PROCEEDINGS OF THE SYMPOSIUM ON THE ECONOMIC GEOLOGY OF THE SOUTHEASTERN INDUSTRIAL MINERALS

Sponsored by the Southeastern Section of the
Geological Society of America, Atlanta, Georgia
April 6, 1989

Edited by
Sam J. Pickering, Jr.

GEORGIA DEPARTMENT OF NATURAL RESOURCES
ENVIRONMENTAL PROTECTION DIVISION
GEORGIA GEOLOGIC SURVEY

BULLETIN 120

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PREFACE

A symposium on the economic geology of Southeastern Industrial Minerals was included in the 1989 Southeastern Section meeting of the G.S.A., held in Atlanta. This volume includes six of the papers presented orally at the symposium.

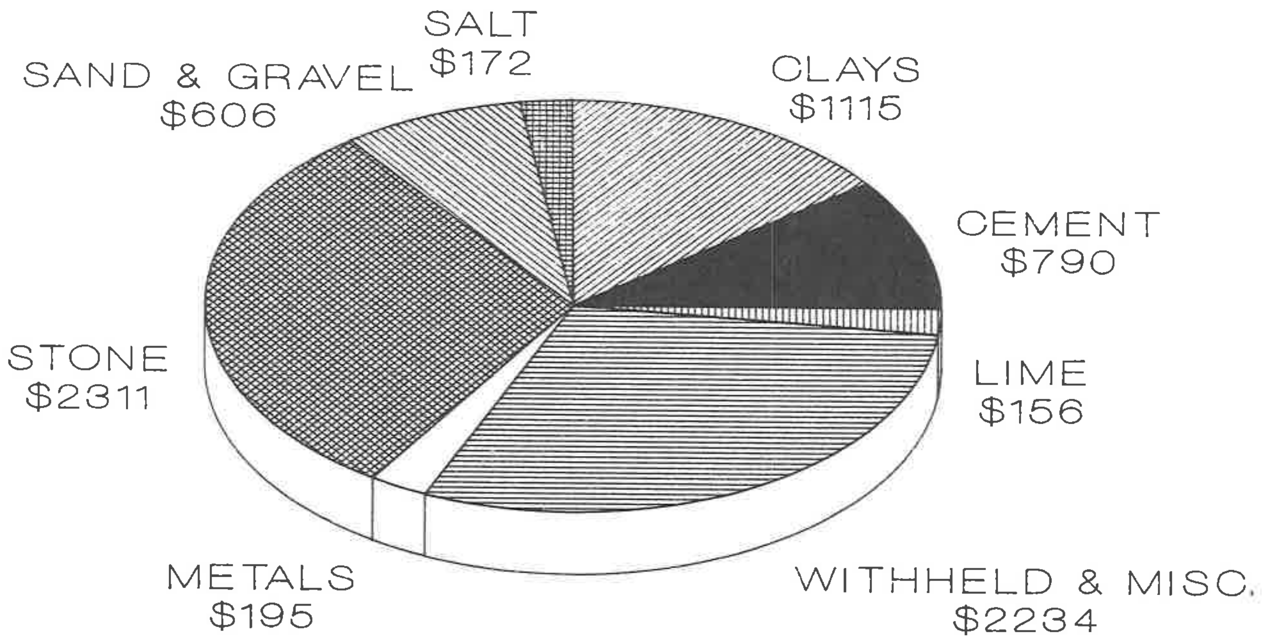
Many sessions on Southeastern economic geology seem to concentrate almost exclusively on metals. The major focus of this symposium has been to highlight the way "common" nonmetallic minerals and rocks dominate the mining economy of our area, and to indicate a few of the ways in which applied geology, mineralogy, weathering history, etc. are essential to profitability.

Industrial minerals are all commercially mined earth materials not consumed as fuels or refined for end use as metals. Typical examples include sand and gravel, clays, crushed and dimension stone, phosphate, salt, barite, heavy minerals for titania pigments and zirconia refractories and abrasives, etc.

Compilation of individual state production records from the U.S. Bureau of Mines *Mineral Facts and Figures* for Alabama, Florida, Georgia, Kentucky, Louisiana, Mississippi, North Carolina, South Carolina, Tennessee, Texas, and Virginia, shows that in 1988 industrial mineral production totalled $7.35 billion, while metals mining accounted for less than $0.19 billion.Somewhat surprisingly, therefore, industrial minerals accounted for 97.5 percent of Southeastern production value, while metals made up only 2.5 percent.

These statistics may be seen graphically as follows:

1988 NON-FUEL MINERAL PRODUCTION IN MILLIONS OF DOLLARS, SOUTHEAST U.S.



adapted from U.S.B.M. Minerals Yearbook

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INDUSTRIAL MINERALS - THEIR IMPORTANCE TO THE UNITED STATES AND THE SOUTHEAST

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ABSTRACT

Industrial or non-metallic minerals have over three times the dollar value of metallic minerals in the United States. Industrial minerals are functional and necessary in many process industries including petroleum, iron and steel, refractories, glass, cement, paper, paint, plastics, rubber, and many others. Our high standard of life correlates with the availability of quality and reasonably priced industrial minerals. The annual growth of industrial minerals in the United States is steady and increases with the value of our gross national product.

Their value ranges from a few dollars per ton for sand and gravel to millions of dollars per ton for industrial diamonds. Geographic location is important in marketing some industrial minerals such as crushed stone for use as aggregate in concrete and relatively unimportant for others such as kaolin and phosphate. Some including phosphate, kaolin, talc, and Wyoming bentonite are exported to all parts of the world. Transportation costs are critical for those industrial minerals that have low unit and place values.

The Southeastern States have a wealth of industrial minerals that are important domestically and for export. These include phosphate in Florida, North Carolina, and Tennessee; kaolin in Georgia and South Carolina; ball clays in Tennessee and Kentucky; fuller's earth in Georgia, Florida, Mississippi, and Tennessee; feldspar in North Carolina and Georgia; marble in Alabama, Georgia, and Tennessee; granite in Georgia; mica and lithium in North Carolina; and others.

Industrial minerals are exceedingly important to continued growth and prosperity but are taken for granted. They merit much more attention than they receive.

INTRODUCTION

A precise inclusive definition of industrial or non-metallic minerals is difficult because many unrelated minerals that range from low priced materials such as sand and gravel to very high priced minerals like industrial diamonds are involved. Noestaller (1987) defines industrial minerals as comprising all non-metallic, non-fuel minerals extracted and processed for industry end uses. His definition includes some metallic ores such as bauxite and chromite which are consumed in non-metallurgical applications, consolidated and unconsolidated rock materials like sand, gravel, crushed rock, and dimension stone, and manufactured products such as cement and refractories. The great diversity of the industrial minerals gives the field as a whole an acute problem of identity.

The industrial minerals penetrate the entire fabric of our industrialized society from such fundamental operations as drilling for oil and smelting iron ore to the manufacture of virtually the entire spectrum of consumer products. There is no industrial minerals industry as such because there are many industries. An aspect of some industrial minerals that differentiates them from the metals is that their physical properties carry over into the ultimate use of the product. Mica, diatomite, kaolin, calcium carbonate, and graphite owe their value to physical properties that persist from the mine face to final application. Although metallic minerals are much better known and popularized, the annual value of the industrial minerals in the United States is over three times that of the metallic minerals.

The wide range and numerous peculiarities of the industrial minerals make their classification challenging and difficult. Many classifications have been proposed such as a combined end-use and genetic classification (Bates, 1960), one based on unit price and bulk produced (Wright and Burnett, 1962), and one by Kline (1970) dividing industrial minerals into two main groups - chemical minerals and physical minerals. The most recent classification appeared in *The Mining Journal* (Anon., 1988) in which industrial minerals are classified into three economic groups: (1) low-price, large volume commodities such as sand, gravel, and construction materials; (2) medium to high price, large volume commodities such as chemical and fertilizer minerals like salt, sulfur, phosphate, and potash; and (3) high price low volume commodities such as fluospar, talc, barite, and industrial diamonds.

Industrial minerals are essential to the development of a modern industrialized society. The developed countries of the world are generally rich in industrial minerals and in fact one can define a developed country on the basis that the value of the industrial minerals exceeds the value of the metallic minerals. Industrial minerals are essential and functional parts of most manufactured products. Our standard of living is related to the fact that the United States has an abundant supply of most industrial minerals. Our industrialized society uses tremendous quantities of industrial minerals annually including crushed stone and sand and gravel in the construction industry, bentonite and barite for drilling oil wells, high calcium limestone as a flux in the iron and steel industry, kaolin as a coating material for paper, silica sand as a major ingredient in making glass, phosphate for the fertilizer industry, and many others.

The United States is well endowed with an adequate supply of most industrial minerals. One of the major factors in the cost of industrial minerals is transportation. Sand and gravel cannot be transported very far because of cost and therefore, these operations must be located near major use centers which are normally large cities. Talc and kaolin, on the other hand, are transported great distances and in many instances the cost of transportation exceeds the cost of the material at the processing plant. Sand and gravel are low priced, high volume materials that are rather common whereas talc and kaolin are medium to high priced materials that are rather uncommon. In general, low priced high volume materials are not shipped very far whereas high priced, low volume materials can be shipped great distances and exported around the world.

INDUSTRIAL MINERALS IN SOUTHEASTERN UNITED STATES

The Southeastern United States contains a wealth of many industrial minerals which are very important to the economy of the individual state and to the region. The Southeastern United States includes the following states; North Carolina, South Carolina, Georgia, Florida, Alabama, Mississippi, Tennessee, and Kentucky (Fig. 1). Some of the more important industrial minerals in the Southeastern United States include ball clays, barite, bauxite, bentonite, feldspar, fuller's earth, granite, high silica sand, kaolin, lithium, marble, mica, phosphate, and talc. The occurrence of these minerals are located on figure 1. Although such industrial minerals as sand and gravel, crushed stone, and common clays and shales are important locally they are not discussed in this paper. The industrial minerals listed above are described and discussed alphabetically in the following pages.

Ball Clays

The ball clay district in Western Kentucky and Tennessee (Fig. 1) is the largest producer of ball clays in the world. The district extends north-south from Mayfield, Kentucky to Paris, Tennessee. The annual production is over 900,000 tons. Ball clays are secondary or sedimentary clays characterized by the presence of organic matter, high plasticity, high dry strength, long vitrification ranges, and light color when fired. Kaolinite is the principal mineral constituent of ball clay and typically makes up more than 70% of this type of clay. Other minerals commonly present include quartz, illite, and a minor amount of smectite.

The ball clay deposits are found in Lower, Middle, and Upper Eocene beds where they occur as lenticular units in which the clay is interstratified with sand, silt, and lignite (Olive and Finch, 1969). The clay units range in thickness from less than 1 m to more than 5 m and generally are thick bedded and massive. They range in color from dark gray to very light gray and contain black carbonized imprints of fossil leaves and other plant debris.

Ball clays are used primarily as a ceramic raw material. These fine particle size very plastic clays are used in whitewares, sanitary ware, stone ware, enamels, and as a bond in certain refractory clays. Ball clays are an important industrial mineral and are shipped all over North America and exported to South America and the Far East.

Barite

Barite ($BaSO_4$ - barium sulfate) is the chief commercial source of the element barium and because of its high specific gravity is used as a weighting material in oil well drilling fluids. Barite is also used in the manufacture of glass and as a pigment, filler, and extender. Pure barite has a specific gravity of 4.5 which is very heavy. In the Southeastern United States barite is mined and processed in north Georgia and eastern Tennessee (Fig. 1). In the Sweetwater district of Tennessee and in the Cartersville district of Georgia, the barite occurs as residual deposits formed by the weathering of preexisting rocks. The

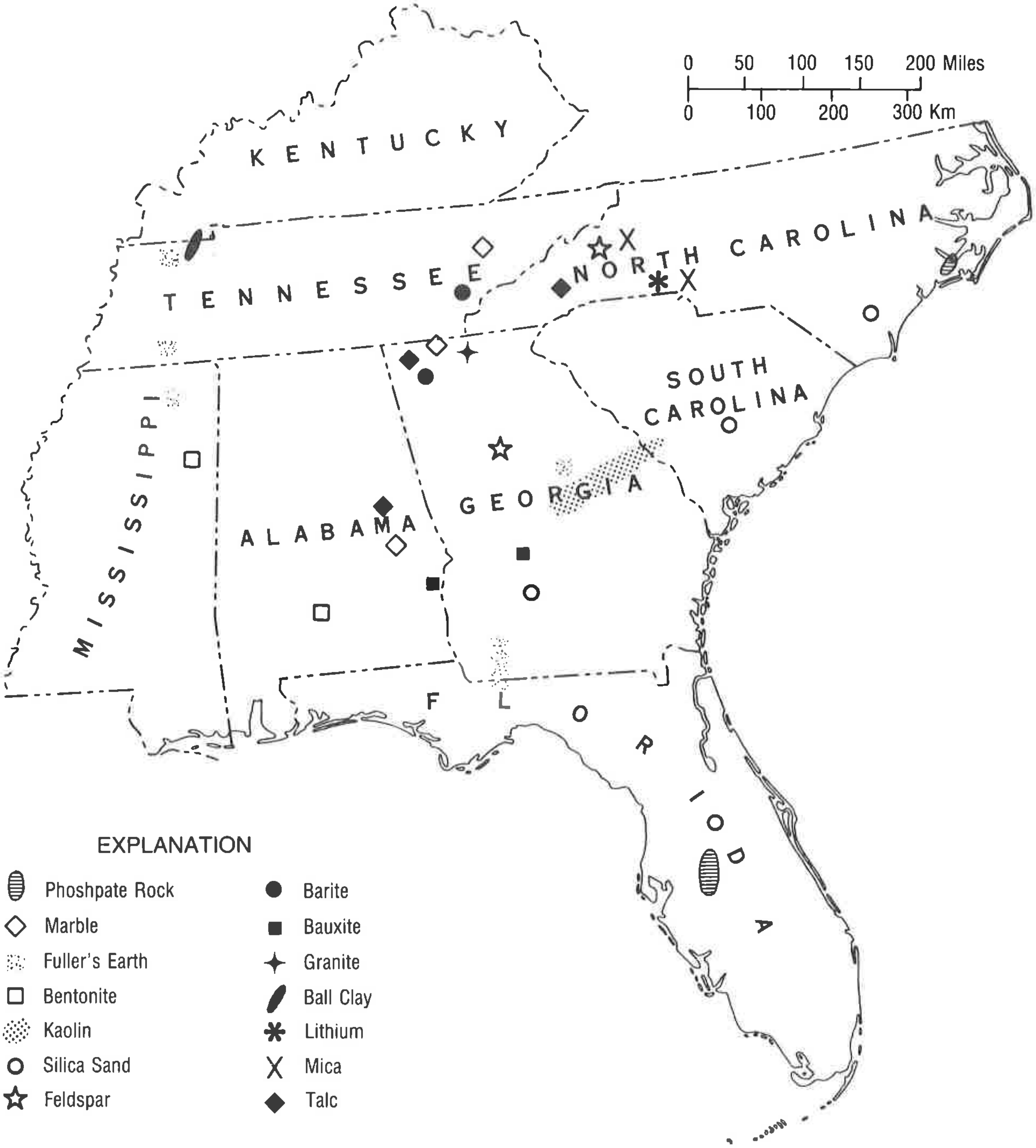

Figure 1. Map of Southeastern United States showing locations of industrial minerals discussed in this paper.

size and shape of the residual barite deposits vary greatly but the larger deposits in Georgia and Tennessee extend over several hundred acres. The barite nodules may be distributed randomly through the residuum or concentrated near the contact with bedrock.

In Georgia the barite deposits are associated with the residuum of the Weisner, Shady, and Rome formations of Cambrian age (Kesler, 1950). In Tennessee the barite is associated with the residuum overlying the upper part of the Knox Group of Ordovician age (Maher, 1970). Most of the barite produced in Georgia and Tennessee is used in the preparation of barium compounds, for glass, and as fillers and extenders. Almost 5,000,000 tons of barite has been produced from Georgia and over 2,000,000 tons from Tennessee. The quality of the barite is good but new reserves are getting more difficult to locate.

Bauxite

Bauxite is the basic ore of the aluminum industry and is also an important industrial mineral. As an industrial mineral bauxite is used as a refractory raw material, an abrasive raw material, for the production of aluminum chemicals, and in the manufacture of high-alumina cements. Bauxite is mined in Alabama and Georgia in the Southeastern states. Bauxite is comprised of the mineral gibbsite and in Georgia and Alabama also contains kaolinite and other minor accessory minerals. The bauxite mined in Alabama is near Eufala (Fig. 1) and is within kaolinitic clay deposits. This bauxite is used for high temperature refractory products, abrasives, and chemicals. The bauxite mined in the Andersonville area of Georgia (Fig. 1) is also associated with kaolin clay deposits and is used to make a calcined refractory grog. One of the grades made has the composition of mullite (Al_2SiO_5). This refractory grog material is calcined, crushed, and screened and is shipped to refractory companies and foundries in the United States, Japan, Europe, and elsewhere. Bauxite is an important industrial mineral both in Alabama and Georgia.

Bentonite

Calcium bentonite, sometimes referred to as Southern bentonite, is mined in Mississippi and Alabama (Fig. 1). The bentonite in Mississippi is mined from the Eutau Formation of Late Cretaceous age and also from Oligocene and Miocene age beds (Bicker, 1970). In Alabama the bentonite occurs in the Ripley Formation of Upper Cretaceous age (Monroe, 1941). The bentonite is waxy and varies from blue when fresh to yellow when weathered. Calcium montmorillonite is the major clay mineral in these deposits and quartz is the most common accessory mineral. Some of these bentonites in Mississippi reach a thickness of 4 to 5 m. The major use of this bentonite from Mississippi and Alabama is as a bonding agent for foundry molding sands. The molding sands used in foundries are composed of sand and clay. The clay provides bonding strength and plasticity. The important physical properties are green compression strength, dry compression strength, hot strength, flowability, permeability, and durability. Calcium bentonites are also acid activated to decolorize mineral, vegetable and animal oils. They are also used for pelletizing animal feed, for drilling muds, as carriers and diluents in pesticide preparations, and in water clarification. Several hundred thousand tons of Southern bentonite are produced annually. Mississippi ranks second in the United States in the production of bentonite and Alabama ranks third.

Feldspar

This mineral is comprised of three types - potash feldspar, sodium feldspar, and calcium feldspar. These are almost never found in pure form in nature but occur together generally in a three component system. Feldspars are mined in North Carolina and Georgia (Fig. 1). The major occurrence of feldspar is in pegmatites where they are associated with many other minerals but dominantly with quartz and mica. The largest production of feldspar in the United States is from North Carolina and the third largest production is from Georgia (Rogers, Nealy and Teague, 1985).

Feldspar is used in the manufacture of glass, in the production of porcelain enamel, as a flux in ceramic whitewares and sanitaryware, as a filler in paint and plastics, and as an abrasive in cleaners and polishes. The largest use is in glass where about 65% of the feldspar is used and 20% is used in ceramics. The annual production of feldspar in the United States is about 800,000 tons. The major specification is chemical purity and for most applications the iron content must be extremely low particularly for use in glass and whiteware ceramics.

Fuller's Earth

The term fuller's earth is more or less a catch-all term for clays or other fine-grained earthy materials suitable for bleaching or decolorizing and sorbent uses. The term has no compositional or mineralogical meaning and was first applied to earthy material used in cleaning and fulling wool, thereby removing the lanolin and dirt; thus, it acquired the name fuller's earth. Most fuller's earth is comprised of palygorskite (attapulgite), sepiolite and, or calcium montmorillonite. Fullers' earth is produced in Florida, Georgia, Mississippi, and Tennessee in the Southeastern region (Fig. 1). In south Georgia and Florida, the fuller's earth deposit are attapulgite and/or mixtures of attapulgite and calcium montmorillonite. In Mississippi and Tennessee the fuller's earth deposits are largely calcium montmorillonite along with smaller quantities of illite and kaolinite. The major non-clay component in all these deposits is quartz. In some of the Mississippi deposits opaline silica is present and in south Georgia some of the deposits contain diatoms.

The fuller's earth district of south Georgia-north Florida (Fig. 1) extends from Quincy, Florida, on the south to Meigs, Georgia, on the north. The deposits are Miocene in age (Patterson, 1974). The southernmost portion of the district contains deposits of relatively pure attapulgite (Fig. 2) and the northern half of the district contains deposits which are mixtures of attapulgite and calcium montmorillonite. The attapulgite deposits range in thickness from 0.5 to 3 m and the mixed clay deposits to the north are up to 6 m in thickness. The

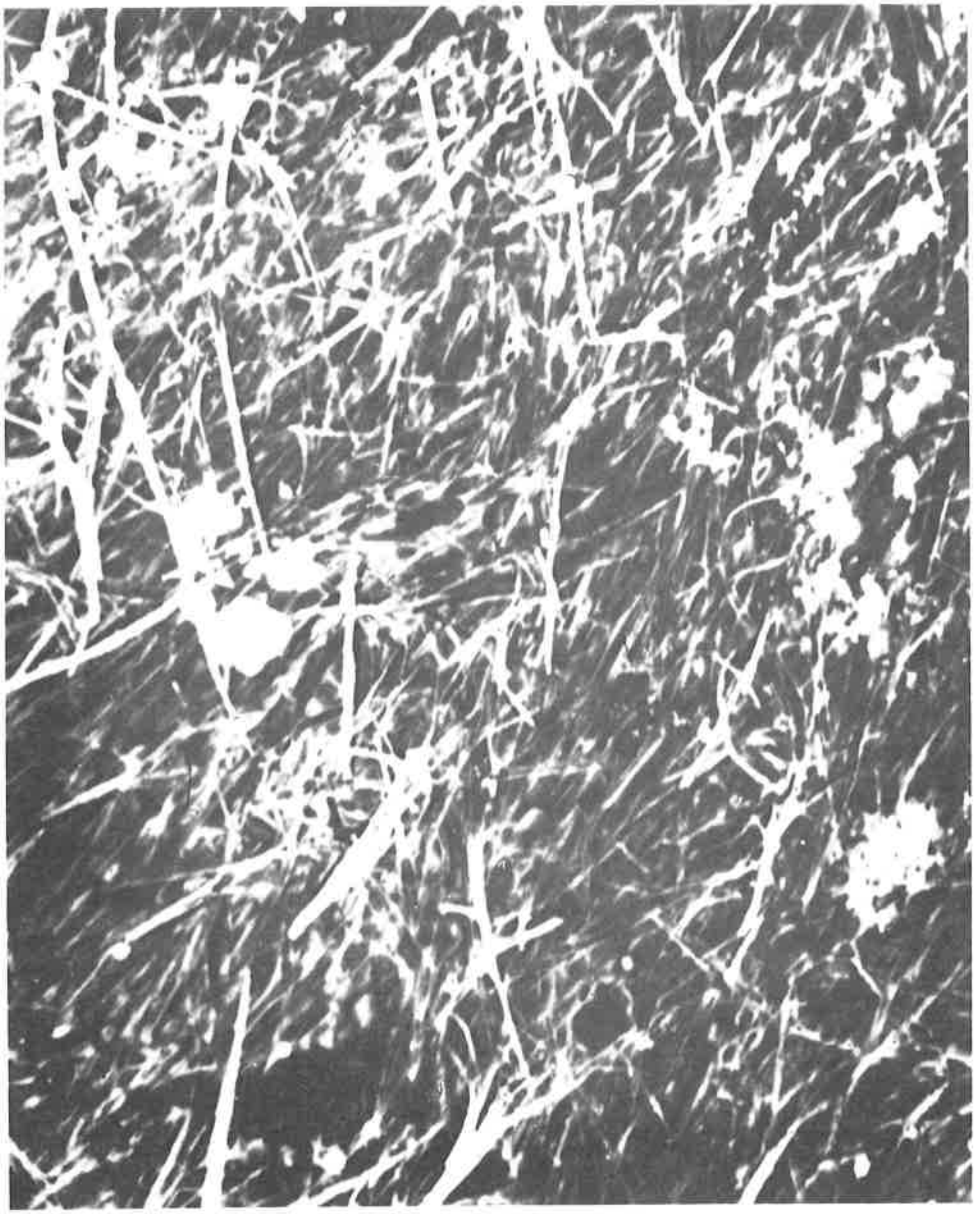

Figure 2. Electron micrograph of attapulgite.

production from the district is over 2 million tons of fuller's earth annually. The attapulgite is used in drilling fluids particularly in areas where the drilling mud can become contaminated with salt water brines, as suspending agents in paint, pharmaceuticals, medicines, and cosmetics, in floor sweep compounds for absorbing oil and grease spills, and in agriculture as absorbents and adsorbents for chemicals and pesticides plus many other special uses. The fuller's earth that is a mixture of attapulgite and calcium montmorillonite from the Georgia area of the district is used primarily for pet litter for absorbing animal waste particularly for domestic cats. Other uses are for animal feed binders, agricultural sorbents, decolorizing oils, anti-caking agents, and other special uses.

In East Georgia near Wrens (Fig. 1) is another fuller's earth that is Lower Tertiary in age and is called the Twiggs Clay. This sorbent clay is almost white in color and is comprised of calcium montmorillonite. This clay occurs above the kaolin deposits in this area and is used for pet litter, agricultural sorbents, and other special uses where color is important.

In Mississippi the fuller's earth deposits occur in the Ripley Formation of Upper Cretaceous age and in the Porters Creek Formation of Eocene age and in Tennessee in the Porter's Creek Formation. Sorbent clay is produced from Northeastern Mississippi, Southwestern Tennessee, and Northwestern Tennessee (Fig. 1). These clays are used primarily for the production of pet litter, oil and grease sorbents, and agricultural sorbents. The total production is well over a million tons from these areas.

Granite

Granite is an igneous rock that is widely used as a building or dimension stone and for monumental stones. The principal requirements are uniformity of texture and color, freedom from flaws, suitability for polishing and carving, and resistance to weathering. In north Georgia (Fig. 1) there are several large granite intrusive bodies that occur as bare exposures or domes (Furcron, 1965). Two well known granites that are quarried for dimension stones and monumental stone are the Elberton granite and the Lithonia granite. Georgia ranks first among the states in the production of granite.

High Silica Sands

Quartz sands that are light in color, friable, and have at least 95% of the sand grains between 20 mesh (850 um) and 140 mesh (106 um) are potentially an industrial silica raw material (Murphy and Henderson, 1983). Depending upon its use the chemical and physical specifications differ. The principal uses of these high silica sands are for glass making, foundry molds, ceramics, chemicals, cement, oil well fraccing, filter sands, and other special uses. For glass the sands have very strict chemical specifications for iron, alumina, and alkali content, whereas for oil well frac sands the chemical compositions is not important but the size and shape of the quartz grains are very important.

High silica sands are an important industrial mineral and there are some very pure silica sand deposits located in the Southeastern United States. High silica sands are mined in North Carolina, South Carolina, Georgia, and Florida (Fig. 1). Silica pebble conglomerates are mined in Alabama and Tennessee. Silica sand is an example of a high bulk, low unit-value commodity.

Kaolin

Kaolin is a white, soft aluminum silicate clay (Fig. 3) that has many industrial applications. The sedimentary kaolins of the Coastal Plain of Georgia and South Carolina have been known since colonial times and today the kaolin district, which extends from Macon, Georgia to Aiken, South Carolina (Fig. 1), produces the largest tonnage of kaolin annually of any district in the world. Georgia ranks as the largest producing state and South Carolina the second. In 1988 over 8 million tons of kaolin were mined and shipped from the kaolin district. The largest user of kaolin is the paper industry where it is used to coat paper to provide a good printing surface and as a filler in the paper sheet. The paper industry uses about 70% of the total production from the Georgia and South Carolina district. Other uses are as a filler for paint, rubber, plastics, and inks and as a raw material for whiteware, sanitaryware, and refractory ceramics. Kaolin is also used as a raw material in making petroleum cracking catalysts and for many other specialized uses such as a suspending agent in medicinal formulations.

The kaolins occur in a belt about 30 kilometers wide that parallels the fall line which is the boundary between the crystalline rocks of the Piedmont and the coastal plain sedimentary rocks (Fig. 4). The kaolins are of two different geologic ages, Upper Cretaceous and Lower Tertiary. The Upper Cretaceous kaolins occur in lenticular or saucer-shaped bodies ranging greatly in thickness and extent. Some are as much as 12 m thick and more than 2 km long (Patterson and Murray, 1984). The Tertiary kaolin deposits tend to be larger than the Cretaceous deposits where thicknesses are 10-25 m and extend for distances as long as 18 kms. There are significant physical and chemical differences between the Cretaceous and Tertiary kaolins. The Cretaceous kaolins are coarser, and contain less iron and titanium than the Tertiary kaolins (Patterson and Murray, 1984). There are also textural and color differences that are noteworthy. The kaolins from Georgia are relatively low viscosity at high solids content (70%) which makes them excellent paper coating clays. These high quality paper coating clays are exported to paper companies all around the world.

Kaolin is a unique industrial mineral because of its excellent properties which include: (1) chemically inertness over a relatively wide pH range, (2) white or near white in color, (3) fine particle size, (4) soft and non-abrasive, (5) good covering or hiding power (opacity), (6) low conductivity of both heat and electricity, (7) low viscosity which permits flow at high solids concentration, (8) relatively low cost.

Some uses of kaolin, for example paper coating, require rigid specifications including particle size, brightness, color, grit content, and viscosity whereas other uses such as in cement, the specifications

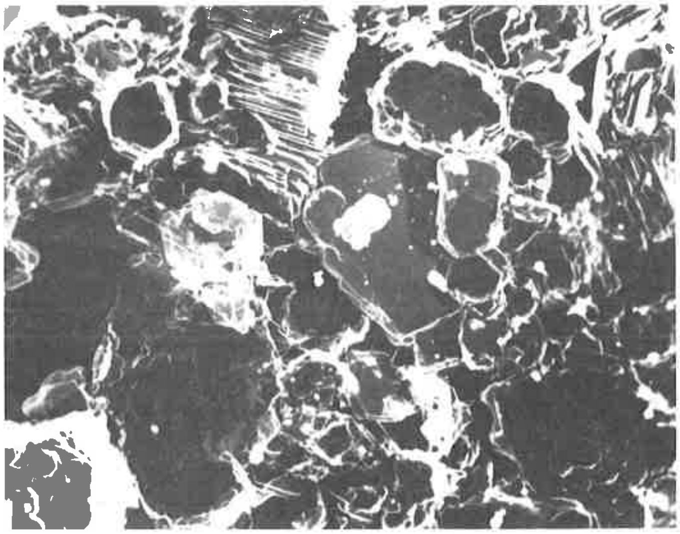

Figure 3. Electron micrograph of kaolin.

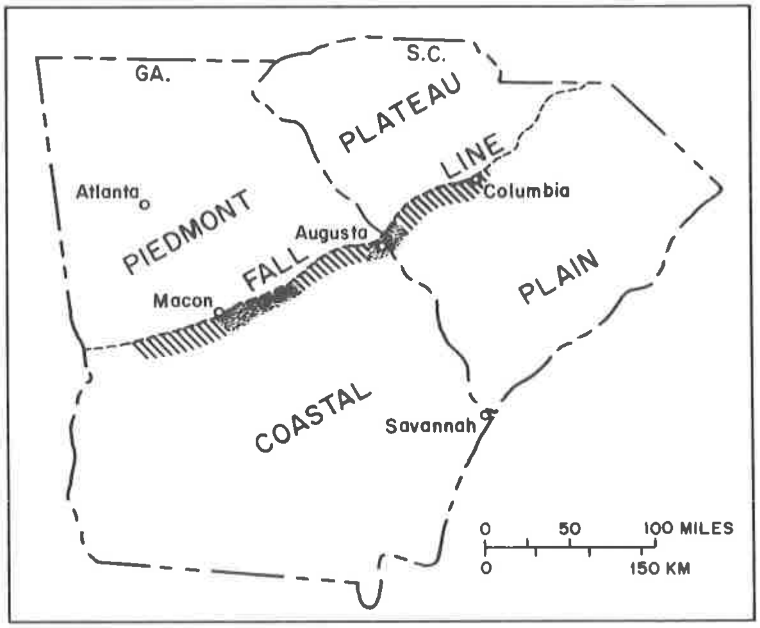

Figure 4. Map showing fall line and kaolin belt in Georgia and South Carolina.

are not critical (Murray, 1986). Kaolin is a most important industrial mineral to Georgia and South Carolina and will continue to be so in the foreseeable future.

Lithium

Lithium is an important element that is derived from lithium minerals and from some dry lake brines. In the Southeastern United States lithium is produced from an area in North Carolina called the tin-spodumene belt (Fig. 1). This belt constitutes the largest developed reserve of lithium in the western world. The mineral which is mined for its lithium content is spodumene ($LiAlSi_2O_6$). Spodumene occurs in pegmatites in the above mentioned belt (Kunasz, 1985).

Lithium is marketed and used in three basic forms; as an ore and concentrate, as a metal, and as chemical compounds. Ores and concentrates are used by the glass, ceramic, and porcelain enamel industries. In metal form, lithium is the lightest solid element having an atomic weight of 6.94 and a specific gravity of 0.534. Lithium is used in aluminum and magnesium alloys where it imparts high temperature strength, improves elasticity, and increases the tensile strength. An important development is the production of lithium batteries which are long life and used in such things as pacemakers, electric calculators, and watches. Lithium chemicals that are marketed include lithium carbonate, lithium hydroxide, lithium chloride and many others. Lithium is still a developing commodity and the future applications for this light metallic element are indeed bright. North Carolina ranks first in the production of lithium.

Marble

Commercial marble is a crystalline rock composed predominantly of calcite and is capable of taking a polish. Marble in scientific usage is a metamorphosed limestone and is quarried in Alabama, Georgia, and Tennessee (Fig. 1). The stone is mined in large blocks which are cut into sheets and shaped and polished. Marble of various patterns and colors (usually gray or white) are mined in all three states. In Georgia the marble is quarried from a series of rocks which occur in the Murphy marble belt near Tate and Marble Hill. The age of the marble is believed to be early Paleozoic (Furcron, 1965). In Alabama, marble is quarried near Sylacauga and is very pure and white. Marble is the official rock of Alabama and this white marble is shipped all over North America. The age of this marble is believed to be Ordovician. The marble industry in Tennessee is centered in the general vicinity of Knoxville and the age of the marble is Middle Ordovician. Marble production in all three states is important. It is used for dimension stone, monument stone, for chips used in terrazzo floors, for high calcium lime, and is ground and pulverized for a variety of filler and pigment uses. The largest production comes from Georgia which ranks first in the United States.

Mica

Muscovite mica is a colorless, platy mineral comprised of potassium, aluminum, and silicon with some magnesium and iron substituting for aluminum. Muscovite has excellent basal cleavage that allows it to be split into very thin sheets exhibiting a high degree of flexibility, elasticity, and toughness. Mica is classified as sheet mica, which are large crystals or books of muscovite, and scrap and flake mica which are small mica crystals or flakes. Sheet mica is generally found in pegmetites and scrap and flake micas are recovered from various mica-bearing sources such as mica schist, granite, and in some pegmatites. Flake or scrap mica is produced in North Carolina from the Tin-Spodumene belt and in the Spruce Pine district (Fig. 1). This mica is used in plasterboard joint cements, paint, plaster, oil well drilling, plastics, and for special uses such as in wallpaper to provide sheen and in rubber tires for mold lubrication and dusting. The mica is prepared for market by either wet or dry grinding depending on the particle size needed. North Carolina is an important producer of flake and scrap mica products.

Phosphate Rock

Phosphate is extremely important to life both plant and animal. Phosphate rock production has experienced a very steady growth since 1945 (Emigh, 1985). Phosphate rock is commonly called rock in sedimentary deposits and apatite in igneous deposits. In the Southeastern United States phosphate rock is mined in Florida, North Carolina, and Tennessee (Fig. 1). The United States produces over 50 million tons of phosphate rock annually with about 85% coming from Florida and North Carolina. The deposits of phosphate rock in all three states are sedimentary. The Tennessee deposits are mined near Columbia and are Ordovician in age. The North Carolina phosphate deposits are near Beaufort and are Lower Miocene in age. The Florida deposits are in the vicinity of Bartow and Lakeland and are Middle Miocene in age.

Fertilizers consume 95% of the worlds phosphate rock production. The United States is the worlds largest producer and also user of fertilizer. In addition to use in fertilizers, phosphate rock is used to make phosphorous chemicals including phosphoric acid which is used in the manufacture of many industrial phosphates including detergents, industrial cleaners, and forest fire retardants. Important by-products from phosphate rock processes include gypsum, uranium, vanadium, and fluorides. Phosphate rock mining in Florida is under very strict reclamation and environmental restrictions but still produces about 70% of the total U.S. production. Phosphate rock mining and processing is an important industry in both Florida and North Carolina.

Talc

The mineral talc is the softest mineral on the Mohs scale of hardness and is a hydrous magnesium silicate. Steatite was originally a mineralogical name applied to pure talc but today steatite generally refers to a massive variety of talc. Soapstone is a talcose rock that is soft and exhibits a high degree of lubricity. Talc is an extremely versatile industrial mineral that is used in the ceramics, paint, rubber, paper, plastics, and cosmetics industries. It is also used in many miscellaneous applications such as textile sizing, foamed latex rubber backing for carpets, lubrication aids, cereal polishing, floor wax, insecticides, and many others.

Talc is a metamorphic rock that is generally associated with dolomites or ultramafic igneous rocks. Talc is mined in Alabama, Georgia, and North Carolina (Fig. 1). Near Chatsworth, Georgia, talc occurs as lenticular bodies in either dolomite or ultramafic rocks. In North Carolina talc occurs as small pods or lenses associated with metamorphosed dolomites. Pure white talc is mined in Talladega County, Alabama which goes into cosmetics and pharmaceuticals. The parent rock is a Cambro-Ordovician dolomite (Roe and Olson, 1985). Because of the softness of talc and its unique surface chemistry, it is an important filler. Although the production of talc is small in each of the three states, it is used for very special purposes and is therefore an important and unique industrial mineral.

SUMMARY

Industrial minerals are very important to the Southeastern United States and particularly to the state in which each material is mined and processed. In the Southeastern States the following industrial minerals rank first in production in the nation - ball clay, fuller's earth, granite, kaolin, lithium, marble, and phosphate. Ball clay, fuller's earth, kaolin, lithium, and phosphate are exported and thus are important to the balance of payments of the United States.

Industrial minerals are essential to the process industries and most are functional parts of the products into which they are placed. The United States has one of the highest standards of living in the world if not the highest and this is related to the fact that functional and high quality industrial minerals are available at reasonable cost to the process industries. No country can be a developed country without a large supply of necessary and functional industrial minerals. The Southeastern United States is well endowed with a large number of important industrial minerals.

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HEAVY MINERAL DEPOSITS OF THE SOUTHEASTERN ATLANTIC COASTAL PLAIN

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ABSTRACT

Heavy minerals have been mined from surface sands and near surface sands of the Atlantic Coastal Plain in the southeastern United States for decades. Important heavy mineral deposits in northern Florida and southeastern Georgia formed in beach ridges developed at the crest of major marine transgressions. Examples are the Trail Ridge and Highland (Maxville) deposits along Trail Ridge and the Yulee, Cabin Bluff, and Altama deposits along the Pamlico shoreline. Other deposits in the region developed in beach ridges formed at times of temporary halts or at times of slight transgressions during periods of general marine regression. The Green Cove Springs, Boulougne, and Folkston deposits on the Duval Upland are examples of such occurrences. These concepts on the origin of the ore bodies are drawn from studies of sediment characteristics, heavy mineral suites, and field relations.

INTRODUCTION

Heavy minerals have been mined from the sands of the southeastern Atlantic Coastal Plain since the early part of this century (Table 1). Not all of the ore-grade concentrations have the same origin or the same heavy mineral suite. In this report only heavy mineral deposits in northern Florida and southeastern Georgia are discussed. These heavy mineral concentrations occur in beach ridges of quartz sand that formed along ancient shorelines during late Cenozoic time.

