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Clays of the Central Georgia Kaolin Belt: A Preliminary Evaluation

John Reed, Carl R. Froede, Jr.*

Abstract

Clays of the Central Georgia kaolin belt comprise a significant percentage of commercial grade kaolin produced worldwide. Kaolin lenses occur in terrestrial Coastal Plain sediments in east-central Georgia, in updip sections near the Fall Line. Uniformitarian models of the clay's origin suggest the following sequence occurring over millions of years: (1) kaolinite minerals slowly formed as weathering products of updip igneous and metamorphic rocks of the Piedmont and Appalachian provinces, (2) kaolinite was transported by rivers to the ancient coastline, and (3) extensive, slow post-depositional changes resulted in nearly pure kaolin bodies. However, present theories are troubled by a number of inconsistencies and the diluvial paradigm may prove more fruitful for understanding the occurrence of the clay. Though a diluvial model is not presented, bounding parameters and key questions for such a theory are proposed.

Introduction

Kaolin is a white plastic clay composed of various minerals of the kaolinite group. Its name comes from its early use at Kao-Lin in China—it is often called "China Clay." When found in sufficient purity, kaolin is useful in many commercial applications. It forms the coating on the pages of this magazine, is an ingredient in tires, paint, and even food. Both your toilet and your antique china are made with kaolin. It is used as a refractory material, a catalyst, and as filler in cement and fiberglass. Its unique properties, especially its bright white color, make it an important economic resource. Mining constraints are rigid; small changes in the makeup of a clay lens can change its physical properties significantly and make or break a potentially viable deposit. Even among the comparatively pure deposits of the Central Georgia kaolin belt, less than one percent of the total clay bodies explored are considered commercial grade (Pickering et al., 2000).

Kaolin is composed of minerals of the kaolinite group, including kaolinite, dickite, nacrite, and halloysite. They often occur as microscopically stacked plates similar to the micas, but kaolin is a much simpler alumino-silicate. Its basic formula is $Al_2Si_2O_5[OH]_4$. Because it is the diagenetic end product of micas, volcanics, and other clays, kaolinite is common in many sedimentary rocks, but it forms deposits of commercial quality kaolin in only a few places; notably Australia, Brazil, China, Ethiopia, England, and in central Georgia. The Central Georgia kaolin belt has been the world's center of commercial kaolin mining for many years because it contains large bodies of very pure clay that are easily extracted through open pit mining operations, although in recent years, increasing production costs and the reduction in the volume of the economic deposits has shifted more kaolin production to Brazil.

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* John Reed, Ph.D. (Lead Author), 915 Hunting Horn Way, Evans, GA 30809, e-mail: jkenr2@comcast.net
Carl R. Froede, Jr., B.S, P.G., 2895 Emerson Lake Drive, Snellville, GA 30078-6644

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In Georgia, kaolin is mined from open pits; the commercial lenses range up to 150 ft (45-m) thick, and extend across many acres (Figure 1). Mines typically yield between 50,000 and 400,000 tons (45.4 to 363 metric tons) of clay (Pickering et al., 2000). The origin of these pure clay deposits in Georgia remains unresolved. In other locations, commercial deposits have clearly been formed diagenetically from the alteration of igneous rocks. Kaolin clay has also been observed as a direct alteration product (Chen et al., 1997; Cravero et al., 2001; Pickering et al., 2003), often by hydrothermal activity. Kaolinite is a common product of plagioclase feldspar or mica alteration, especially under the influence of acidic pore fluids. It is also a diagenetic end product of other clays, such as smectite.

However, the origin of the clay bodies in the Central Georgia kaolin belt presents problems, not only because they are large, pure, and abundant, but because they are also part of a continuous sedimentary sequence. Kaolin is abundant in the surrounding sediments as matrix and as framework clasts. Many of these framework clasts may be from the in situ alteration of feldspars after deposition, but in some cases kaolin clay beds have clearly been ripped up by erosion and redeposited (Figure 2). Until recently, emphasis had been placed on a depositional origin for the clay bodies; now the focus has moved to diagenetic processes (Hurst and Pickering, 1997). But questions remain. All current theories assume deep time and low-energy paleoenvironments similar to modern coastal settings. It is possible that a new perspective—relatively rapid formation in a catastrophic setting—may solve some longstanding problems and open new areas of research. This paper

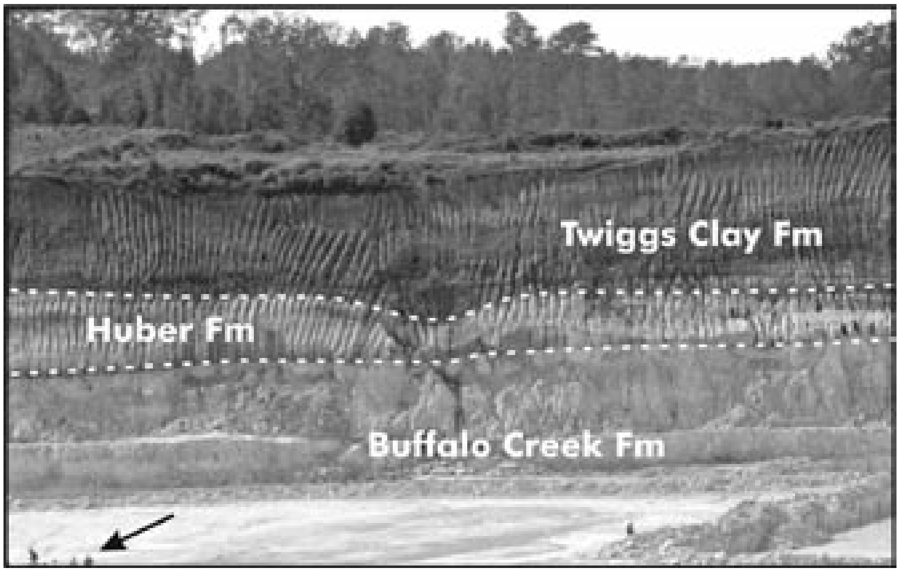


Figure 1. The Imerys Company Sheppard Mine exhibits all of the stratigraphic units associated with the central Georgia kaolin mining industry. Note the people located on the lower left side of the image for scale. Image from October 2000.

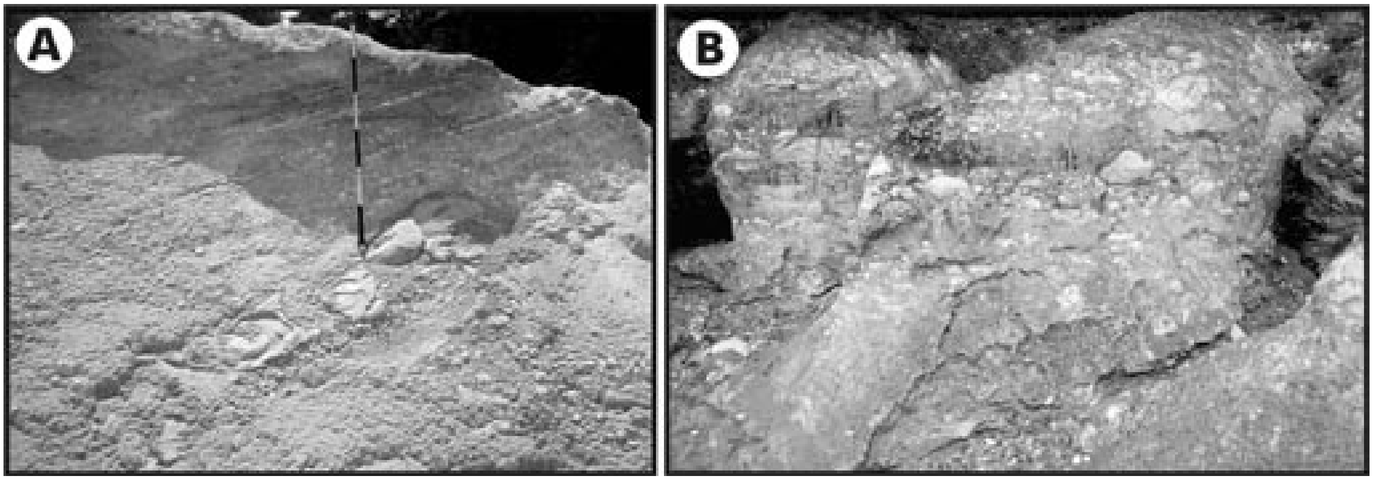


Figure 2. Huber Member kaolin clasts in a sandy-kaolin clay matrix. (A) These clay balls show evidence of transport but are not obviously armored. This suggests rapid transport in a fluidized state. This would require extremely energetic conditions, much higher than the posited fluvial setting. Scale in 6 in (15 cm) divisions. (B) The layering of the kaolin suggests normal-graded bed load transport. The successive levels of graded bedding suggest transport and deposition in a series of pulses rather than as a continuous process. Scale in inches and centimeters.

will review the geology of the Central Georgia kaolin belt, evaluate uniformitarian models, and propose constraints on potential diluvial theories.

