American Petroleum Institute.

Kiersch, G.A. and Keller, W.D. (1955) Bleaching clay deposits, Sanders-Defiance Plateau District, Navajo County, Arizona. *Economic Geology,* **50,** 469–494.

Knechtel, M.M. and Patterson, S.H. (1962) Bentonite deposits of the northern Black Hills District, Wyoming, Montana and South Dakota. *U.S. Geological Survey Bulletin* **1082-M,** 893–1030.

MacEwan, D.M.C., Ruiz Amil, A. and Brown, G. (1961) Interstratified Clay Minerals. Pp. 393–445 in: *The X-ray Identification and Crystal Structures of Clay Minerals* (G. Brown, editor). Mineralogical Society, London.

Merkl, R.S. (1989) A sedimentological, mineralogical and geochemical study of the Fuller's Earth deposits of the Miocene Hawthorne group of south Georgia–north Florida. Ph.D. thesis, Indiana University, 182 p.

Millot, G. (1970) *Geology of Clays. Weathering, Sedimentology, Geochemistry.* Springer Verlag, Paris, 429 p. (Translated by W.R. Farrand and H. Paquet).

Moll, W.F., Jr. (1979) Origin of CMS Samples. Pp. 69–125 in: *Data Handbook for Clay Materials and Other Non-Metallic Minerals* (H. van Olphen and J.J. Fripiat, editors). Pergamon Press, Oxford.

Patterson, S.H. (1974) Fuller's Earth and other mineral resources of the Meigs-Attapulgus-Quincy District, Georgia and Florida. *U.S. Geological Survey Professional Paper,* **828,** 45 pp.

Patterson, S.H. and Buie, B.F. (1974) Field Conference on Kaolin and Fuller's Earth, November 14–16, 1974. *Georgia Geological Survey, Guidebook,* **14,** 53 pp.

Pickering, S., Jr. and Murray, H.H. (1994) Kaolin. Pp. 255–277 in: *Industrial Minerals and Rocks* (D.D. Carr, editor). Society for Mining, Metallurgy and Exploration, Littleton, Colorado.

Pruett, R.J. and Webb, H.L. (1993) Sampling and analysis of KGa-1b well-crystallized kaolin source clay. *Clays and Clay Minerals,* **41,** 514–519.

Ross, C.S. and Hendricks, S.B. (1945) Minerals of the montmorillonite group. *U.S. Geological Survey Professional Paper* **205-B.**

Slaughter, M. and Earley, J.W. (1965) Mineralogical and geological significance of the Mowry Bentonites, Wyoming. *Geological Society of America, Special Paper 83.*

Sloane, R.L. and Guilbert, J.M. (1967) Electron-optical study of alteration to smectite in the Cheto clay deposit. *Clays and Clay Minerals,* **15,** 35–44.

Wright, A.C., Granquist, W.T. and Kennedy, J.V. (1972) Catalysis by layer lattice silicates I. The structure and thermal modification of a synthetic ammonium dioctahedral clay. *Journal of Catalysis,* **25,** 65–80.

E-mail of corresponding author: lakewood@dls.net