STUDIES OF THE COASTAL PLAIN TERRACES

Workers have studied the terraces and ridges of the

TABLE 1

CHRONOLOGY OF HEAVY MINERAL MINING ATLANTIC COASTAL PLAIN OF THE SOUTHEASTERN UNITED STATES[1]

Operator (Deposit)	Dates of Operation
North Carolina Monazite Mining	1895-1916
Buckman-Pritchard, Inc. (Mineral City, FL)	1916-1929
Riz Mineral Company/Florida Ore Processing (Palm Bay near Melbourne, FL)	1940-1955
Humphries Gold Corp.[2] (Arlington, FL)	1943-1964
Hobart Brothers (Vero Beach, FL)	1956-1963
Humphries Gold Corp./E. I. Du pont de Nemours & Co., Inc. (Trail Ridge, FL)	1949-Present
Marine Minerals (Horse Creek, Aiken, SC)	Late 1950's-early 1960's
Humphries Gold Corp. (Folkston, GA)	1964-1974
Titanium Enterprises/Associated Minerals USA (Green Cove Springs, FL)	1972-Present
Humphries Mining Company (Bolougne, FL)	1974-1980

[1] Modified from Garnar 1978; 1980

[2] Humphries Gold Corp. later became Humphries Mining Co.

Atlantic Coastal Plain for decades. Lyell (1845) recognized a series of ancient shoreline scarps in Georgia. McGee (1887) investigated the Chesapeake Bay region. Shattuck (1901, 1906) made detailed studies of terraces in Maryland. Johnson (1907) considered terraces of North Carolina. Veatch and Stephenson (1911) described the Coastal Plain terraces of Georgia, and Stephenson (1912) studied terraces in North Carolina.

Many other studies followed the investigations of these earlier workers. Some of these contributions include those by Prettyman and Cave (1923), Cooke (1925, 1931, 1932, 1936, 1943, 1945, 1966), Flint (1940), MacNeil (1950), Price (1951), Richards (1954), Doering (1960), Johnson and DuBar (1964), Herrick (1965), Thom (1967), Hoyt and Hails (1967, 1971, 1974), Colquhoun (1969, 1974), Colquhoun and Pierce (1971), Oaks and Coch (1973), Oaks and DuBar (1974), DuBar *et al.* (1974), Winker and Howard (1977), Howard and Scott (1983), Kussel and Jones (1986), Markewich (1987), and Huddlestun (1988). There was, and still is, much dispute as to the total number and ages of terraces present in the Atlantic Coastal Plain.

HEAVY MINERAL DEPOSITS

Numerous heavy mineral deposits have been identified within ridges on the Atlantic Coastal Plain. Some of these deposits are currently being mined, some have been mined with reserves depleted, some have been lost to mining because of cultural developments, and some likely will be mined in the future.

The largest deposit in the southeastern United States is the Trail Ridge ore body presently being mined by E. I. Du Pont de Nemours and Company east of Starke, Florida (Fig. 1). The deposit occurs in the southern part of Trail Ridge. Most of the quartz sand composing the Trail Ridge landform is medium (1/2 to 1/4 mm) to fine (1/4 to 1/8 mm) in size (Table 2). The medium sand fraction typically constitutes from 50 to 70 percent of the total sand, and the fine sand fraction usually constitutes from 20 to 40 percent of the sand (Pirkle and Yoho, 1970). The heavy mineral suite of Trail Ridge sands consists of ilmenite, leucoxene, rutile, zircon, kyanite, sillimanite, staurolite, spinel, corundum, and tourmaline (Cannon, 1950; Garnar, 1972). Of these heavy minerals, 46 percent by weight are the titanium minerals ilmenite, leucoxene, and rutile (Table 3). These titanium minerals and zircon constitute the principal economic minerals of the deposit. Other economic minerals include kyanite, sillimanite, and staurolite.

The Highland (or Maxville) ore body is present just north of the Trail Ridge ore body (Fig. 1). This deposit actually is a continuation of the Trail Ridge deposit and is presently under development. The grain sizes of the quartz particles and the heavy mineral suite are essentially the

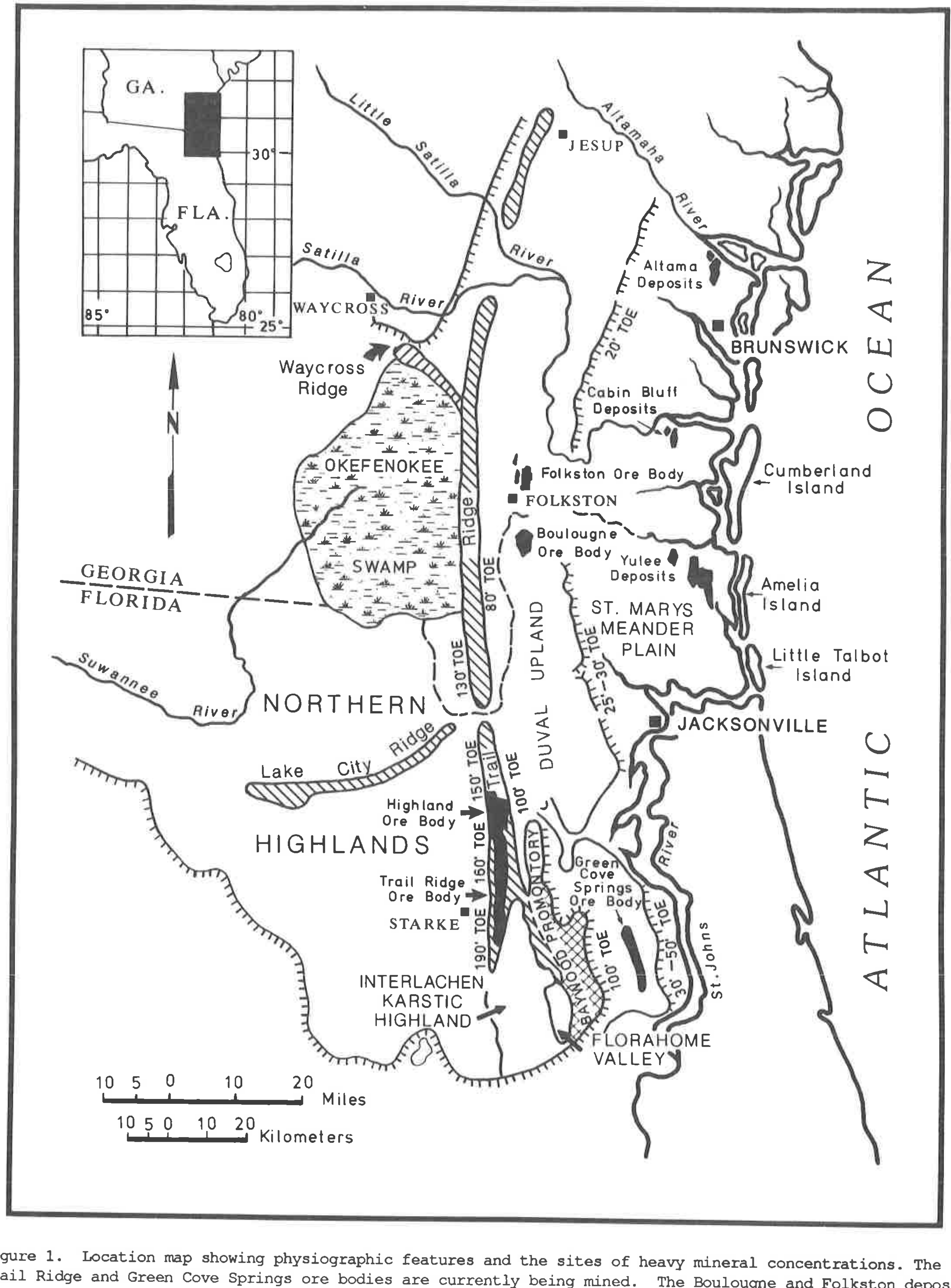

Figure 1. Location map showing physiographic features and the sites of heavy mineral concentrations. The Trail Ridge and Green Cove Springs ore bodies are currently being mined. The Boulougne and Folkston deposits have been mined out, and the Highland (Maxville), Yulee, Cabin Bluff, and Altama deposits have not been developed.

TABLE 2

Sieve Analyses of Sediments Encountered in Trail Ridge Drill Hole #1 (Pirkle and Yoho, 1970)

NE 1/4, SE 1/4, Sec. 31, T. 6 S., R. 23 E., Clay County, FL

				Percent sand[1] retained on mesh						
Spl.	Depth in ft. & in.	Sand in %	Silt & Clay in %	10 (>2 mm)	18 (2 to 1 mm)	35 (1 to 1/2 mm)	60 (1/2 to 1/4 mm)	120 (1/4 to 1/8 mm)	230 (1/8 to 1/16 mm)	HM[2] in %
Trail Ridge Sands, Humate and Ore Zone (Elev.: 239 ft.)										
1	0-1′3"	95.91	2.89			4.62	61.26	29.99	4.14	1.80
2	1′3"-5′	92.64	4.58		.04	3.74	57.69	32.83	5.69	2.43
3	5′-10′	94.13	3.16		.01	3.86	48.58	43.42	4.03	3.46
4	10′-17′6"	92.34	6.37		.06	4.08	59.27	33.81	2.78	3.34
5	17′6"-25′	97.13	1.70			4.15	68.17	26.16	1.52	3.02
6	25′-30′	96.13	2.68			3.43	55.11	37.57	3.89	4.02
7	30′-35′	96.54	2.39		.08	5.16	72.59	21.20	.97	2.48
8	35′-40′	97.84	1.40		.02	12.31	70.84	14.72	2.10	2.12
9	40′-45′	97.31	1.20			.64	53.88	36.13	9.35	13.54
10	45′-50′	98.72	.60			.61	48.96	42.02	8.41	16.29
11	50′-55′	98.94	.14			1.33	50.27	41.81	6.58	9.78
12	55′-60′	98.43	.10			1.35	57.53	36.27	4.85	8.82
13	60′-63′	98.53	.40		.02	1.80	70.42	25.75	2.02	2.55
Intercalated Layers of Peaty or Sapropelic Sediments and Quartz Sand Underlying Trail Ridge Sands (Elev.: 176 ft.)										
14	63′-68′	8.39	.01			.89	22.80	47.50	28.81	1.22
15	68′-73′	89.70	3.20			6.89	46.19	27.98	18.95	.90
16	73′-74′6"	83.98	12.52		.09	8.76	51.44	26.79	12.92	.55
17	74′6"-77′	92.36	4.78	.06	.04	3.43	26.85	36.68	32.92	.65
18	77′-78′	85.53	11.98		.07	6.70	47.40	33.49	17.34	.70
19	78′-80′6"	96.25	2.29		.08	5.98	38.02	40.61	15.30	.90
20	80′6"-84′6"	68.91	28.22		.09	12.27	54.27	24.95	8.42	.43
21	84′6"-86′	77.65	20.37		.15	15.72	59.00	20.83	4.30	.63

[1] Quartz sand and heavy mineral sand

[2] Heavy Minerals

TABLE 3

WEIGHT PERCENT OF TOTAL HEAVY MINERALS

	Deposit					
Mineral	Trail Ridge	Highland (Maxville)	Green Cove Springs	Yulee	Cabin Bluff	Altama
Ilmenite	34.7	32.8	47.0	52.7	62.0	54.6
Leucoxene	7.9	10.1	6.4	2.2	3.0	1.7
Rutile	3.4	1.8	4.6	7.4	5.6	6.9
Zircon	20.6	16.2	15.1	16.0	14.1	10.5
Kyanite/ Sillimanite	17.5	12.3	6.7	6.7	5.1	8.4
Staurolite	11.0	19.5	9.4	5.2	3.7	6.0
Spinel	0.0	0.1	0.1			0.0
Corundum	0.6	0.4	0.3		0.1	0.1
Tourmaline	4.2	6.7	6.2	1.7	1.4	2.7
Monazite[1]	0.1	0.1	0.7		1.7	0.9
Garnet	0.0	0.0	0.5	0.4	0.8	0.3
Epidote	0.0	0.0	3.1	6.6	1.8	7.3
Hornblende	0.0	0.0	0.1	0.8	0.8	0.6
Total	100.0	100.0	100.2	99.7	100.0	100.0

[1] Monazite includes zenotime

same as those of the Trail Ridge ore deposit (Fig. 2, Table 3).

Another large heavy mineral deposit in Florida currently is being mined by Associated Minerals U.S.A. just south of Green Cove Springs (Fig. 1). These accumulations are present in ridges of quartz sand that occur on the Duval Upland. Generally 90 percent or more of the quartz sand composing the ridges falls into the fine (1/4 to 1/8 mm) and very fine (1/8 to 1/16 mm) sand fractions (Table 4). The heavy mineral suite, though similar to that of the Trail Ridge deposits, contains minor amounts of epidote and garnet, minerals usually not found in the Trail Ridge sediments (Table 3). Titanium minerals constitute about 58 percent by weight of the total heavy minerals of the Green Cove Springs deposits.

The Boulougne and Folkston deposits (Fig. 1) are depleted. They were mined by Humphries Gold Corporation (later renamed Humphries Mining Company). These heavy mineral concentrations, like those of the Green Cove Springs area, accumulated in ridges of quartz sand on the Duval Upland. The size of the quartz sand containing the heavy minerals of the Boulougne and Folkston deposits is essentially the same as that of the Green Cove Springs deposits. The heavy mineral suite is characterized by the presence of minor amounts of epidote and garnet.

The Yulee, Cabin Bluff, and Altama deposits (Fig. 1) occur in beach ridges on barrier islands formed along the Pamlico shoreline. The heavy mineral suites of these deposits are similar to those of the deposits on the Duval Upland. They contain epidote and minor amounts of garnet (Table 3). In general, the fine and very fine sand fractions of these deposits constitute 90 percent or more by weight of the total quartz sand (Table 5). In the Yulee deposits the titanium minerals ilmenite, leucoxene, and rutile constitute about 62 percent by weight of the total heavy minerals (Table 3). Analyses of composite samples from various parts of the Cabin Bluff and Altama deposits show that these sediments have essentially the same grain size distributions of quartz sand and the same heavy mineral suites as the Yulee deposits (Fig. 2, Table 3).

Characteristics of the sediments composing the various ridges and the nature of the heavy mineral suites prove very helpful in studies related to the origin of the heavy mineral concentrations.

UNDERLYING SEDIMENTS

The deposits on which the ridges containing heavy mineral ore bodies rest have been studied and discussed by many investigators. Fenneman (1938) described the materials underlying the terrace surfaces as consisting of poorly stratified, sometimes cross-bedded, sheets of sand, gravel, and clay. Herrick (1965) described these sediments in

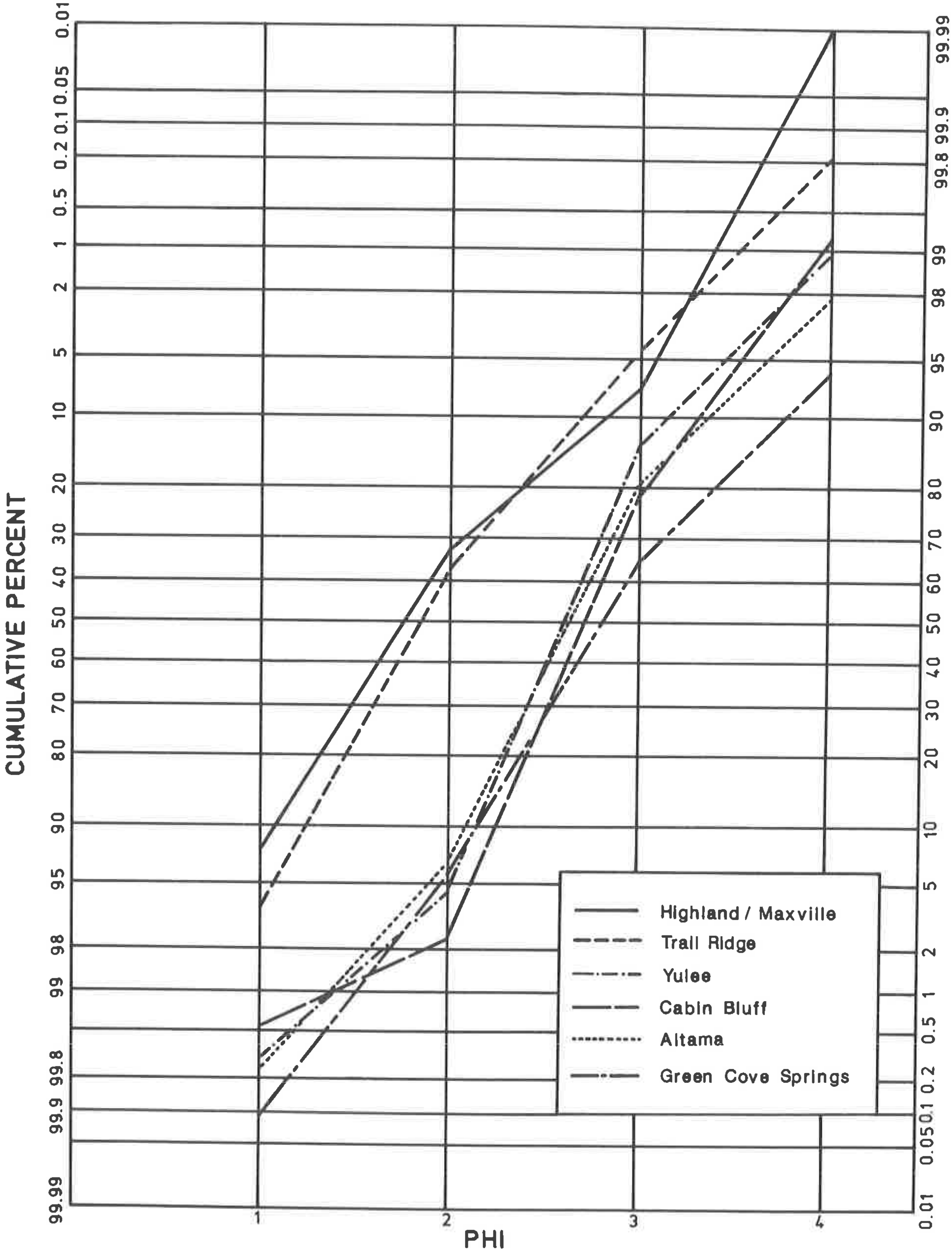

Figure 2. Cumulative size distribution curves of sediments from heavy mineral concentrations located in northern Florida and southeastern Georgia.

TABLE 4

Sieve Analyses of Sand From Selected Holes Drilled in the Green Cove Springs Deposit (from Pirkle _et_ _al_., 1974)

Depth in Feet & Inches	Percent sand[1] retained on mesh					Heavy Minerals in %
	18 (2 to 1 mm)	35 (1 to 1/2 mm)	60 (1/2 to 1/4 mm)	120 (1/4 to 1/8 mm)	230 (1/8 to 1/16 mm)	
UC No. 1, NW 1/4, SW 1/4 Sec. 21, T. 7 S., R. 26 E.: Elev. 112 ft.						
0′-3′		.09	5.71	61.24	32.97	1.12
3′-5′		.13	5.59	63.12	31.15	1.17
5′-10′		.15	5.87	67.25	26.72	3.49
10′-15′6"		.07	4.75	67.73	27.45	9.39
15′6"-17′6"		.09	3.86	65.65	30.41	1.63
17′6"-21′		.06	4.53	71.08	24.33	1.03
21′-24′6"	.02	.06	7.37	70.48	22.06	1.02
24′6"-25′		.02	2.66	47.24	50.08	1.61
UC No. 2, SE 1/4, SE 1/4 Sec. 10, T. 8 S., R. 26 E.: Elev. 85 ft.						
0′-1′		.10	5.54	58.13	36.23	1.54
1′-5′		.15	4.56	59.85	35.44	2.18
5′-10′		.04	5.26	66.73	27.97	5.29
10′-15′		.13	6.91	65.10	27.86	1.28
15′-20′		.53	11.75	63.17	24.53	.28
20′-22′6"	.02	.19	9.12	63.93	26.74	.23
22′6"-25′	.02	.24	5.48	41.88	52.38	1.19
UC No. 3, SE 1/4, SE 1/4 Sec. 6, T. 7 S., R. 26 E.: Elev. 118 ft.						
0′-5′		.13	7.00	67.12	25.75	1.30
5′-10′	.02	.04	5.08	69.44	25.42	5.16
10′-15′		.04	4.46	68.41	27.08	4.84
15′-20′		.04	4.32	73.39	22.25	3.36
20′-25′		.11	4.96	73.51	21.42	1.53

[1] Quartz sand and heavy mineral sand

TABLE 5

Sieve Analyses of Sediments from Selected Holes Drilled in the Yulee Heavy Mineral Deposits (from Pirkle *et al.*, 1984)

Depth in Feet & Inches	Percent sand[1] retained on mesh				Pan	Heavy Minerals in %
	35 (1 to 1/2 mm)	60 (1/2 to 1/4 mm)	120 (1/4 to 1/8 mm)	230 (1/8 to 1/16 mm)	(<1/16 mm)	
Yulee Drill Hole #10 Sec. 46, T. 3 N., R. 27 E.: Elev. 42 ft.						
0′-2′6″	.20	2.00	78.39	18.08	1.33	6.13
2′6″-5′	.12	1.55	81.33	16.09	.91	6.06
5′-7′6″	.02	1.10	81.36	16.66	.86	6.58
7′6″-10′	.04	1.51	83.25	14.32	.88	4.16
10′-12′6″	.02	2.29	85.23	11.37	1.09	2.33
12′6″-15′	.28	5.02	83.40	10.46	.84	.44
15′-20′	.27	5.80	80.10	13.22	.61	2.00
20′-25′	.81	8.13	79.75	10.66	.65	5.50
25′-30′	1.40	4.79	74.53	17.96	1.32	2.68
Yulee Drill Hole #6 Sec. 50, T. 3 N., R. 27 E.: Elev. 42 ft.						
0′-2′6″	.07	1.06	84.99	12.92	.96	6.02
2′6″-5′	.04	.93	86.69	11.49	.85	5.96
5′-7′6″	.02	1.02	86.25	11.58	1.13	5.84
7′6″-10′	.02	1.02	85.85	11.71	1.40	5.64
10′-12′6″	.06	1.94	86.73	9.85	1.42	2.92
12′6″-15′	.07	4.07	87.38	7.83	.65	1.07
15′-20′	.30	6.59	82.84	9.27	1.00	.82
Yulee Drill Hole #4 Sec. 44, T. 3 N., R. 28 E.: Elev. 29 ft.						
0′-2′6″	.73	13.70	77.24	7.83	.50	2.80
2′6″-5′	.91	13.98	75.00	9.44	.67	3.21
5′-7′6″	.52	9.73	80.79	8.30	.66	2.50
7′6″-10′	.22	6.44	81.17	11.16	1.01	3.01
10′-12′6″	.47	7.20	77.10	13.45	1.78	4.90
12′6″-15′	.43	4.90	75.60	16.79	2.28	5.23
15′-20′	1.07	9.45	80.11	8.43	.94	1.54

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[1] Quartz sand and heavy mineral sand

Georgia as composed of interbedded sands and clays with the clays becoming more prominent in downdip coastal areas. He further stated that many investigators have treated the deposits as "physiographic forms, classifying them as marine terraces consisting of marine and fluvial sediments." Huddlestun (1988) points out that the terraces are geomorphic features, not stratigraphic units.

In general, the sediments on which the ridges rest are predominantly sand and clayey sand with the clay content usually increasing in the lower parts of the sediments. At some sites thin stringers and small lenses of massive clay are common and become more abundant with depth. Also, in some areas granules and small pebble size particles of quartz are common, especially in the lower portions of the sediments. Deltaic materials constitute an important part of the surface blanket of sediments at those sites where major rivers emptied into the seas as the sediments were accumulating. Some areas where the formation of deltas was significant have been recognized by Winker and Howard (1977). The following brief comments concerning materials immediately underlying ridges containing heavy mineral concentrations add additional insight as to the nature of these sediments and aid in an understanding of the origin of the sand ridges.

In Trail Ridge #1 drill hole (Table 2), ore sands were encountered from the crestal area of the Trail Ridge landform to a depth of approximately 63 feet. These ore-grade sands (primarily medium to fine in size) are separated by an unconformity from an underlying 23-foot zone consisting of intercalated layers of peaty or sapropelic sediments and quartz sand. The quartz sand of this underlying unit is primarily medium, fine, and very fine. Approximately 92 percent by weight of the upper 5 feet of this 23-foot zone is woody or peaty material. Sediment characteristics and heavy mineral data for these sediments are given by Pirkle and Yoho (1970) and Pirkle _et al._, (1970).

Holes have been drilled through the Highland (Maxville) ore body on Trail Ridge to determine the nature of the sediments on which the ridge sands rest at that locality. In one hole (Highland #1, Pirkle _et al._, 1977), Trail Ridge size quartz sand was encountered from the land surface to a depth of about 53 1/2 feet. Of this interval the upper 35 to 40 feet contain ore-grade concentrations of heavy minerals. The sediments beginning at a depth of 53 1/2 feet consist of intercalated lenses or layers of quartz sand, clayey sand, sandy clay, and massive clay. The quartz sand in this underlying unit ranges from very fine to coarse, but most of the sand is very fine. As is true at the site of Trail Ridge #1 drill hole, brown woody (peaty) material occurs in the sediments underlying the Trail Ridge sands at this locality. Characteristics of the sediments and heavy minerals are given by Pirkle _et al._ (1977).

The sediments beneath the ridges containing the Green Cove Springs ore body also have been described in the literature. In one hole (U. C. #3, Pirkle et al., 1974), 25 feet of gray and moderate brown quartz sand with black organic zones overlie about 19 feet of brown sand. Over 90 percent of the quartz sand in the top 25-foot zone is fine to very fine (Table 4). Also, over 90 percent of the quartz sand in the upper part of the underlying 19-foot zone is fine to very fine (Pirkle et al., 1974). However, the sand in the lower part of the 19-foot zone becomes somewhat coarser. Ore sediments extend from the land surface to a depth of about 20 feet. The sediments in the areas of the Boulougne and Folkston ore bodies, now mined out, are similar in grain size to the Green Cove Springs deposits. The heavy mineral suites are also similar.

In general, over 90 percent of the quartz sand of the Yulee ore deposits (Fig. 1) is fine to very fine (Table 5). The sediments underlying the ore ridges have been discussed by several investigators. Pirkle et al. (1984) state,

> Sediments consisting of fine quartz sand and clayey sand underlie the Yulee ridges. At some sites these sediments contain stringers and lenses of coarse quartz sand and clay. Excellent exposures of these underlying materials are present along bluffs bordering the St. Marys River and Bells River.

Fossil lenses have been encountered in these underlying sediments. An example of lenses exposed at Reids Bluff along the St. Marys River is discussed later in this report.

The sediments upon which the Cabin Bluff ridges rest consist of fine to very fine quartz sand and clayey sand. The quartz sand commonly increases in coarseness in the lower part of these underlying sediments. The clay occurs disseminated throughout the sands and as stringers and thin lenses of massive clay. In general, the clay stringers and clay lenses increase with depth. At some sites these underlying sediments contain granule to small pebble size, angular quartz particles. Fossil shells have been encountered in the sediments that underlie these ridges. Studies of these fossils suggest that the deposits are late Pleistocene or late Pleistocene to Recent.

Studies also have been made of the materials that underlie the Altama deposits. In one drill hole (Altama #7, Pirkle et al., 1989), quartz sand extends downward to a fossil zone at a depth of 62 1/2 feet below the land surface. The sand is primarily fine to very fine. At this hole site the upper 7 1/2 feet of sand contain ore-grade heavy mineral concentrations. At 27 feet stringers and lenses of massive gray clay become important. The quartz sand becomes coarser and gravel and small pebble-size quartz particles more abundant at a depth of 47 feet. This lithology continues downward to the shell bed at 62 1/2 feet. The shell bed is separated from the overlying sediments by an unconformity. Sieve analyses of these sediments, discussions of the heavy minerals, and identification of and comments concerning the fossils are given by Pirkle *et al.*, (1989).

SEDIMENT CHARACTERISTICS AND DEPOSIT ORIGIN

According to one current working hypothesis the Florida-Georgia Coastal Plain ridges containing heavy mineral concentrations generally fall into one of two categories:

1) beach ridges formed at the crest of major marine transgressions. These deposits occur in ridges formed in the general crestal regions of the transgressions. The Trail Ridge, Highland (Maxville), Yulee, Cabin Bluff, and Altama deposits are present in ridges that belong in this category.
2) beach ridges formed on regressional beach ridge plains during intervals of lengthy stillstands of the regressing seas or during intervals of temporary transgressions of the regressing seas. The Green Cove Springs, Boulougne, and Folkston deposits are considered as examples of heavy mineral concentrations that accumulated in ridges of this category.

Trail Ridge and Highland (Maxville) Ore Bodies

As previously mentioned, Trail Ridge sands are mostly medium to fine grained and have a heavy mineral suite that is generally devoid of epidote and garnet. In contrast, all sediments composing ridges and underlying terrace surfaces east of Trail Ridge consist primarily of fine to very fine quartz sands which are characterized by a heavy mineral suite that often contains some epidote and garnet. At various localities along the more coastal regions, the sands may contain substantial amounts of epidote and hornblende. Differences in the size of the quartz sand, comparisons of heavy mineral suites, and studies of field relations are of much value in considering the depositional history and origin of the beach ridges and heavy mineral deposits. As discussed by Pirkle, W. A. and Pirkle, E. C. (1984), the sand particles of the sediments underlying the Northern Highlands (Fig. 1) are of a size range that, if reworked in a shoreline environment, might be expected to give a size distribution of quartz grains similar to that comprising the Trail Ridge landform.

Also, the general lack of epidote and garnet in Trail Ridge sands is consistent with the formation of Trail Ridge as a beach ridge developed at the height of a major marine transgression. During the transgression the seas eroded landward into the Northern Highlands. The sands underlying large areas of the Northern Highlands contain little or no epidote or garnet. Since these are the major source sands for Trail Ridge, the general absence of epidote and garnet in Trail Ridge sands would be expected.

It should be mentioned, however, that small amounts of epidote and garnet have been found in some areas of Trail Ridge sands. Sediments deposited in tidal inlets that developed through Trail Ridge in post-Trail Ridge time may carry epidote, garnet, and very small amounts of hornblende. One such possible occurrence was reported by Pirkle and Czel (1983). Also, along the western side of Trail Ridge adjacent to such ancient inlets, sands may carry a small amount of epidote and garnet. Furthermore, fine sands carrying small amounts of epidote and garnet are banked up along the eastern side of Trail Ridge at some sites. These occurrences suggest that at those localities younger seas encroached onto the Trail Ridge landform from the east. Moreover, in some exploration drilling, especially along the more eastern side of Trail Ridge, rather coarse sands containing minor amounts of clay and some clay lenses have been penetrated beneath various thicknesses of typical Trail Ridge sands. These sediments carry minor amounts of epidote and garnet. Actually the presence of epidote and garnet in some areas of Trail Ridge should be expected. Even though the advancing Trail Ridge seas were eroding into the sediments of the Northern Highlands over long distances, the seas most certainly eroded into Pliocene sediments and older Hawthorne sediments at some localities. Both the Pliocene and the older Hawthorne sediments contain epidote and garnet in their heavy mineral suites.

An important relation of the Trail Ridge landform relates to organic materials. At some sites Trail Ridge sands overlie a thick zone of lignitic peat derived from trees, shrubs, and aquatic herbs that grew in a fresh water swamp (Rich, 1985). Some cypress stumps of this swamp are still in place. These relations show that sands of Trail Ridge migrated westward (landward) over a fresh water swampy area. Migration of beach ridges can be seen at a number of sites along the present Atlantic coast. One excellent example occurs on Cumberland Island off the southeastern Georgia coast (Figs. 3 and 4). There a long, active sand ridge is migrating westward (landward) over marshy sediments.

Field relations are crucial in the determination as to whether the Trail Ridge landform developed in the general crestal area of an eroding, transgressing sea. Trail Ridge seems to truncate older landscape features in a landward direction. To illustrate, Trail Ridge is parallel to the present Atlantic coast and appears to truncate the Lake City and Waycross ridges (Fig. 1). Also, the land surface east (seaward) of Trail Ridge is lower in elevation than the plains area west (landward) of the ridge. These field

Figure 3. View of part of a large, migrating sand ridge along the western side of Cumberland Island off the southeastern coast of Georgia. Along the left side of the photograph the sand ridge is covering trees as it migrates landward (toward the reader).

Figure 4. Trunks of trees uncovered as the sand ridge shown in figure 3 moved from this site to a position farther west (landward). Carbon-14 dating of one of the uncovered tree trunks gave an age of 205 years B.P.

relations are consistent with the concept that Trail Ridge formed as a beach ridge in the crestal area of an eroding transgressing sea.

Yulee, Cabin Bluff, and Altama Deposits

Hoyt and Hails (1974) consider the areas in which the Yulee, Cabin Bluff, and Altama ridges occur as parts of Pamlico barrier islands. White (1970, Fig. 34) shows that in some areas of eastern Florida older relic beach ridges are truncated by the Pamlico shoreline. Thus, the ridges containing these heavy mineral concentrations can be correlated with the crestal area of the Pamlico transgression.

Many holes have been drilled in the Yulee, Cabin Bluff, and Altama deposits. Sediments in these crestal areas reflect ancient sea level fluctuations. Some sediments penetrated were deposited under marine conditions, some under brackish conditions, and others under subaerial conditions. These environments were identified through studies of fossil invertebrates, fossil vertebrates, fossil wood, palynological data, and diatoms.

Excellent exposures of sediments along the northern end of the Yulee deposits are present in bluffs along the St. Marys and Bells rivers. According to Kussel and Jones (1986), the sediments exposed in these bluffs were laid down "in a marine to marginal marine setting with sedimentation proceedings along a prograding shoreline during marine regression." One of the bluffs, Reids Bluff (Fig. 5) has been designated by Huddlestun (1988, p. 134) as a reference locality and a parastratotype of the Satilla Formation. At this bluff about 15 feet of sand are exposed immediately above the level of the St. Marys River (Fig. 6). These sands contain trunks and root systems of cypress trees (Fig. 7). The buried cypress trees are in place. Kussel and Jones (1986) reported the presence of fossil burrows of the marine decapod Callianassa in these lower sands. The sediments with the buried cypress trunks are overlain by blue-gray clayey sediments containing oyster lenses (Figs. 6 and 7). At most sites a thin layer of the blue-gray clayey sediments separates the sands with the buried trees from the first overlying oyster lens. About 4 or 5 feet of the blue-gray clayey sediments separate this oyster lens from a higher oyster lens. The higher oyster lens, in turn, is covered by about 4 to 6 feet of the blue-gray clayey sediments. Approximately 30 to 35 feet of loose quartz sand extend from the upper blue-gray clayey material to the land surface. The upper 10 to 12 feet of these upper sands are wind-blown accumulations, the sands having been blown up the present cliff face to accumulate as ill defined ridges bordering the river (Fig. 8). Kussel and Jones (1986) believe that this bluff possesses the characteristic sedimentary structures and faunal assemblages of a tidal

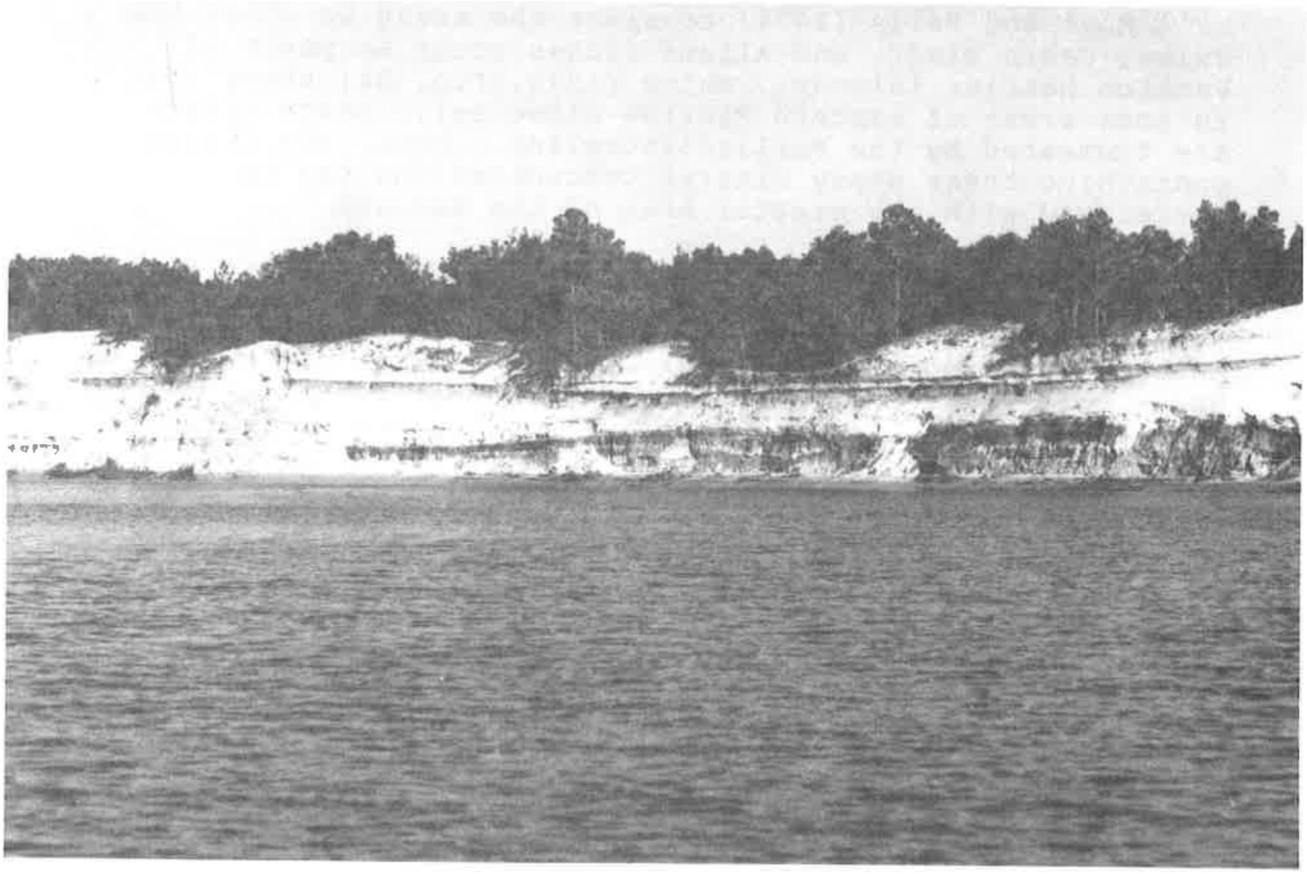

Figure 5. Distant view of Reids Bluff along the St. Marys River at the northern end of the Yulee heavy mineral sand deposits.