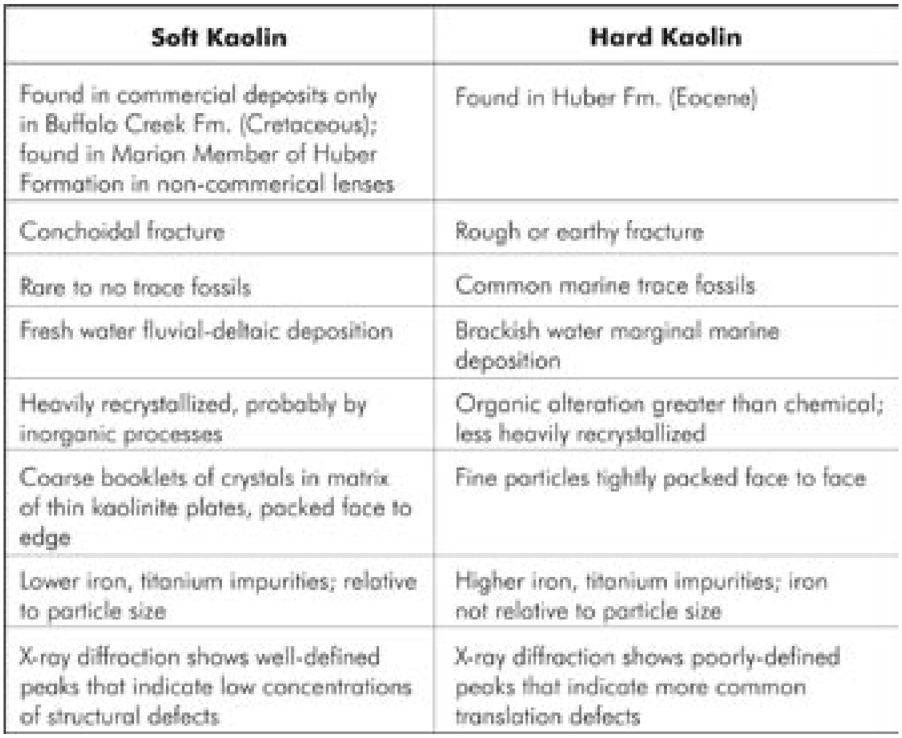
Geology of the Kaolin Belt

The Central Georgia kaolin belt is located just to the south of the Fall Line, between Macon and Aiken, South Carolina (Figure 3). The Fall Line stretches from New Jersey to Texas, and is the surface expression of a significant erosional unconformity cut into igneous and metamorphic rocks of the crystalline basement (exposed updip in the Piedmont Province), and beneath sediments of the Coastal Plain Province. Coastal Plain sediments form a wedge from their pinchout at the Fall Line to thicknesses of many thousands of feet beneath the continental shelf (see Froede, 1997). Updip Coastal Plain sediments are composed of unconsolidated gravels, sands, silts, and clays, with rare calcareous beds. In the kaolin belt, many updip facies are interpreted as terrestrial in origin and downdip facies are interpreted as marine, though some of the younger marine strata extend nearly to the Fall Line (see Appendix).

Uniformitarians date the oldest Coastal Plain strata in the area as Late Cretaceous, based primarily on fossil pollen spores. Most strata exposed at the surface in the kaolin belt are dated as the Late Eocene Barnwell Group. However, dating and correlation of all the sediments are hindered by the absence of fossils in many critical formations, abrupt lateral lithologic transitions, similarities between sediments in different formations, unresolved nomenclature, and rare exposures. Much of the dating is done by reference to pollen zones.

The stratigraphically lower Cretaceous kaolin is called “soft kaolin” and is mineralogically distinct from the overlying Eocene or “hard” clays (Figure 4). The soft kaolin is the primary economic resource of the area; nearly 70%

Figure 3. Map of the Central Georgia Kaolin Belt and surrounding areas. Counties comprising the kaolin belt are shaded in light gray, as is the Department of Energy Savannah River Site. Granite outcrops north of the Fall Line are shaded in darker gray.



Soft Kaolin	Hard Kaolin
Found in commercial deposits only in Buffalo Creek Fm. (Cretaceous); found in Marion Member of Huber Formation in non-commerical lenses	Found in Huber Fm. (Eocene)
Conchoidal fracture	Rough or earthy fracture
Rare to no trace fossils	Common marine trace fossils
Fresh water fluvial-deltaic deposition	Brackish water marginal marine deposition
Heavily recrystallized, probably by inorganic processes	Organic alteration greater than chemical; less heavily recrystallized
Coarse booklets of crystals in matrix of thin kaolinite plates, packed face to edge	Fine particles tightly packed face to face
Lower iron, titanium impurities; relative to particle size	Higher iron, titanium impurities; iron not relative to particle size
X-ray diffraction shows well-defined peaks that indicate low concentrations of structural defects	X-ray diffraction shows poorly-defined peaks that indicate more common translation defects

Figure 4. Differences between “hard” and “soft” commercial kaolin deposits. From Pickering et al. (2000).

of Georgia kaolin is of the soft, coarse particulate type. In some instances they are separated by organic-rich clays, some even considered lignitic (Figure 5).

Stratigraphic Summary

Upper Coastal Plain stratigraphy is marked by some uncertainty. It has been refined over recent decades, but questions remain. Pickering et al. (2000) identified ten stratigraphic units in the kaolin belt. Of these, commercial clay occurs only in two. The general kaolin belt stratigraphy is shown in Figure 6 and summarized below. Lateral facies variations account for disagreements between stratigraphers as do subjective nomenclature differences between locations. The United States Department of Energy Savannah River Site lies just within South Carolina (Figure 3), and its upper Coastal Plain nomenclature is quite different from that of the kaolin belt (Figure 7) between the basement and the Barnwell Group. Some of the differences are undoubtedly in the rocks, but others may also be artifacts of stratigraphers' subjectivity.

The oldest rocks beneath the kaolin belt are the Piedmont Crystalline Rock Complex, which include gneiss, amphibolite, schist, phyllite, and intrusive granites and mafic rocks. The metamorphic rocks are thought to be Precambrian and the igneous intrusives are dated to the middle Paleozoic. Where they are exposed, these basement rocks are often covered by a layer of saprolite, up to 165 ft (50 m) thick. Saprolite is an alteration product probably resulting from in situ weathering since it often retains remnants of the original rock texture and residual quartz veins. In every current uniformitarian theory of the origin of kaolin, this saprolite is identified as the precursor material of the commercial clay accumulations. The top of the saprolite (or crystalline basement where the saprolite is absent) marks the Fall Line Unconformity. The slope of the basement at the Savannah River aver-

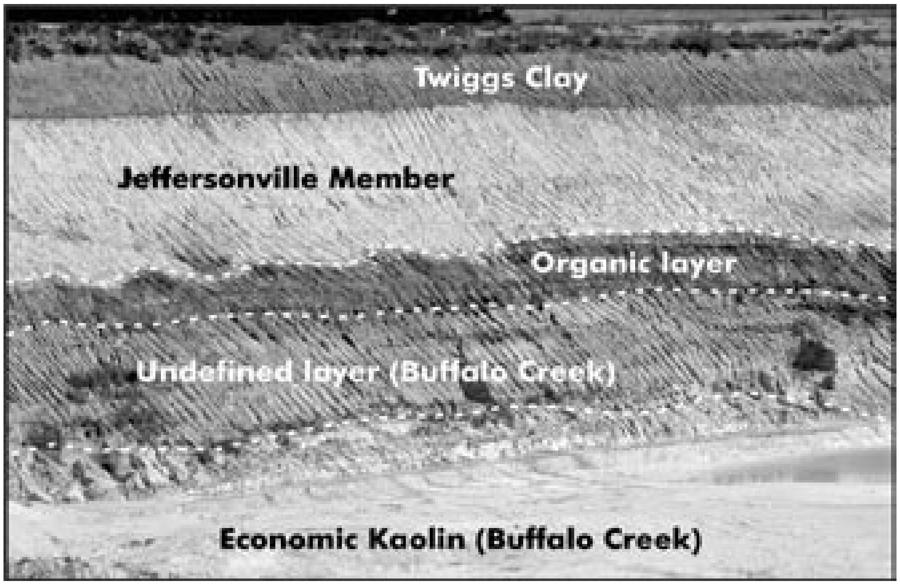
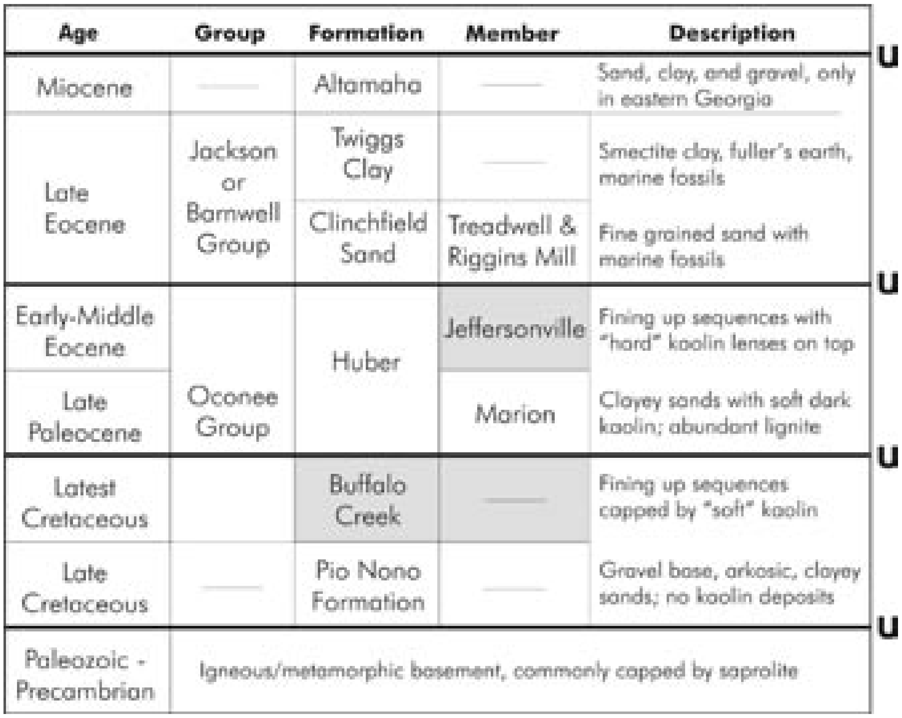


Figure 5. This sidewall at the Thiele Avant Mine shows the Buffalo Creek Formation, an organic rich clay layer, and the Jeffersonville Member of the Huber Formation. At many locations, an organic layer overlies or underlies economic kaolin deposits. This sidewall is approximately 50 ft (15 m) high. Image from October 2000.