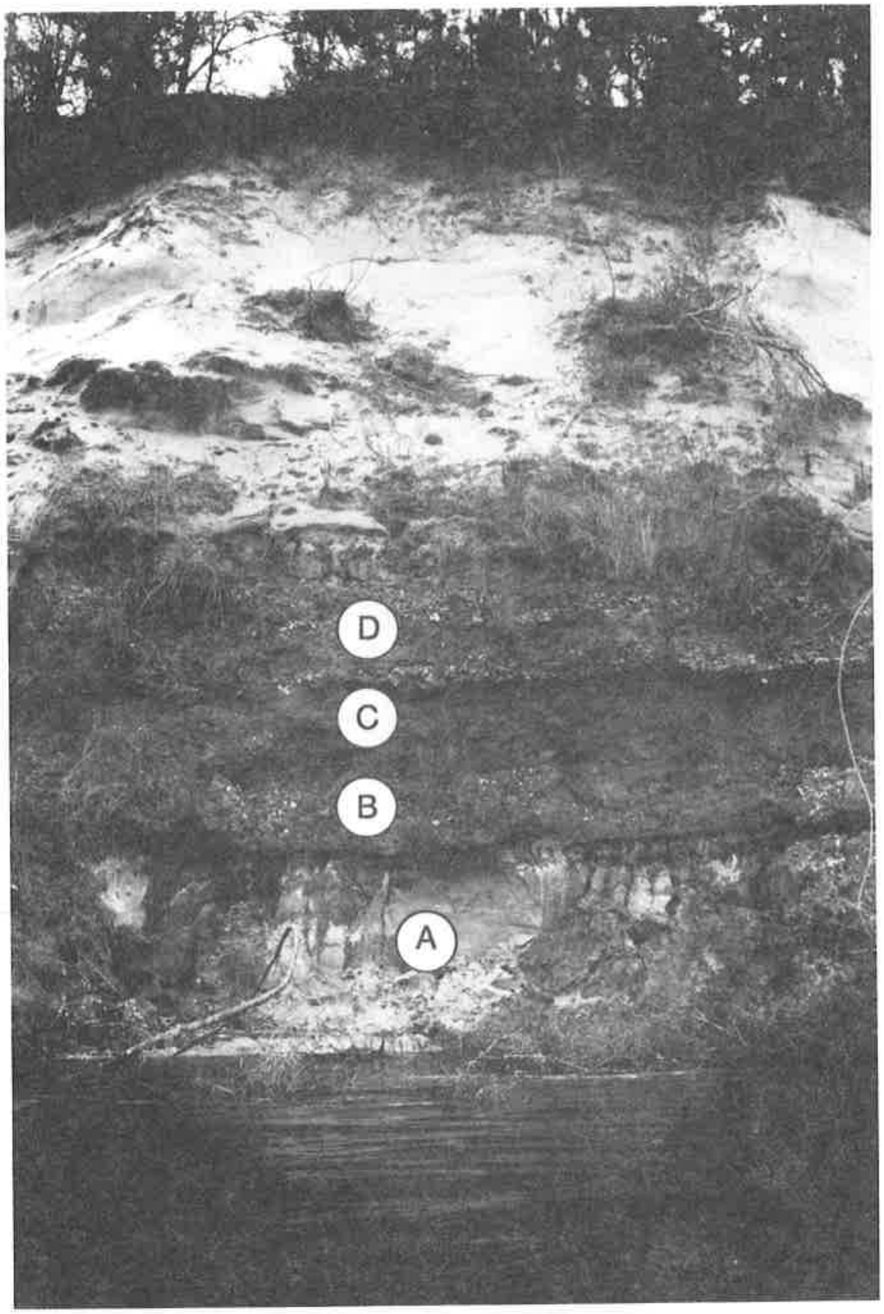

Figure 6. Closer view of Reids Bluff. Sediments from the river level upward are loose quartz sand (A), an oyster lens (B), blue-gray clayey sediments (C), and an upper oyster lens (D). A thin zone of blue-gray clayey sediments underlies the lower oyster lens, and a few feet of blue-gray clayey sediments overlie the upper oyster lens. These upper blue-gray clayey sediments are overlain by loose quartz sand that extends to the land surface.

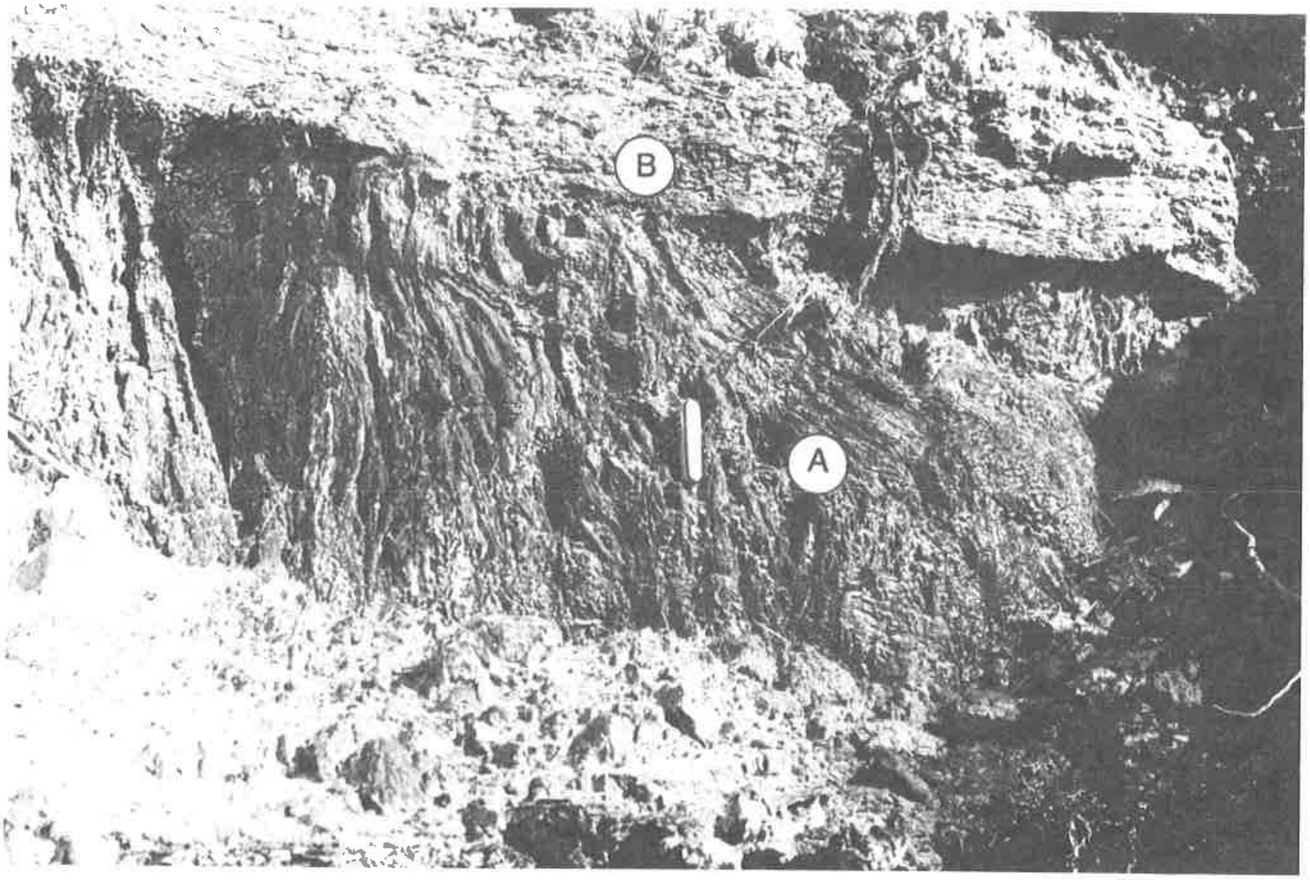

Figure 7. View of buried cypress stump in place. The cypress (labeled A) is dark in appearance and occupies the central part of the photograph. A knife, in the middle of the exposed cypress material, indicates the scale. The material (labeled B) that lies above the cypress stump is an oyster lens.

Figure 8. Tree being covered with sand along top of bluff. The river is to the left in the photo.

flat/salt marsh environment of a barrier island complex. The bluff furnishes some of the best exposures along the St. Marys River, and the sediments reflect deposition during sea level fluctuations. It is of interest to note that the land surface to the east of the Yulee ridges is lower in elevation than the land surface to the west of the ridges, a relationship consistent with the concept that the Yulee deposits formed at the height of a marine transgression.

Green Cove Springs, Boulougne, and Folkston Deposits

According to the current working hypothesis, the Duval Upland east of Trail Ridge is a regressional beach ridge plain (Pirkle et al., 1974). As the seas regressed, lengthy stillstands and possibly slight transgressions took place. During these intervals beach ridges, some containing heavy mineral concentrations, were formed. It must be recognized, however, that it also can be argued that the beach ridges formed in the crestal areas of marine transgressions, perhaps the Penholoway (95-foot) seas of Winker and Howard (1977) or the Wicomico (100-foot) seas of Cooke (1945) and MacNeil (1950). Nevertheless, there are several lines of evidence that are favorable to the first concept -- that the Duval Upland topographically is a regressional beach ridge plain and the ore bodies formed in beach ridges developed during stillstands or during times of temporary transgressions of regressing seas. Some of the evidence can be mentioned.

The Green Cove Springs, Boulougne, and Folkston ridges are not well-defined ridges as are Trail Ridge and ridges in the crestal areas of the Pamlico transgression. White (1970) believes that the presence of shells in sediments that accumulate to form ridges along shorelines may play a role in the preservation of the ridges. He believes some ridges that formed at the crest of eroding transgressing seas are distinct and well defined partly because of the lack of fossils in the original sediments that accumulated to form the ridges. In these cases the transgressing seas eroded into sediments from which fossil shells, if originally present, had been leached out or dissolved over long periods of time. White believes that landward sediments are the main source sediments for beach ridges developed in crestal regions of eroding, transgressing seas. Thus the ridges would not become diminished with age as a result of the removal of fossils through solution. In contrast, ridges formed along shorelines of regressing seas or along prograding shorelines are built of sediments brought by longshore drift or shoreward transport across the fore beach. These sediments from the sea contain a relatively high percentage of shells. During later weathering under warm and humid climatic conditions, the shells would be dissolved, and the ridges, having lost a considerable amount of their original bulk, would become less well defined and less distinct.

The Green Cove Springs, Boulougne, and Folkston deposits are in the more interior part of the Duval Upland, rather than along its eastern or seaward edge. The ridges do not appear to lie atop erosional scarps. Of most importance, perhaps, is the fact that no physiographic features in a landward direction appear to be truncated by the shorelines along which the mineral-bearing ridges formed. Thus, from various field relations it appears that the Green Cove Springs, Boulougne, and Folkston deposits formed during stillstands or during periods of slight transgression of a generally regressing sea. The evidence, however, is not conclusive.

CONCLUSIONS

The heavy-mineral deposits of the south Georgia-north Florida Atlantic Coastal Plain appear to have two major origins. Deposits such as Trail Ridge, Highland (Maxville), Yulee, Cabin Bluff, and Altama formed in beach ridges developed in crestal areas of major marine transgressions. The second type of deposit formed during marine regression when temporary stillstands or slight transgressions of the regressing seas occurred. During these intervals beach ridges formed and heavy minerals were concentrated in the ridges to give such deposits as the Green Cove Springs, Boulougne, and Folkston ore bodies.

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KAOLIN IN THE SOUTHEASTERN UNITED STATES

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In the Southeastern United States, kaolin occurs in deposits of sufficient purity and volume to be of major economic value. Of these, the most important are those which occur in Cretaceous and early Tertiary sedimentary strata in a belt extending from Middle Georgia to eastern South Carolina. The belt of so-called "sedimentary kaolin" actually extends throughout the Atlantic and Gulf Coastal Plains, from the Mid-Atlantic states to Texas, but purity, brightness, and viscosity are best in Georgia and South Carolina.

Primary kaolin deposits also are present. These are much more localized in nature, having developed in feldspathic igneous and metamorphic rocks of the Blue Ridge, Piedmont and similar areas. The residual cap of kaolin with bauxite which overlies syenite west of Little Rock, Arkansas, is a classic example. In the Piedmont and Blue Ridge provinces, some pegmatites and relatively leucocratic portions of some granites and gneisses have been thoroughly altered to remarkably white kaolin as well.

Other deposits of kaolin occur among younger Cenozoic sedimentary strata of the Coastal Plain of Florida, Georgia and other states. Typically, these deposits are impure or sandy kaolin or kaolinitic sand and have low yield and limited quality for commercial applications.

The geological framework of most of the Southeastern deposits including the Cretaceous and Early Tertiary sedimentary types (as well as much and possibly most of the kaolins associated with pegmatites, and other felsic intrusive and metamorphic rocks) is that of an aluminous laterite. On close examination, there are many similarities between these depoits and those of other major kaolin areas of the world. These include the lateritized sedimentary strata occurring throughout much of northern Australia (with significant kaolin production in Northern Queensland) and the Coastal Plain of the northern and eastern countries of South America (with important production in northern Brazil). Lateritized igneous and metamorphic rocks cover vast areas of southwestern Australia and the shield regions of the northeastern countries of South America. Both regions have several scattered mines and plants.

Aluminous laterites, however, do not always signify the existence of commerical deposits of kaolin. Laterites are recognized by a number of well-known signatures including bauxites and bauxitic kaolins, layers of ferrugenous concretions, and lateritic soils. Such soils commonly are aluminous, clayey, concretionary and red, mottled or white in color They are impoverished of plant nutrients. For years, farmers in laterite areas have received blame for depleting soils which actually have had little value since Eocene time.

The development of kaolin deposits having commercial value depends on geological serendipity. First, an aluminous host is required. These typically include arkosic sands, clays, silts, syenites, and granitic rocks. Next, laterization must be sustained long enough and the host material of sufficient porosity and permeability so that leaching and subsequent recrystallization can thoroughly alter the host. The profound nature of past episodes is demonstrated by kaolinitic gneisses which occur beneath hundreds of feet of Tertiary and Cretaceous strata in the Georgia Coastal Plain.

Finally, solution and removal of non-aluminous constituents must be enabled by an adequate flux of groundwater. In the extreme, however, too much leaching will prohibit formation of kaolinite and induce formation of gibbsite instead. High levels of oxygen can fix undesired iron in forms which act as strong pigments. Following the episode of laterization, relative stability is required so that the deposits will not be too deeply buried by younger sediment, destroyed by erosion, or altered because of a significantly changed geochemical environment.

The special nature of the kaolin deposits (see figure 1) in Georgia is reflected by the nearly 8.0 million tons of refined products produced annually and their value of $860,000,000 in 1988. The kaolin industry in Georgia (see figure 2) has roots going back to the 1700's, but it was not until the 1930's that the unique nature of these deposits was fully recognized. Over the 50 years which have followed, countless improvements in refining technology have led to the development of a

Fig. 1. Twin engine motor scraper mining kaolin.

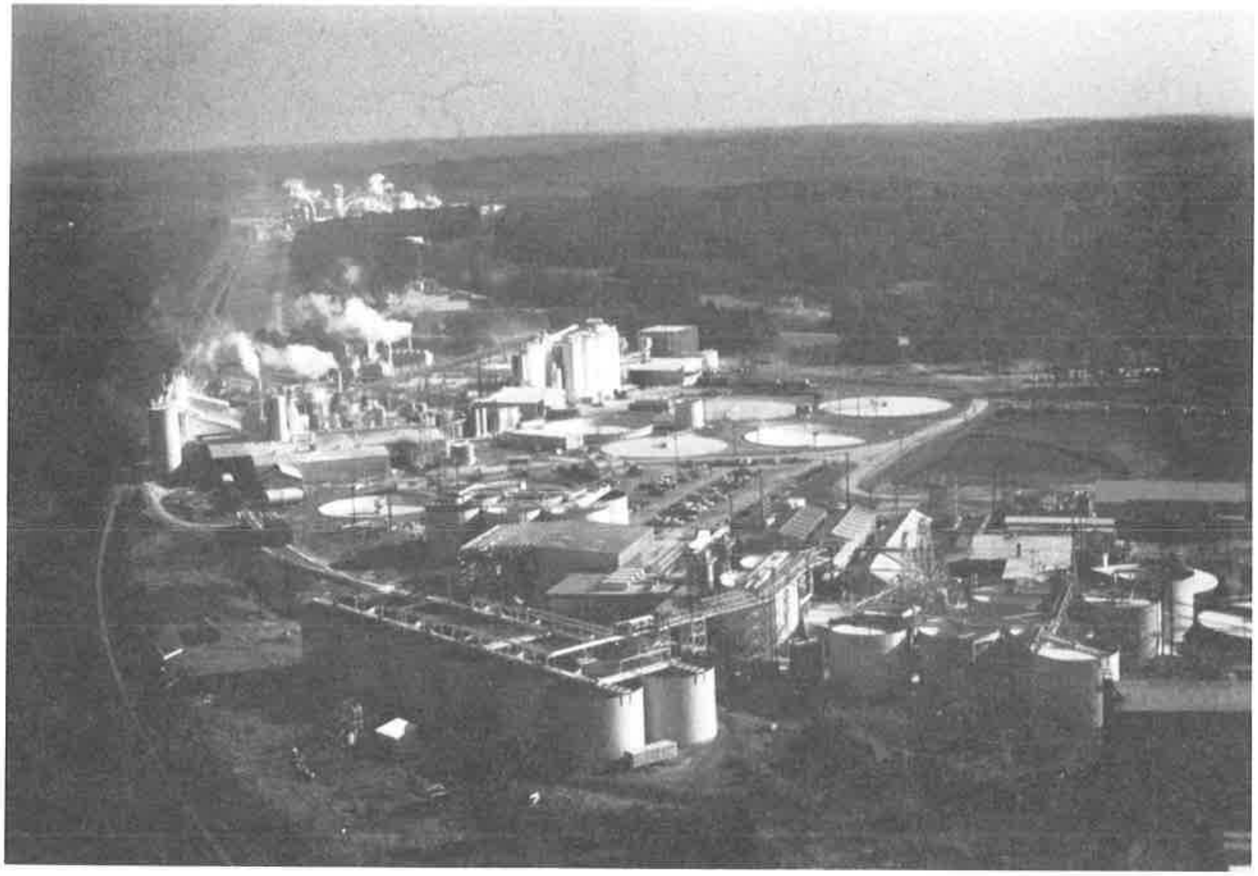
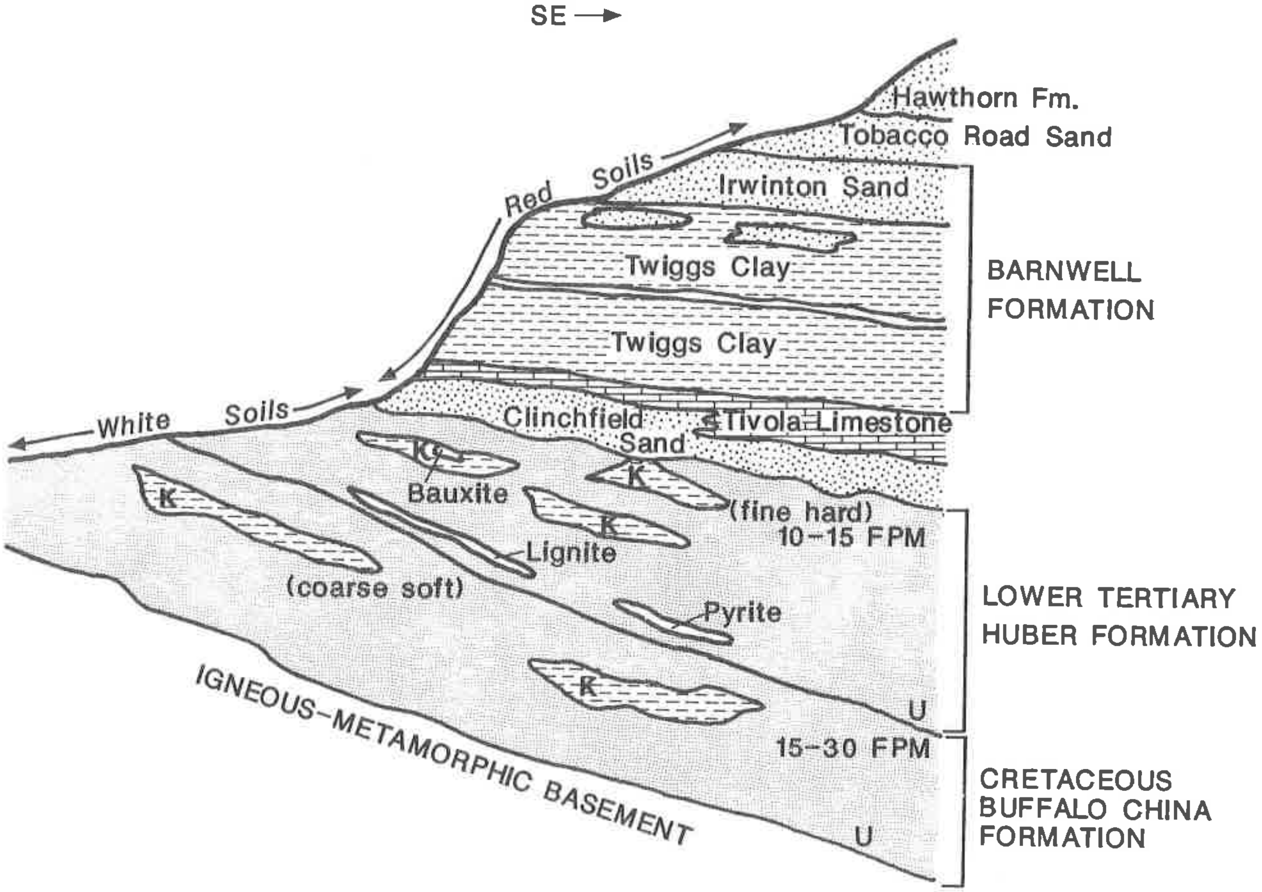


Fig. 2. Kaolin plants at McIntyre, Georgia.

vast spectrum of products which now serve very broad and well developed markers.

The circumstances which favored Georgia over almost every other southeastern state include deposition of Cretaceous sediments at the edge of the high, youthful Piedmont, and their uplift and exposure to sub-aerial weathering during Early Tertiary time. This thick blanket of feldspathic sand and clay was subject to the appropriate amount of leaching and recrystallation to form kaolin. This period was sufficiently prolonged that erosion and redeposition of portions of the lateritized sediment took place, and the deposits themselves became altered to kaolin after further modest uplift. The results of these episodes are thoroughly altered Cretaceous and Early Tertiary sediments in which there are thick, nearly pure beds of kaolin (see figure 3).

The differing histories of the Cretaceous and Tertiary kaolins are reflected in the greater lateral continuity of Tertiary kaolin and important differences in particle size and shape of the contituent kaolinite crystals. The Cretaceous particles more commonly have a well defined crystal morphology and abundant vermiform crystal growths. The Tertiary kaolin particles are typicallly finer and less well crystallized. The kaolinite crystal structural order is typically better in the Cretaceous. The fine particles of Titania appear to have been mechanically concentrated in the Tertiary kaolin, expecially where it has the typical fine particle size distribution.



K- Kaolin deposits

Fig. 3. Generalized geologic section from the Georgia kaolin mining district.

The beds of kaolin in many areas are preponderantly composed of kaolinite (see figure 4), because of the relatively high original abundance of aluminum silicates in the parent material as well as the removal of non-aluminous portions of the parent by solution. Quartz is the second most abundant mineral and is present by virtue of its original abundance and relative chemical stability. Evidence is clear, however, that the original quartz sand component in many portions has been substantially reduced by solution (see figure 5). White mica commonly is present because of its original abundance and relative geochemical stability. Portions of most mica particles have been altered to kaolinite (see figure 6). In some cases, intimately interlayered muscovite and kaolinite form individual platelets.

Iron which was liberated during the breakdown of certain silicates largely has been removed, but oxidation of small quantities has fixed it in sufficient volume to affect the color and brightness of the kaolin. Liberated titanium appears to have remained largely in the vicinty of the parent and now is present as anatase. The anatase contains a minor amount of iron, causing it to be yellow-brown and making it a significant colorant as well.

Where leaching has proceeded too far and conditions have permitted, gibbsite has formed, commonly a significant component where the typical pisolitic texture of bauxite is present. Montmorillonite is present in the pisolites apparently formed when gibbsite and kaolinite became exposed to infiltrating salt water from the encroaching Late Eocene sea.

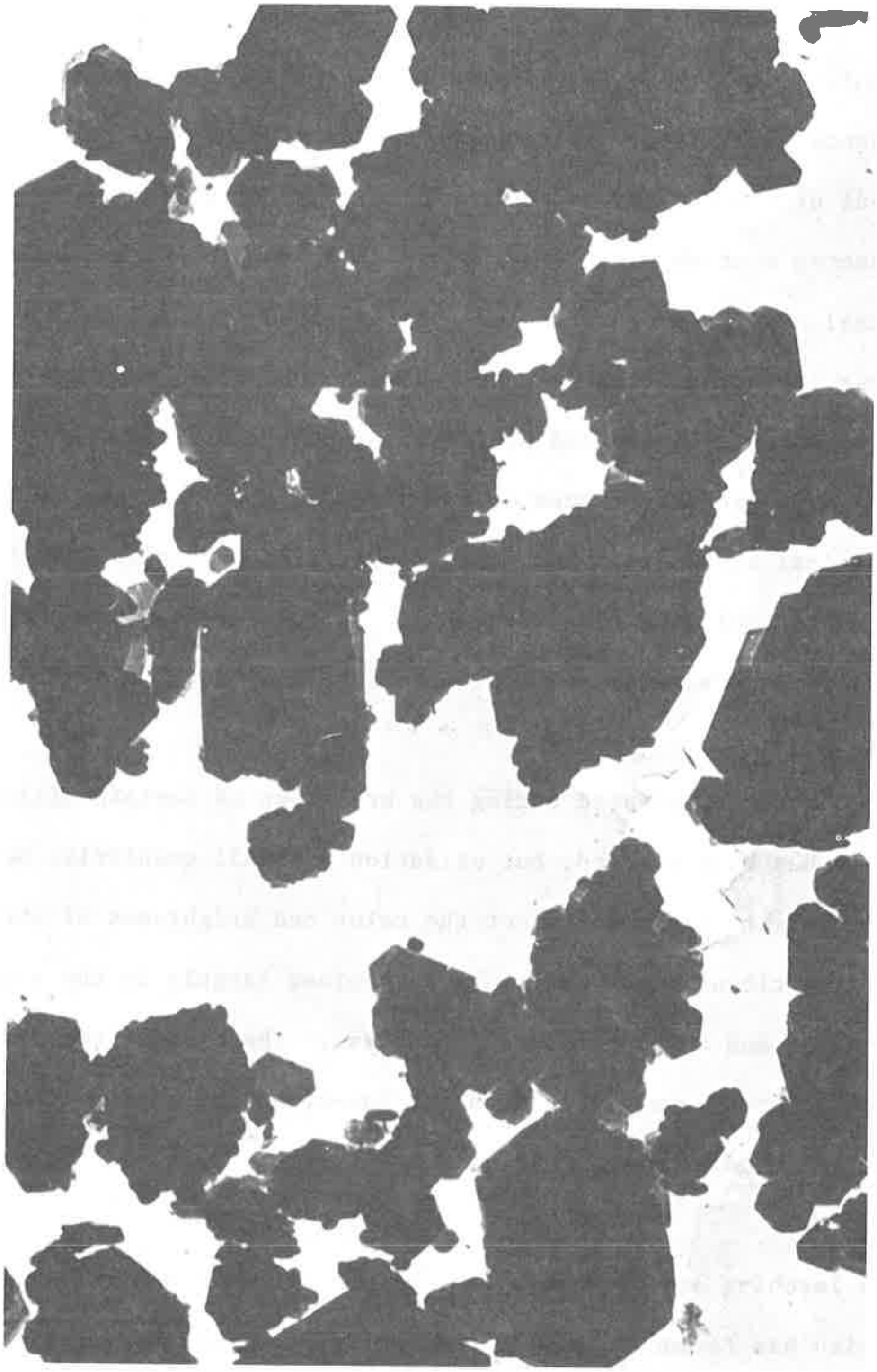


Fig. 4. Transmission electronmicrograph of clay sized particles of Cretaceous kaolin. 75X

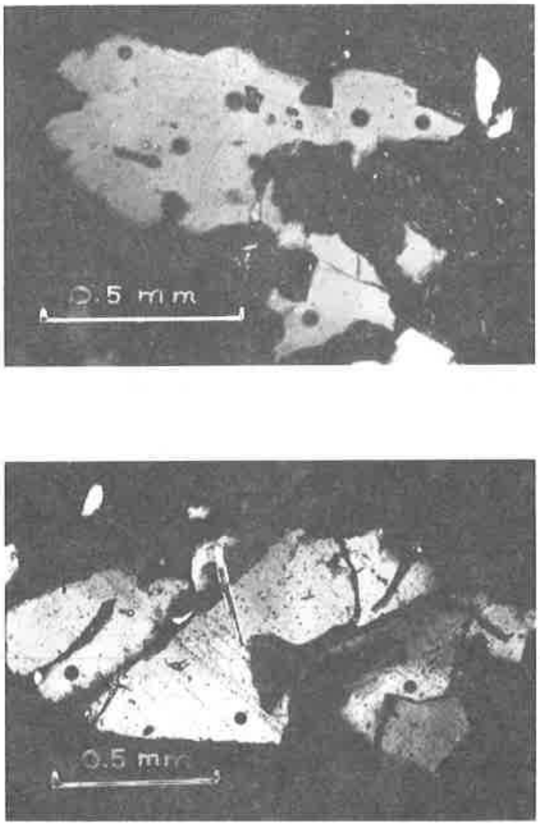


Fig. 5. Photomicrographs of thin sections of kaolin showing corroded and embayed quartz grains. Crossed polarizers.

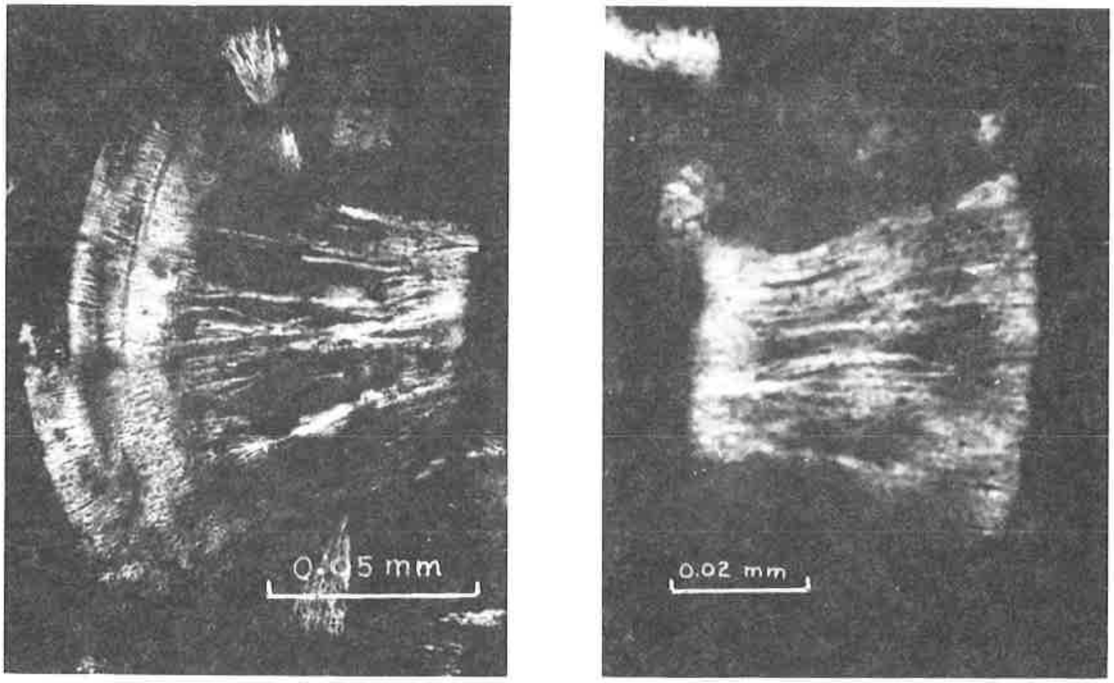


Fig. 6. Photomicrographs of thin sections of kaolin showing expanded grains of mica altered to kaolinite.

The consequence of this remarkable depositional and lateritic weathering episode is a vast quantity of kaolin of commercial value in an area only 50 miles long and little more than 10 miles wide. Estimates of its total size are in the billions of tons range, including only kaolins which have sufficient purity to provide the brightness, white color, rheological properties as well as inherent particle size distribution and shape making them suitable for beneficiation. Far more kaolin is present which is not beneficiatable by present technology and thus virtually has no value.

Refined kaolin primarily is used in paper coating and filling applications. However, it is also an important paint pigment and filler and extender in rubber and plastics. Competition among key producers over many years has been a classic example of the free enterprise system at its best. Present markets are offered a wide variety of kaolin products with excellent quality and performance at low cost. Most kaolin products are still sold by the ton, even though they compete with and sometimes replace some pigments sold by the pound.

Refined kaolin is produced by dry or wet methods. The former typically is referred to as air-float processing in which raw kaolin is dried, pulverized, and air-classified to remove silt and sand. The product has good value based on relatively low production cost, and depends on specially selected crude kaolins which require minimal beneficiation.

Most kaolin products are refined by wet processing, even those which ultimately require calcination at high temperature. Beneficiation basically is a series of processes which produce a consistent product and which eliminate or suppress the effects of non-kaolinite components. Quartzose and micaceous sand and silt are removed using conventional sand classifiers, hydroseparators, hydrocylones, or screens. These yield a material typically more that 97% pure, largely composed of micron sized kaolinite platelets or the previously mentioned vermiform stacks (see figure 7). Some products utilize platelets derived from these stacks. These are separated by delamination, a process using fine (sand size) grinding media and energy sufficient to cleave platelets without breaking them.

All products have specific particle size specifications (see figure 8) which are achieved using high speed centrifuges. Submicron size anatase is removed utilizing high untensity magnetic separators (see figure 9). In certain cases, it is reduced to very low levels, utilizing conventional or column flotation systems (see figure 10) modified to capture the sub micron anatase or by selective flocculation and gravity separation. Leaching with reductive compounds can remove or suppress the Fe2O3 component. Some kaolins warrant oxidation to remove organic compounds which limit brightness. Certain contaminants such as montmorillonite and white mica can be so intimately associated with the kaolinite that the contaminated kaolin must be cast aside by selective mining.

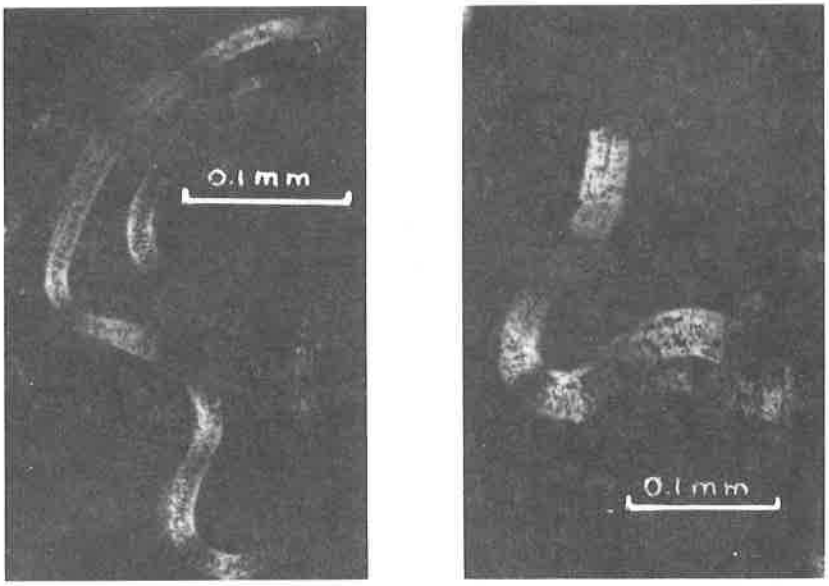


Fig. 7. Photomicrographs of thin sections of kaolin showing vermicular kaolinite crystals. Crossed polarizers.

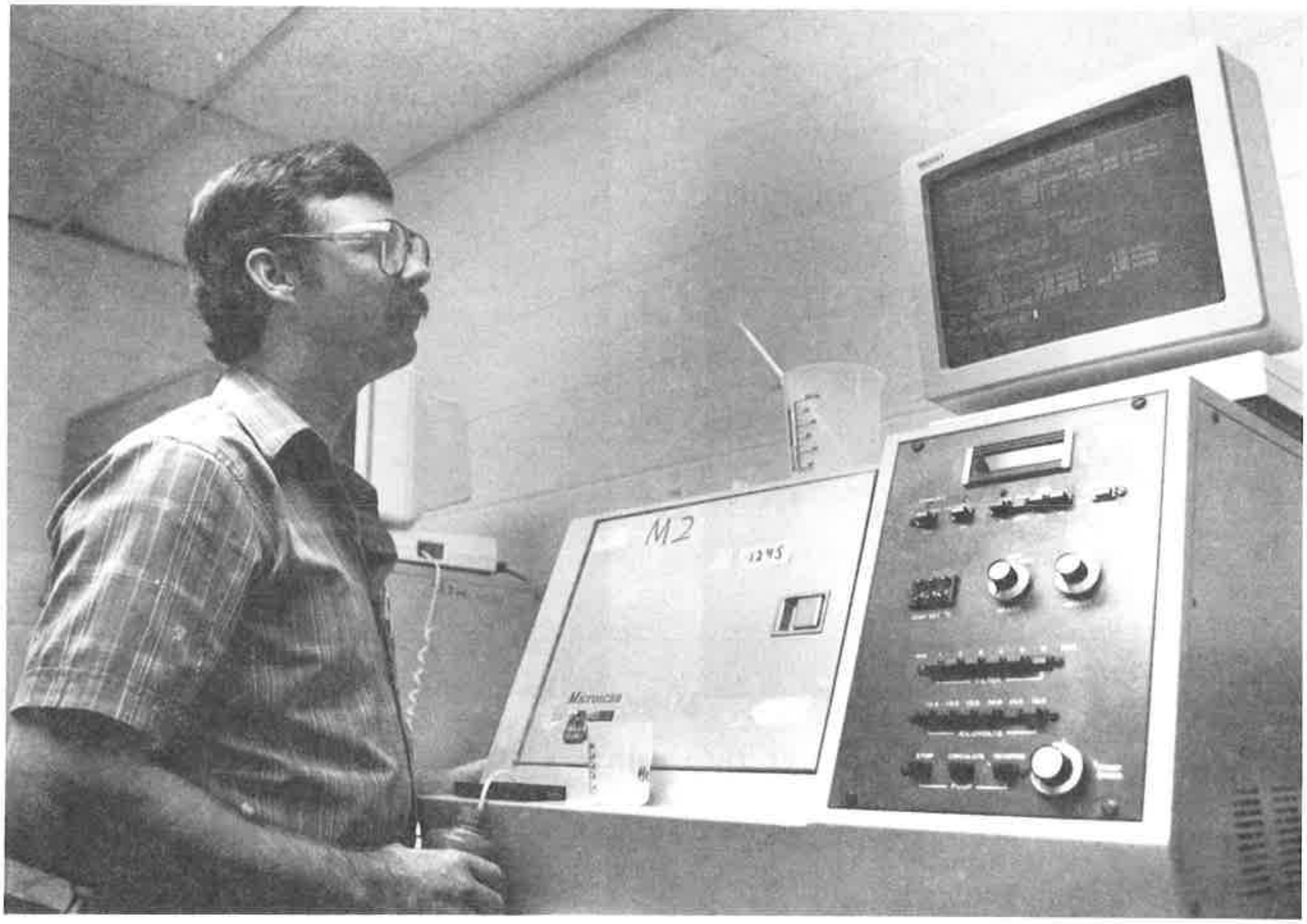


Fig. 8. Kaolin particle size analyzer used to monitor production quality.