Age	Group	Formation	Member	Description	
Miocene	—	Altamaha	—	Sand, clay, and gravel, only in eastern Georgia	U
Late Eocene	Jackson or Barnwell Group	Twiggs Clay	—	Smectite clay, fuller's earth, marine fossils	
		Clinchfield Sand	Treadwell & Riggins Mill	Fine grained sand with marine fossils	
Early-Middle Eocene	Oconee Group	Huber	Jeffersonville	Fining up sequences with "hard" kaolin lenses on top	U
Late Paleocene			Marion	Clayey sands with soft dark kaolin; abundant lignite	
Latest Cretaceous		Buffalo Creek	—	Fining up sequences capped by "soft" kaolin	U
Late Cretaceous	—	Pio Nono Formation	—	Gravel base, arkosic, clayey sands; no kaolin deposits	
Paleozoic - Precambrian	Igneous/metamorphic basement, commonly capped by saprolite				U

Figure 6. Uniformitarian stratigraphic chart of the Central Georgia Kaolin Belt. Shaded units show location of commercial clay deposits. Solid lines marked by "U" depict regional unconformities important to stratigraphic correlation. The lowest is the Fall Line unconformity. Note that some units are restricted by geography and may indicate facies relationships rather than true age relationships. Modified from Pickering et al. (2000) and Hetrick and Fridell (1990).

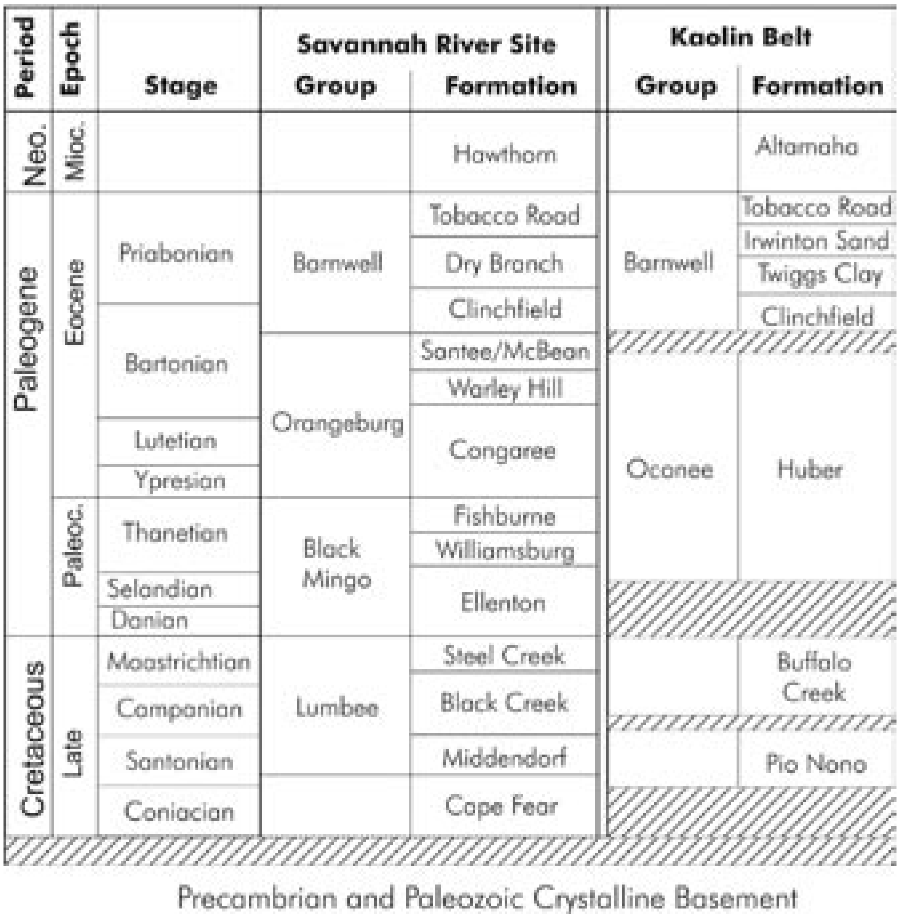


Figure 7. Stratigraphic charts of Coastal Plain sediments between the Central Georgia kaolin belt and the United States Department of Energy Savannah River Site near Aiken, South Carolina. The differences beneath the Barnwell Group are surprising, since the two areas are located approximately along strike and within 100 miles of each other. Both areas have large amounts of well and core data to support interpretation. Differences can probably be explained by facies changes along strike and interpretive subjectivity of different workers. Shaded areas represent unconformities.

ages 40 ft/m (7.58 m/km), decreasing up through the sedimentary section to 15 ft/m (2.84 m/km) on top of the kaolin bearing Eocene sediments (Hetrick and Fridell, 1990). The slope decreases to the west and downdip (Hurst and Pickering, 1997, their figure 5).

Immediately overlying the basement/saprolite is the Pio Nono Formation, composed of coarse red, brown, and yellow gravels, arkosic sands, and clays. Its type locale is Macon, and the formation is assumed to be basal Late Cretaceous, despite the absence of fossils. Huddlestun and Hetrick (1991) included this formation in the Oconee Group, but Pickering et al. (2000) were uncertain, since it lacks commercial grade kaolin and the gravel-sized clay balls common in other Oconee Group sediments. They noted a "subtle unconformity" between the Pio Nono Formation and the overlying Oconee Group.

The Oconee Group is a relatively recent name replacing the informal "Tuscaloosa Formation" dating back to the early 1900s. It ranges from the Late Cretaceous to the Middle Eocene. All commercial-grade kaolin occurs in two strata of the Oconee Group; the Buffalo Creek Formation and the Jeffersonville Member of the Huber Formation. The type locale for the Oconee Group is along the Oconee River in Wilkinson and Washington Counties. It is composed of "fining-upward sand/clay sequences over a wide range of geologic time from Early Late Cretaceous to Middle Eocene" (Pickering et al., 2000, p. 8). The bases of these fining-upward units often include beds of gravel or kaolin ball clasts that grade up into sands with large cross beds up to 80 ft (24.4 m) thick. The tops of these sequences are kaolin lenses, often of commercial grade. The commercial lenses range from a few square feet up to hundreds of acres, and can reach 150 ft (45.7 m) in thickness. Terrestrial facies extend from the erosional pinchout at the Fall Line to 20–35 miles (32–56 km) to the southeast. The terrestrial Oconee sediments reach a thickness of more than 2,500 ft (762 m) at that transition (Pickering et al., 2000).

The Buffalo Creek Formation forms the basal Oconee Group (Pickering and Hurst, 1989). Based on pollen dating, it is late Campanian and is the updip equivalent of the marine Ripley Formation. It is composed of fining upward channel fills which include cross bedded quartz gravel, kaolin clast gravel, sand, silt, and clay, including large commercial lenses (Figure 8). The soft kaolin of the Buffalo Creek Formation is usually cream to white, and occasionally pink, gray, violet, or yellow. The top of the formation marks a major regional unconformity, marked by early Paleocene erosion that cuts into commercial clay bodies, although it is less prominent than those atop the basement or the Huber Formation.