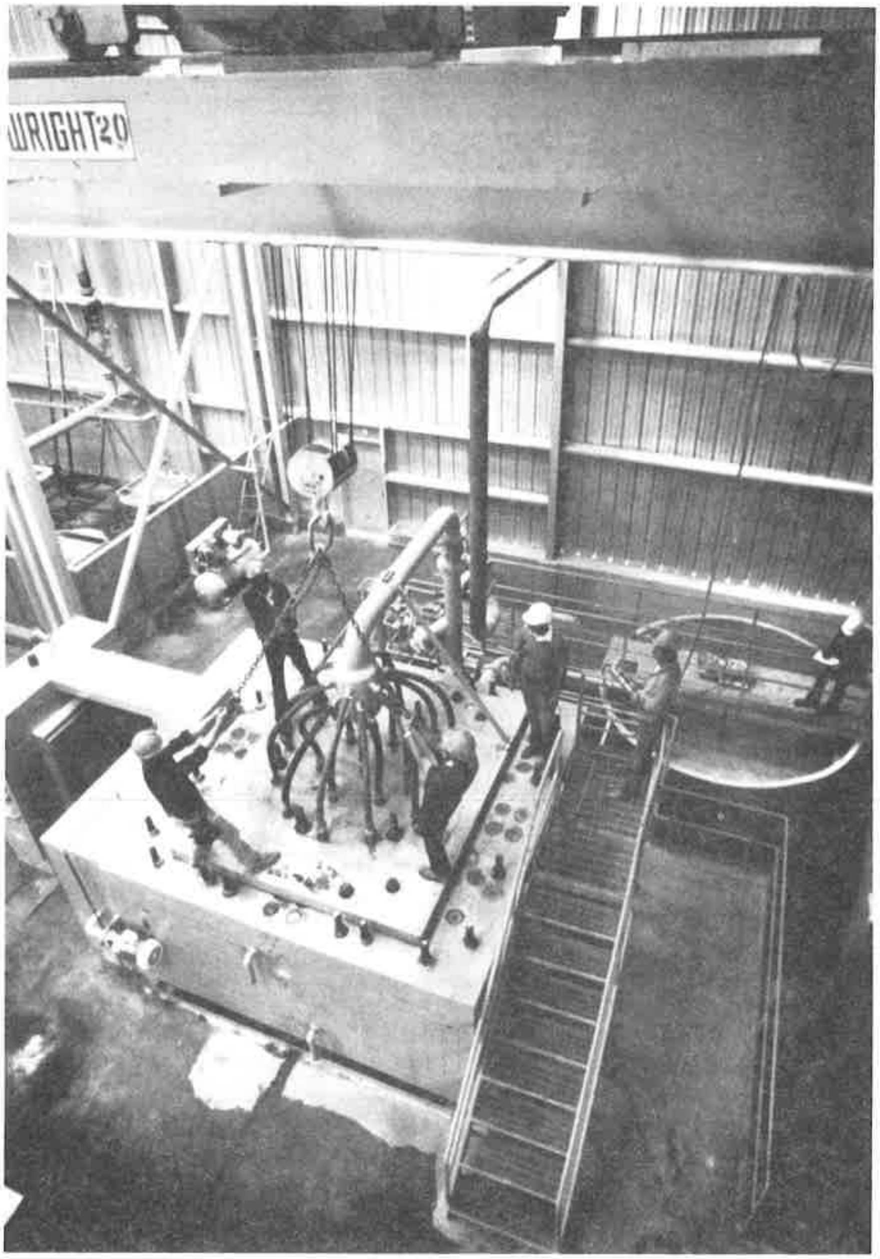


Fig. 9. High intensity magnetic separation for improving brightness.

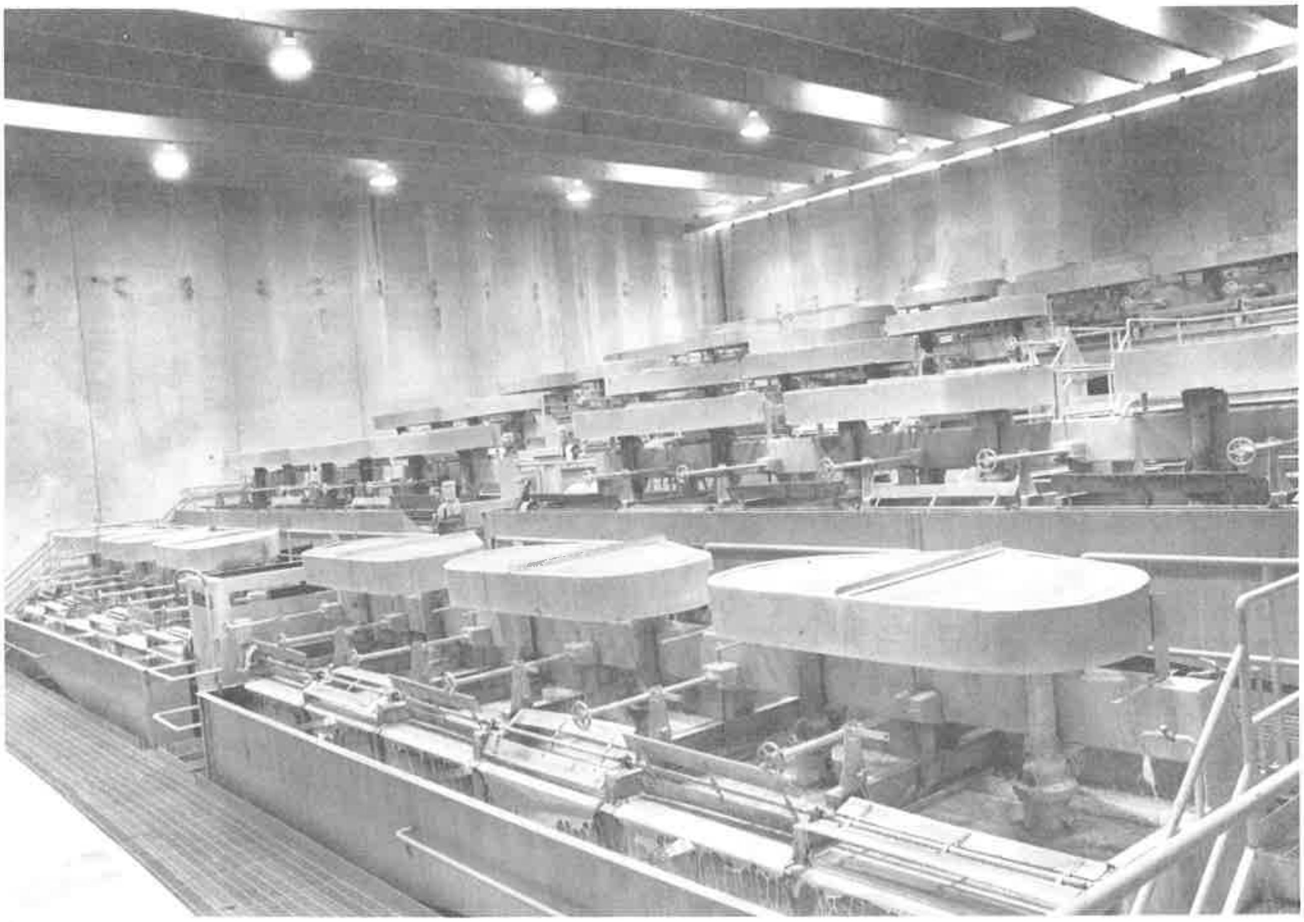


Fig. 10. Ultraflotation process to improve brightness.

The resulting products consist of nearly pure kaolinite. About 15 per cent of these have been calcined (see figure 11) subjected to sustained temperatures in the range of 1100°C, resulting in the destruction of the kaolinite structure. Calcined products range from a metakaolin to mixtures of high temperature silica and alumina phases.

Other processes including thickening, filtration (see figure 12) and drying are geared to the removal of water from the product in preparation for shipping. Product is shipped in dry or bulk bag forms (see figure 11 and 13) or as high solids slurry.

Sufficient reserves of kaolin exist in the Southeast so that production will continue through the twenty first century. The continuing development of new process methods, products, and applications will maintain kaolin as a major industrial mineral well into the future.

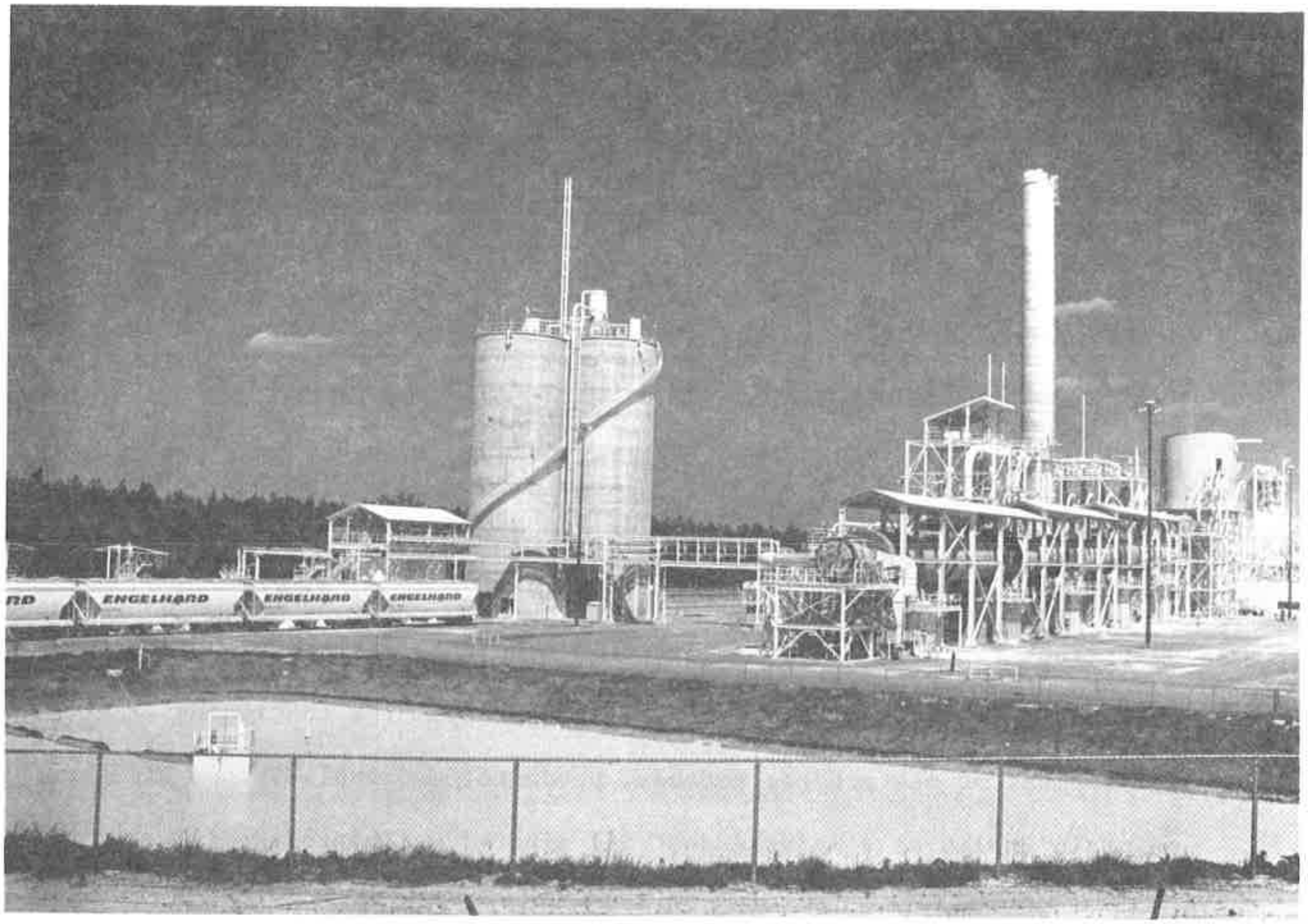


Fig. 11. Horizontal calciner with bulk rail car loading facility.

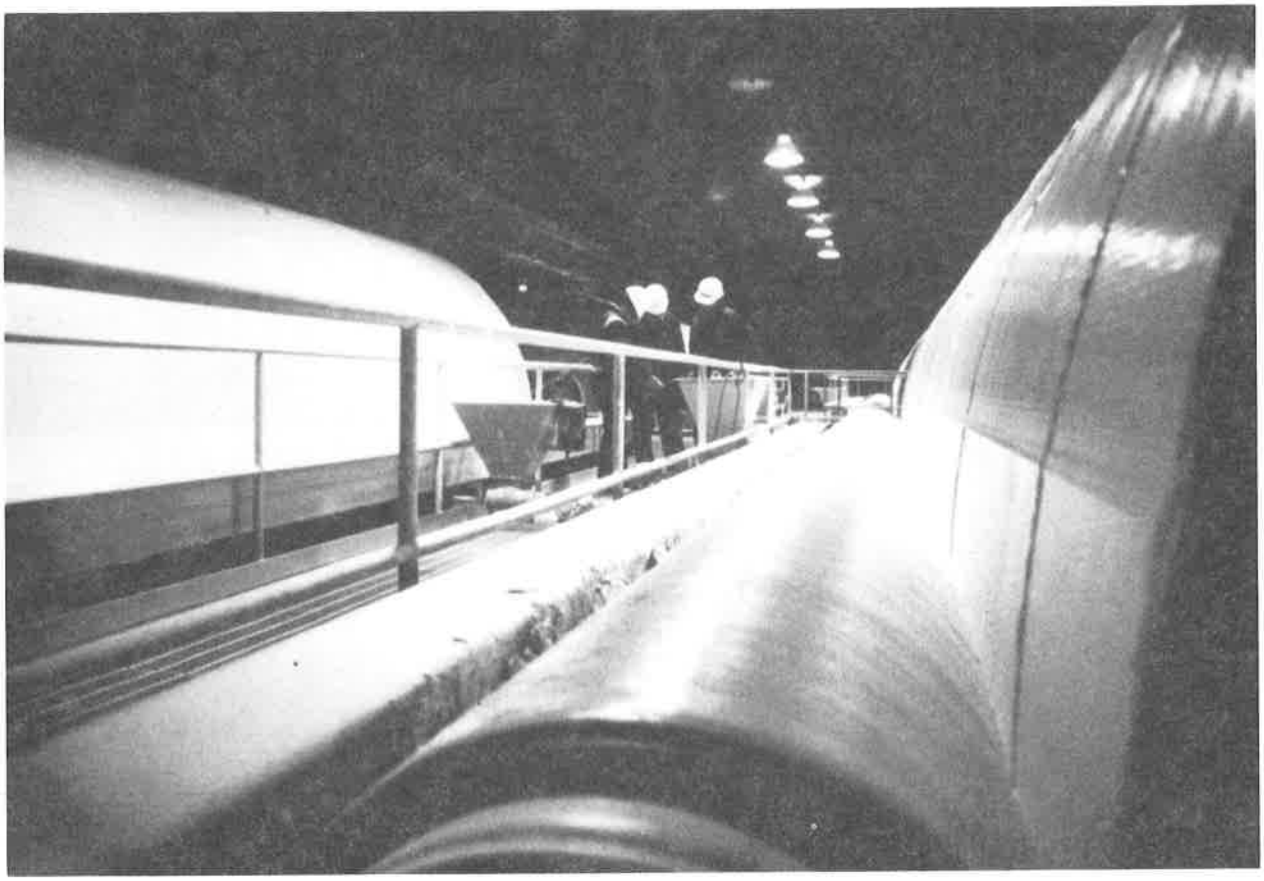


Fig. 12. Vacuum filtration using rotating drum filters.

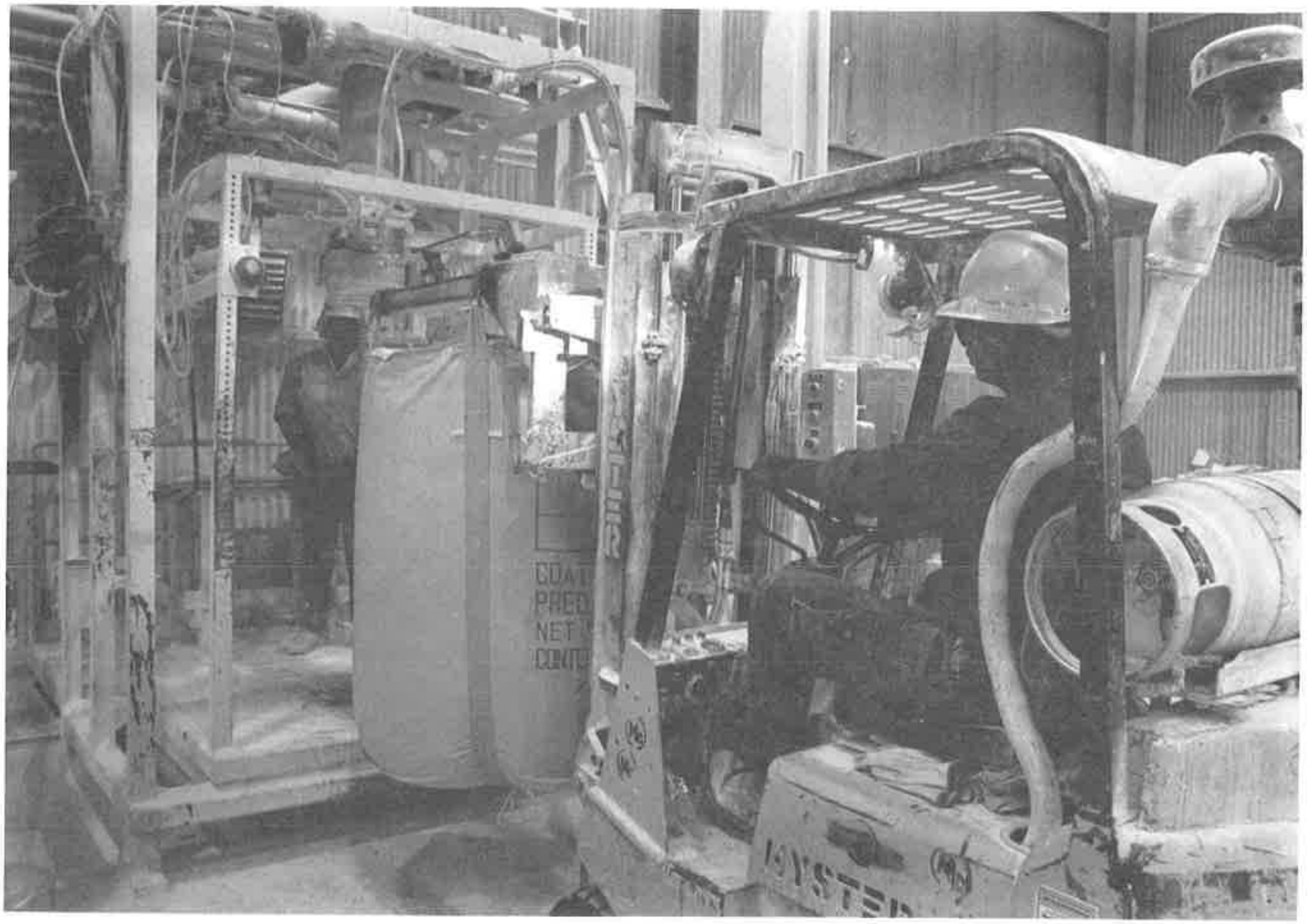


Fig. 13. One ton bag of kaolin pigment.

SIGNIFICANCE OF CRYSTALLITE SIZE AND HABIT IN DETERMINING ORIGIN AND INDUSTRIAL APPLICATIONS OF GEORGIA KAOLINS

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Abstract

The size, habit, mineralogy, and proportion of crystallites composing kaolins vary greatly, and largely determine what commercial products can be made from kaolin. Also, these variations reflect the sediment sources, depositional environments, and diagenetic histories of these clays.

Text

Unlike some other mineral pigments, kaolin does not require costly grinding. Its dispersed particles are individual crystallites, twinned crystallites, or intergrowths whose physical characteristics hardly relate to comminution or abrasion but relate instead to:

(1) Conditions of initial crystallization in saprolite during weathering,
(2) Chemical and structural modification of crystallites in weathering profiles or soils,
(3) Sorting during alluvial transport and deposition, sometimes followed by post-depositional weathering, and
(4) Diagenetic change.

The size, habit, twinning, aspect ratio, and proportion of natural crystallites vary greatly in commercial kaolins, and these variations significantly affect the types of pigment products which can be made. Also, the variations reveal important details about the origin of kaolin deposits and therefore can be utilized in exploration and development.

Among the important commercial attributes of kaolin are viscosity, color, brightness, abrasiveness, particle size and size distribution, gloss, and opacity. These bulk properties reflect the kinds and proportions of minerals in kaolin and the size, shape, structure, and surface characteristics of the individual clay minerals, such as surface charge and charge distribution, and surficially attached species.

The principal mineral in most commercial kaolins is kaolinite. Quartz, mica, metahalloysite, feldspar, illite, smectite, and relict accessory minerals from weathered source rocks, along with gibbsite and organic matter, are the usual detrital minerals associated with kaolinite in kaolins. The pyrite in bedded kaolins developed in situ, generally soon after kaolin deposition. Anatase typically is detrital, but may be secondary. Hematite and goethite, the principal colorants, may be detrital, but commonly are younger, secondary crystallization products.

The typical habit of kaolinite is a thin hexagonal platelet, though other platelet shapes occasionally are seen (Figure 1A). Generally, the platelets are not individual but are aggregated in some way, as parallel or pseudo-parallel intergrowths, which are interpenetration twins (Figure 1B), random intergrowths resulting from en situ recrystallization (Figure 1C), or face-to-face aggregates of platelets (Figure 1D). Euhedral untwinned platelets are uncommon, perhaps rare. Those appearing to be individual nearly always can be resolved at very high magnification to two or more interpenetrating platelets. Random intergrowths are much less common than twins. Other common forms of kaolinite are coarse books or stacks (Figure 2A) and even coarser vermiforms (Figure 2B and 2C). They are characteristic of soft Cretaceous kaolins of the Buffalo Creek Formation (Figure 9A) and some ancient saprolites. Face-to-face aggregates of kaolinite platelets are common only in kaolins deposited in brackish to salt water. They are characteristic of hard Tertiary kaolins (Figure 9B) of the Huber Formation. Kaolinite in different deposits can vary considerably in chemical composition and order (Pickering and Hurst, 1989). This is apparent from variations in certain d-spacings (Radoslovich, 1962), from differences in the (02,11) and (20,13) diffraction bands (Plancon et al., 1989), and from lattice imaging. Lattice images of sections normal to (001) typically show layer spacing irregularities which divide each kaolinite crystallite into tabular packets, the thickness of which is reflected in XRD patterns. Boundaries of the packets may be dislocations or one or more layers of another mineral. High resolution electron micrographs and XRD both indicate that detrital kaolinite, as opposed to diagenetic kaolinite, was supplied from more than one source (Hurst and Pickering, 1989). The fine kaolinite in hard Tertiary kaolins commonly exhibits two habits: euhedral, multiply twinned platelets like those formed by recrystallization in oxidized, leached saprolite and rounded, degraded platelets like those found in soils (see Figure 1D). A-Horizon and B-horizon kaolinite commonly is rounded and may have a degraded appearance, either because it is poorly crystallized (Figures 3A and 3B) or because it has been chemically degraded (Figure 3C). In the fine fraction of ancient saprolites and in pre-Tertiary kaolins, diagenetically recrystallized, the kaolinite is sharply euhedral (Figure 3D). Kaolinite now being transported by the Oconee River from the Georgia Piedmont includes both types of kaolinite (Figure 4A), as well as halloysite or metahalloysite elongates (Figure 4B). In reduced Tertiary kaolins, which have not recrystallized, both types of kaolinite and metahalloysite are still found. In Cretaceous kaolins, on the other hand, recrystallized by diagenesis and sometimes by postdepositional weathering as well, the features indicative of soil-derived kaolinite and smaller halloysite elongates have not survived. Relicts of coarser halloysite elongates sometimes remain in the form of long "saw-toothed" masses of kaolinite twins.

The initial khandite mineral to form during weathering of most Piedmont rocks is halloysite in the form of tubules or other elongates

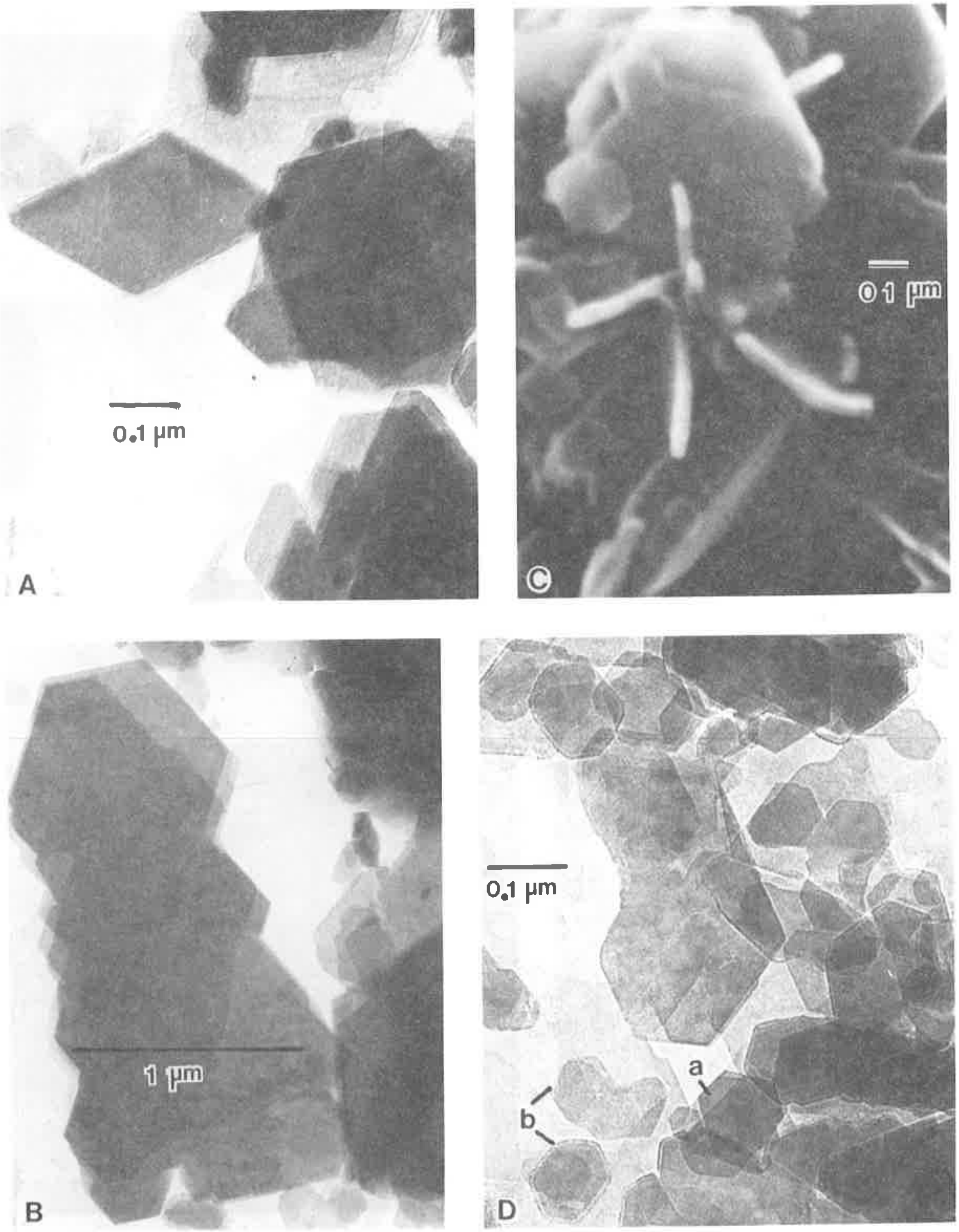

Figure 1 - (A) Uncommon rhomboid kaolinite platelets. TEM. (B) Kaolinite interpenetration twins in which edge faces are parallel or pseudo-parallel, the most frequent type of kaolinite intergrowth in Georgia kaolins. TEM. (C) Randomly intergrown kaolinite platelets in soft Cretaceous kaolin from Middle Georgia. SEM. (D) Face-to-face aggregates of kaolinite platelets in a hard Tertiary kaolin from East Georgia. Two types of platelets are admixed: sharply euhedral recrystallized kaolinite (a), and rounded soil kaolinite (b). TEM.

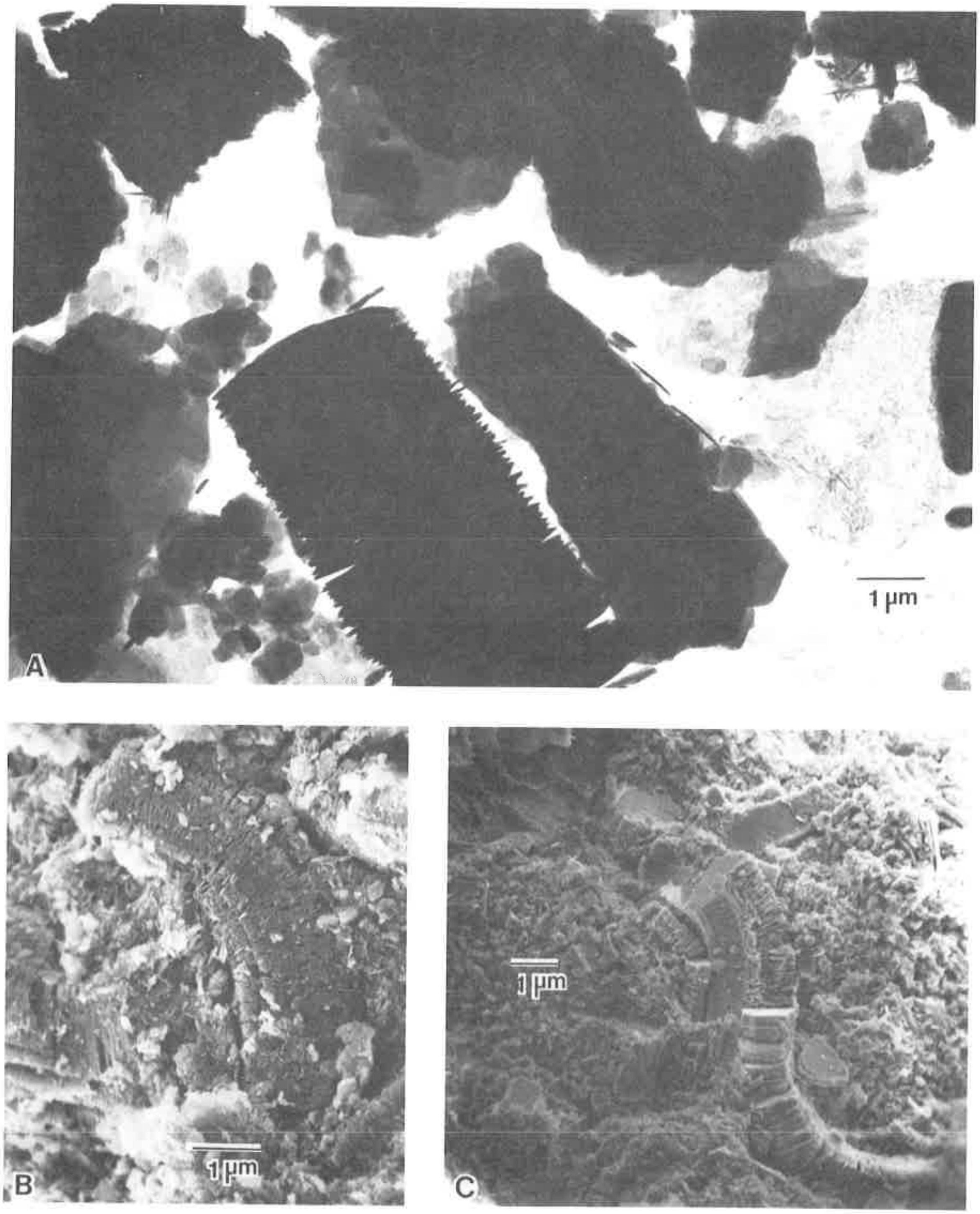

Figure 2 - (A) Coarse books or stacks characteristic of the soft Cretaceous kaolins. TEM. (B) Common type of kaolinite vermiform in the Buffalo Creek Formation. SEM. (C) Sinuous kaolinite vermiform from the Hodges Mine, Middle Georgia. SEM.

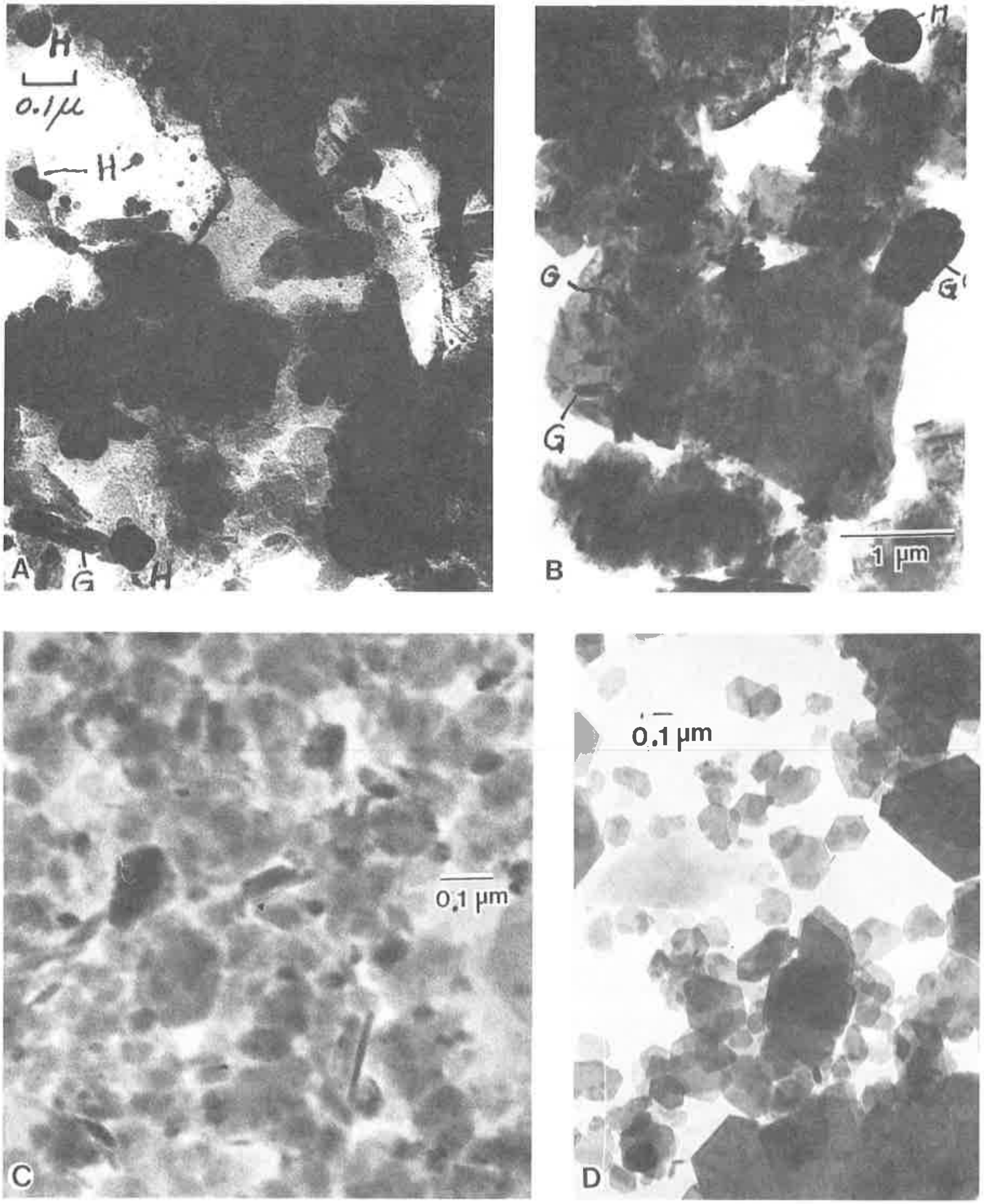

Figure 3 - (A and B) Recently formed kaolinite in oxidized B-horizon, north side of Graves Mtn, Georgia. The black minerals are ferric pigments, prismatic goethite (G) and equant hematite (H). TEM. (C) Clay fraction of the Orangeburg soil collected 30 cm below the present soil surface. Note the rounded, degraded appearance of the kaolinite in this soil. TEM. (D) Ultrafine fraction of a soft Cretaceous kaolin showing the sharp euhedralism of the recrystallized kaolinite. TEM.

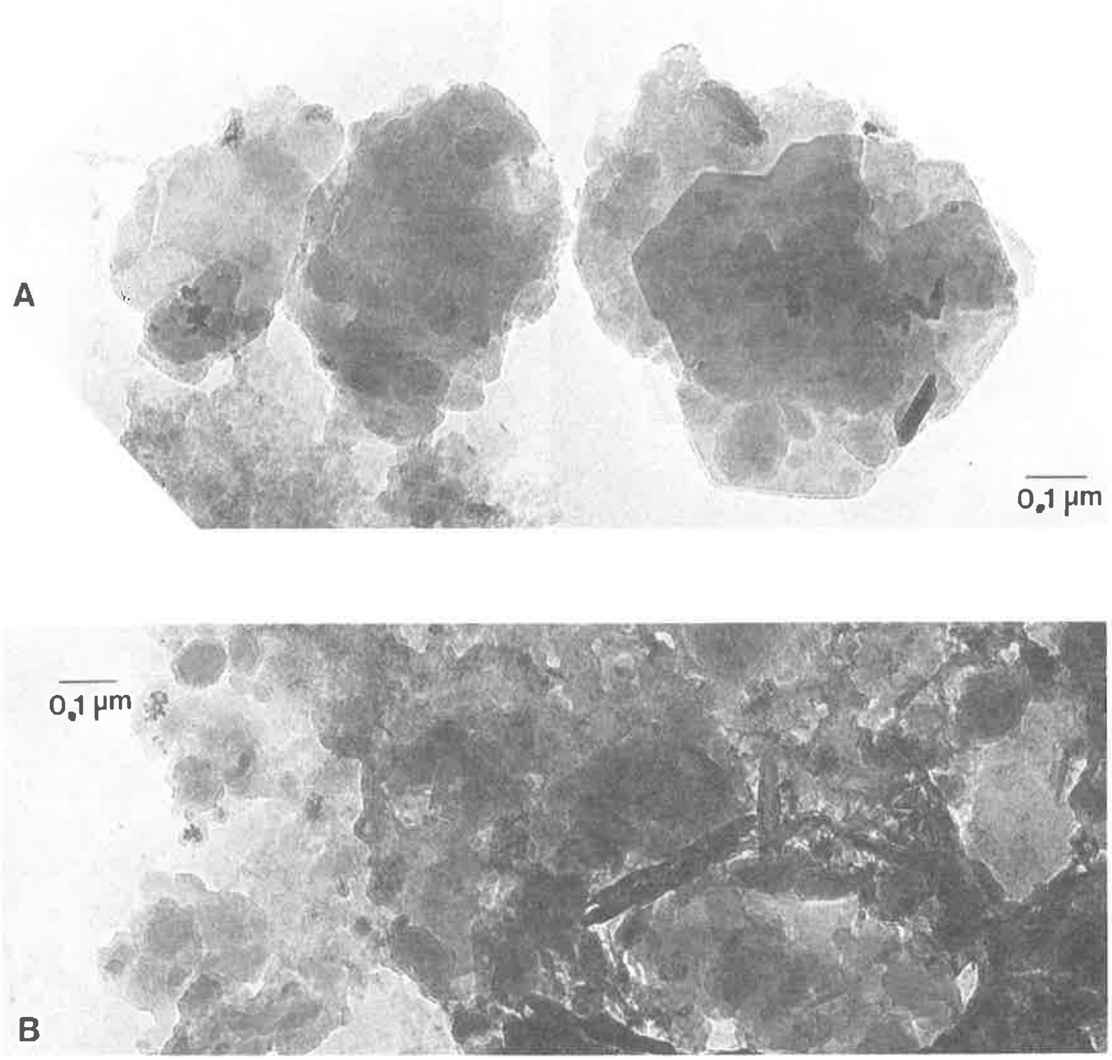

Figure 4 - (A) Rounded platelets of soil kaolinite and euhedral crystallites of kaolinite being transported seaward in suspension by the Oconee River at Athens, Georgia. TEM by John Dodge. (B) Another view of the suspended load of the Oconee River showing tubes and other elongates of metahalloysite (arrows) in addition to kaolinite. TEM by John Dodge.

(Kremer, 1983). Halloysite is unstable above the water table (Hurst and Kunkle, 1985), where it irreversibly loses interlayer water, after which it gives an XRD pattern like kaolinite - it has changed to metahalloysite. The tubular and elongate shapes of metahalloysite are common in Tertiary kaolins, but not in Cretaceous kaolins.

Mica is a common kaolin mineral, particularly in Cretaceous kaolins. Frequently the mica is splayed (Figure 5A) and partly altered to kaolinite (Figure 5B). Illite, clay-size mica lower in K and higher in Si and water than muscovite, constitutes as much as 10 or 15 percent of some Georgia kaolins (Figure 6). Its K_2 may be as low as 5-7%, and it may be interlayered with smectite. Possibly it is gradational to a celadonite-like clay mineral or high-charge smectite. The proportion of illite in kaolin is estimated better from SEM photos than from XRD patterns. Illite may significantly increase viscosity.