The Huber Formation was named by Buie and Fountain (1967) to distinguish generally finer-grained clayey

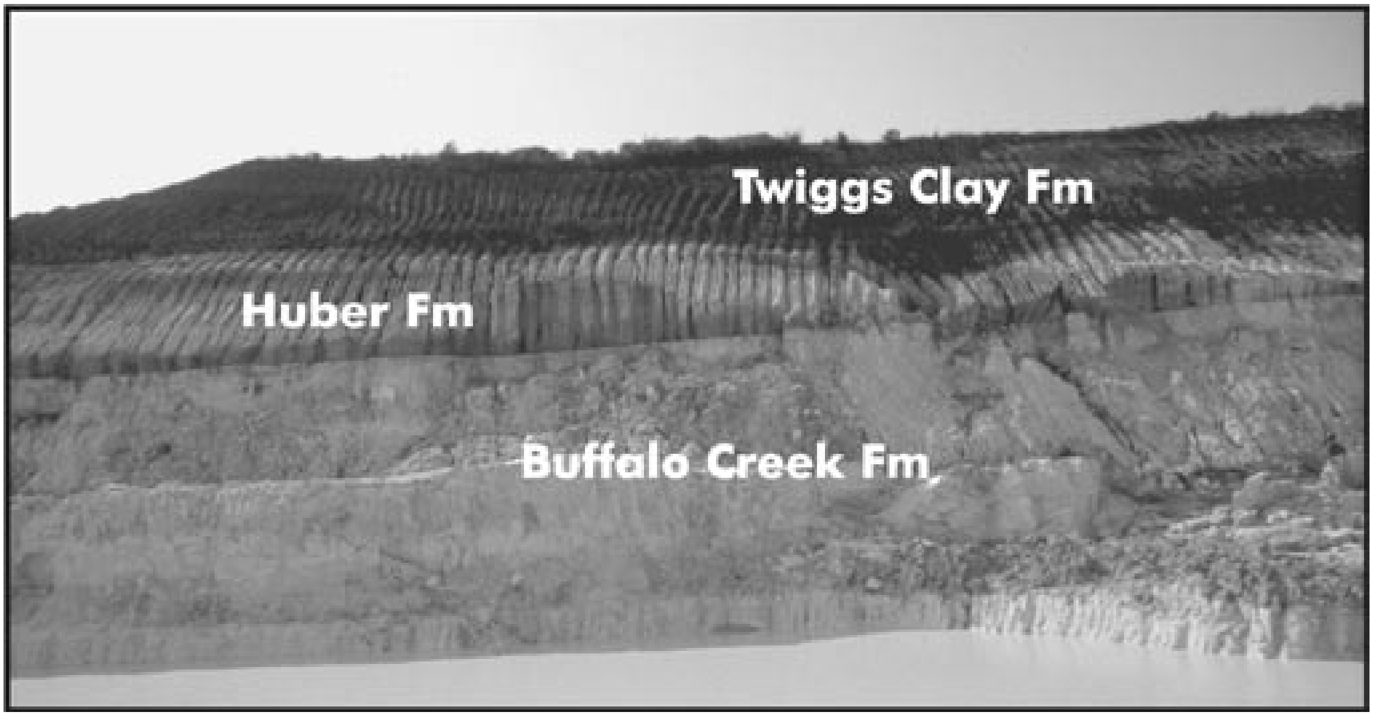


Figure 8. This close-up view of the mine sidewall from Figure 1 shows the clay purity typical of the Buffalo Creek Formation. Note the sharp contact between the Buffalo Creek Formation and the overlying Huber Formation. Man (to right) for scale. Image from October 2000.

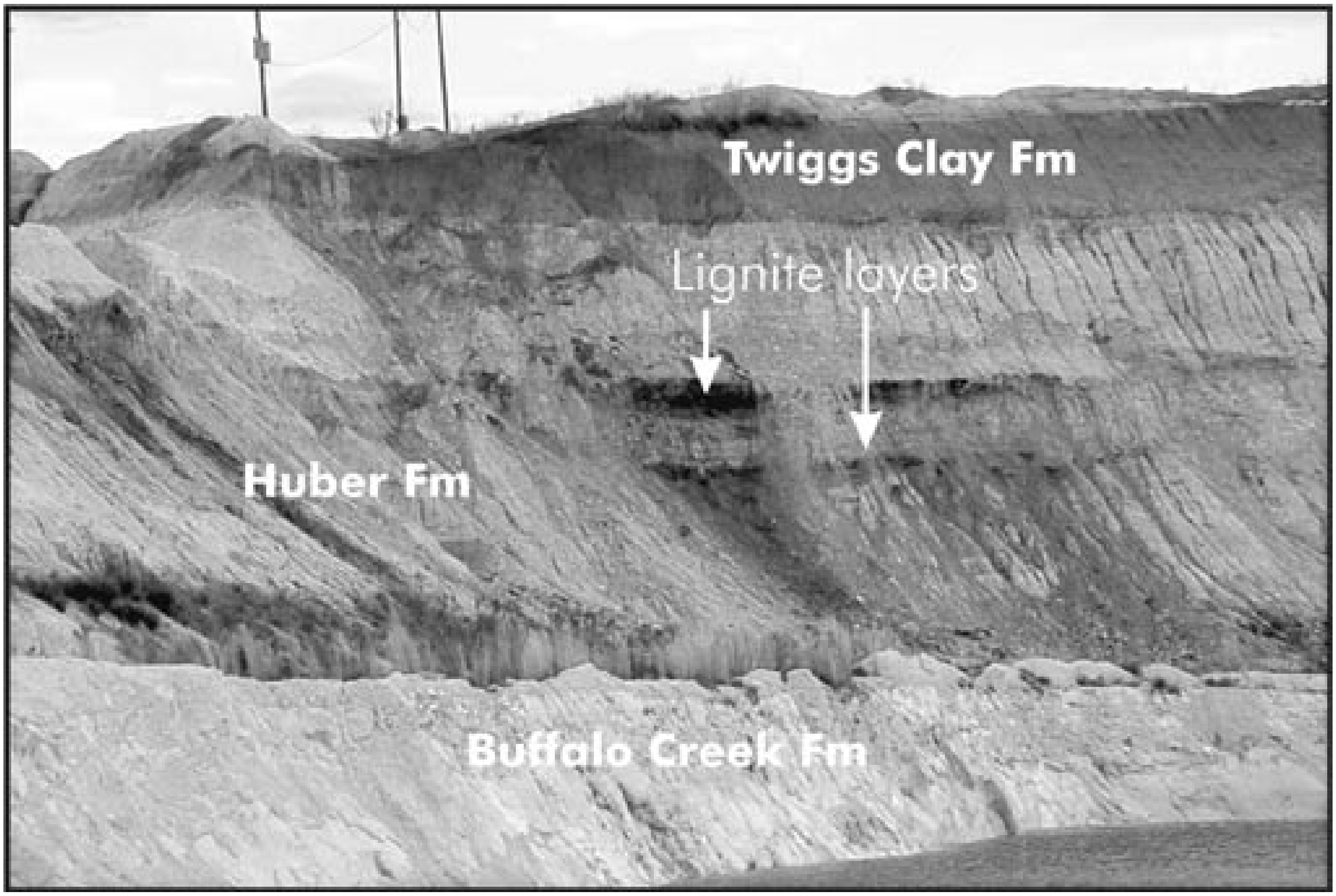
sand from the underlying Cretaceous sediments, though its sediments also form a series of fining upward, cross-bedded sand-clay cycles. It differs from the Buffalo Creek Formation by being thinner, having finer-grained sands, more heavy minerals, and pollen of late Paleocene to Eocene age. Huber Formation kaolins are of finer particle size, are less recrystallized, less oxidized, grayer, and contain more lignite than the Buffalo Creek clays. The formation is found between Andersonville and Hepzibah, illustrating how lateral variation influences stratigraphy. Interestingly, similar sediments are found in a fault-bounded basin near Warm Springs and in the Piedmont of northwest Georgia:

> Further, palynology studies by Darrell (1966) of numerous bauxite and kaolin filled limesinks in Cambrian rocks in Northwest Georgia show considerable lithologic and biostratigraphic similarity to the Huber Formation (Pickering et al., 2000, p. 11).

The Huber Formation consists of the lower Marion Member—generally richer in organics with abundant lignite seams—and the upper Jeffersonville Member, which contains the upper commercial clays. The Marion Member includes at least one fining upward sequence, from a basal quartz and kaolin-clast conglomerate atop the eroded Buffalo Creek, to a dark clay that is often rich in pyrite, organic matter, and lignite seams (Figure 9). The boundary with the overlying Jeffersonville Member is a "subtle unconformity and not easily distinguished" (Pickering et al., 2000, p. 11). This is unusual; present day conditions create significant relief within fluvial valleys and thick soil horizons on the interfluve surfaces.

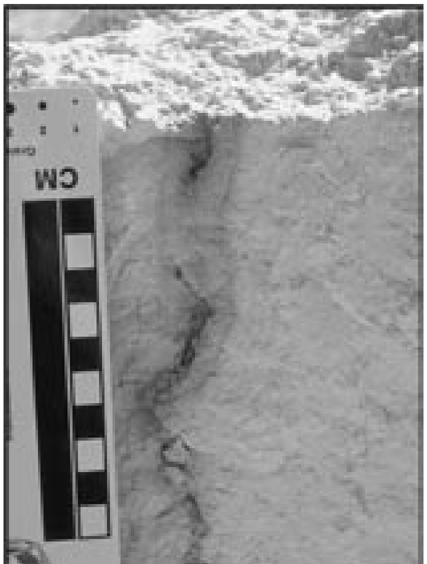
The Jeffersonville Member consists of fining upward cycles of sand to hard clay lenses, which contain traces of shrimp and other brackish water fauna (Figure 10). Microscopic examination shows evidence of significant bioturbation. This stratum is dated to the Middle Eocene by pollen. The top of the member is a prominent unconformity that marks a shift to marine deposition. There is no commercial-grade kaolin above that unconformity.