Smectite is in virtually all kaolins, ranging from a few percent in low-viscosity kaolins to more than 50% in some ceramic kaolins (Figure 7). More than one variety of smectite may be present. Smectite is a principal cause of high viscosity.

Pyrite and high organic matter are characteristic of reduced marine kaolins. In marine Cretaceous kaolins, high organic matter appears to have hindered diagenetic recrystallization to the extent that relicts of depositional textures may be preserved. Where these clays have undergone post-depositional weathering, the sulfide has oxidized to ferric pigments which impart some shade of yellow, red, or brown.

Anatase is the prevalent form of TiO_2 in bedded kaolins (Figures 8A and 8B). The octahedral crystals typically are squarish in cross-section. Less commonly the anatase is a skeletal mass pseudomorphous after an earlier mineral. In soft kaolins anatase generally is 1-3% by weight, and is more abundant in the fine fraction. In hard kaolins its proportion generally ranges from 2-8% and hardly increases in the fine fraction. A higher anatase content is expectable in hard kaolins because they are the fine fraction of source clays. The anatase generally is ferruginous and mostly is yellow to brown. Its removal by high intensity electromagnetic separation or by flotation significantly improves kaolin brightness.

Euhedral hematite and goethite are the predominant coloring agents of all kaolins except gray kaolins, which owe their color largely to fine sulfide and organic matter. Hematite and goethite occur not in stains or coatings but in discrete crystallites. These may be scattered over and adsorbed to the surfaces of other minerals, like the goethite in Figure 3B, or may be interstitial, like the hematite in Figure 3A. The characteristic habit of hematite is shown in Figure 8C, the characteristic habit of goethite in Figure 8D. Where ferric pigment crystallized under alkaline conditions, as during the weathering of a carbonate-bearing rock, goethite tends to dominate and impart a yellowish or brownish color, depending on crystallite size. Hematite, which imparts a pink to red or purple color, is more prevalent where the weathering environment was acidic.

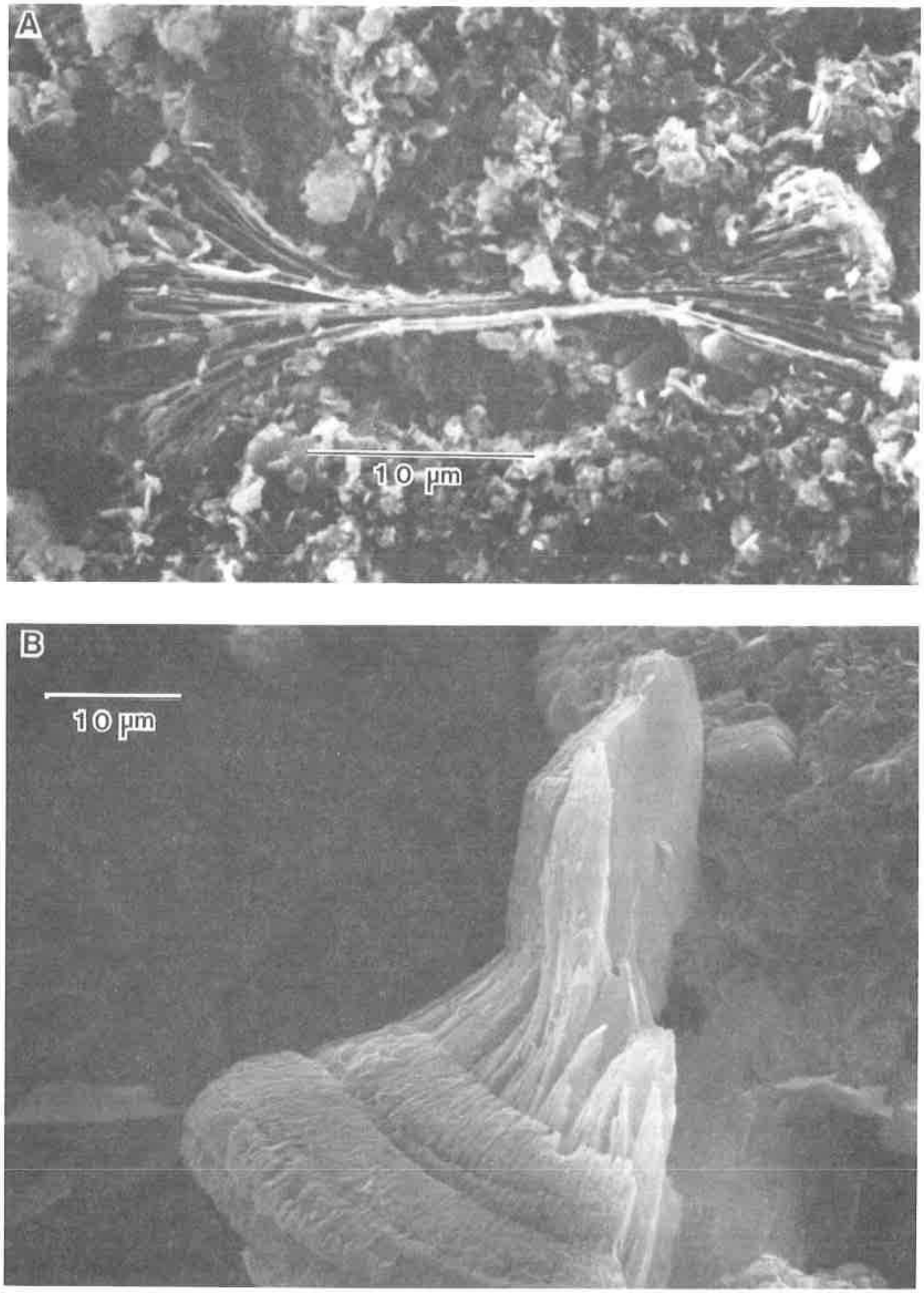

Figure 5 - Alteration of mica/illite in soft kaolin from GK Mine 73, Georgia. (A) Splayed mica only partly altered to kaolinite. (B) Fragment of splayed mica altered to a curved stack of kaolinite along the outer edge of the mica booklet. SEM.

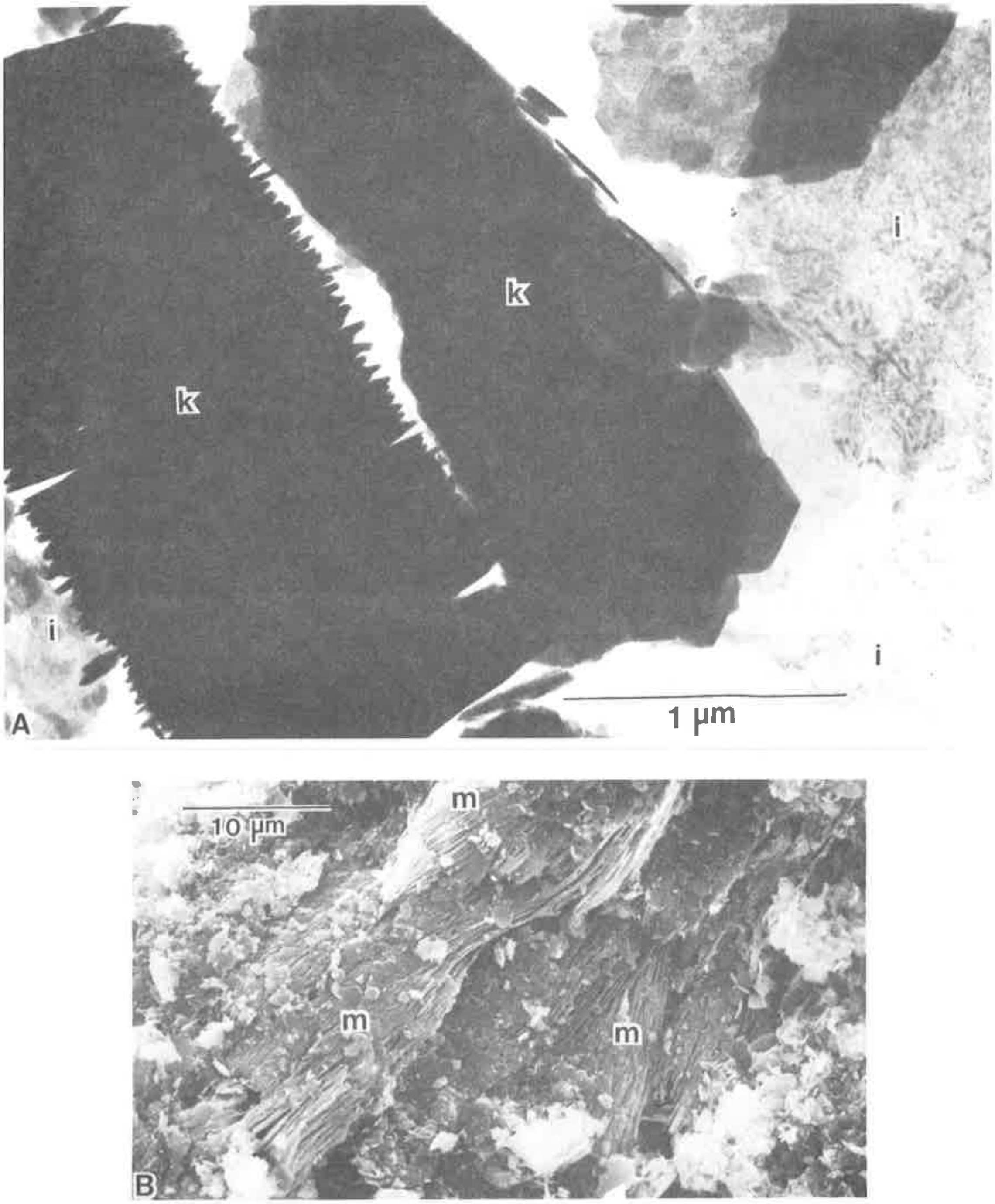

Figure 6 - (A) Illite (i), which is degraded mica, and kaolinite (k) in Middle Georgia kaolin. TEM. (B) Hydrolyzed mica (m) with about 8 percent of potash in Middle Georgia kaolin. SEM.

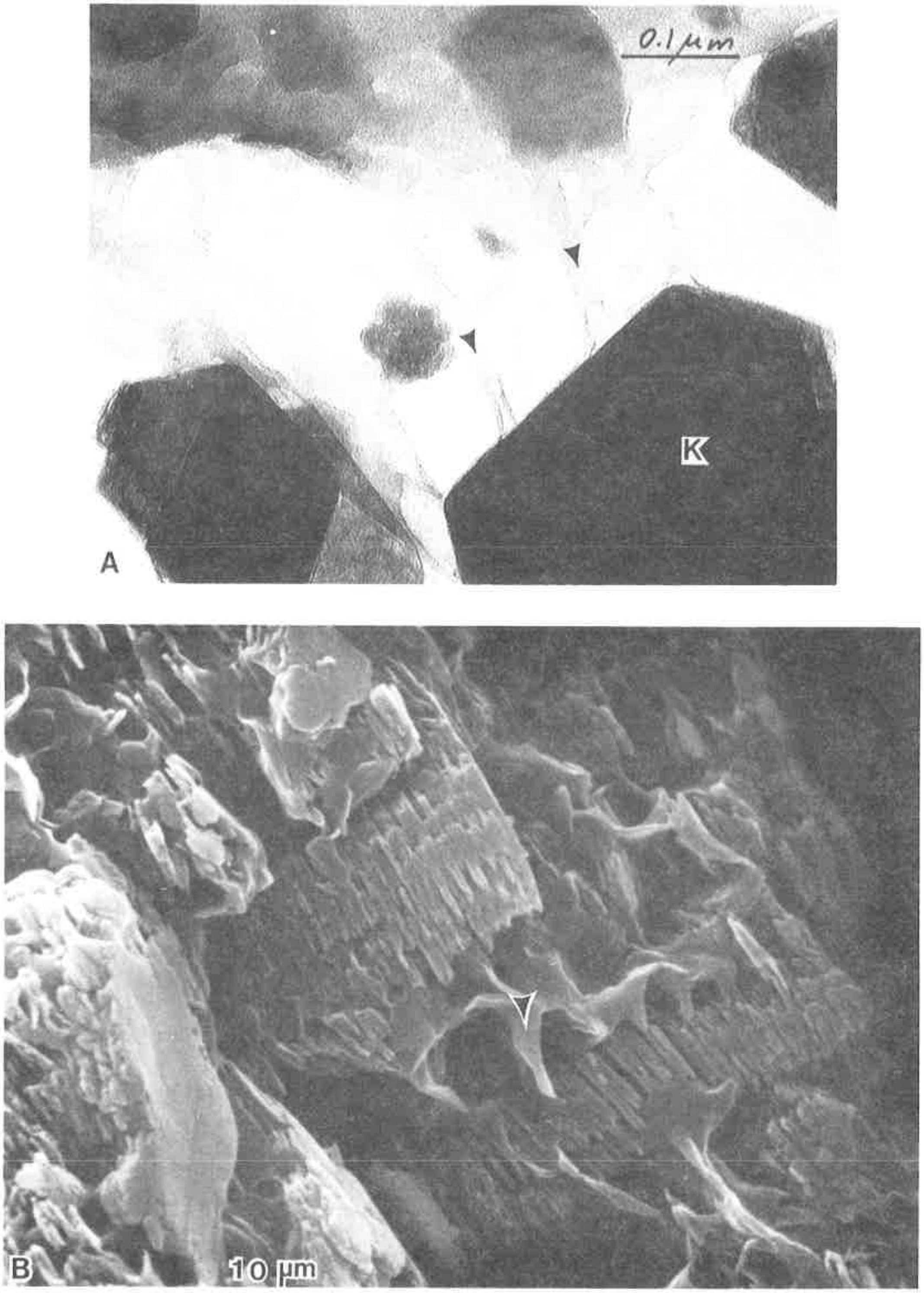

Figure 7 - (A) Smectite (arrows), a viscosity-causing impurity, attached to edge faces of kaolinite (K) in Middle Georgia kaolin. TEM by Tracy Jones. (B) Smectite filling spaces between oriented, thick kaolinite stacks in ceramic kaolin from the Bloodworth Mine, Middle Georgia. SEM.

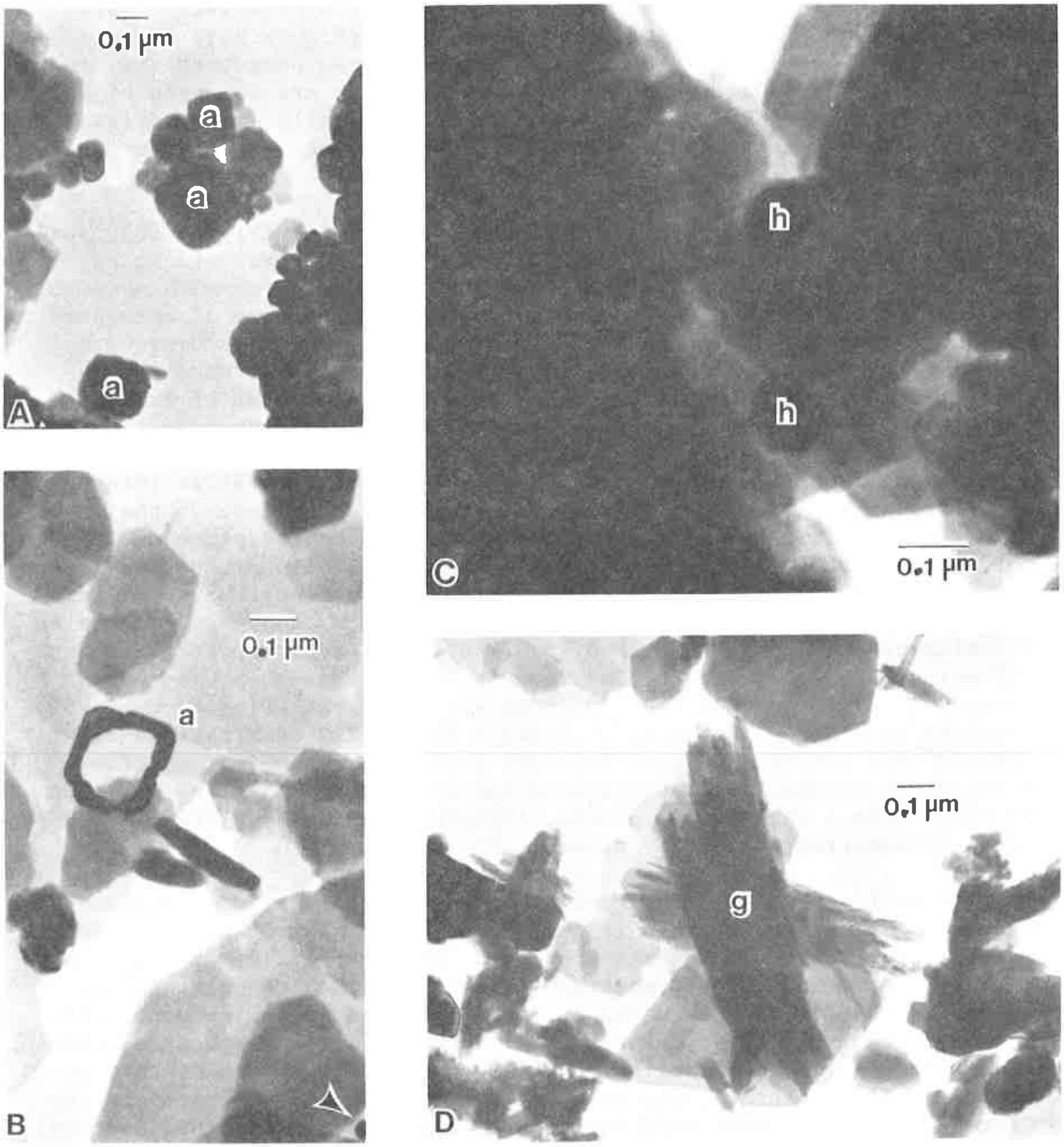

Figure 8 - Kaolin impurities that impart color. (A) Common habit of anatase from a hard Tertiary kaolin. TEM. (B) A less common skeletal habit of anatase (a). The dark elongate mass below (a) is a kaolinite platelet oriented vertically. The arrow points to a hematite crystallite. TEM. (C) Characteristic rhombohedral habit of submicroscopic hematite (h) in kaolins. TEM. (D) Characteristic prismatic habit of goethite (g) in kaolins. TEM.

On the basis of mineralogical, textural, compositional, and other differences, two principal types of commercial Georgia kaolins can be distinguished: Soft and Hard. The soft kaolins are relatively coarse and generally contain vermiforms up to 10u long (Figure 9A). Some are coarse enough to be megascopically visible. Coarse books, stacks, and vermiforms are 30-40% of soft kaolins. Vermiforms are composed of many crystallites, multiply twinned, and sometimes spirally arranged (Figure 10). The large stacks and vermiforms are indicative of slow recrystallization during weathering or diagenesis.

Hard kaolins, in contrast, are very fine-grained (Figure 9B), sometimes 95% finer than 2u. They are devoid of non-detrital stacks or vermiforms, and are relatively dense. They tend to break with a rough hackly fracture as compared to the subconchoidal fracture of more porous, soft kaolin. These are marine clays. They show some diagenetic changes, but no general recrystallization. Originally, these clays contained abundant bacteria which were encased by a cutan of kaolinite platelets. Death and decay of the bacteria left microspheroidal voids into which biogenic silica gradually migrated and crystallized as lepispheric cristobalite-tridymite (Figure 11). These were first interpreted as trace fossils of bacteria by Barker (1985). Because of their porosity the siliceous microspheroids, sometimes called pinheads, can defy gravity separation. When they remain in a kaolin product in large numbers, they deleteriously increase abrasivity. Minor recrystallization of kaolinite is occasionally seen as delicate, feathery growths in the microspheres, but the bulk of the kaolin has not recrystallized and the morphology of clay particles remains the same as when they were deposited. Only through local postdepositional weathering have microtextures undergone much change. Careful EM and XRD examinations show clearly that the fine-grained Tertiary kaolins are not just the fine fraction of eroded, older Cretaceous kaolins but are the fine fraction of clays from a variety of sources, including soil clay, like clays being transported seaward by present streams.

In contrast, Cretaceous kaolins have undergone striking diagenetic changes. Organic matter has largely transformed toward kerogen. No lepispheric traces of bacteria are found, though doubtlessly they once were present. The transformation of biogenic silica to cristobalite-tridymite and finally to quartz in unheated clays is a slow diagenetic change (Mitzutani, 1970; Calvert, 1971). It requires 15-40 my to attain the stage seen in hard kaolins, and about 60 my for the complete transformation of biogenic silica to quartz. Original microtextures in the Cretaceous kaolins have been replaced by a recrystallizational texture. Commonly feldspar and mica particles are partly transformed to kaolinite. Relatively coarse books and even coarser vermiforms of kaolinite are conspicuous. The coarser kaolinite, formed by slow recrystallization, typically is purer than the kaolinite in younger hard kaolins. The present grain size and texture of the Cretaceous kaolins are diagenetic rather than sedimentational.

Cretaceous kaolins in the updip area of the Georgia Coastal Plain are more likely to have undergone postdepositional weathering, which improved them, than downdip kaolins. Some downdip Cretaceous kaolins are gray, pyritic, marine kaolins unbenefitted by postdepositional weathering. Because of their age they have undergone diagenetic change and

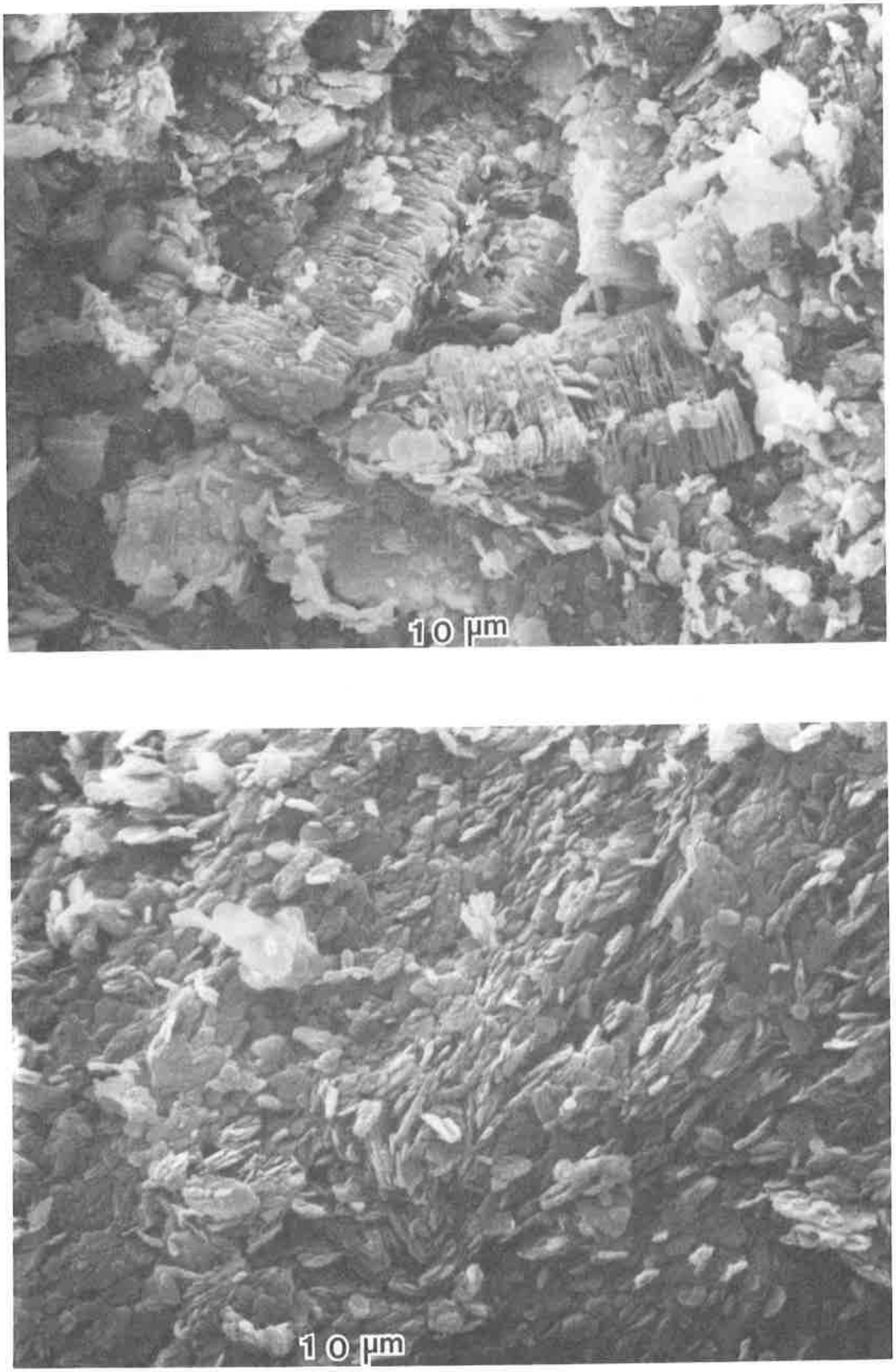

Figure 9 - (A) Typical microtexture of soft kaolin. SEM. (B) Typical microtexture of hard kaolin. SEM.

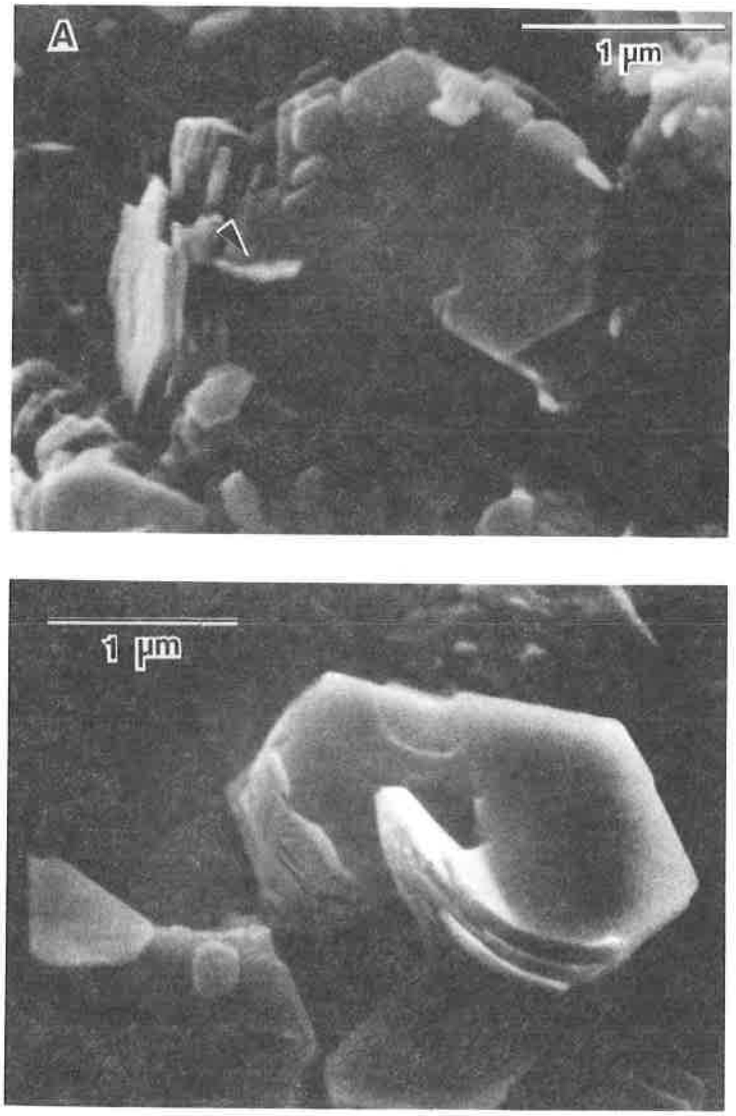

Figure 10 - (A) SEM view down the long axis of a vermiform in kaolin from the Tucker Mine, Middle Georgia. An intergrown kaolinite platelet is on the left side of the vermiform (arrow). Note apparent spiraling of crystallites in the vermiform. (B) Kaolinite crystals, all of them twinned, from a Middle Georgia kaolin. The largest array of spirally intergrown crystallites is deformed. This illustrates the flexible and inelastic behavior of kaolinite. SEM.

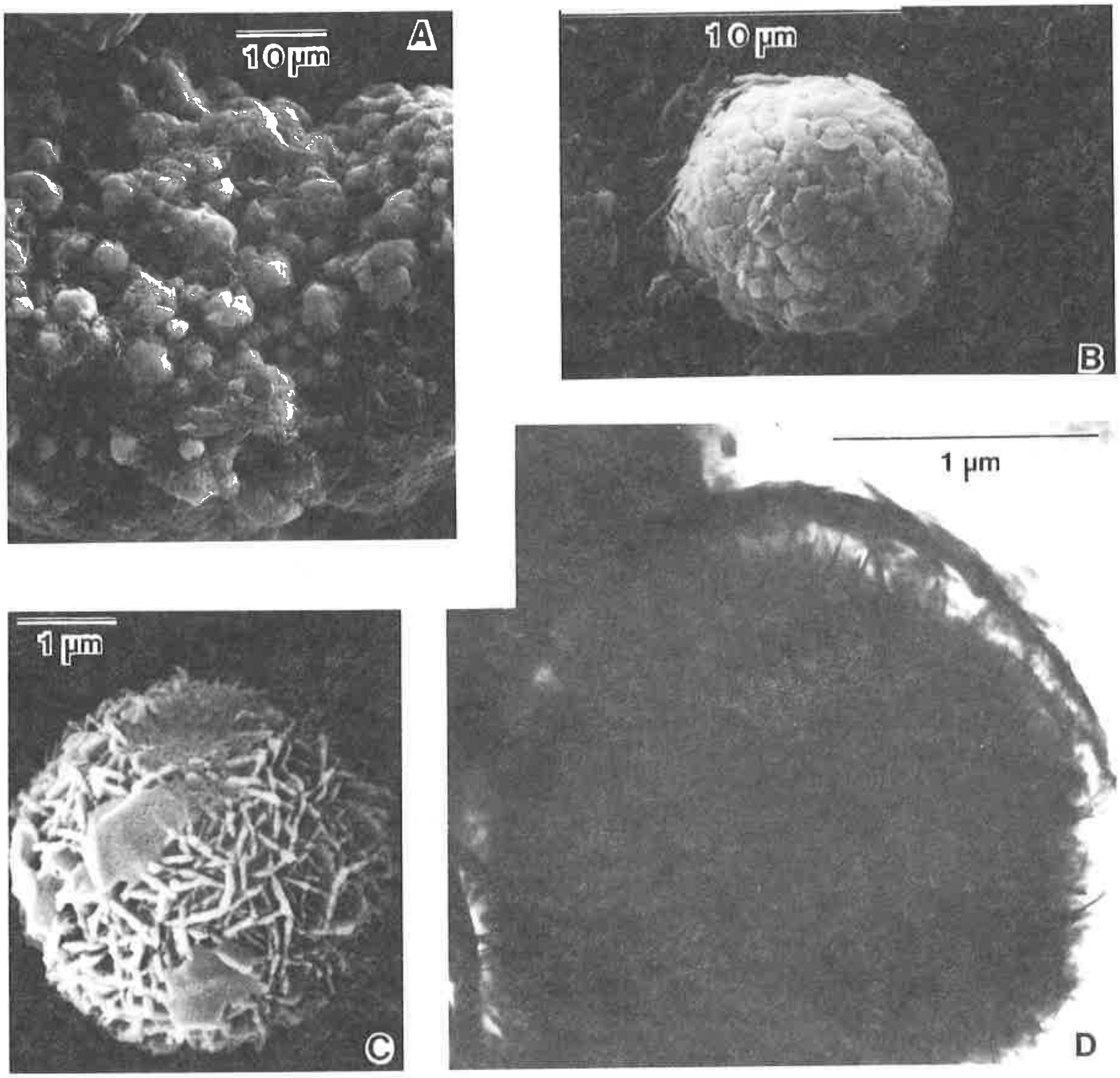

Figure 11 - Microspheroids in hard kaolin from GK Mine 19 Purvis. (A) SEM photo of a cluster of microspheroids. (B) SEM photo of a kaolin-clad microspheroid; its interior is cristobalite-tridymite. (C) SEM photo of a microspheroid like that in (B), but with most of the kaolinite cutan removed. (D) TEM photomicrograph which shows the cristobalite-tridymite filling and the kaolinite cutan (partly removed). These microspheroids are interpreted as bacterial trace fossils.

thereby acquired a new microtexture. Otherwise, they resemble the gray, marine, Tertiary kaolins.

Most commercial kaolin products are made from soft, coarse clays of the Buffalo Creek Formation. The fine particle size fraction is used as a naturally sized pigment. The coarse fraction consisting of large stacks and vermiforms is delaminated to produce a high aspect ratio pigment of good opacity and covering power. Up to about 15 years ago, oversize stacks and vermiforms were mostly disposed of as a waste. Since development of the delamination process, the coarse fraction has changed from a waste to a material that may be actively sought. Delaminated clay gives better optical quality to coated paper, superior opacity, with a thinner coating of clay.

The fine platelets in hard kaolins may be blended with soft kaolin to improve the latter's viscosity, used as a glossing agent in paper coating, or used as a rubber filler to increase toughness. They are used also as a feed for calcination and as a catalyst base for petroleum refining.

Whiteness and brightness of kaolins are improved by eliminating discolorants such as ferric pigments, anatase, and organic matter. Viscosity may be lowered by decreasing the proportion of smectite and illite, and by blending to improve particle size distribution.

Crystallite size, habit, and mineralogy largely determine the industrial applications of Georgia kaolins in ceramics, paper coating, paints, rubber, and hundreds of other uses. They also reflect the sediment sources, depositional environments, and diagenetic histories of these clays.

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MINERAL FILLER AND EXTENDER RESOURCES IN ALABAMA

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ABSTRACT

Industrial-grade mineral filler and extender resources in Alabama include limestone, dolomite, marble, chalk, tripoli, kaolin, talc, shale, slate, phyllite, barite, mica, and anthophyllite asbestos. Approximately 40 geologic units in the state are potential sources of filler and extender material. Whereas general physical and chemical data have been determined for most of these units, utilization of specific deposits will require testing for desired characteristics.

Carbonate rock materials, which include limestone, dolomite, chalk, and marble, constitute the most abundant filler-extender resource and have the broadest geographic distribution in the state. These materials range upward to "high-calcium" grade with medium to high brightness and whiteness values. Carbonate rocks with the highest $CaCO_3$ and brightness values are found within the Sylacauga Marble Group, Newala Limestone, and Marianna Limestone. Tripoli deposits with up to 98.7 percent SiO_2, particle size less than 4 microns, and high brightness occur in northwest Alabama and to some extent in the northeastern Valley and Ridge province. Kaolin with alumina values up to 57.6 percent (Al_2O_3) occur primarily in southeastern Alabama, but small kaolin deposits also have been identified in northeastern and northwestern Alabama. Sedimentary clays of the Pottsville Formation, particularly refractory-grade clays with high kaolinite content and low brightness, occur in central and northern areas. Shale, slate, and phyllite resources with highly variable chemical characteristics occur in the Valley and Ridge and in the low-grade rocks of the Northern Piedmont. These are an almost wholly unassessed group of rock materials with filler-extender potential. High-purity talc deposits overlying altered dolomites have been mined in Talladega County. Other potential filler-extender resources include barite associated with some carbonate rocks, mica in granitic pegmatites and highly micaceous schists, and anthophyllite asbestos occurring as an alteration mineral near the margins of mafic and ultramafic plutons.

INTRODUCTION

Mineral and rock fillers and extenders have been defined as inert materials that are included in a composition or mixture for some useful purpose (Severinghaus, 1983). Physical properties of a product, such as hardness, brittleness, impact strength, compressive strength, softening point, fire resistance, surface texture, electrical conductivity, color, and reflectivity, may be modified by the inclusion of fillers. The major economic and potential natural fillers and extenders in Alabama are carbonate rocks (including limestone, dolomite, marble, and chalk), tripoli, kaolin and other clays, talc, shale, slate, phyllite, barite, muscovite, and anthophyllite.

CARBONATE ROCKS

Carbonate rock materials constitute the most abundant filler-extender resource and have the broadest geographic distribution in the state. Large quantities of limestone and dolomite exist in the Appalachian Plateaus, Valley and Ridge, and Coastal Plain physiographic provinces in Alabama. Substantial marble deposits occur in the extreme eastern and extreme western parts of the Alabama Piedmont province. Three thick chalk units occur in the Alabama Coastal Plain province (figs. 1 and 2). Many of these carbonate rocks are or have been quarried in Alabama, but only the Sylacauga Marble Group has been utilized as an inert filler.

Known and potential carbonate resources are identified by geologic unit and their respective average chemical analyses are given in table 1. Many of the carbonate rocks in Alabama, especially the marbles, are very white, have medium to high brightness, are high in calcium carbonate, and contain little or no deleterious elements. Carbonate rocks with the highest calcium carbonate and brightness values are found principally within the Sylacauga Marble Group and in the Newala and Marianna Limestones.

Table 1.--Average chemical analyses of known carbonate resources in Alabama.

Geologic unit	Chemical composition (weight percent)				
	$CaCO_3$	$MgCO_3$	Al_2O_3	Fe_2O_3	SiO_2
Chewacla Marble	55.87	41.90	--	1.24	1.57
Sylacauga Marble	90.73	7.58	0.23	0.25	1.84
Conasauga Formation	78.96	12.29	1.11	0.69	4.70
Ketona Dolomite	53.01	40.95	.36	.24	2.66
Longview Limestone	81.61	13.62	.16	.53	4.11
Newala Limestone	95.97	1.37	.77	.17	1.83
Lenoir Limestone	76.58	3.55	1.39	.73	16.17
Chickamauga Limestone	87.88	4.42	.65	.40	5.02
Tuscumbia Limestone	91.28	3.19	.25	.37	3.30
Monteagle Limestone	92.83	3.37	.36	.20	2.23
Bangor Limestone	93.01	3.36	.67	.28	1.91
Mooreville Chalk	60.80	2.90	7.17	2.62	23.31
Arcola Limestone Member	91.10	1.00	.53	.65	1.58
Demopolis Chalk	75.53	1.32	4.60	1.80	13.90
Ripley Formation	48.72	3.03	8.58	3.20	29.76
Prairie Bluff Chalk	66.85	1.26	4.25	1.50	22.64
Clayton Formation	80.00	1.48	1.08	.67	13.67
Salt Mountain Limestone	93.68	1.35	.86	1.04	2.53
Moodys Branch Formation	69.52	1.52	3.05	1.07	23.28
Pachuta Marl Member	77.73	.87	--	--	14.52
Crystal River Formation	90.99	1.02	.57	.86	4.99
Red Bluff Clay	88.83	.58	--	--	5.00
Marianna Limestone	94.48	.76	1.48	.83	2.28
Glendon Limestone Member	77.44	14.65	1.04	1.72	2.41
Chickasawhay Limestone	72.40	5.04	4.70	2.86	12.44

The Gantts Quarry Formation of the Sylacauga Marble Group, a white and pale-blue to light-gray calcite marble with localized interlayered dolomitic marble and thin phyllite layers, has been produced commercially as an inert filler. Average $CaCO_3$ content is 91 percent with large areas of thick marble in Talladega County having maximum $CaCO_3$ contents of 98 to

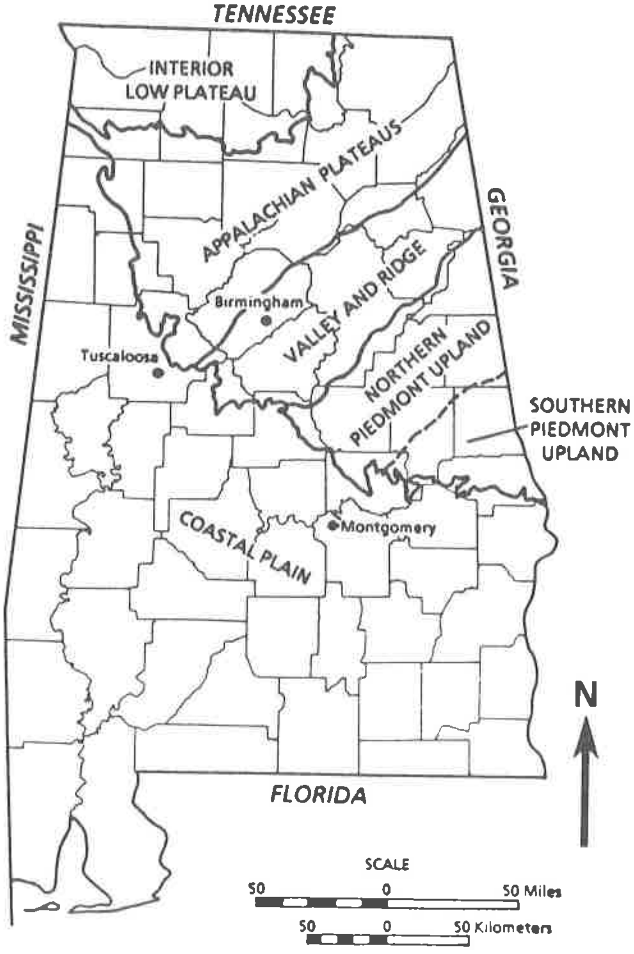

Figure 1.--Physiographic provinces of Alabama (modified from Sapp and Emplaincourt, 1975).