The Barnwell Group or Jackson Group (depending on the author) is dated to the Late Eocene and contains marine sediments. The type locale is in Barnwell, South Carolina. It is composed of the lower Clinchfield Sand Formation, the Tobacco Road Sand, and the Twiggs Clay Formation (Hetrick and



***above*: Figure 9. Lignite rich lenses in the Huber Formation at the Thiele Ennis Mine. The exposure is approximately 40 ft (12 m) high. Image from March 1999.**

***below*: Figure 10. Pyritized vertical shrimp(?) trace in the Jeffersonville Member. The density of the clay and lack of shortening of the trace suggests limited compaction. Scale in centimeters.**



Fridell (1990) defined the lower unit of the Barnwell Group as the Dry Branch Formation, which includes the Twiggs Clay, Irwinton Sand, and Griffins landing Members). In the kaolin-mining district, the Barnwell Group is exposed or locally covered by recent alluvium. The Clinchfield Sand Formation is best seen in its type locale in Houston County and extends east to Deepstep. It has also been called the "Albion Member" and is an opal cemented sand and clay called the "flint clay," which contains shark and fish teeth, mollusks, and small pectens. Harris (2003) suggested that this member might include fallout debris from the Chesapeake Bay impact event. The overlying Twiggs Clay Formation is a relatively continuous, thick layer of marine fuller's earth, ranging from Cordele to Hepzibah. Hetrick and Fridell (1990) interpreted the depositional environment of the Twiggs Clay as intertidal mud flats because it consists of fissile smectite with laminae of silt and sand, contains pelecypods and abundant plant fossils, and includes facies of fuller's earth, smectite, and cristobalite. It is present as overburden in most kaolin pits. The Twiggs Clay is important in recent theories of kaolin formation because it is thought to form a groundwater barrier to downward recharge in areas that correlate with gray, pyrite-rich kaolin, while in areas where the Twiggs Clay is breached, the underlying kaolin is heavily oxidized to white, pink, purple, or tan (Yuan, 2000).

The Tobacco Road Sand is the uppermost formation of the Barnwell Group. It is a medium-grained sand that is often cross-bedded. It contains discontinuous clay laminae, and a basal zone of flattened, rounded small gravel. It is interpreted as a shoreline deposit. The Tobacco Road Sand weathers to a reddish brown, and is marked by *Ophiomorpha* burrows. Its type locale is Fort Gordon, near Augusta (Hetrick and Fridell, 1990).

In far eastern Georgia, the Miocene Altamaha Formation of the Hawthorne Group is present. It is a pebbly, poorly sorted sand, clay, and gravel, thought to be of fluvial to estuarine origin. Its lower bed is 2–6 ft (0.61–1.8 m) thick, and composed of gray-green silty sandy clay. In many cases, it is difficult to distinguish the lower Altamaha from the underlying Tobacco Road Sand. Often stratigraphers must rely on elevation and location (Hetrick and Fridell, 1990) to differentiate the two units. The upper part of the Altamaha is composed of gravel beds with angular to rounded clasts, some more than two inches in diameter.

Regional Unconformities

Stratigraphic correlation is difficult in the upper Coastal Plain. In addition to the physical lack of outcrops and restricted access to proprietary subsurface data, the sediments lack diagnostic fossils. Correlation rests on subsurface regional unconformity surfaces. There are three such unconformities: (1) the boundary between the crystalline basement and the Pio Nono or Buffalo Creek formations, (2) the boundary between the Buffalo Creek and Huber formations, and (3) the boundary between the Jeffersonville Member and the Barnwell Group (Figure 6).

This focus on unconformities pushes the uniformitarian interpretation towards the principles of sequence stratigraphy. This approach is emphasized because commercial clay occurrence is theoretically tied to fluctuations between terrestrial and marine environments (Hurst and Pickering, 1989). The lowstands that generated these unconformities are thought to be significant, as are their intervening highstands in the Late Cretaceous and Eocene that match the dating of kaolin-bearing strata. An additional highstand in the Late Eocene is thought to correlate to the deposition of the Twiggs Clay (Pickering et al., 2000).

Kaolin Composition

Commercial grade kaolin in the kaolin belt generally contains 90–95% kaolin group minerals and 5–10% impurities. In addition to kaolinite, nacrite and dickite, all of the Georgia kaolin group clay minerals occur in both hard and soft varieties, although in soft clays they are confined to the fine particle size fraction. Impurities in commercial grade kaolins include mica, illite (an alteration product of mica), smectite, pyrite, marcasite, and iron and titanium oxides such as anatase, goethite, and hematite. Organic content varies; it is usually higher in hard clays and in downdip clays.

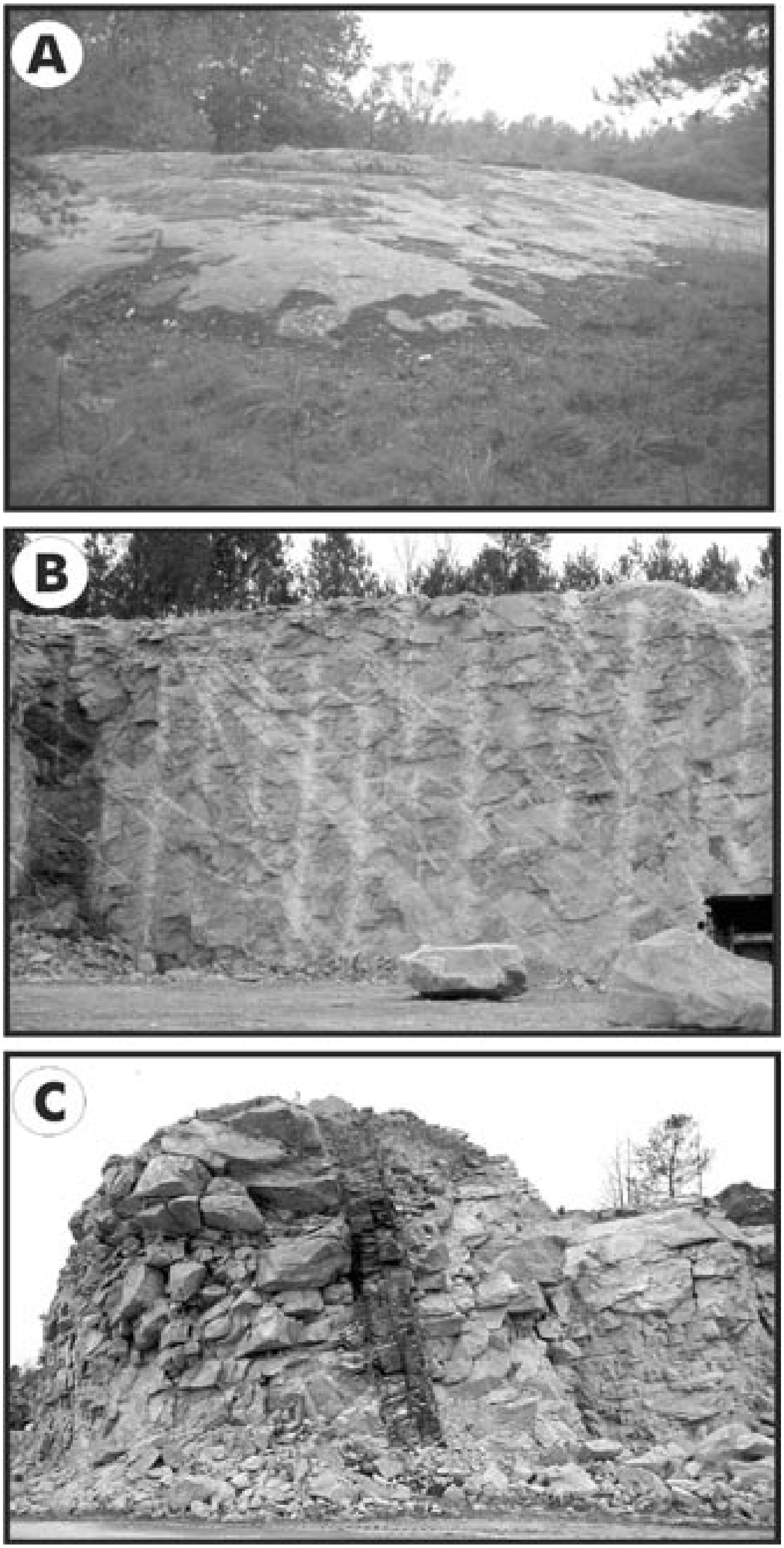
Of the hard and soft varieties of kaolin, each type displays an apparent stratigraphic affinity. Soft kaolin is restricted to the Buffalo Creek Formation. It is characterized by its coarse particle size, soapy texture, and conchoidal fracture. Soft clay is thought to be the result of extensive in situ recrystallization. It is also called “low defect kaolin” because of its well-defined X-ray diffraction peaks. Hard kaolin is found in the Jeffersonville Member of the Huber Formation. It is characterized by its finer particle size, earthy texture, and evidence of little in situ recrystallization. It is thought to have formed by flocculation in marginal marine settings, and is also called “high defect kaolin” because of its broad X-ray diffraction bands which result from crystallographic translation defects. Soft clay is noted for its low iron content (0.1–0.45%), while hard clay’s iron content ranges between 0.7–1.0%. A similar stratigraphic occurrence of soft and hard kaolin is found in the Capim River kaolins of Brazil (Sousa et al., 2006).

Discussion

Uniformitarian Theories

There are several possible methods of forming kaolinite clay minerals, almost all of which are diagenetic. Kaolinite minerals can form by the in situ diagenetic and hydrothermal alteration of feldspar-rich igneous and metamorphic rocks, such as granite and rhyolite, as documented in Ethiopia (Fentaw and Mengistu, 1998), Argentina (Cravero et al., 2001), and China (Chen et al., 1997). Kaolinite is also thought to form by intense weathering (Sousa et al., 2006). It is the primary component of saprolite forming in the Georgia Piedmont (Pickering et al., 2003). Of particular interest is the Sparta Granite (Figure 11), an intrusive belt 50 miles (80 km) long, just updip of the Georgia kaolin belt (Pickering et al., 2003).

The Georgia kaolins are thought to have formed by a complex combination of several methods, all-originating with the saprolite that covers Piedmont rocks. Once formed, the saprolite would have been transported by rivers to the ancient coast and deposited as lenses of less pure kaolin (~80%) in marginal marine lagoons and deltaic ponds. Those lenses were later refined by a series of diagenetic processes: weathering, winnowing, bacterial action, and oxic and anoxic groundwater action (Hurst and Pickering, 1997).



***left*: Figure 11. The feldspar-rich Sparta Granite is thought to be a source of Coastal Plain kaolin. (A) A weathered outcrop of southeast of Macon, Georgia. (B) A 40 ft (12 m) sidewall in a open pit mine where the Sparta Granite is mined for aggregate. Note the extensive feldspar dikes cross-cutting the granite. There is no free iron in this rock and it would naturally weather to kaolin clays in an acidic environment. (C) A 40 ft (12 m) sidewall of the Sparta Granite cross-cut by a diabase dike. The dike is approximately 5 ft (1.5 m) wide. Uniformitarians date the diabase as Jurassic (~190 Ma) and the Sparta Granite as Pennsylvanian (~300 Ma).**

As might be expected, the continuity of environment, climate, and processes are emphasized:

> These kaolins (and associated bauxites) are located on what has been a passive continental margin for the last 100 my (Hurst and Pickering, 1997, p. 277).

Therefore, the initial conditions of the clay deposits are extrapolated from present day mud content of local river systems:

> Essentially the same patterns of drainage and relief have existed since Cretaceous time…. Kaolinite-metahalloysite has been the dominant component of detritus from the source area since Cretaceous time (Hurst and Pickering, 1997, pp. 279, 280).

Given these initial conditions, it follows that a multimillion-year process of clay polishing by various diagenetic processes would result in the present-day commercial kaolin deposits.

Yuan (2000) summarized recent theories of the origin of commercial kaolin in east-central Georgia, noting the mysterious nature of these deposits:

> Even though numerous studies have been devoted to understanding the genetic relationships of the different types of kaolin, there is still no universally accepted explanation for their origin (Yuan, 2000, p. 37).

Next, he noted two key phenomena that must be explained: (1) why there are hard and soft varieties of clay, and (2) the relative roles of deposition and diagenesis in the formation of commercial grade kaolin. However, there is another key aspect that Yuan (2000) failed to mention—the restricted geographic extent of commercial clays relative to the widespread conditions under which they supposedly formed. In other words, why are commercial grade deposits not found elsewhere in Georgia, North Carolina, South Carolina, Alabama, or Mississippi? Hurst and Pickering (1997) attributed it to the slightly higher percentage of suspended load kaolinite carried in modern Georgia rivers, but provided no geochemical basis for correlating such a threshold to commercial deposits.

All theories revolve around three key factors: (1) source, (2) depositional environment, and (3) diagenetic history (Yuan, 2000). Most geologists who have studied the clays agree that the ultimate source is the igneous and metamorphic basement of the Piedmont and Appalachian provinces, because: (1) the surrounding sediments originated in the Piedmont and Appalachian provinces, (2) kaolinite minerals are a common diagenetic product of those rocks, and (3) the historical gradient would have caused the transport of rocks from the Piedmont and Appalachians to the Coastal Plain. Yuan (2000) noted that clays and micas of Piedmont rocks show similar K-Ar ages to the commercial clays. However, other precursors have been considered. Buie (1964) argued for a volcanic origin of the clays, although recent studies indicate this to be unlikely because the physical properties of the clay particles are unlike those forming from volcanic ash. Dombrowski (1993) speculated that different types of crystalline rocks caused the different types of clay; with hard clay originating from phyllite and soft clay from granite or gneiss. He noted a physical correlation between specific source rocks (e.g., the Sparta Granite) and kaolin-rich sedimentary rocks of the Buffalo Creek Formation.

The original depositional environments are important because most geologists believe that hard and soft clays were formed in different settings. The soft clays lenses are thought to be the top of fining up deltaic sequences, far enough updip to be in freshwater conditions. They contain few sedimentary features, no body or trace fossils, and no distinctively marine sediments such as lime, gypsum, or manganese nodules, although the lack of these features is sometimes attributed to diagenesis. But the consensus remains for freshwater deposition:

> This non-marine environment is indicated by the presence of upland pollen grains and spores, large logs and stumps, and abundant terrestrial plant cuticle and woody fibers (Pickering et al., 2003, pp. 73–74).

Hard clays are thought to have been deposited in transitional to nearshore marine conditions similar to the modern coastal setting in Georgia. That interpretation is supported by the geometry of the clays, the lithology of the surrounding sediments, and the presence of marine trace fossils, microfossils, and bioturbated zones. Possible environments include intertidal salt marshes (Horstmann, 1983), brackish or shallow marine (Schroeder, 1979), tidal flats (Patterson and Murray, 1984), and the neritic zone (Hurst and Pickering, 1997). Note the rather broad marine setting in clays above the "freshwater" soft clays (see Appendix).

Of course, the most fundamental question is why the clays are so pure. Most geologists believe that the primary cause of that purity is diagenetic. Up until recently, that scenario emphasized the chemical effects of long ages of subariel tropical weathering, or "laterization." But recent emphasis on groundwater and the role of bacteria in the subsurface have driven new theories of diagenesis by both chemical and bacterial interactions between groundwater and clay bodies (Hurst and Pickering, 1997). Groundwater circulation and bacterial activity lead to the oxidation of iron, destruction of organics, recrystallization of clay minerals, weathering of remaining feldspar and mica to kaolinite, alteration of titanium minerals to Anatase, and conversion of biogenic silica to opal-CT and quartz. The importance of groundwater is emphasized by Yuan (2000), who noted that kaolin purity seems related to the presence or absence of the overlying Twiggs Clay—a permeability barrier restricting groundwater recharge down to the kaolin lenses. The importance of groundwater seems indicated by the occurrence of pisolitic or bauxitic kaolins on top of some commercial clay lenses, the upward transition from reducing to oxidizing conditions in the clays, the more oxidized condition of updip clays, and the presence of etched and corroded quartz grains that support leaching:

> Original sediment color was quite dark due to its abundant decomposing plant material.… Reducing conditions led to recrystallization of iron as pyrite/marcasite.… Intense post-depositional alteration, but by ground water oxidative weathering and microbial action, has removed most of the dark organic matter and altered pyrite to hematite and goethite. This alteration process has also resulted in considerable recrystallization in the older, soft, coarse kaolin, which was likely mediated by carbonic and sulfuric acids released during alteration of the organic matter and pyrite (Pickering et al., 2003, pp. 73, 74).

However, the level of diagenetic activity seems to be more severe in the soft clays than the hard clays, which is the opposite of what might be expected if groundwater diagenesis was the primary purification agent. Tertiary clays, which would be more accessible to groundwater action for many millions of years, show preservation of sedimentary features, a similar mineralogy to that of modern marshes, abundant gray (unoxidized) clay, and well-preserved sequence from sand to micaceous kaolin to clay.

Yuan dismissed the idea that the upper hard clay formed from the reworking or redeposition of the soft clay, although that idea was advocated for Brazilian clays by Sousa et al. (2006). Yuan (2000) argued that reworking was impossible because the lower soft clay is purer and more extensively recrystallized than the upper hard clay. However, this assumes that the lower clay was not diagenetically affected after the deposition of the upper clay, and that the upper clay was not altered during the redeposition process. Yuan (2000) admitted that the soft clays may have contributed in small part to the upper clay because sedimentary clasts of the lower clay are found above the Cretaceous unconformity.

In summary, Yuan (2000) described the following sequence:

1. Updip crystalline rocks weather (aided by bacteria) over long periods of time to saprolite.
2. Saprolite is eroded and transported by high-energy streams to Coastal Plain deltas during the Late Cretaceous.
3. Clay minerals accumulate in organic rich marshes by flocculation in ponds and lagoons on the delta. Decaying organic material creates anoxic conditions, which result in pyrite and anaerobic bacteria.
4. Sea level falls, leading to subaerial weathering, erosion, unconformity surfaces, and pervasive paleosol horizons. Kaolinite recrystallization begins and bioturbation is intense, especially in upper kaolins. Aerobic bacterial action contributes to leaching of Na, Ca, and K from feldspar and mica, creating more kaolinite. Pyrite oxidizes to hematite and goethite.
5. The above sequence is repeated during Eocene sea level changes, but the clays are deposited in a marine, rather than freshwater, setting.
6. Sea level rises in the Late Eocene, resulting in the deposition of the Clinchfield Sand and Twiggs Clay, sealing lower kaolins from groundwater recharge. Bacterial action consumes most of organics.
7. Subsequent erosion breaches the Twiggs Clay and leads to the recharge of oxygenated groundwater "to saturate the clay lenses" (Yuan, 2000, p. 44). There, organics are removed and recrystallization of kaolinite minerals starts. Also, muscovite is altered to very coarse vermiform kaolinite and pyrite is again oxidized.