Figure 2.--Generalized map of carbonate rocks in Alabama (modified from Smith and Gilbert, 1975).

99.5 percent The marble, which is actively quarried near the city of Sylacauga in Talladega County, has GE brightness values of 93 for the coarsest dry-ground material to over 96 for the finest sized wet-ground product. Whiteness ranges from 87 to 92 for wet-ground marble (oral commun., David Leverett, ECC American Calcium Products, Inc., 1989).

The Ordovician Newala Limestone is a dark-gray, light-gray, or bluish-gray, compact, thick-bedded, high-calcium, micritic limestone with an average $CaCO_3$ content of 96 percent. Large areas of Newala Limestone in Bibb and Shelby Counties have maximum $CaCO_3$ values of 98 to 99 percent. This limestone, which ranges from 200 to 1,000 feet (61.0 to 609.7 meters) thick, is quarried extensively in Shelby County, where samples exhibit GE brightness values of approximately 75 and whiteness values around 88 (written commun., Sam Pickering, Georgia Kaolin Company, 1989).

The Lower Oligocene Marianna Limestone, which occurs in southwest Alabama, is a white to cream-colored, soft, porous, chalky limestone between 40 and 75 feet (12.2 and 22.9 meters) thick. The Marianna has an average $CaCO_3$ content of 95 percent with values up to 97 percent in limestone covering extensive areas of Conecuh, Covington, and Monroe Counties. Brightness and whiteness values for the Marianna Limestone are not available.

Another potential economic carbonate filler in Alabama is the Upper Cretaceous Demopolis Chalk, which extends from the Mississippi State line eastward to Bullock County. The Demopolis is a light-gray to medium-light-gray chalk with an average $CaCO_3$ content of 75.5 percent. Maximum $CaCO_3$ contents of over 86 percent are found over several square mile areas of chalk in Sumter County. This chalk, which has a GE brightness of 54 and a whiteness value of approximately 78 (written commun., Sam Pickering, Georgia Kaolin Company, 1989), is actively quarried just south of the city of Demopolis in Marengo County.

For filler uses requiring a more dolomitic composition, the Chewacla Marble, a light-gray to yellowish-gray, medium to coarsely crystalline dolomitic marble, could be a potential resource. The marble, which has a GE brightness of 59 to 70 and whiteness values of 77 to 88 (written commun., Sam Pickering, Georgia Kaolin Company, 1989), is actively quarried in the Auburn area of Lee County.

TRIPOLI

Tripoli is a naturally occurring, very finely divided, microcrystalline, more or less friable form of silica that appears to be the product of leaching of siliceous limestone or calcareous chert. Tripoli averages 98 to 99 percent silica with minor amounts of alumina, titania, and iron oxide, which allows tripoli to be a relatively inert material. Individual grains of tripoli lack distinct edges and corners, and grain sizes generally range from 0.1 to 7 microns in diameter. Tripoli color ranges from white or yellow through brown to red, depending on the nature and degree of staining of the individual particles and the amount of impurities present. GE brightness values range from moderate to high and whiteness averages approximately 91 (written commun., Sam Pickering, Georgia Kaolin Company,1989). Typical physical characteristics of tripoli are given in table 2 (Bradbury and Ehrlinger, 1983; Harben, 1983).

Because of its chemical inertness and resistance to abrasion, tripoli is an important filler and extender in paint, plastic, rubber, and various enamels. Extender grades of tripoli for paint use are generally required to have 65 percent or more of the material smaller than a 325-mesh sieve size (Harness,1943). As an extender in paint, tripoli aids in tint retention, durability, leveling, and flowability. Uniform particle size, which is characteristic of tripoli, results in ease of dispersion and film uniformity in paints and enamels. Tripoli is also used as a filler and extender in plastics, where it imparts excellent dielectric properties and flexural and compressive strength. Tripoli is also a valuable filler in the rubber industry.

Large, good quality, commercially undeveloped deposits of tripoli associated with the upper part of the Mississippian Fort Payne Chert are scattered over an extensive area in west Lauderdale and Colbert Counties in northwest Alabama (fig. 3). Deposits of white- to cream-colored tripoli in this area are as much as 80 feet (24.2 meters) thick. Small, scattered tripoli deposits occur in the Mississippian Fort Payne Chert, Bangor Limestone, and Cambrian-

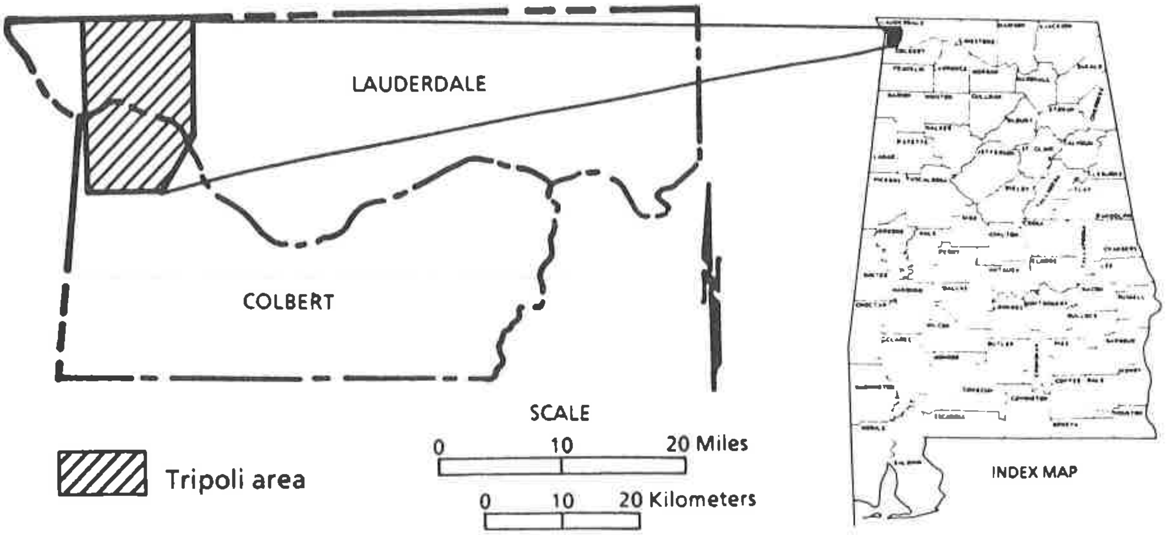

Figure 3.--Tripoli area, northwest Alabama (modified from Rheams and Richter, 1988).

Table 2.--Typical physical characteristics of tripoli (modified from Harben, 1983).

Specific gravity	2.65
Weight per solid gallon (lbs)	22.07
Bulking value	0.04531
pH value	7
Refractive index	1.54 - 1.55
Hardness (Mohs')	6.5
Melting point (°C)	1772
Specific resistance (ohms)	25.7

Ordovician Knox Group undifferentiated in Calhoun, Etowah, and Talladega Counties in northeast Alabama (fig. 4). Observed tripoli zones in this region are as much as 60 to 70 feet (18.2 to 24.2 meters) thick (Rheams and Richter, 1988).

Generally, the tripoli from northwest Alabama is white to pinkish gray to very pale orange in color. The individual particles of tripoli are actually aggregates of white, microcrystalline quartz. Crystal faces in the aggregates are visible under a microscope, indicating some amount of crystallinity of the quartz constituents. Tripoli samples from Lauderdale and Colbert Counties are composed almost entirely of silica with less than 1 percent iron-oxide between the 50- and 230-mesh-size fractions (Rheams and Richter, 1988). Chemical analyses of tripoli samples from northwest Alabama are given in table 3.

Table 3.--Chemical analyses of tripoli, northwest Alabama (Rheams and Richter, 1988).

County/location	Chemical composition (weight percent)					
	SiO_2	Al_2O_3	Fe_2O_3	MgO	MnO	CaO
Colbert						
SE¼NE¼ sec. 27, T. 2 S., R. 15 W.	98.42	0.53	0. 18	0.05	0.01	0.16
Lauderdale						
NE¼SE¼ sec. 31, T. 1 S., R. 14 W.	97.69	1.06	.14	.06	.01	.22
NE¼NW¼ sec. 32, T. 1 S., R. 14 W.	97.56	.84	.14	.06	.02	.26
NW¼SE¼ sec. 29, T. 1 S., R. 14 W.	98.26	.56	.13	.03	.02	.23
SE¼NW¼ sec. 2, T. 1 S., R. 14 W.	98.10	.63	.17	.03	.01	.23
SW¼NE¼ sec. 1, T. 2 S., R. 15 W.	98.42	.56	.13	.01	.01	.07
NE¼SE¼ sec. 1, T. 1 S., R. 15 W.	98.27	.39	.47	.01	.01	.09
NE¼SE¼ sec. 1, T. 1 S., R. 15 W.	97.10	.99	.62	.03	.02	.07
SW¼NW¼ sec. 13, T. 1 S., R. 15 W.	98.75	.37	.08	.02	.01	.06
SW¼SW¼ sec. 30, T. 1 S., R. 15 W.	98.32	.42	.13	.05	.01	.25
NW¼SW¼ sec. 11, T. 1 S., R. 14 W.	98.38	.49	.10	.05	.01	.24

Scanning electron microscopy (SEM) micrographs of tripoli samples from Lauderdale County show aggregates of very fine-grained silica. Many of the quartz grains are euhedral, doubly terminated, and range in size from 1 to 4 microns. Based on available SEM micrographs, these tripoli samples appear to be composed of almost 100 percent quartz with no identifiable accessory minerals (Rheams and Richter, 1988).

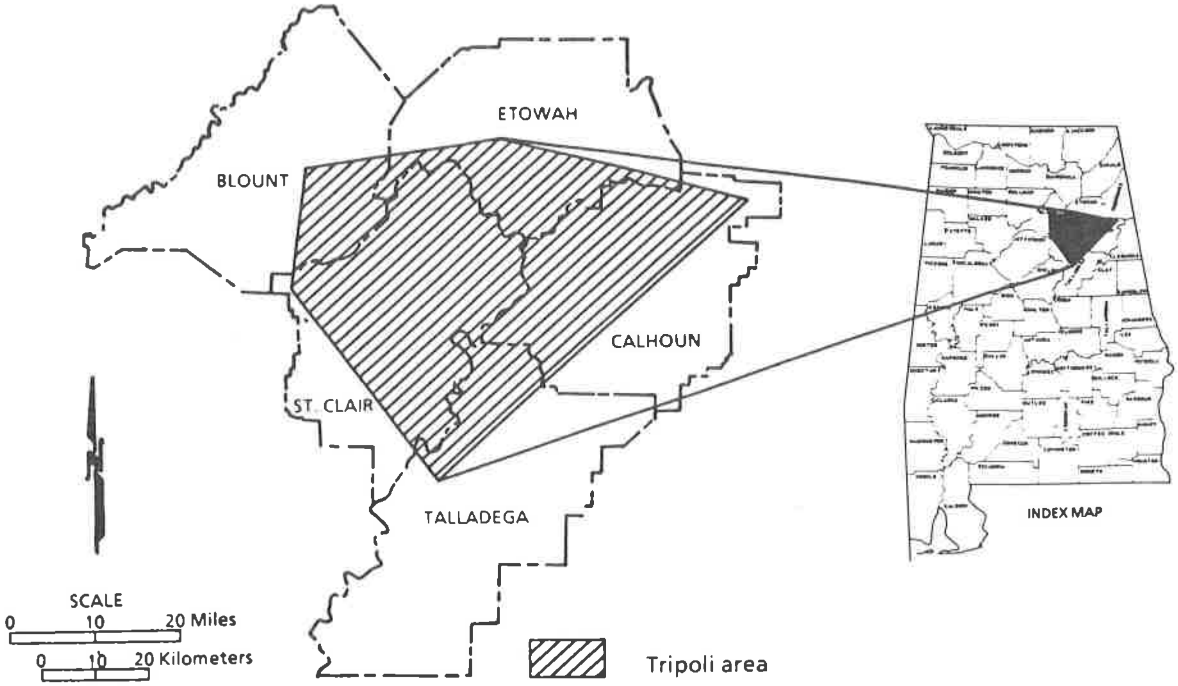

Figure 4.--Tripoli area, northeast Alabama (modified from Rheams and Richter, 1988).

Microscopically, the tripoli from northeast Alabama is composed predominantly of subangular to rounded, often frosted, individual grains of quartz (in contrast to the quartz aggregates found in the northwest Alabama tripoli samples). Many of the tripoli particles are iron stained to various shades of orange, and iron-oxide percentages range from 0.1 to 3 percent (Rheams and Richter, 1988). Chemical analyses of tripoli samples from northeast Alabama are given in table 4.

Table 4.--Chemical analyses of tripoli, northeast Alabama (Rheams and Richter, 1988).

County/location	Chemical composition (weight percent)					
	SiO_2	Al_2O_3	Fe_2O_3	MgO	MnO	CaO
Calhoun						
NE¼SE¼ sec. 17, T. 13 S., R. 7 E.	97.03	1.22	0.57	0.09	0.01	0.20
NW¼NW¼ sec. 27, T. 13 S., R. 8 E.	97.77	1.08	.10	.11	.01	.24
SW¼NW¼ sec. 27, T. 13 S., R. 8 E.	98.07	.83	.07	.07	.01	.21
SW¼NE¼ sec. 34, T. 13 S., R. 8 E.	87.48	6.87	1.87	.46	.01	.43
NE¼SE¼ sec. 4, T. 13 S., R. 9 E.	96.09	2.14	.15	.29	.01	.16
SE¼NW¼ sec. 2, T. 14 S., R. 6 E.	98.48	.71	.10	.06	.01	.07
Talladega						
SW¼NW¼ sec. 34, T. 17 S., R. 4 E.	89.20	6.75	.66	.17	.01	.04

SEM micrographs of tripoli samples from northeast Alabama show individual quartz grains and minor amounts of clay. The quartz grains are rounded and do not have the crystalline nature of the quartz in the northwest Alabama tripoli. Larger quartz grains (1 to 5 microns) and clay plates are also visible in the micrographs (Rheams and Richter, 1988).

Tripoli was produced near Tredegar, Calhoun County, Alabama, from the early 1900's to the 1920's. Very little information is available on the approximately 20-year operation (Weigel, 1927). During the mid-1960's, Industrial Fillers, Incorporated, developed a tripoli deposit near Piedmont in northeastern Calhoun County and a small amount of tripoli production from this deposit was reported (Bradbury and Ehrlinger, 1983; Rheams and Richter, 1988).

KAOLIN

Kaolin, commonly known as china clay, is a soft, earthy, generally white or nearly white clay composed essentially of the mineral kaolinite derived from in-situ decomposition (weathering) of aluminous minerals. Kaolin has many industrial applications because it is relatively chemically inert, generally white, has good covering power, is soft and nonabrasive, has low heat and electrical conductivity, and costs less than most comparable materials. The paper industry is the leading consumer of kaolin, but it is also used as a filler and extender in natural and synthetic rubber, paint, and plastics.

In Alabama, economic deposits of kaolin are associated with bauxite deposits in the Nanafalia Formation in the Eufaula district of Barbour and Henry Counties (fig. 5). High-quality kaolin frequently surrounds and overlies the bauxite deposits. The kaolin may grade outward to a sandy clay or sandy ferruginous clay (table 5) (Clarke, 1972). Three companies, the A. P. Green Refractories Company, Incorporated, in Barbour County, and the Eufaula Minerals Company and the Harbison-Walker Refractories Company, Incorporated, in Henry County, produced kaolin in Alabama in 1987.

Massive and pisolitic bauxite surrounded by kaolin occurs in the residuum of the lower part of the Cambrian Shady Dolomite not far above the stratigraphic contact with the

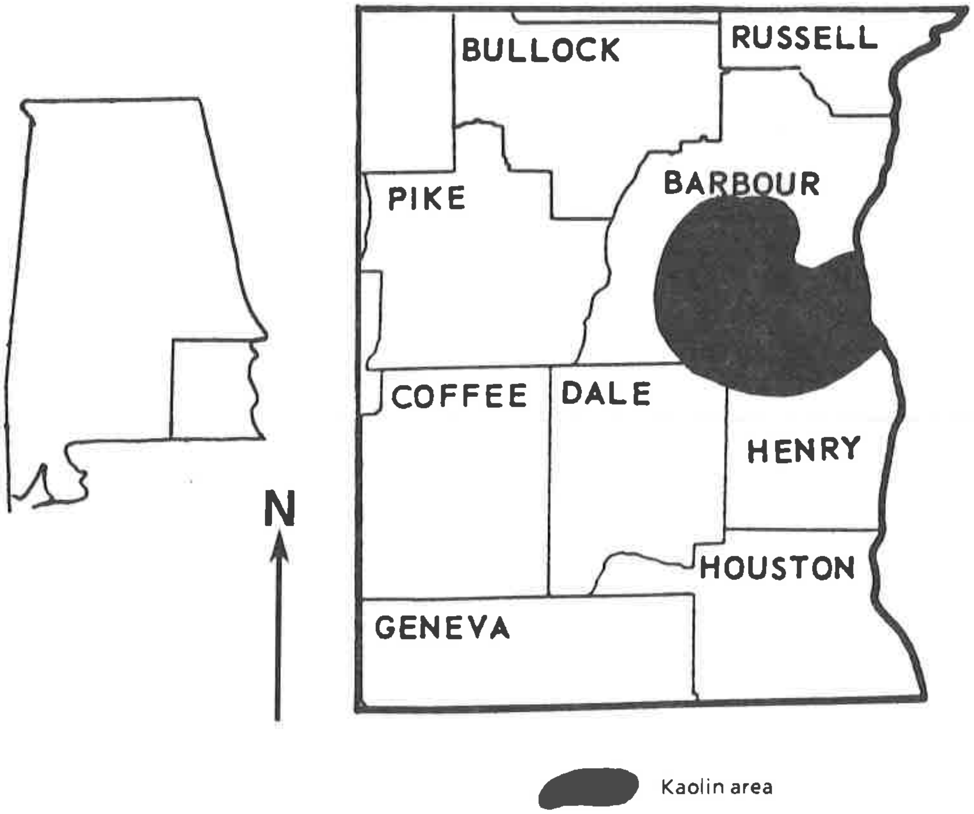

Figure 5.--Kaolin area, Eufaula district, Barbour and Henry Counties, Alabama (modified from Smith, 1984).

Table 5.-- Mineralogical analysis of a drill core sample of representative bauxite and kaolin material from the Eufaula district, Alabama, SE¼ sec. 13, T. 9 N., R. 27 E. (modified from Clarke, 1972).

Depth (feet)	Material	Mineralogy (percent)			
		Gibbsite	Kaolinite	Illite	Quartz
0 - 20	Bauxite	65	30	ND	ND
20 - 30	Kaolin	5	80	10	ND
30 - 40	Kaolin	ND	95	ND	ND
40 - 50	Clay	ND	45	45	5
50 - 60	Clay	ND	50	40	5
70 - 103	Clay	ND	25	50	20

ND = Not Determined

Weisner and Wilson Ridge Formations undifferentiated in Calhoun County, and in the Knox Group undifferentiated in Calhoun and Cherokee Counties (fig. 6). The kaolin in these deposits is typically white, hard, nonpisolitic, nonplastic, and grit free. It is often mixed with soft, semiplastic, light-gray to yellowish-gray kaolin. Good quality kaolin zones may be up to 8 feet (2.4 meters) thick. Several kaolin deposits have been prospected in the Anniston area and kaolin and lignitic kaolin have been mined and processed from one deposit in this area (table 6).

Commercial-quality kaolin occurs within sediments of the Cretaceous-age Tuscaloosa Group in Marion County in northwest Alabama (fig. 7). One large deposit at Chalk Bluff was mined to a large extent and the kaolin was used as filler in insecticides and pharmaceutical preparations. Clay with kaolinite contents as high as 90 percent occur in this area (table 7) (Clarke, 1966).

High-kaolinite clay (up to 75 percent kaolinite) also occurs within the stratigraphically lower underclays of the Pennsylvanian-age Pottsville Formation in the southeastern part of the Warrior coal field in western Alabama (Metzger,1964; Rheams and others, 1987).

TALC

Talc is an extremely soft, white, light-green, hydrated magnesium silicate mineral. It has a characteristic greasy or soapy feel, a hardness of 1 on Mohs' scale, and a specific gravity of 2.58 to 2.83. Talc is a common secondary mineral derived by the alteration of other magnesium silicates such as serpentine, pyroxene, or siliceous dolomite (Roe and Olson, 1983; Bates and Jackson, 1987). Chemical inertness and fine particle size are two characteristics that make talc an appealing filler to the paint, paper, plastic, and rubber industries.

Talc orebodies occur in the outcrop area of the Cambrian Shady Dolomite in the valley of Wewoka Creek southwest of Winterboro and west of Piedmont in the Valley and Ridge province of Talladega County (fig. 8). The orebodies are surrounded by Cambrian Rome Formation and Weisner and Wilson Ridge Formations undifferentiated.

Talc in the orebodies occurs as nonfoliated massive white, tan, or gray rock. Most of the deposits are 95 to 99 percent talc with some associated chlorite and very small amounts of calcite and pyrite. The impurities are generally concentrated in the outer zones of the orebodies. Typical properties of the processed talc from the Winterboro area are given in table 8.

Talc was discovered in this area in 1916 and the deposits were explored by test pits prior to World War I (Smith and Klinefelter, 1943). Talc was commercially produced from shallow pits in 1930 and 1931. Approximately 1,000 tons of talc were shipped to Birmingham for use in foundry facings (McMurray and Bowles, 1941). During 1941-43 (Smith and Klinefelter,

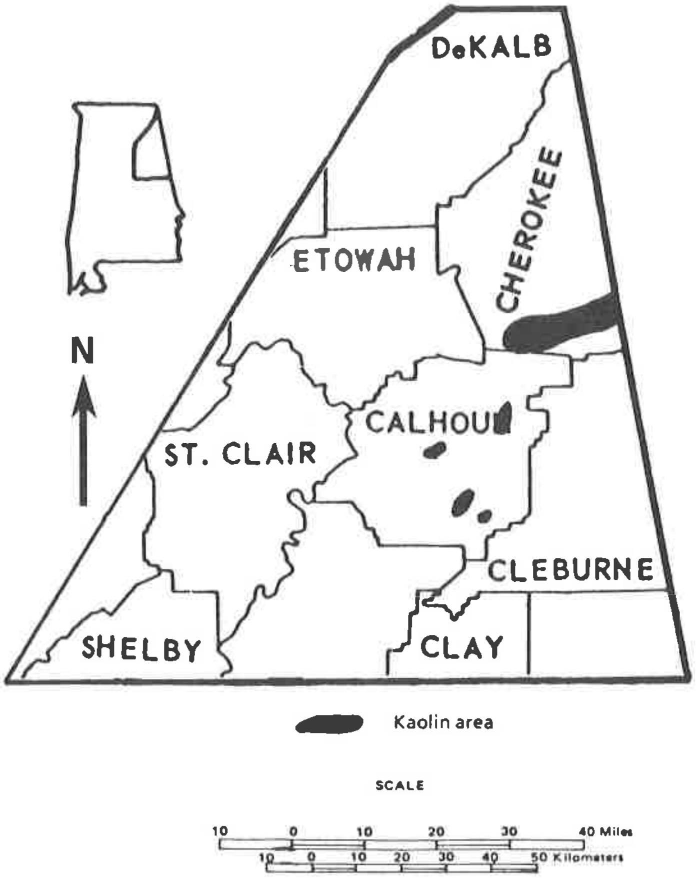

Figure 6.--Kaolin areas, Calhoun and Cherokee Counties, Alabama (modified from Smith, 1984).

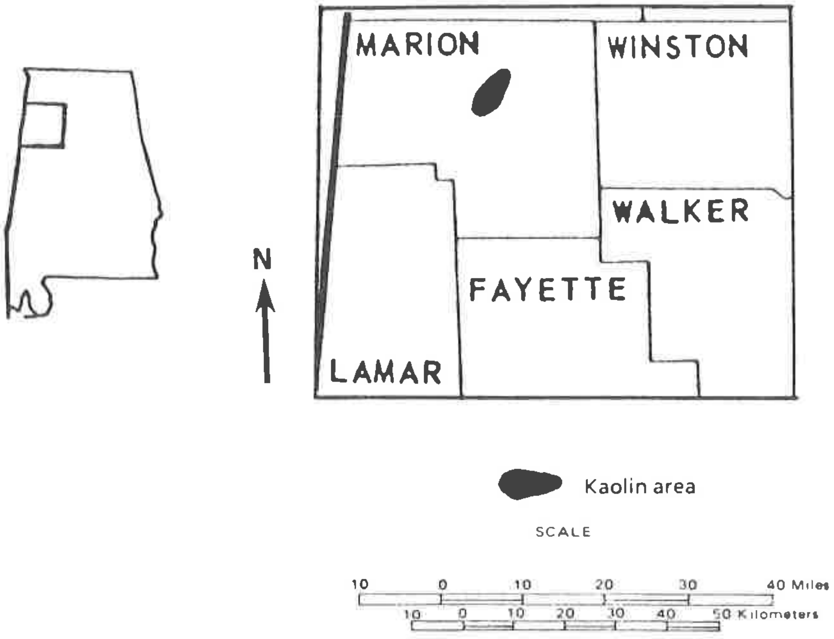

Figure 7.--Kaolin area, Marion County, Alabama (modified from Smith, 1984).

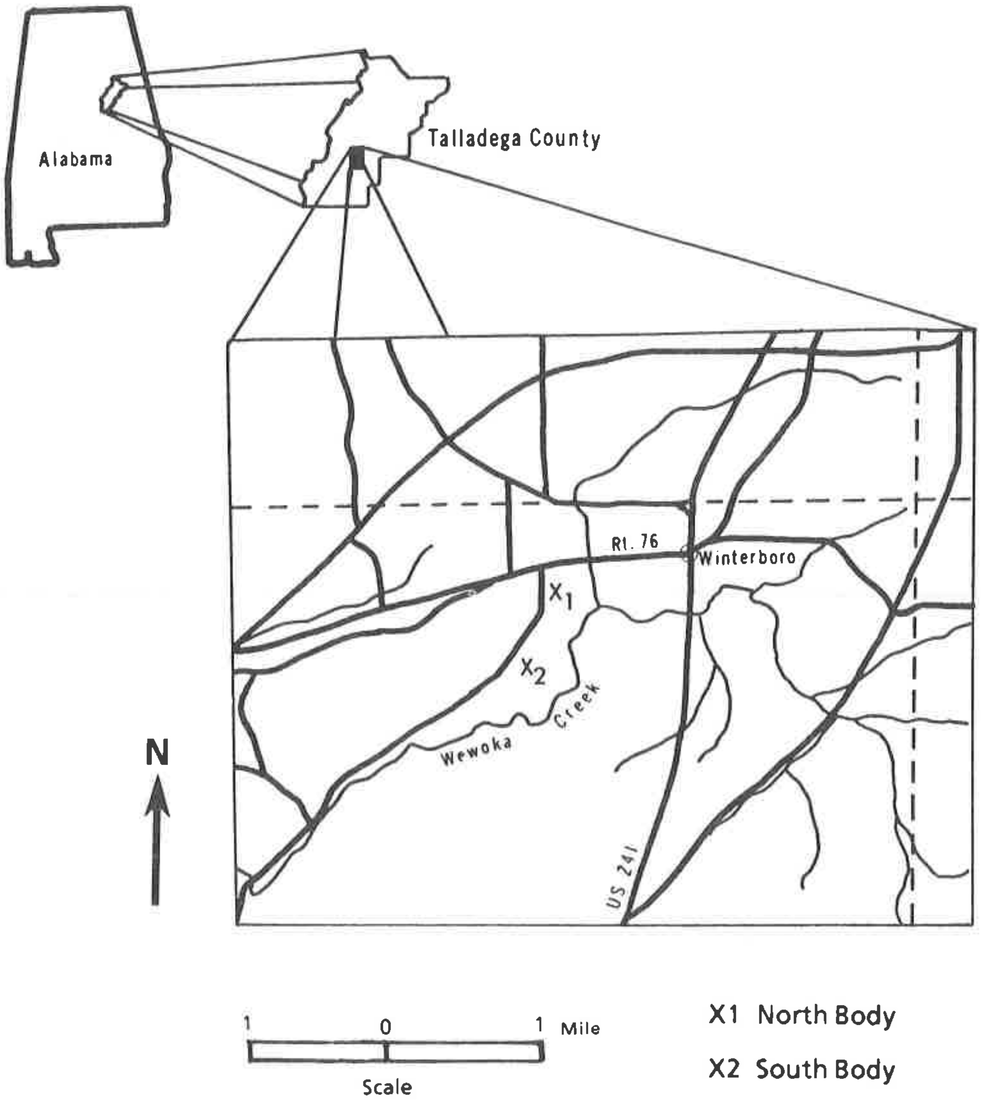

Figure 8.--Location of talc orebodies in the Winterboro area, Talladega County, Alabama (modified from Blount and Helbig, 1987).

Table 6.--Known locations of kaolin and/or bauxite clay in the Knox Group undifferentiated in the Anniston area, Calhoun County, Alabama (modified from Denson and Waage, 1966).

Name	Location	Chemical composition (percent)					Description
		Al_2O_3	SiO_2	Fe_2O_3	TiO_2	LOI	
Eulaton Pike kaolin deposit (Lackey mine)	NE¼ sec. 11, T. 16 S., R. 7 E.	36.9	47.0	0.8	2.3	13.0	White kaolin
		35.1	44.8	4.9	2.3	12.9	Purple kaolin
		34.7	48.4	1.0	2.5	13.0	Light-brownish-gray kaolin
		32.9	49.5	1.0	2.5	13.3	Lignitic clay
Carter Street kaolin deposit	NE¼NW¼NW¼ sec. 12, T. 16 S., R. 7 E.	38.4	45.4	.4	2.0	13.8	Significant tonnage of white kaolin
14th Street kaolin deposit	NW¼SW¼SW¼ sec. 1, T. 16 S., R. 7 E.	NA	NA	NA	NA	NA	No considerable volume of kaolin
Parkwin Street kaolin deposit	S½SW¼NE¼ and N½NW¼ sec. 1, T. 16 S., R. 7 E.	39.5	44.6	.5	1.5	14.2	Composite sample of white, mauve, and purple kaolin; considerable amount of kaolin
Fort McClellan kaolin deposit	Fort McClellan Military Reservation	NA	NA	NA	NA	NA	Kaolin deposit reported by Jones (1940)
Quintard Avenue kaolin deposit	Quintard Avenue, Anniston	NA	NA	NA	NA	NA	Bauxitic clay exposed during building excavations

NA = Not Available

Table 7.--Mineral analysis of kaolin from Chalk Bluff (SE¼NE¼ sec. 7, T. 10 S., R. 12 W.), Marion County, Alabama (modified from Clarke, 1966).

Minerals	Silt (50 - 2 microns) (percent)	Clay (-2 microns) (percent)
Kaolinite	85	90
Quartz	5	Trace
Chlorite	5	5
Illite	5	5

1943) and 1948-49 (Reed, 1950), further exploration was done in the area of the known talc deposits but there was no commercial talc production.

In 1953, the talc properties were leased by the American Talc Company of New Jersey and major talc production commenced. Initially, the mined talc was shipped to Georgia for grinding, but in 1963, a flotation mill was constructed at Alpine near the Winterboro

Table 8.--Typical properties for processed talc from Winterboro, Alabama* (modified from Blount and Helbig, 1987).

Color	White
Brightness	92
Physical constants (typical)	
Tapped bulk (tapped 500 times)	
20 grams	26.5 cc
Apparent density	47.1 lbs/cu ft
Loose bulk	
20 grams	71.4 cc
Apparent density	17.4 lbs/cu ft
Specific gravity	2.79
True density	23.16 lbs/gal
	0.426 gal/lb
Reflectance	
Green tri-stimulus filter	92
Oil absorption (rub out)	38
Sieve fineness	
Through 200 mesh	99.96%
Through 325 mesh	99.74%
Hegeman fineness	3.5
pH	7.15
Slip	Good
Chemical composition (typical)	
SiO_2	61.22%
Al_2O_3	.42%
Fe_2O_3	.58%
CaO	.05%
MgO	32.56%
LOI	5.16%
Acid soluble substances	.13%
Water-soluble substances	.02%
Water-soluble iron	None

*Information supplied by vendor, 1960.

deposits. High-quality water-floated talc was produced at the mill for filler, cosmetic, and pharmaceutical applications. The American Talc Company was acquired by Cyprus Industrial Minerals in 1979 (Blount and Vassilou, 1980; Raymond and Gilbert, 1984; Blount and Helbig, 1987) and talc mining resumed in the Winterboro area in 1988.

Talc is generally formed under intense dynamic or contact metamorphic conditions. The Winterboro talc bodies in the Shady Dolomite are geologically unusual in that they are associated with a dolomite that has undergone little, if any, metamorphism (Brown,1973;

Blount and Vassilou, 1980; Blount and Helbig, 1987). Original dolomite textures are preserved in the massive talc near Winterboro, indicating that regional deformation and thrust faulting occurred prior to the formation of the talc. It appears that the volume-for-volume dolomite-to-talc transformation resulted from hydrothermal solutions and metasomatic processes in or near fractures in the dolomitic bedrock following regional deformation and faulting. The close association of chloritic rocks with the talc deposits substantiates the movement of magnesium-bearing fluids in the area. The presence of chloritic rocks and chlorite-rich soils in association with dolomite may be an indicator of similar talc occurrences in the Winterboro area (Blount and Vassilou, 1980; Blount and Helbig, 1987).

SHALE, SLATE, AND PHYLLITE

Ground, unfired aluminous rocks, such as shale, slate, and phyllite, are potential economic fillers in numerous industries. These rocks are abundant, inert, and compatible with bitumens. Shale, slate, and phyllite are useful fillers in the production of roofing materials, sealing compounds, asphalt, linoleum, paints, and hard rubber (Severinghaus, 1983).

Variable quality shale, slate, and phyllite occur within the Appalachian Plateaus, Valley and Ridge, and Piedmont physiographic provinces (fig. 1). Some of these units (especially the Parkwood Formation, Floyd Shale, Brewer Phyllite, and Wash Creek Slate) have been quarried on small scales for use as filler in the manufacture of structural brick (Rheams, 1986). Chemical analyses of major shale, slate, and phyllite units in Alabama are given in table 9. Colors of the ground material range from very light gray to black.

BARITE

Barite is the most common and abundant ore mineral of barium. Well-formed barite crystals are generally tabular and have three cleavages. Colors generally range from colorless to white to browns to dark gray to black. Barite has a vitreous luster and a hardness of 2.5 to 3.5 on Mohs' scale. Barite is relatively insoluble in water and, therefore, can be used as a chemically inert material. Ground barite (both bleached and unbleached) is a common industrial filler in paper, rubber, paint, and plastics (Brobst, 1983).

Barite was produced in Alabama for many years and known economic occurrences are restricted to vein and residual deposits associated with carbonate rocks in the Valley and Ridge province (fig. 8). Large deposits of primary barite occur as epigenitic vein or breccia deposits in the Newala and Longview Limestones and in the layered cherty residuum of the Knox Group undifferentiated. The barite occurs as veins or fracture fillings and is commonly found in association with one or more gangue minerals (calcite, dolomite, rhodochrosite, fluorite, pyrite, marcasite, native sulfur, and goethite). Important secondary deposits occur as residual concentrations of barite in the residuum overlying the Newala and Longview Limestones and the cherty Knox Group undifferentiated. Dissolution of the host rock by weathering allows for a concentration of less soluble constituents, including barite. This results in a high-grade barite ore that is more easily mined than the primary deposits. Nearly all of the economic barite production in Alabama has come from residual deposits (Hughes and Lynch, 1973). Chemical analyses of barite samples from Bibb County are given in table 10.

MICA

Mica is a general name for a group of platy, hydrous aluminum silicate minerals with perfect basal cleavage that allows the mineral to be split into very thin sheets. Commercially, the most important member of this mineral group is muscovite, a potassium mica. Average chemical and physical properties of muscovite are given in tables 11 and 12, respectively.

On the basis of size and quality, commercial mica is divided into two categories: sheet mica, which must be relatively flat, free of defects and inclusions, and large enough to be trimmed into pieces 1 inch (2.54 centimeters) square; and scrap mica, which includes all mica

Table 9.--Chemical analyses of major shale, slate, and phyllite units in Alabama.

County	Geologic unit	Location	Chemical composition (weight percent)											
			SiO_2	Al_2O_3	Fe_2O_3	TiO_2	MnO	CaO	MgO	K_2O	Na_2O	P_2O_5	SO_3	LOI
Cherokee	Conasauga Formation	SE¼SE¼ sec. 13, T. 10 S., R. 10 E.	54.80	23.25	6.76	0.81	0.07	0.03	0.61	2.45	0.79	0.10	NA	7.36
		SW¼NE¼ sec. 19, T. 11 S., R. 11 E.	55.89	24.11	8.45	0.23	0.06	0.04	0.29	2.13	0.91	0.16	NA	6.25
Chilton	Parkwood Fm. and Floyd Shale undif.	NE¼SW¼ sec. 29, T. 24 N., R. 13 E.	67.31	14.05	.81	.77	.02	.22	.52	2.74	.32	.27	.15	7.18
		NE¼NW¼ sec. 15, T. 24 N., R. 13 E.	63.80	14.82	4.47	1.01	.02	.11	.43	3.18	.32	.20	.09	6.70
	Waxahatchee Slate	SW¼SE¼ sec. 7, T. 23 N., R. 13 E.	59.52	26.00	0	.61	.03	.26	.15	3.82	1.48	.10	.07	5.63
	Wash Creek Slate	SW¼NW¼ sec. 31, T. 24 N., R. 14 E.	60.61	14.92	.34	.64	.10	.65	1.61	2.47	.76	.11	.12	4.21
	Stumps Creek Formation	NW¼NW¼ sec. 28, T. 24 N., R. 14 E.	53.09	21.22	0	1.39	.08	.88	1.57	3.81	1.45	.14	.15	4.39
		SE¼SE¼ sec. 22, T. 24 N., R. 14 E.	52.23	23.36	7.44	1.02	.07	.33	.97	2.92	2.11	.23	.09	4.46
	Brewer Phyllite	SE¼SE¼ sec. 34, T. 24 N., R. 13 E.	52.05	26.00	1.92	.72	.15	.58	1.27	2.44	1.92	.46	.09	4.88
		SE¼SE¼ sec. 34, T. 24 N., R. 13 E.	61.97	14.46	.12	1.14	.06	.20	1.09	3.21	.60	.17	.08	4.14
	Lay Dam Formation	SW¼NW¼ sec. 5, T. 23 N., R. 14 E.	58.74	19.75	6.09	.48	.05	.78	.31	3.54	.63	.13	.11	6.20
		SW¼NE¼ sec. 24, T. 23 N., R. 15 E.	60.38	17.11	3.54	1.05	.01	.26	1.55	5.77	1.12	.16	.09	4.33
Shelby	Pottsville Formation	Sec. 3, T. 15 S., R. 3 W.	60.46	20.39	5.78	.84	.07	.25	.47	4.39	1.06	.18	NA	5.46
	Parkwood Formation	Secs. 29, 31, and 32, T. 19 S., R. 3 W.	59.63	19.55	8.01	.91	.14	.23	.61	3.94	.72	.25	NA	6.03
	Athens Shale	SW¼SW¼ sec. 19, T. 11 S., R. 11 E.	42.70	9.31	3.64	.57	.09	19.59	2.42	2.47	.37	.14	NA	18.84

NA = Not Available

Table 10.--Typical chemical analyses of barite, Bibb County, Alabama (modified from Chaffin and others, 1976).