Critique of Uniformitarian Theories

There are several weaknesses to the uniformitarian theories. On a conceptual level, it is clear that the assumptions of deep time and past depositional environments similar to modern settings are not part of Earth's history. One of the key weaknesses is that these theories do not explain the geographic uniqueness of the kaolin belt in east-central Georgia. This point cannot be over emphasized but is often ignored. Current models posit conditions that would have existed in many other places near the Fall Line. Anywhere crystalline rocks were weathered, rivers were carrying the resulting clay to the Coastal Plain, and sea level changes created transitional environments for both the accumulation and purification of clay, pure kaolin lenses should have formed. The real mystery is why east-central Georgia contains large accumulations of virtually pure clay relative to the rest of the Coastal Plain.

Second, there are a number of inconsistencies in the uniformitarian framework. The Marion Member of the Huber Formation has only one clearly identifiable fining upward sequence. Surely during millions of years of deltaic deposition, more than one fining upwards sequence would have been deposited. This is especially puzzling when we realize that the vast modern Mississippi delta formed in just a few thousand years. Perhaps the Marion Member sequence is a single hydraulic event and was deposited rapidly. And the Marion Member is not unique. Several other key stratigraphic units—each spanning millions of years—contain very few sequences.

It is interesting that the inferred Campanian (Cretaceous) and Ypresian (Eocene) highstands produced terrestrial commercial kaolin deposits, while the Priabonian (Eocene) highstand produced a marine smectite—the Twiggs Clay. This is especially surprising given that the latter highstand was 164–328 ft (50–100 m) lower than earlier highstands (Pickering et al., 2000, their figure 1.2). This curiosity is noted, but not explained:

> Locally in Georgia, the Late Eocene was also a major highstand, but accompanied by marine smectite clays (Twiggs Clay) rather than fluvial to marginal marine kaolin (Pickering et al., 2000, p. 16).

Why did higher sea levels produce non-marine kaolinite and lower sea levels produce a marine smectite?

Geologists consider kaolin purity is a function of oxidation and winnowing during lowstands:

> Lowstands would have led to erosion and unconformities, but would

> also have exposed large areas of new coastal plain to weathering and leaching by groundwater; this during an interval of geologic time when greenhouse climates prevailed (Pickering et al., 2000, p. 16).

Why was this not also true for the younger Twiggs Clay? Millions of years of weathering and leaching should have altered the smectite in the Twiggs Clay. Purification during lowstands also presents problems for the kaolins. The same lowstands that supposedly "cleaned up" the kaolin should have created thick soil horizons and plant growth on top of the clay deposits that would have contaminated the exposed clays. Additionally, millions of years would have created a well-established drainage system that would have been transporting organics and the less pure clay of the Piedmont and mixing both with the kaolin, further decreasing clay purity.

In the same vein, it is interesting that the stratigraphically higher hard clays are not as dramatically altered as the lower soft clays. After all, they are closer to the surface, should have been exposed to more than 20,000,000 years of groundwater and microbial action; and would have been exposed to a similar climate for weathering, winnowing, etc. as the soft clays (since the setting has remained unchanged for 100 million years). Observation of the natural world suggests that the preservation of any pure mineral deposit is the product of unusual conditions, and common sense suggests that such preservation must be rapid to avoid dilution—a more common process than concentration. Timing is also a factor with regard to the role of the Twiggs Clay. The absence of the Twiggs Clay appears to correspond to the oxidation of kaolin bodies in stratigraphically lower units. However, the Twiggs clay was supposedly absent for 60,000,000 years, with kaolin buried in a shallow sedimentary environment near the recharge zone. The time prior to the Twiggs Clay should have been sufficient to create well-oxidized sediments throughout the entire recharge zone.

Finally, concepts explaining the origin of lateritic or bauxitic soils by long periods of weathering have many problems. Despite claims that these soils require up to a million years to form, modern examples demonstrate otherwise (Froede, 2007; Klevberg and Bandy, in press). The primary mechanism of "laterization," leaching by infiltration, has been shown to be less of a factor than groundwater action. Even uniformitarian geologists now trumpet the role of groundwater and bacteria in clay diagenesis, and admit that the process can occur rapidly. Hurst and Pickering (1997, p. 283) noted:

> In permeable layers or zones, however, where conditions were oxic and groundwater contained chelating organics or H_2SO_4 (from bacterially mediated oxidation of sulfides), the rate of weathering was high, and could accomplish strong kaolinization in a few thousand years.

Thus, parameters other than deep time could have contributed to a relatively rapid chemical purification of the Georgia kaolins.

The kaolin of east-central Georgia is thought to have originated from the alteration of updip igneous and metamorphic rocks to saprolite, the transport and deposition of kaolinite muds, and their subsequent diagenesis. This is not inconsistent with the Flood, once issues of timing are resolved. The problem is not so much the formation of kaolinite minerals in sufficient bulk quantity, but their concentration and preservation as nearly pure lenses. That problem is doubled by the occurrence of two distinct types of commercial clay (hard vs. soft), and their apparent stratigraphic separation (Figure 4). As noted, geologists (e.g., Yuan, 2000) do not believe that the upper kaolin was derived from the lower in Georgia, but Brazilian geologists believe that the analogous Capim River deposits are genetically related (Rossetti and dos Santos, 2006). Furthermore, the distinctions between the two types of clay may not be as clear cut as first thought:

> Attempts to substitute the term Cretaceous kaolin for soft kaolin and the term Tertiary kaolin for hard kaolin have not been very successful because occasional Tertiary kaolins have soft kaolin textures and unusual Cretaceous kaolins have somewhat hard textures.... Austin (1998) also noted that Tertiary kaolin clays in Georgia could be as coarse as 50% finer than two microns, which would be coarser than many of the typical Cretaceous kaolins (Yuan, 2000, p. 37).

Another problem that uniformitarians face is the difficulty of deriving a clear stratigraphic succession in the area. In the upper Coastal Plain, classification and correlation are based primarily on lithology. Because lithology is a function of environment and source as well as time, correlation may or may not follow time lines. For example, the Pio Nono Formation was excluded from the Oconee Group because it contains no commercial grade clay. But is that relationship one of lateral facies variation? Geologists support their contention by claiming that the Pio Nono is separated from Oconee sediments by an unconformity, but by their own admission it is "subtle." The problem is not unique to the Pio Nono and Oconee Group sediments. Other stratigraphic units could very easily be distinct facies of similar age. Correlation is quite difficult. Figure 7 illustrates the variation between the stratigraphy of the kaolin belt and that from just the other side of the South Carolina border. In both areas, there are abundant well and core data. But even so, the stratigraphic complexity may be largely artificial. As the early stratigraphers noted, the bulk of the sediments consist of fining upward cycles of gravel, sand, silt, and clay; some capped by kaolin lenses, and others not.

Geologists expecting to see the remains of millions of years of deposition may see complexity of a time-based system, rather than the simplicity of a hydraulic and environmental one. For example, they note that unconformities are crucial in their allostratigraphic approach, yet are the "regional" unconformities really regional and do they represent long periods of time? Often, it appears not:

> The boundary with the overlying Jeffersonville Member is a "subtle unconformity and not easily distinguished" (Pickering et al., 2000, p. 11).

Finally, there is a geomorphological reason to doubt the proposed uniformitarian history. Landscapes are not stable, and for any region to remain basically unchanged for 100 million years stretches credulity, given modern erosional rates or even plate tectonic cycles. This is even more true given the subtropical climate of the area.

A Diluvial Setting

At this time, we cannot offer a complete diluvial model for the formation of soft or hard kaolin clay minerals, but we do propose a number of constraints that any such model must consider. Before any specific diluvial interpretation can be attempted, the bounding assumptions must be revised. These include, of course, the time available for clay formation and the probability of depositional conditions much different from the low-energy paleoenvironments posited by uniformitarians. Because the uniformitarian model depends on millions of years of groundwater and bacterial polishing of very low permeability clays, the major challenge for a diluvial explanation is to find other mechanisms to explain clay purity or to show that the same mechanisms operating over thousands of years could yield the requisite purity.

What are the bounding parameters for a diluvial model? First, we must set the context in terms of the Flood stage. The Coastal Plain sediments as a whole consist of a massive and continuous blanket from the Northeast around the Atlantic and Gulf coasts, where many thousands of feet of sediment accumulated to form the present day continental slope, shelf, and exposed coastal plains. As a whole, these sediments and their subsequent modification by erosion probably resulted from receding floodwaters. However, the variety of facies suggests rapid changes in sea level and lateral hydraulic variation. The late-Flood interpretation is also supported by the unconsolidated nature of the sediments and the dip-oriented interfingering of marine and freshwater facies throughout the vertical record. Therefore, we conclude that the kaolin was probably deposited late in the Flood. The updip, near surface location of the clays also means that they would have been subject to physical and chemical groundwater fluctuations expected from the Flood recession up to the present, although clearly there was not time for the extended exposure of the clay surfaces to weathering and winnowing posited by uniformitarian workers.