Location	Chemical composition (percent)				
	$BaSO_4$	SiO_2	$CaCO_3$	CaF_2	Fe_2O_3
SE¼SE¼ sec. 17, T. 24 N., R. 11 E.	98.18	0.54	0.70	0	--
Sec. 30, T. 24 N., R. 11 E., and secs. 24, 25, and 26, T. 24 N., R. 10 E.	96.00	Tr	.70	.20	.60
NW¼ sec. 3, T. 23 N., R. 10 E.	98.18	.62	--	--	.13

Tr = Trace

Table 11.--Average chemical properties of muscovite mica (modified from Chapman, 1983).

Chemical constituents	Percent
SiO_2	46.0
Al_2O_3	35.0
K_2O	10.5
MgO	.5
Fe_2O_3	1.0
FeO	1.0
Na_2O	1.0
Minor	.5
H_2O	4.5

Table 12.--Average physical properties of muscovite mica (modified from Chapman, 1983).

Specific gravity	2.77 - 2.88
Mohs' hardness	2.5 - 3
Optic axial angle	30 - 47 degrees
Temperature of decompression	400 - 500 °C
Dielectric constant	6.5 - 9
Specific heat (25 °C)	0.206 - 0.209

that does not meet sheet mica specifications. Scrap mica, generally produced from large-scale, low-grade deposits, or as a byproduct in the mining and trimming of sheet mica, is processed to a fine size for use as a filler in roofing, siding, shingles, wallboard, drilling mud, rubber, plastic, paints, and other synthetic materials (Fleming, 1976; Epperson and Rheams, 1984).

Muscovite is a very common mineral and is a major constituent of various granitic, gneissic, schistose, and phyllitic rocks in the Piedmont province of Alabama (figs. 1 and 9). Mica-bearing pegmatites have been mined in five major areas in Clay, Coosa, Randolph, and Tallapoosa Counties in the Alabama Piedmont (table 13). Large concentrations of scrap mica also occur as disseminated flakes in micaceous schists within these counties (Epperson and Rheams, 1984). Systematic mining of mica deposits in Alabama began around 1870 (Heinrich

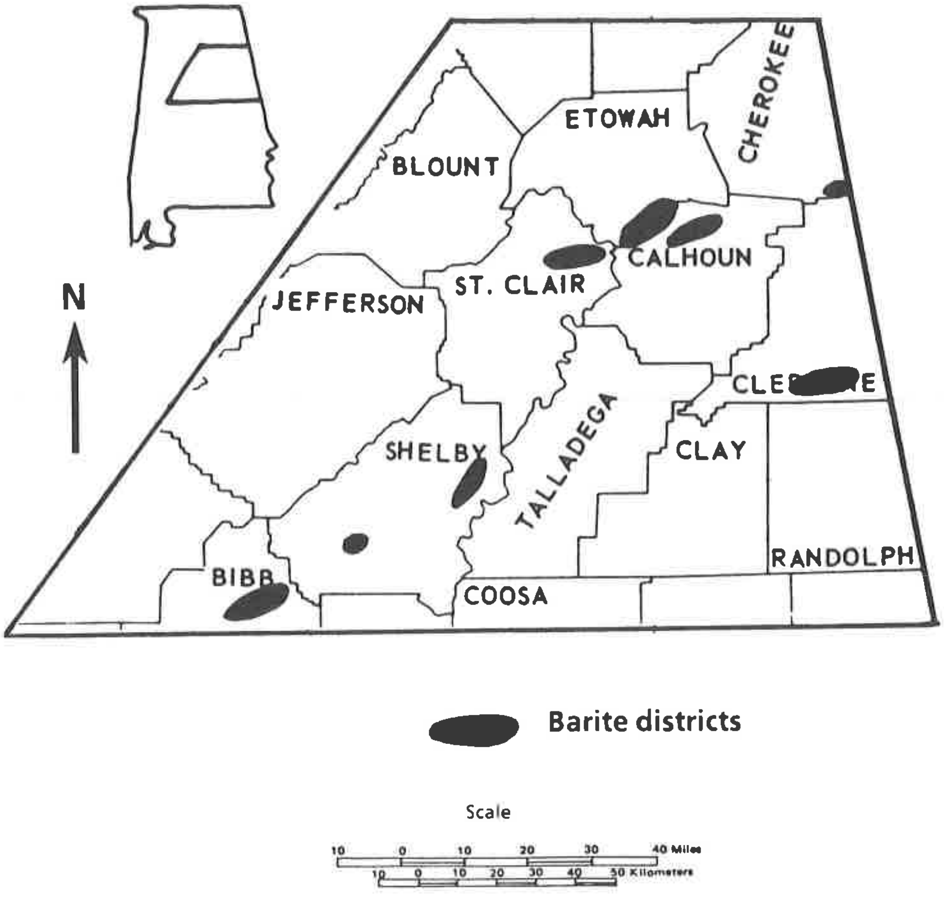

Figure 9.--Barite districts in the Valley and Ridge province of Alabama (modified from Smith, 1984).

Table 13.--Major mica mining areas in Alabama (modified from Epperson and Rheams, 1984).

County	Area	Description
Clay	Pyriton area	Western Clay County-approximately 21 mi (33.6 km) long and 3 mi (4.8 km) wide
	Lineville area	Eastern Clay County-approximately 5 mi (8 km) long and 1 mi (1.6 km) wide
Coosa	Rockford area	Central Coosa County-approximately 8 mi (12.8 km) long and 4 mi (6.4 km) wide
Randolph and Cleburne	Pinetucky area	Western Randolph and Cleburne Counties-approximately 13 mi (20.8 km) long and 7 mi (11.2 km) wide
Tallapoosa	Dadeville area	Eastern Tallapoosa County-approximately 8 mi (12.8 km) and 3 mi (4.8 km) wide

and Olson, 1953) and was almost continuous until U.S. Gypsum ceased mica production in Randolph County in 1980 (Epperson and Rheams, 1984). A complete list of known mica mines and prospects, their locations, and production history are given in Epperson and Rheams (1984). Preliminary beneficiation studies by the U.S. Bureau of Mines indicate that an acceptable grade of scrap mica could be produced from weathered schists in Clay, Coosa, Randolph, and Tallapoosa Counties, but low brightness is a detrimental property. A number of sericite schist and phyllite units in the low-grade metamorphic rocks of the northwestern Alabama Piedmont could contain up to 98 percent sericite, a white, fine-grained potassium mica occurring in small flakes as an alteration product of various aluminosilicate minerals (Neathery, 1977).

ANTHOPHYLLITE

Anthophyllite (a variety of asbestos) is a brownish to colorless iron magnesium silicate mineral of the amphibole group, which occurs in metamorphosed basic and ultrabasic rocks, generally in association with olivine or talc or as monomineralic aggregates of parallel or radiating asbestiform fibers. Average chemical and physical properties of anthophyllite are given in tables 14 and 15, respectively. Anthophyllite can be easily separated into strong fibers that are heat resistant and chemically inert (Bates and Jackson, 1987). Resistance to chemical reaction allows anthophyllite to be used as a filler. It has been used as a fibrous filler in the production of resin and polyester parts, such as automobile heater and air conditioner housings, and other appliance parts. Anthophyllite also has been used in the manufacture of joint filler cements and texture paints. Generally, inertness, whiteness, and fineness are important properties in the use of anthophyllite as a filler (Mann, 1983).

Fibrous anthophyllite occurs in Chambers and Tallapoosa Counties in the Alabama Piedmont province (fig.11) in talc-rich alteration zones surrounding mafic and ultramafic plutons. These rocks crop out in two narrow arcuate bands extending from Dudleyville to the southwestern part of Tallapoosa County (fig. 10). Anthophyllite is most abundant in the eastern part of this area and is associated with major deposits of talc. Boulders of anthophyllite or talcose anthophyllite are disseminated throughout much of the saprolite

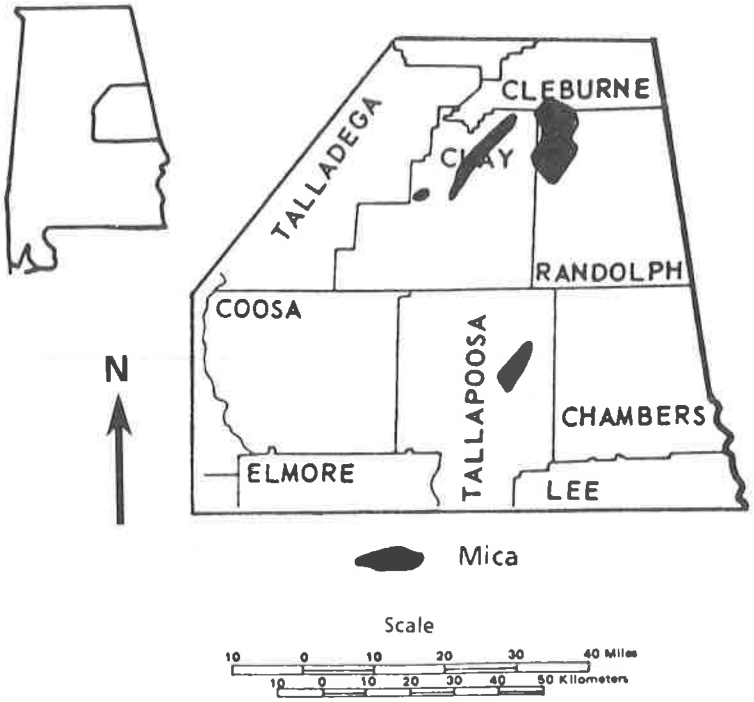

Figure 10.--Mica areas in the Piedmont province of Alabama (modified from Dean, 1988).

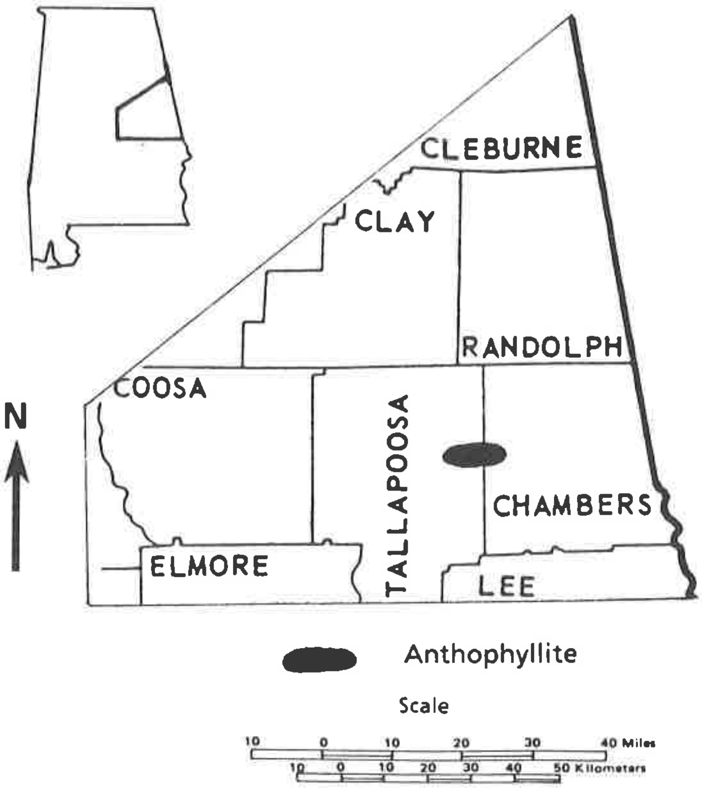

Figure 11.--Anthophyllite area, Chambers and Tallapoosa Counties, Alabama (modified from Dean, 1988).

Table 14.--Average chemical analysis of anthophyllite (modified from Mann, 1983).

Chemical constituents	Percent
SiO_2	56 - 58
Al_2O_3	0.5 - 1.5
FeO	3 - 12
MgO	28 - 34
CaO	--
Na_2O	--
H_2O	1 - 6

Table 15.--Average physical properties of anthophyllite (modified from Badollet, 1951).

Structure	Lamellar; fibrous asbestiform
Mineral association	In crystalline schists and gneisses
Origin	Metamorphic; usually from olivine
Veining	Slip; mass fiber unoriented and interlacing
Essential composition	Mg silicate with iron
Crystal structure	Prismatic; lamellar to fibrous
Crystal system	Orthorhombic
Color	Grayish white; brownish gray or green
Luster	Vitreous to pearly
Hardness (Mohs')	5.5 - 6
Specific gravity	2.85 - 3.1
Cleavage	110 perfect
Optical properties	Biaxial positive; parallel extinction
Refractive index	1.61
Length	Short
Texture	Harsh
Specific heat (Btu per lb per °F)	0.21
Tensile strength (psi)	4,000 or less
Temperature at maximum ignition loss (°F)	1800
Electric charge	Negative
Fusion point (°F)	2675
Spinnability	Poor
Resistance to acids and alkalies	Very good
Flexibility	Poor
Resistance to heat	Very good

overlying the mafic and ultramafic rocks in the area. The talc is probably an alteration product from the anthophyllite (Neathery and others, 1967; Neathery, 1968).

Anthophyllite deposits near Dudleyville, Tallapoosa County, have been mined on a small scale intermittently since 1873 (Cook and Smith, 1982). Extensive prospecting and analytical investigation of the anthophyllite in this area were conducted during the 1960's (Neathery and others, 1967; Neathery, 1968; Wilkins and others, 1968). During this time period, bulk samples of talc-anthophyllite material from surface outcrops in the NE1/4 SE1/4 sec. 2, T. 22 N., R. 24 N.,1 were analyzed and product research was conducted. Chemical analyses of the sampled anthophyllite are given in table 16. Measured chemical resistance of the anthophyllite to common acids and alkalies is reported in table 17. Based on the thermal and chemical stability of the sampled anthophyllite, possible product applications were investigated by the U.S. Bureau of Mines Research Center at Tuscaloosa, Alabama (Wilkins and others, 1968). It was determined that the high-temperature and acid/alkali-resistant anthophyllite would make useful filler for various types of paints, asphalt-base products (including pipe and tank coatings, automobile undercoatings, and roofing tar), and vinyl tile mixtures. Health concerns may present a problem to the use of this mineral resource as a filler.

Table 16.--Chemical analyses of anthophyllite from Tallapoosa County, Alabama (modified from Wilkins and others, 1968).

Sample number	Chemical composition (percent)					
	SiO_2	Al_2O_3	Fe_2O_3	MgO	CaO	Na_2O
1	54.22	0.19	10.58	31.12	0.26	0.87
2	48.73	.34	11.31	34.09	--	.93

Table 17.--Resistance of anthophyllite from Tallapoosa County, Alabama, to common acids and alkalies (modified from Wilkins and others, 1968).

Chemical treatment	Weight loss (percent)
Sulphuric acid	2.80
Nitric acid	1.79
Hydrochloric acid	11.89
Sodium hydroxide	1.42
Ammonia hydroxide	2.36

CONCLUSION

Many proven and potential mineral and rock filler-extender materials exist in various parts of Alabama. The economic significance of many of these resources as fillers and extenders is presently unknown. However, demand is increasing for good quality, inexpensive filler-extender materials. With more extensive geologic exploration and industrial testing of these known and potential rock and mineral resources in Alabama, the filler-extender needs of particular industries may be met.

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GEOLOGY AND ORIGIN OF A TALC PROSPECT IN THE BURKS MOUNTAIN COMPLEX, COLUMBIA COUNTY, GEORGIA

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ABSTRACT

Investigation of an occurrence of talc boulders southeast of Pollards Corner, Columbia County, Georgia defined a potentially economic talc deposit. The talc boulders are a weathering residuum of a multilithic breccia overlying an Alpine-type serpentinite. The serpentinite is part of the Burks Mountain complex, a belt of ultramafic and mafic rocks enclosed within migmatitic gneisses, amphibolites and granites of the northeast-trending Kiokee belt.

The origin of the talc is a result of a complex series of events beginning with upper amphibolite-grade (sillimanite facies) metamorphism of a ultramafite of harzburgite composition during the Alleghanian orogeny. Extensive retrograde, prehnite-pumpellyite facies metamorphism formed predominantly lizardite serpentine and nearly obliterated earlier high-grade assemblages. Fracturing and brecciation of the serpentinite allowed the influx of CO_2-bearing solutions which altered the lizardite to a mixture of talc, magnesite, dolomite and calcite. A subsequent influx of Al-rich fluids through the same conduits produced an overprint of coarse-grained chlorite concentrated in and adjacent to those earlier fractures. Locally extensive, late-stage silicification in several other serpentinite masses of the Burks Mountain complex replaced the talc and serpentinite, thereby significantly reducing their economic potential. Finally, uplift, weathering and erosion resulted in a residual concentration of talc boulders at and near the present surface.

The talc deposit is a bulk-tonnage, medium-grade resource. Estimated talc concentrations in the talc-bearing breccia are on the order of 25%. The chemical purity of the talc is good. The talc's brightness could be enhanced by removal of magnetite and use of unweathered talc. Tonnages conservatively calculated from drill-hole intercepts and surface indications of the talc-bearing breccia are on the order of 1.8 million tons. With little or no overburden, an open-pit operation is feasible, and anticipated ease of mining and ore separation favor low-cost production. Prospects for additional talc-mineralized zones within non-silicified serpentinites of the Burks Mountain complex are good and would further enhance the mining economics.

INTRODUCTION

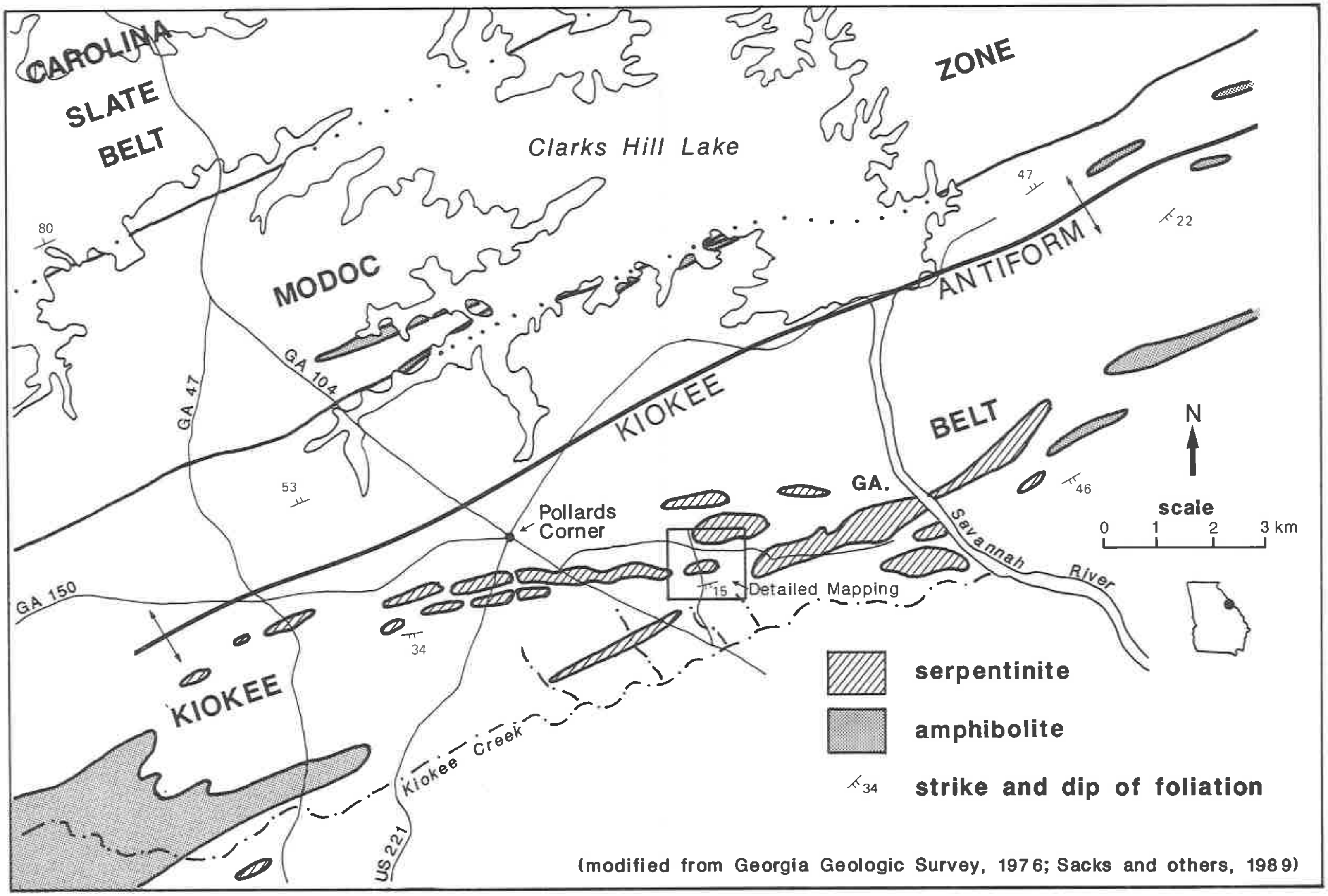
Although most talc production in the United States is from metamorphosed sedimentary rocks in New York, Montana, North Carolina, Texas, California, and Nevada, significant talc production is from metamorphosed ultramafic and mafic igneous rocks (Chidester and others, 1964; Brown, 1973; Roe and others, 1983; Vitra, 1987). Talc deposits of this type are associated with belts of ultramafic and mafic igneous rocks in the Appalachian and Piedmont Provinces extending from Alabama through New England. Talc is commonly developed as a rind in the serpentinite along the contact with the enclosing rocks, or as a complete replacement of the serpentinite. Deposits are generally small and vary in shape from thin shells to irregular masses. Current talc production in the Chatsworth district in northwest Georgia is from a cluster of ultramafic pods.

Talc was recognized near Pollards Corner at an early date by Hopkins (1914); however, interest in the area focussed on the mining of serpentinite for magnesium sulfate in the early 1940's (LeGrand and Furcron, 1956), and exploration for nickel and chrome in the early 1960's by the J.M. Huber Corporation, Worthington (1964), and Hurst and others (1966). McLemore (1965) first recognized the talc potential suggested by the extensive boulder fields occurring 2.2 miles (3.5 km) ESE of Pollards Corner. During the Georgia Geologic Survey's Accelerated Minerals Program, an examination of the ultramafic rocks by Vincent and others (1990) initiated a drilling program to test the extent of the talc mineralization.

In the latest phase of the investigation (1988-89), evaluation of the talc mineralization near Pollard's Corner consisted of detailed (1:2400) field mapping, a ground magnetic survey (on a 200x100 foot grid), drilling and logging of 10 core holes, whole-rock and trace-element geochemistry, petrography and x-ray diffraction (XRD) analyses. Fresh drill core samples were analyzed by Skyline Labs., Inc. (Wheat Ridge, CO) using standard whole-rock and trace-element techniques. Petrographic studies consisted of transmitted and reflected light optical mineral identification, textural descriptions and modal analysis of 41 samples principally from fresh, unweathered drill core. The geologic mapping, ground magnetic survey and drilling defined the surface exposure and subsurface distribution of the serpentinite and talc. Whole-rock and trace element geochemistry, petrography and XRD analyses defined the mineralogical and chemical composition of the talc and associated rocks.

GENERAL GEOLOGY

The Burks Mountain complex is a narrow band of elongate pods of mafic and ultramafic rocks (Fig. 1) extending over a strike-length of 20 miles (33 km) from Richmond County and Columbia County in Georgia into South Carolina. The Burks Mountain complex is located within upper amphibolite grade



(modified from Georgia Geologic Survey, 1976; Sacks and others, 1989)

Figure 1. Generalized Geologic Map of the Pollards Corner Area.

migmatitic metamorphic rocks of the Kiokee belt in the southeastern part of the Piedmont Province. A second belt of small pods and lenses of ultramafic rock and amphibolite located approximately 2.5-3.1 miles (4-5 km) north of and roughly parallel to the Burks Mountain complex (Fig. 1) may be part of the Burks Mountain complex which was folded over on the northwest limb of the Kiokee antiform (Sacks and others, 1989).

The Burks Mountain complex includes serpentinite, metagabbro, talc and several types of amphibolite. The complex is interpreted as a suite of harzburgite, cumulate wherlite or olivine clinopyroxenite, cumulate gabbro and anorthositic gabbro, rodingite and possibly mafic volcanic rocks metamorphosed to serpentinites, metagabbros, and amphibolites plus felsic paragneisses and schists (Sacks and others, 1987; Sacks and others, 1989). Ultramafic rocks south and southeast of Pollards Corner are dominantly serpentinized harzburgites. The Burks Mountain complex may be a slice of Iapetus ocean crust (Higgins and others, 1988; Sacks and others, 1989) or possibly a layered ultramafic/mafic plutonic complex (Sacks and others, 1989; Cocker, 1989c and in review (a).

The Kiokee belt is a northeast-trending, middle to upper-amphibolite grade, lithostratigraphic belt bordered on the north by cataclastic rocks of the Modoc Zone and by lower-grade greenschist facies metamorphic rocks of the Carolina slate belt (Fig. 1) and on the south by similar lower-grade metamorphic rocks of the Belair belt. The Kiokee belt consists mainly of metamorphosed igneous and sedimentary rocks with a minor component of syn- or post-metamorphic felsic intrusions. The principal metamorphic lithology is a fine- to medium-grained, migmatitic, felsic to intermediate gneiss with lesser amounts of migmatitic, sillimanite-bearing, two-mica schist; metaquartzite; biotite gneiss; leucocratic granite; amphibolite and serpentinite (Maher, 1978; Secor, 1987; Sacks and others, 1989).

Kiokee belt rocks are considered to be Late Precambrian or Cambrian island arc and oceanic crust developed adjacent to the African craton (Cook and others, 1979; Secor and others, 1983; Secor and others, 1986a and 1986b; Higgins and others, 1988). Closure of the Iapetus ocean during the Appalachian orogeny moved these rocks adjacent to the North American craton. Emplacement of the Kiokee belt into its present position occurred during the Alleghanian orogeny, the last recognized major episode in the development of the Appalachian orogen. In the Kiokee belt, the Alleghanian orogeny is characterized by folding and thrusting with accompanying prograde regional metamorphism. Magmatic activity formed numerous synkinematic, felsic intrusions and may have produced the regional metamorphism. Although deformation events lasted from 315 to 268 Ma, peak metamorphism and penetrative deformation is dated at 305 +/- 10 Ma (Dallmeyer and others, 1986).

Recent detailed studies of the serpentinites in the central portion of the Burks Mountain complex revealed a vertical geochemical zoning interpreted as a relict igneous differentiation trend (Cocker, 1989c and in review (a)). The serpentinite is zoned from MgO-rich (rich in normative olivine) at the base to SiO_2-rich (rich in normative enstatite) at the top (Fig. 2). Apparent trend lines were drawn to connect sample analyses from four drill holes (DDH's 87-1, 87-4, 87-5 and 88-2). Closely spaced pairs of analyses are from different drill holes at similar horizons and reinforce the concept of igneous differentiation during cooling and crystallization of the magma. Possible igneous contact chill-zone effects (also possibly explained by a more siliceous talc overprint) may occur near the base of the serpentinite. Millimeter-scale, and larger, mineralogical layering is locally developed, particularly in the upper part of one of the serpentinite bodies. In addition, Ti-V-REE-P-rich, Cr-poor, magnetite plus ilmeno-hematite-rich layers are spatially associated with the mineralogical layering suggest a more highly differentiated system than is normally associated with Alpine-type ultramafic masses (Cocker, 1989c and in review (a)) .

Drilling intercepts indicate that the talc-bearing serpentinite is a 95-145 feet (24-44 m) thick mass which is concordant to the regional foliation of the enclosing rocks. The serpentinite strikes approximately N60°E and dips 10-30°S. (Fig. 3). The serpentinite pinches out to the northeast approximately 1000 feet (300 m) east of the Old Petersburg Road (Fig. 4), possibly due to faulting (perhaps manifested as the multilithic breccia). In Figure 3, faults and the approximate top of the southern serpentinite (partially underlying the multilithic breccia) are inferred from the ground magnetic survey and the drilling results. Also shown in Figure 3 are the locations of the drill holes and geologic section (Fig. 4). In Figure 5, two large, pronounced ground magnetic anomalies (+2000 gammas) (Cocker, 1989a and in review (a)) are coincident with the location of the serpentinites and multilithic breccia shown in Figure 3. A regional aeromagnetic anomaly (Daniels, 1974) is coincident with the southern serpentinite. The ground and aeromagnetic anomalies indicate that the serpentinite extends to the southwest beneath overlying Kiokee gneiss. On the east side of the Old Petersburg Road, the numerous smaller magnetic anomalies within the southern magnetic anomaly (Fig. 5) may be caused by large blocks of serpentinite within the multilithic breccia.

Brittle deformation and retrograde metamorphism in the eastern Piedmont probably occurred as a result of and subsequent to rapid uplift accompanying thrusting which immediately followed high-grade metamorphism (Dallmeyer and others, 1986; Frazier and Schwimmer, 1987). Retrograde metamorphism is attributed to release of fluids from an underlying slab during thrusting (Tull, 1978). Retrograde assemblages containing epidote, blue-green hornblende, and Na-rich plagioclase (McLemore, 1965; Sacks and others, 1989; Cocker, in review (a)) indicate retrograde metamorphism to the

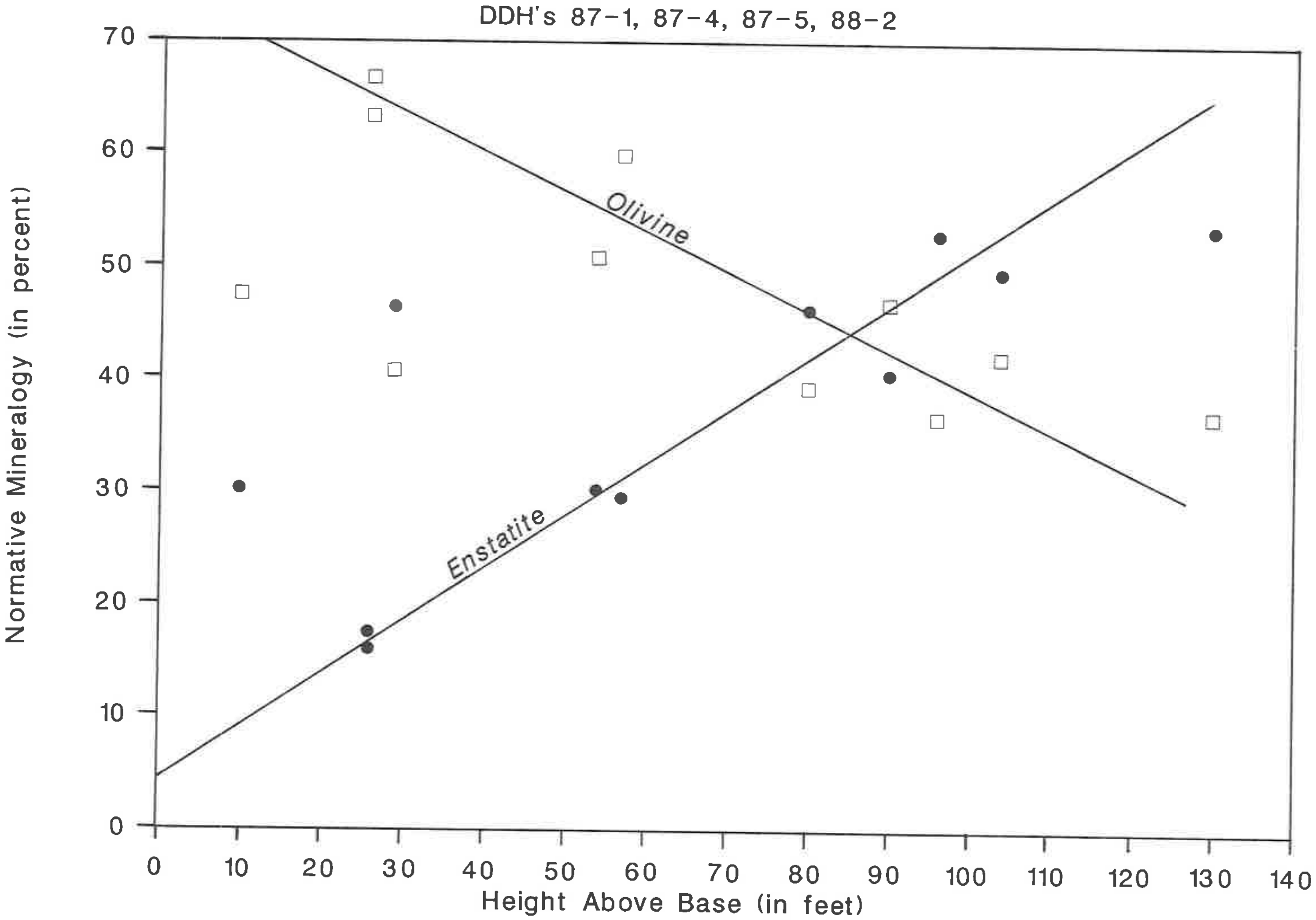


Figure 2. Normative Olivine and Enstatite vs Height Above Base.

epidote-amphibolite facies. Younger, lower-grade, zeolite facies metamorphism produced zeolites in fractures (McLemore, 1965). Retrograde lizardite-carbonate-talc-chlorite assemblages in the ultramafites (Cocker, 1989a) suggest low-grade, prehnite-pumpellyite (lower greenschist) facies metamorphism. Fracturing, veining and brecciation of the ultramafites occurred after serpentinization and was accompanied or followed by alteration of the serpentinite. Alteration adjacent to fractures resulted from an influx of metamorphic/ hydrothermal fluids (Cocker, 1989a, 1989b and in review (a)). Brittle deformation may be related to Mesozoic rifting associated with the opening of the Atlantic Ocean (Secor and others, 1986a).

Extensive brecciation of the serpentinite formed a zone of multilithic breccia, 70-140' (21-43m) thick, along the upper contact of the serpentinite (Fig. 4). The breccia (Fig. 6) is characterized by numerous subangular to rounded clasts of serpentinite with a minor component (<10%) of Kiokee gneiss and kaolinized granite clasts embedded in a matrix of coarsely crystalline chlorite. The serpentinite clasts are steatized around their rims and along through-going fractures, with many of the smaller clasts completely altered to talc.

This breccia provides critical information regarding the timing of regional metamorphism, serpentinization, brecciation and talc genesis. The presence of serpentinite, Kiokee gneiss and granite as clasts within the breccia indicate these lithologies were formed prior to the brittle deformation and brecciation of the serpentinite. Alteration of the serpentinite to talc, carbonate and chlorite matrix occurred subsequent to brecciation and hence after regional high-grade and retrograde metamorphism (Cocker, 1989a and in review (a)).

METAMORPHISM AND TALC GENESIS

Prograde Metamorphism

Within the serpentinites of the Burks Mountain complex, an upper amphibolite, prograde metamorphic assemblage is preserved in the form of the original metamorphic minerals, pseudomorphs of these minerals, and as reactant phases. Sprays of acicular tremolite and anthophyllite are cross-cut and partially replaced by lizardite, talc and carbonate. Prismatic talc pseudomorphs are interpreted to be retrograde replacements of porphyroblastic enstatite which cross-cut primary, millimeter-scale igneous layering. Pitted, embayed and corroded, disseminated Cr-magnetite enclosed in chlorite is the product of a prograde reaction between serpentine, olivine or enstatite and primary, magmatic spinel (Cocker, 1989a and in review (a)). Progressive metamorphism of primary spinel in alpine-type serpentinites commonly results in the formation of chlorite + ferritchromite +/- Cr-magnetite +/- magnetite (Golding and Bayliss, 1968; Onyeagocha, 1974; Springer, 1974; Bliss and McLean, 1975; Frost, 1975; Evans and Frost, 1975; Pinsent and Hirst, 1977; Lipin, 1984). Patchy

EXPLANATION

Kt	Cretaceous-Tertiary sedimentary rocks
Pmg	Permo-Carboniferous granite
mbx	Multilithic breccia
mg	Migmatitic biotite amphibole gneiss
╲ ? ╲	Fault (possible)
⟋ 10°	Low angle thrust(?) fault
⟋ 25	Strike and dip of foliation
⟋ 51°	Strike and dip of centimeter-scale layering
88-2 ⊙	Diamond drill hole

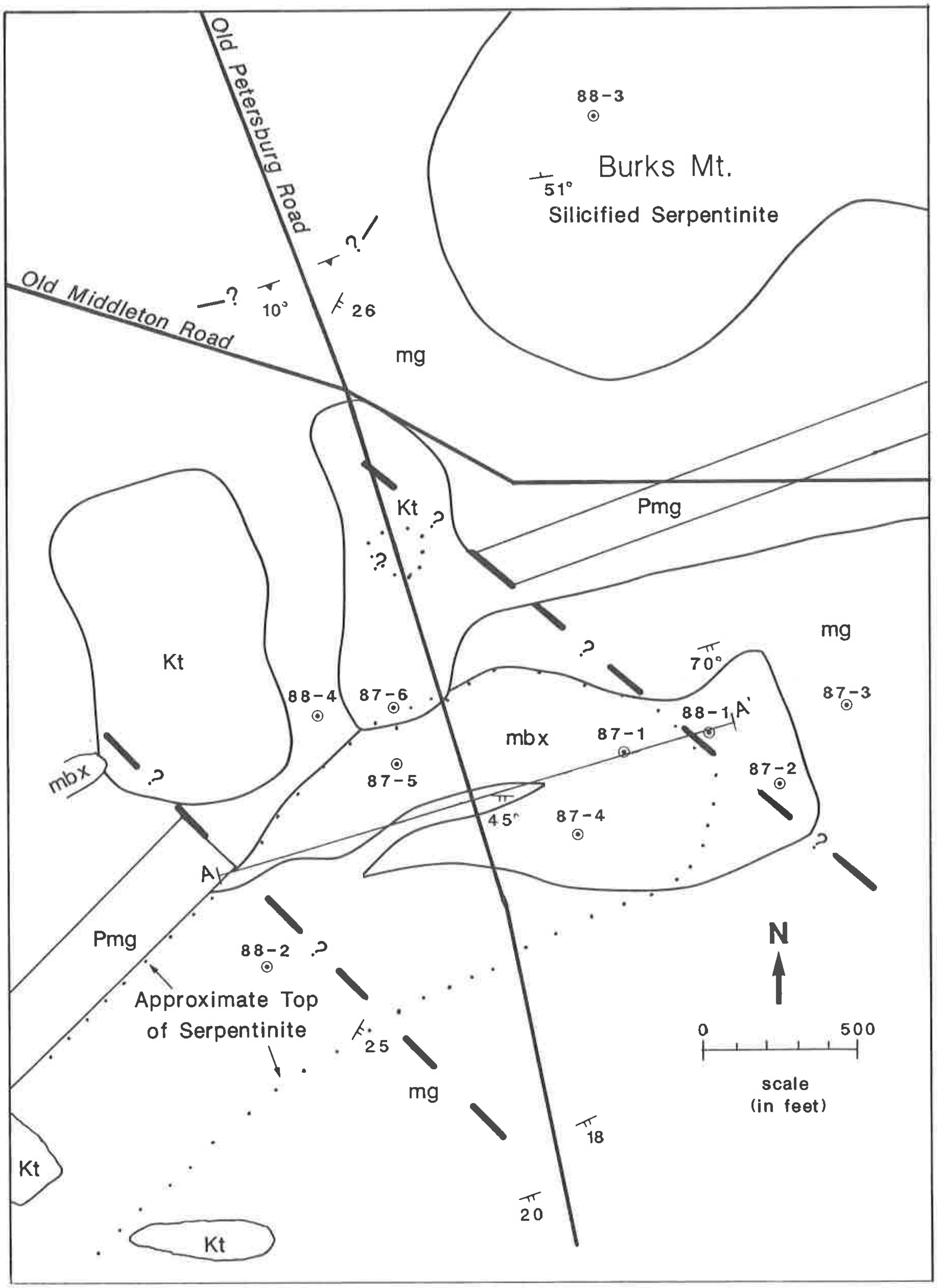
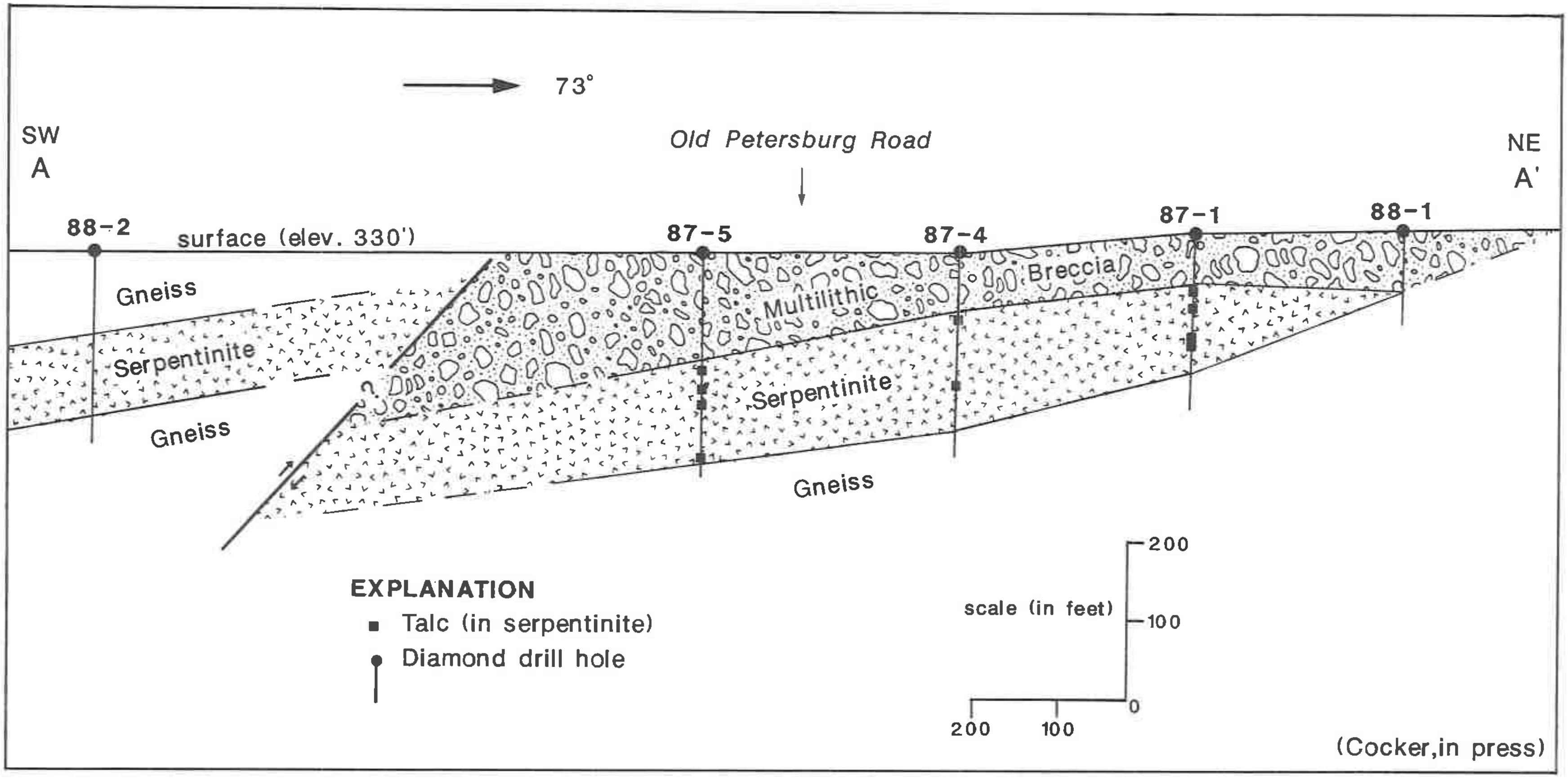
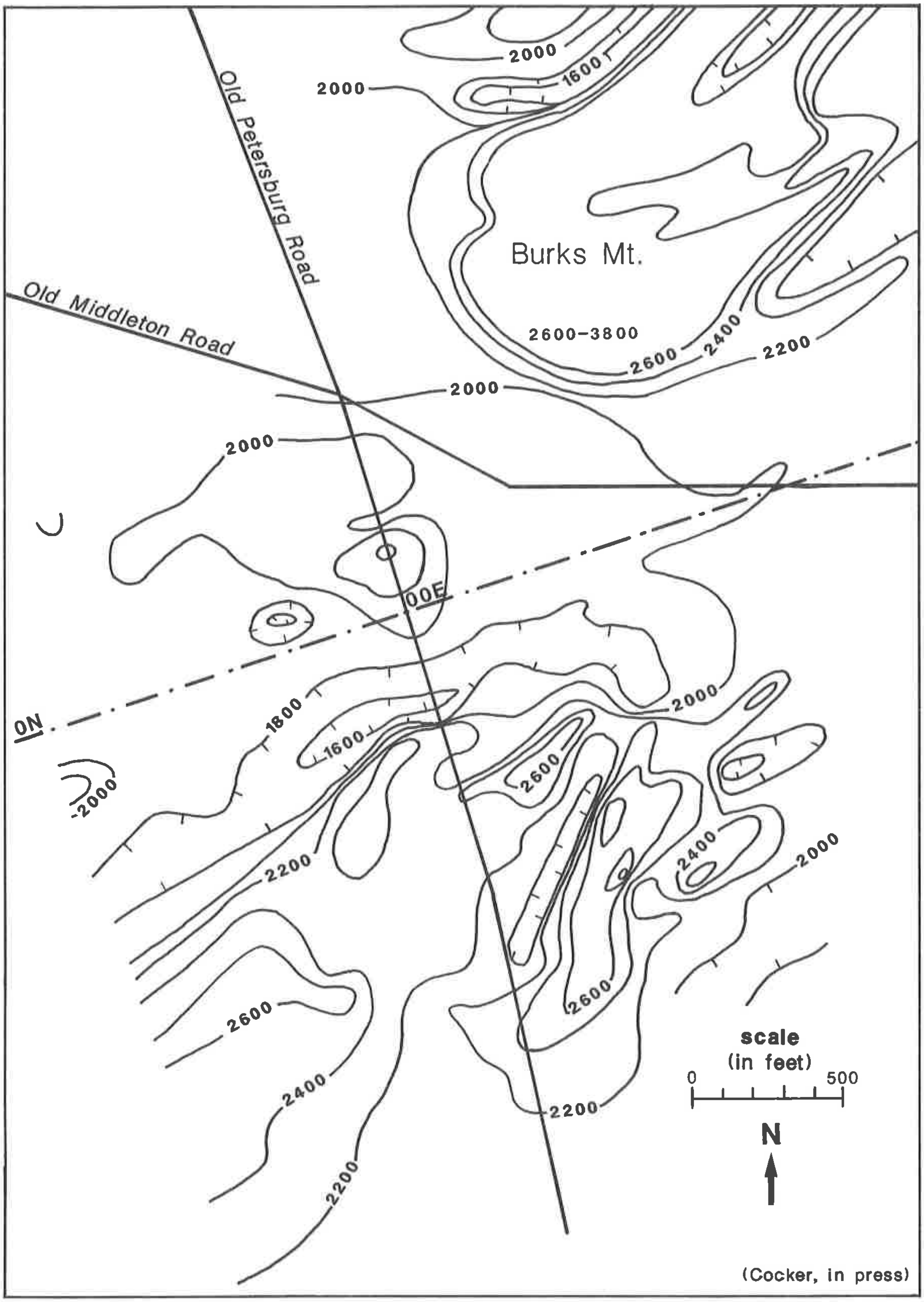


Figure 3. Geologic Map of the Talc Prospect.



(Cocker,in press)

Figure 4. Long Section A-A' of Serpentinite and Multilithic Breccia.



(Cocker, in press)

Figure 5. Detailed Ground Magnetic Map (contour interval 200 gammas).

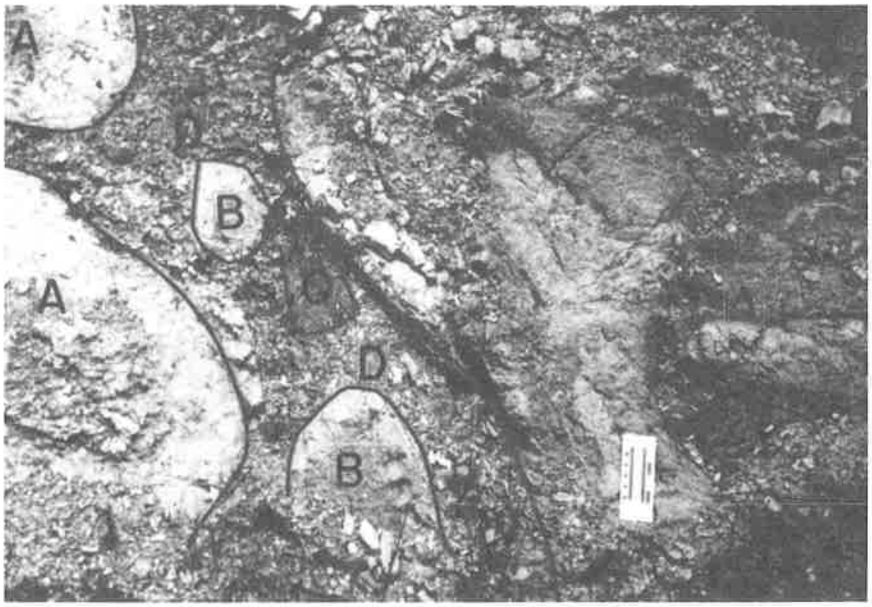


Figure 6. Multilithic Breccia. Location is the Old Petersburg roadcut approximately 1200 feet south of the Old Middleton Ferry Road. Shown are: A) large, rounded clasts of serpentinite with talc-altered rims; B) smaller, rounded clasts completely replaced by talc; C) small, rounded clasts of Kiokee gneiss; and D) coarse-grained chlorite matrix. Left side of scale is 10 cm; right side is 4 inches.

talc disseminated in serpentinite may be a medium-grade phase formed during prograde or retrograde metamorphism. Textural relations suggest lizardite may replace this patchy talc (Cocker, in review (a)). Lizardite pseudomorphs after olivine and pyroxene indicate they were present and stable at a higher metamorphic grade.

Progressive metamorphism of serpentinized ultramafites generally produces relatively anhydrous assemblages beginning with the elimination of chrysotile/lizardite at the lower greenschist facies and antigorite at the lower amphibolite facies. Increasingly higher-grade, progressive metamorphism causes complete re-equilibration of lower grade assemblages. The olivine +/-enstatite +/-tremolite +/- anthophyllite + chlorite assemblage is equivalent to the sillimanite-muscovite facies (Evans and Frost, 1975). Peak metamorphic conditions indicated by this assemblage are approximately 700°C and 3-5 kb (Springer, 1974; Frost, 1975; Pinsent and Hirst, 1977). The presence of this assemblage in the Burks Mountain complex serpentinites and sillimanite-muscovite assemblages in the enclosing Kiokee Belt rocks suggest that similar metamorphic conditions were attained by rocks in this part of the Kiokee Belt.

Serpentinization

The ultramafites in the central portion of the Burks Mountain complex are pervasively serpentinized and contain minor amounts of relict higher grade Mg-silicates and spinels. Although antigorite and chrysotile were reported from Burks Mountain (Hopkins, 1914; McLemore, 1965), the only serpentine mineral identified by XRD and petrography is lizardite (Cocker, 1989a and in review (a); Sacks and others, 1989). Mesh-textured lizardite is pseudomorphic after olivine, orthopyroxene (bastite) (Sacks and others, 1989), anthophyllite, and tremolite. Serpentinization of olivine formed fine-grained magnetite which commonly is concentrated along the edges of the pseudomorphic mesh-texture. This magnetite pattern is preserved in silicified serpentinite but is destroyed in steatized serpentinite. Preservation of coarse-grained magnetite spinels provides a textural and mineralogical link between the serpentinized harzburgite and the silicified and steatized harzburgite (Cocker, 1989a and in review (a)).

Lower temperatures and pressures required for formation and preservation of lizardite, and the absence of antigorite suggest that serpentinization occurred subsequent to peak metamorphism. Antigorite generally is formed during prograde metamorphism (Wicks and O'Hanley, 1988) and reflects high temperatures attending upper greenschist to lower amphibolite facies. Metamorphic conditions during lizardite serpentinization were probably below 250°C and 500 bars pressure with less than 300 bars fluid pressure as suggested in studies by Wenner and Taylor (1971), Savin and Lee (1988), and Wicks and O'Hanley (1988).

The formation of lizardite instead of antigorite, and the preservation of lizardite mesh-texture and delicate textures such as acicular amphiboles and skeletal spinels strongly suggest the Burks Mountain serpentinites were not penetratively deformed except perhaps on a local scale (Cocker, 1989a and in review (a)). The absence of a penetrative fabric in hand sample or thin section, and the lizardite serpentinization that preserves the outlines of the original grains, textures, fracture patterns and cleavages of the parent minerals as pseudomorphs is compatible with a water-diffusion controlled process in a static environment (MacDonald, 1984; Wicks and O'Hanley, 1988).

Steatization, carbonatization and chloritization

Steatization (the formation of massive or impure talc) of the serpentinite followed brittle deformation of the serpentinite. Fracturing and brecciation of the serpentinite created channelways for the influx of hydrous, siliceous, and CO_2-bearing fluids and vastly increased reaction surfaces around serpentinite clasts and along fractures in the serpentinite. Steatization occurred adjacent to fractures within the massive serpentinite, within breccia clasts, and around the rims of breccia clasts (Fig. 6). Commonly, clasts are completely replaced by talc. Carbonates (magnesite, dolomite and calcite in varying proportions) occur with the talc and extend further into the serpentinite. Carbonate minerals are most abundant in assemblages with less than 25 modal percent talc and with 30-50 modal percent lizardite. An increase in CO_2 towards the base of the serpentinite suggests an upward influx of solutions. The spatial and temporal relation of carbonatization to steatization imply that the two processes are related (Cocker, 1989b, in review (a and b)).

Experimentally and theoretically derived stability relations indicate that the observed relations can be achieved through an increase in silica activity or a decrease in temperature during metamorphism (Fig. 7). Figure 7 is a temperature -silica activity diagram modified from Evans and Guggenheim (1988). The antigorite field was divided by a vertical line to show the approximate stability field of lizardite relative to antigorite and chrysotile (Wicks and O'Hanley, 1988). The large black arrows show the anticipated reaction directions for: 1) the formation of patchy talc from forsterite +/- enstatite +/- anthophyllite at high temperatures; and 2) the formation of massive talc during the alteration of lizardite at low temperatures. Talc can form from serpentine (antigorite) at temperatures down to at least $100^{\circ}C$. Because lizardite is the stable serpentine below 200-$250^{\circ}C$ (Wicks and O'Hanley, 1988), talc probably formed at or below that temperature. Pressures are estimated to be low (<2.5 kb) with $P(H_2O)$ less than 300 bars (Wicks and O'Hanley, 1988). An increase in SiO_2 activity can result from: 1) an influx of SiO_2-saturated fluids, 2) removal of MgO, or 3) an increase in the Si/Mg ratio of the silicate fraction of the

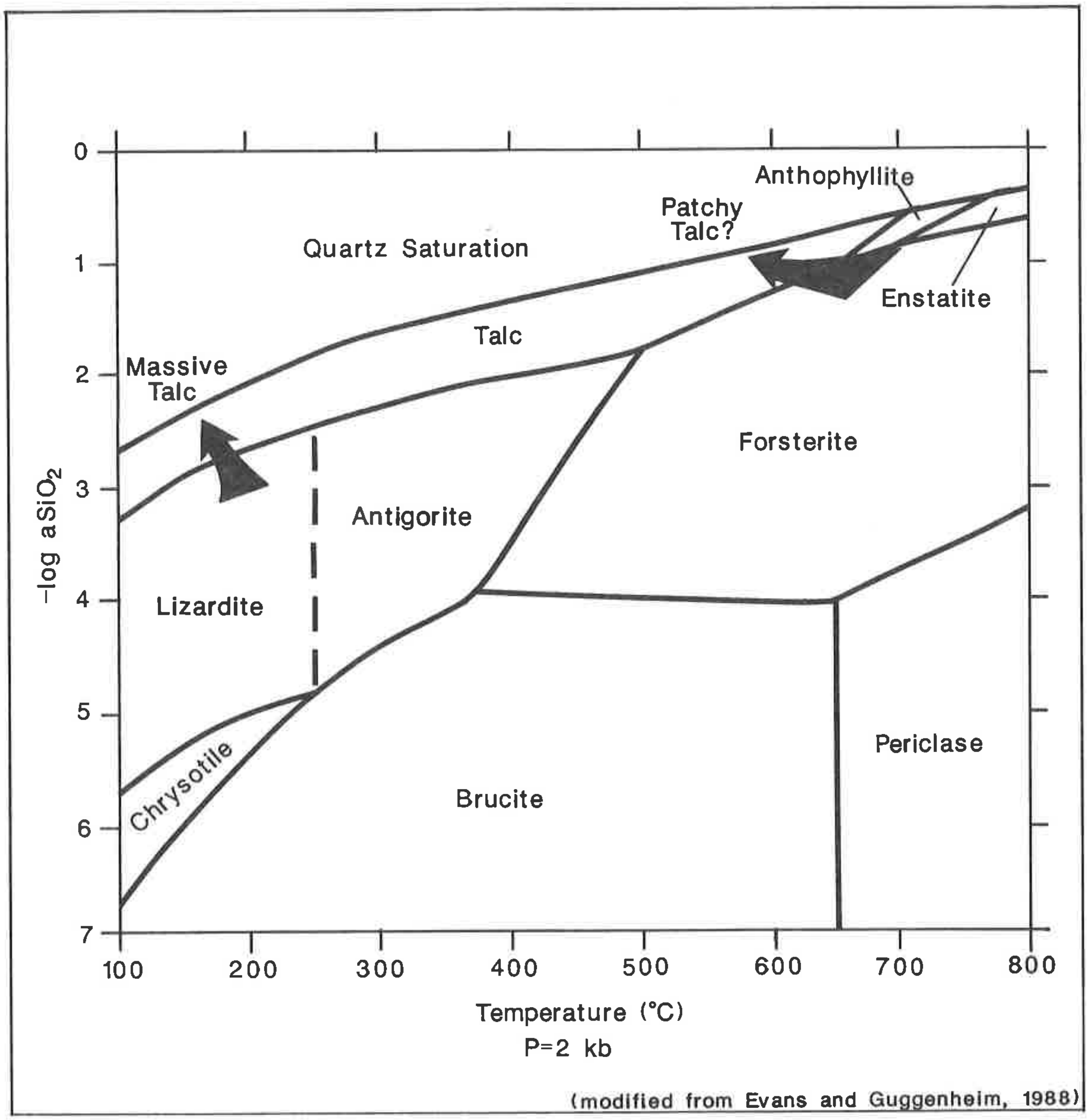


Figure 7. Silica Activity - Temperature Diagram of the MgO-SiO_2-H_2O.

rock due to the conversion of Mg-silicate to Mg-carbonate. A small increase in CO_2 alters serpentine to form Mg-bearing carbonates and releases silica to form talc (Evans and Guggenheim, 1988; Cocker, 1989a, 1989b and in review (b)).

Coarse-grained chlorite fills fractures in the serpentinite, the matrix of the multilithic breccia, and is localized along the serpentinite-country rock contact (Cocker, 1989a and in review (a)) which is commonly referred to as a chlorite blackwall (Chidester, 1962). The coarse-grained chlorite is friable and susceptible to erosion and washout by drilling fluids. Formation of chlorite in fractures, breccias and blackwall from talc requires removal of SiO_2 or addition of MgO +/-FeO and the addition of Al_2O_3 from altered country rock (Cocker, in review (a)).

Chloritization of biotite and amphibole and albitization of plagioclase in the adjacent country rock mobilized CaO, K_2O and TiO_2 to form secondary biotite, titanite and ilmenite (?). Secondary biotite occurs as numerous anastomosing veinlets cutting hornblende, biotite, quartz and plagioclase and as irregular aggregates replacing plagioclase in an amphibolite up to 5 feet (1.5m) below the lower serpentinite - gneiss contact (Cocker, 1989a and in review (a)). Chloritization of biotite and albitization of plagioclase adjacent to the serpentinite mobilized potassium and calcium respectively which diffused further into the country rock. Biotite formed at the expense of calcic amphibole (hornblende) or plagioclase (Sanford, 1982; Chidester, 1962; Cocker, in review (a)). Mobilization of titanium is indicated by the presence of titanite as common but minor individual grains and as overgrowths on Ti-oxides in country rock lithologies. Titanium-enrichment also occurs in the coarse-grained chlorite in fractures and in the multilithic breccia matrix (Cocker, in review (a)). Similar occurrences of secondary biotite, albite and/or titanite are recorded in many localities in New England (Chidester, 1962; Sanford, 1982) and Virginia (Burfoot, 1930), Washington (Frost, 1975); and Georgia (Hopkins, 1914). The presence of this altered zone adjacent to the serpentinite of the Burks Mountain complex indicates substantial tectonic movement did not occur between the serpentinite and the adjacent country rock since the formation of this alteration zone.

Although spatial and temporal overlap of alteration phases obscurred some textural and mineralogical relations, the following alteration zoning is recognized (Cocker, in review (a and b)): 1) a core of "fresh" lizardite serpentinite containing disseminated patches of talc, carbonate and chlorite; 2) +/- fine-grained chlorite; 3) talc + carbonate; 4) massive talc; 5) foliated talc; 6) coarse chlorite; 7) chloritized, albitized and biotitized country rock (generally gneiss or amphibolite); and 8) fresh country rock (gneiss, amphibolite or granite). This zonation is similar to metasomatic alteration sequences commonly developed at ultramafic-country rock contacts (Chidester, 1962; Jahns, 1967; Sanford, 1982).

Silicification

Widespread silicification and quartz veining is common in the northern serpentinite, but is uncommon in the southern, talc-bearing serpentinite. No silicification or quartz veining was observed in country rocks from drill core, outcrop or float. Multistage quartz veins cut across talc, chlorite, and serpentine, with quartz commonly replacing these minerals. The intensity of silicification is directly related to the density of quartz veining suggesting silicification and quartz veining are probably simultaneous and directly related. Crustiform vein quartz is common, indicating open-space filling. The SiO_2 content increases dramatically from 40 wt.% in average Burks Mountain complex serpentinite to 80-90 wt.% in silicified serpentinite. There appears to be no major volume changes, for the modal magnetite and weight percent Fe_2O_3 are essentially the same in unsilicified and silicified rocks (Cocker, in review (a)).

ECONOMIC GEOLOGY

Serpentine and talc are rocks or minerals important in industry for their physical and chemical properties. The two are geologically associated in the Burks Mountain complex and form two deposits in this area with the talc mineralization overlying the serpentinite.

Talc

Talc occurs as a residual surface deposit of subangular to rounded talc pebbles, cobbles and boulders which locally are so abundant as to form a pavement or boulder field. This deposit formed during intense weathering of the talc-bearing multilithic breccia under the subtropical to tropical conditions of the Georgia Piedmont. Tropical conditions during the Eocene are suggested by the presence of bauxites in NW Georgia of Eocene age. Weathering concentrated resistant talc clasts and dissolved, disaggregated and removed less-resistant materials (chlorite, serpentinite, and gneiss) (Cocker, 1989b and in review (b)). Talc's resistance to subtropical to tropical weathering has been documented in Winterboro, Alabama (Blount and Vassiliou, 1980) and in Nigeria (Akpanika and others, 1987).

The concentration of talc in the underlying multilithic breccia is best estimated from the continuous outcrop of multilithic breccia along the Old Petersburg Road. A matrix-rich portion of the breccia is estimated to contain 25% talc. This estimate was obtained by use of a grid over a photograph of the outcrop. An estimate of the talc content from drill core is unreliable, because drilling recovery ranges from fair to poor in the multilithic breccia.

Chemical analyses of four talc samples, core and surface samples, from the Burks Mountain complex are comparable in quality to 40 analyses of talc (rock) ore and pure talc (mineral) from various localities in the U.S. and around the world as reported in the literature (Fig. 8). Average composition of all the talc samples is shown by the circle. Two samples of the Burks Mountain talc are similar in composition to the high purity talc (near 31 wt.% MgO and 60 wt.% SiO_2). The two talc samples from the Burks Mountain complex that are lower in SiO_2 have lower SiO_2 and MgO due to a significantly higher carbonate content. The average composition of talc from the Burks Mountain complex is shown in Table 1. Petrographic studies indicate talc-rich rocks average better than 75 modal percent talc. Impurities in the talc-rich rocks may include: chlorite, lizardite, magnetite, dolomite, magnesite, calcite, and quartz.

The quality of the talc from the Burks Mountain complex was evaluated using brightness measurements. The brightness test consists of drying and pulverizing a sample to form a plaque which is then compared with a standard of known brightness. The brightness is measured and calculated with a reflectance meter constructed, calibrated and operated according to a pulp and paper industry standard (Patterson and Murray, 1975).

Comparison of brightness and talc composition indicates a strong influence of weathering and iron content. Measurements of brightness range from 36.9% in weathered talc boulders to 67.7% in unweathered, drill intercepts (Cocker, 1989b and in review (b)). Ideally, unweathered talc from this deposit would have a weathering index of approximately 90 and a brightness of approximately 80%. The weathering index of a silicate rock provides a chemical index for quantifying weathering (Parker, 1970). The weathering index is calculated from the expression:

$$100 \text{ X } [(\text{Na})a/0.35 + (\text{Mg})a/0.9 + (\text{K})a/0.25 + (\text{Ca})a/0.7]$$

(where (X)a is the atomic percentage of element X divided by its atomic weight). In samples having a total Fe content of 6 wt.% and 2.5 wt.%, the brightness ranges from 46% to 67.7%, respectively. Removal of anhydrous Fe-oxides (principally by magnetic separation) could increase the brightness to approximately 75%. Oxidation of Fe-oxides probably is the principal cause of brightness reduction in weathered samples as suggested by the increase in the oxidation ratio from 42% to 82% and the decrease in brightness from 67.7% to 47% (Cocker, 1989b and in review (b)).

The potential tonnage for the talc-bearing breccia was calculated based on the drill hole intercepts and the mapped surface distribution of the breccia and talc float (Fig. 9). The breccia was divided into two segments, the east segment is 900 feet (275 m) long by 600 feet (183 m) wide by 70 feet (21 m) thick. The west segment is 600 feet (183 m) long by 600 feet (183 m) wide by 130 feet (40 m) thick. Calculated volumes are 4.68×10^7 ft^3 (1.06×10^6 m^3) and 3.78×10^7 ft^3 (1.34×10^6 m^3) respectively. A tonnage factor equal to 11.64

Table 1. Average Major Element Composition of Talc
(Burks Mountain Complex)
(number of samples = 4)

	Average Weight Percent	Standard Deviation	Variance
SiO_2	47.52	11.53	132.85
Al_2O_3	0.58	0.26	0.07
Fe_2O_3	3.05	1.32	1.75
FeO	1.35	0.17	0.03
MgO	28.22	2.48	6.13
CaO	4.06	3.68	13.57
Na_2O	0.06	0.02	0.00
K_2O	0.02	0.01	0.00
LOI	12.72	7.68	59.06
TiO_2	0.01	0.00	0.00
P_2O_5	0.01	0.00	0.00
MnO	0.14	0.14	0.02
SrO	0.0005	-	0.00
Rb_2O	0.0005	-	0.00
Ni	0.163	0.032	0.00
Cr	0.215	0.005	0.00
TOTAL	98.144		

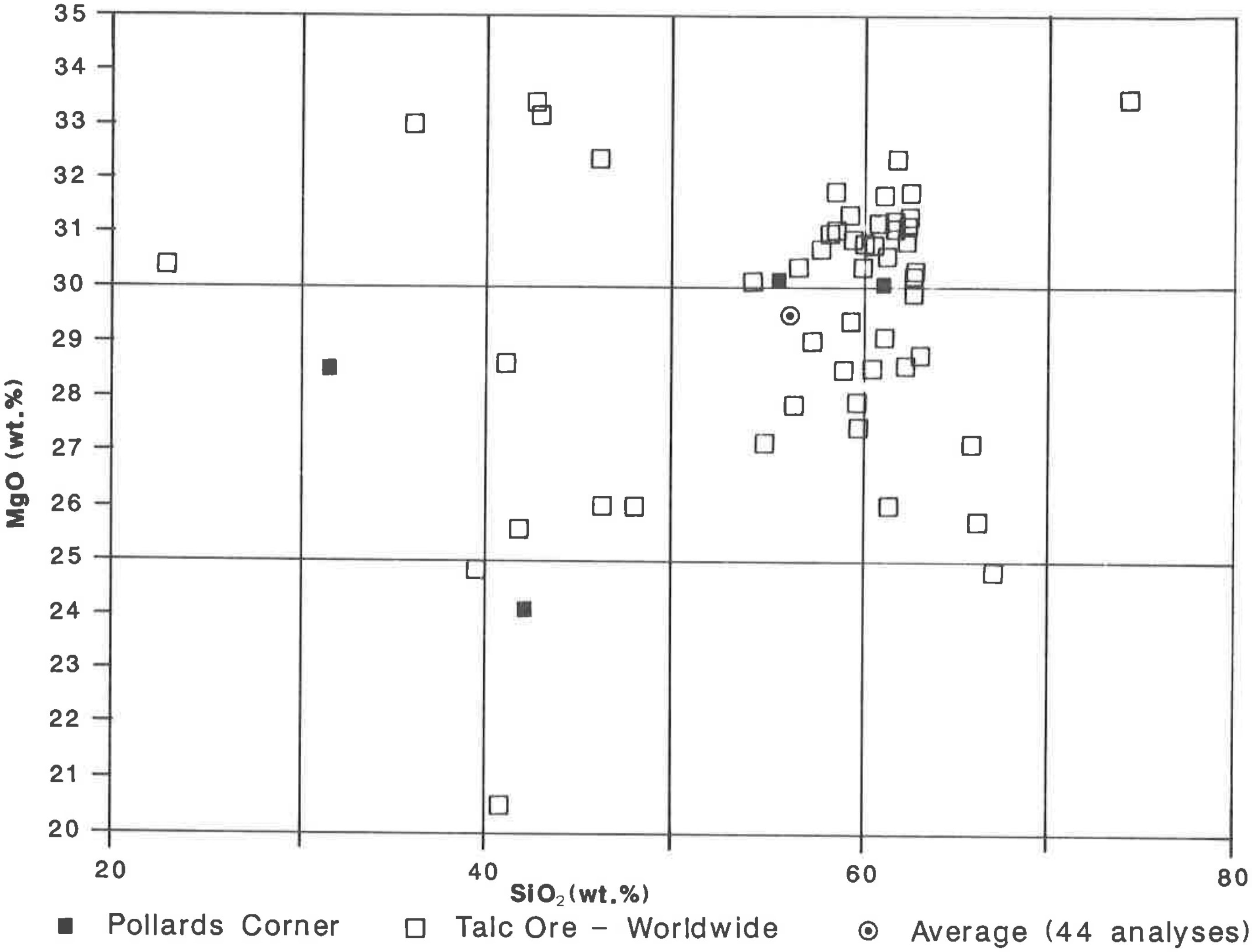


Figure 8. MgO - SiO_2 Content of Talc.

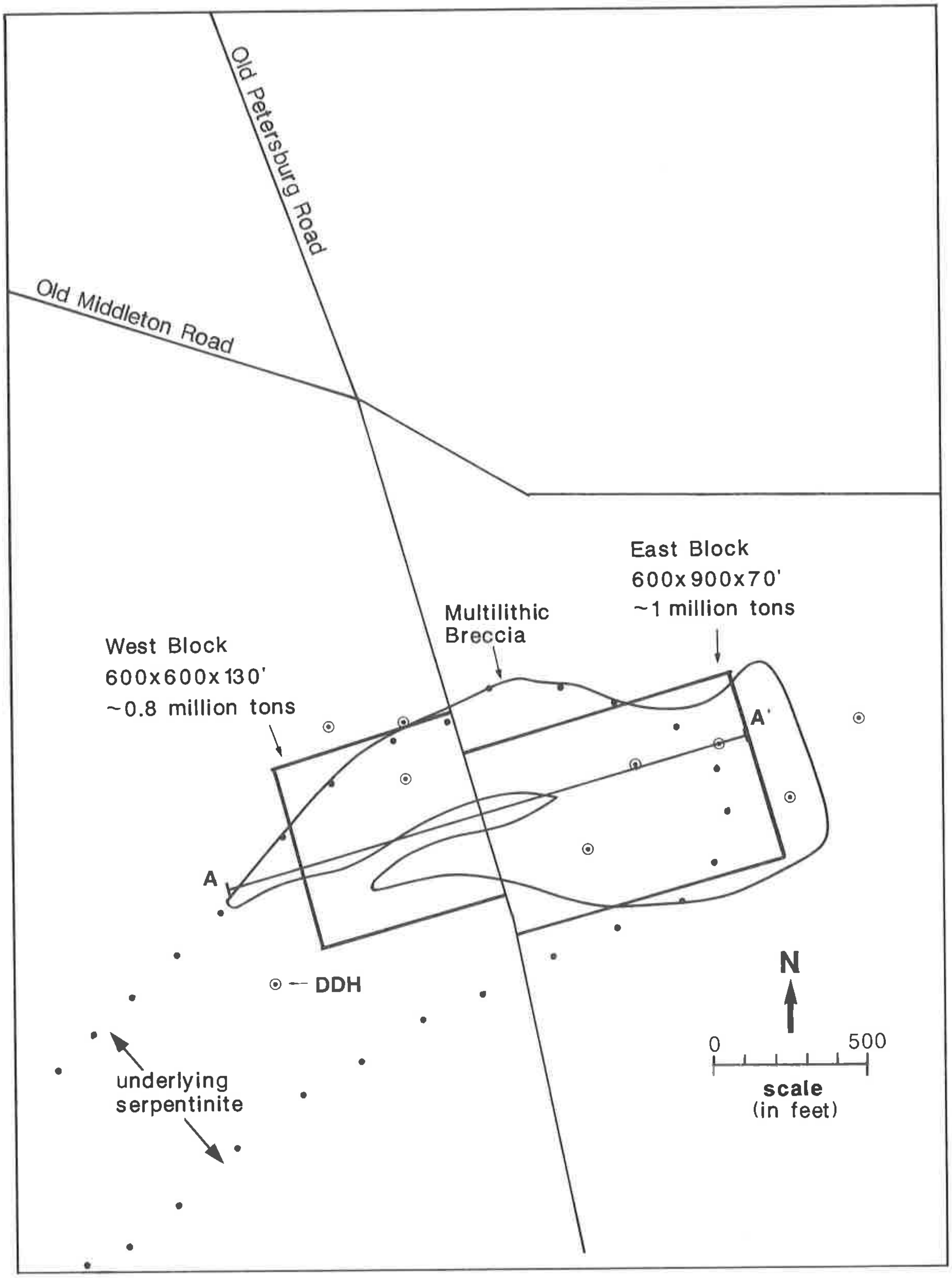


Figure 9. Map of Potential Talc Ore Zones.

ft^3/ton was calculated using a specific gravity of 2.75 (an average density for talc) for the breccia. At a total volume of 8.46×10^7 ft^3 (2.4×10^6 m^3), the potential tonnage is 1.817×10^6 tons (Cocker, 1989b and in review (b)).

The deposit is ammenable to an open pit operation because of: 1) the shallow dip of the breccia, 2) its exposure at the surface, and 3) the occurrence of little to no significant overburden. In addition, the poorly cemented nature of the breccia matrix favors ease of mining (front-end loader) and easy separation of talc clasts from the matrix. The major mineralogical contaminants, carbonates and Fe-oxides, may be removed from the talc ore, by treatment with HCl and magnetic separation respectively. The open-pit configuration, little overburden, and anticipated ease of mining and ore separation favor a low-cost production. The presence of additional minable talc-mineralized zones along the Burks Mountain complex (Hopkins, 1914; Cocker, in review (b)) would further enhance the economics of a processing operation.

Additional talc mineralization is present in the 95-145 foot (29-44 m) thick serpentinite underlying the breccia. Drill intercepts suggest talc is localized along the upper and lower boundaries and adjacent to fractures in the serpentinite. These talc-mineralized intercepts dip at a steeper angle than the serpentinite contacts suggesting that they may extend into the serpentinite and may not be confined to the upper and lower contacts of the serpentinite. Because the serpentinite becomes more enstatite-normative towards the top, talc mineralization, which favors the replacement of enstatite over olivine, should increase upwards within the serpentinite (Cocker, in review (b)).

A pronounced difference in post-steatization alteration between the northern and southern serpentinites significantly influences their talc potential. Widespread and pervasive quartz veining and silicification in the northern serpentinite replaced and/or diluted the observed talc mineralization. Talc mineralization is preserved in the southern serpentinite due to the scarcity of quartz veining and silicification.

Serpentine

Significant continuous drill intercepts of massive, fresh serpentine/serpentinite suggest the southern serpentinite could be a potential source of "verde antique" and/or magnesia. The serpentinite was processed in the 1940's as a source of magnesia for epsom salt (LeGrande and Furcron, 1956; Hurst and others, 1966). The MgO content of 11 samples of fresh serpentinite from drill core ranges from 35.10 to 37.50 wt.% with an average of 36.26 wt.% MgO (Cocker, in review (a)). A recovery of 95% of the average MgO content of 35-38 wt.% was attained in tests run by the Department of Mines, Mining and Geology (LeGrande and Furcron, 1956). Continuous drill intercepts of massive, unweathered serpentinite suggest a potential source of "verde antique". Mining and processing of the serpentinite in conjunction with development of the talc deposit would enhance the economic viability of a mining operation.

CONCLUSIONS

Brittle deformation and alteration of a lizardite serpentinite in the Burks Mountain complex occurred after regional high-grade Alleghanian-age metamorphism and deformation. Fracturing and brecciation of the serpentinite provided conduits that allowed influx of CO_2-bearing solutions which altered the lizardite to a mixture of magnesite, dolomite and calcite. This alteration of lizardite released MgO and SiO_2 to form talc. Addition of Al_2O_3 produced an overprint of coarse-grained chlorite concentrated in and adjacent to those same conduits. Estimated conditions of talc formation are $<200\text{-}250^{\circ}C$, <2.5 kb, and <300 bars $P(H_2O)$. The chloritic alteration occurred in-situ, as evidenced by chloritic, biotitic, and albitic alteration of the adjacent country rocks. Late-stage quartz-veining and silicification is very minimal in this serpentinite body, but is very widespread in many of the other serpentinite bodies of the Burks Mountain complex.

Intensive, subtropical to tropical weathering of the talc-bearing breccia decomposed the enclosing chlorite matrix and serpentinite, gneiss and granite clasts. The highly resistant talc clasts are concentrated at the surface as a residual deposit.

Drilling and mapping results indicate the talc deposit is a near-surface, bulk-tonnage resource which should be amenable to open pit mining. Estimated grade and tonnage is 1.8 million tons with 25% talc. The composition of the talc is generally similar to that in high-purity talc deposits. Brightness of the talc ore could be enhanced significantly through the removal of magnetite.

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