The distribution of marine and terrestrial sediments within the Coastal Plain demonstrates sea level fluctuations during their deposition. Once marine waters had permanently withdrawn from the upper Coastal Plain, the adjustment of climatic conditions to post-Flood weather patterns would have resulted in higher precipitation and more rapid groundwater influx for a period of time as the new hydrologic system was being established. This elevated precipitation/recharge condition would have lasted for several centuries after the Flood, due to climatic changes brought about by the Ice Age. The re-establishment of vegetation and fluvial drainage systems would also have affected the groundwater system. Groundwater chemistry would have also been affected by global late to post-Flood volcanism which would have generated a significant amount of acid rain. Variations in bacterial concentrations in both sediments and groundwater may also have been affected. In any case, early diagenetic processes would have been accelerated by acidic and oxic conditions quite different from the present day. Although evidence does not support a direct volcanic precursor for the kaolins, the overlying Twiggs clay—a siliceous smectite—probably did result in part from volcanic ash, and it is not entirely unreasonable to suspect that part of the kaolin deposits did, too.

Another element bounding a diluvial explanation would have been tectonic instability. Uniformitarians date nearby basement rift basins as "Triassic" and assume they were quiescent by Late Cretaceous time, but in the diluvial paradigm, the rifting occurred immediately prior to Coastal Plain sediment deposition. These rift basins occur throughout the Coastal Plain, from Canada to South Georgia (Schlische, 1993). In Georgia, the Gulf Trough/Suwannee Strait exhibit tectonism synchronous with Coastal Plain sedimentation. Just to the east, the upper Coastal Plain sediments overlie the sedimentary fill of the Dunbarton Basin. Updip, the Piedmont Province exhibits evidence of widespread igneous and tectonic activity during the Flood. These factors may have contributed to elevated levels of hydrothermal activity, including the migration of hydrothermal solutions up from basement rocks into the newly deposited overlying sediments. Furthermore, this activity may also have accelerated the formation of clay minerals in the Piedmont Province. The association of kaolin lenses and carbonate karst in northwest Georgia and with bauxite in the western Coastal Plain certainly suggests hydrothermal influences (Silvestru, 2003).

It may well be that saprolite from the Piedmont Province was the precursor of the commercial kaolin clay, but saprolite does not require long periods of in situ weathering to form, given the proper chemical environment. However, it may also be true that the kaolin and the saprolite are both manifestations of the same geochemical processes occurring at the same time. It is interesting that the mineralogy of most of the Cretaceous updip sediments in east-central Georgia consists of physically immature quartz sand with a kaolin matrix. Perhaps these sands are the diagenetic products of arkosic sands, like the Pio Nono Formation, with the feldspar strongly altered to kaolinite by acidic, oxygenated pore fluids.

Although kaolin is quite common in many sedimentary rocks, it is relatively rare in commercial accumulations, especially when found as an apparent sedimentary deposit. Although exact mechanisms for deposition and preservation are elusive, one fact stands out quite clearly: it is much easier to emplace a lens of pure kaolin rapidly than to do so slowly. In the Coastal Plain, there was an abundant supply of terrigenous gravel, sand, silt, organic material, fossils, and other "impurities." The unusual conditions required to deposit a pure kaolin lens would not be expected to last. Thus, while uniformitarian theories focus on how to refine an organic-rich kaolin deposit following deposition, they ignore contamination that would have been occurring simultaneously, caused by the same factors they propose would create pure clay. Also, evidence of high-energy erosion and redeposition of kaolin bodies must have happened quickly; otherwise the redeposited kaolin clasts would have been disaggregated. The greatest failure of their theories is that many deposits of commercial kaolin along the Atlantic and Gulf Coastal plains should be present, given uniformitarian conditions.

The diluvial paradigm raises several new avenues of research regarding the origin of the clays. These can be summarized in the following questions:

1. Can localized clay purity be explained by local, ephemeral geochemical environments?
2. Could clay "polishing" occur during rapid dewatering of acidic, oxygenated pore fluids during clay compaction rather than over millions of years by slow infiltration by less acidic and less oxygenated groundwater?
3. If the soft kaolin is the result of a very rare combination of sedimentary, chemical, and preservation factors, then is it not reasonable to re-evaluate the genetic relationship between the soft and hard kaolin?

Related questions regarding depositional environments and the timing of the emplacement of the Coastal Plain should also be addressed.

Although at present many geologists reject the hard clays as reworked deposits of soft clay, that possibility should not be rejected. Uniformitarians see the current clay lenses as being approximately the same size and shape as when they were originally deposited. But it is certainly possible that the initial clay deposits were more widespread, and that their current configuration reflects their preservation as much as their original state. If nothing else, deriving the hard clay from pre-existing kaolin saves explaining how the same very unusual depositional/diagenetic processes happened twice—a problem for either paradigm.

Differences between the hard and soft clays are as easily explained in the diluvial paradigm as in the uniformitarian. The absence of fossils, with the rare exceptions of large plant remains (i.e., stumps) in the lower clays would fit their rapid deposition as floodwaters receded—further evidence that they formed in an unusual setting. The presence of fossils in the upper clays is also consistent with a sedimentary origin in the retreating, fluctuating marine waters of the Flood via reworking of soft kaolin. The presence of marine waters at the Fall Line suggests a late Flood rather than a post-Flood setting.

Conclusion

The kaolins of east-central Georgia are unique deposits; not simply in their commercial purity, but also in their origin and history. Uniformitarian explanations focus on modern processes operating over tens of millions of years. But their greatest weaknesses are that these processes should have produced ubiquitous impure kaolin deposits along much of the Fall Line. Like many other unusual features of the rock record, a close examination of the data indicates that the standard uniformitarian scenarios cannot explain the actual phenomena in a consistent manner. Many aspects of the Coastal Plain sediments are better explained by rapid, unique erosional and depositional processes rather than 100 million years of uniformitarian stasis. Like many other phenomenon that present mysteries for uniformitarian geology, a change in paradigms may shed light on the origin of these unusual deposits. Rapid hydraulic and geochemical processes may facilitate explanation, and this cursory examination of the upper Coastal Plain suggests that to be the case. Growing knowledge of the Georgia kaolins will reveal clues to their rapid emplacement and their unusual purity, and we predict that superior models and mechanisms will be found in the diluvial paradigm.

Appendix

Uniformitarian clay mineralogists have defined all of the various clay minerals into formal clay groups based on their atomic structure and charge (Chamley, 1989). While uniformitarian geoscientists recognize that clays can diagenetically alter to other clay mineral groups following burial, they have also used them to recreate paleofacies, which requires the assumption that one type of clay has not subsequently been changed into another. The kaolin clays have historically been identified as indicative of freshwater deposition, although they can and do occur in marine settings (often defined as a shallow setting and usually in association with an active fluvial setting). Furthermore, kaolin can form from the chemical alteration of marine clays, such as smectite. The "freshwater" interpretation of Georgia kaolins depends on the absence of marine fossils, but that might not be a reliable indicator if these clays were eroded, transported, and deposited during the Flood. This is another example of uniformitarian assumptions that are often hidden beneath the surface; taken for granted by most geologists, but inappropriate for diluvial studies. Clay minerals can (and likely have) diagenetically altered following burial. We need to consider the conditions expected during the Flood framework and seek to resolve the kaolin question from that perspective.

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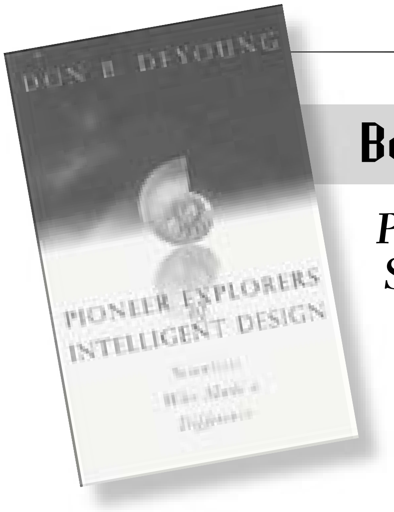

Book Review

Pioneer Explorers of Intelligent Design: Scientists Who Made a Difference

by Don B. DeYoung

BMH Books, Winona Lake, IN, 2006, 128 pages, $13.00.

This is the latest book by prolific author Don DeYoung. It is not that the book represents the plowing of new ground, but at present it is the broadest survey yet of a particular landscape—namely deceased authors important in the history of science along with their religious orientations. DeYoung stresses that "The entire foundation of modern science and technology was laid down by men and women of faith" in a "biblical worldview" (p. xiii).

In my office on the bookshelf are eight other books dealing with comparable topics; however, DeYoung's book has a broader coverage than any other. This coverage includes many Protestants and Catholics, along with Jews and even the Deist Benjamin Franklin.

Dr. John C. Whitcomb writes a brief but excellent foreword in which he describes this pioneer book as "an illuminating and encouraging 'Hebrews 11 Hall of Fame' for creation science. These 144 major contributors to scientific discovery during the past 500 years believed in the God of creation and the biblical record of His mighty works" (p. xi).

The table of contents includes a complete 7-chapter list of the pioneer explorers according to their special fields of interest (astronomy, mathematics, medicine, etc.). Chapter 8 sadly has 16 names of "Missing Persons" from the list of creationist pioneers, including Isaac Asimov, Charles Darwin, and Carl Sagan. There is an alphabetical name index of all the above.

This "Pioneer" publication also has an introduction, conclusion, references, and Scripture index. Many small photos and drawings adorn the pages. An appendix contains an alphabetical list of 106 additional people (Faraday, Newton, Linnaeus, etc.) discussed in Dr. Henry Morris's earlier compilation, *Men of Science—Men of God* (1982).

All of us concerned about the history and impact of science should have DeYoung's book available for reference, as well as to present as a gift to budding scientists.

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Wayne Frair
1131 Fellowship Road
Basking Ridge NJ 07920