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GEOLOGY AND RESOURCES OF THE ANDERSONVILLE, GEORGIA KAOLIN AND BAUXITE DISTRICT

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CONTENTS

ILLUSTRATIONS

Page

TABLES

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ABSTRACT

The kaolin and kaolin-rich sediments of the Andersonville district were deposited in an estuary environment with restricted circulation and little tidal or longshore current influence. Micaceous kaolinitic clays were deposited during late Paleocene time on broad, shallow water flats between deeper water distributary channels in the estuarine system. During the cycle of deposition, kaolinitic sediments were temporarily exposed to weathering leading to bauxitization and further kaolinization. Subsequently, subaerial and/or subaqueous erosion planed off and redeposited some of the weathering products as organic-rich clays and silts, berthierine-bearing clays, and rarely as colluvial bauxite and sedimentary bauxitic clays. Upon resubmergence, gibbsite-rich, porous bauxite, and bauxitic clays were exposed to silica-saturated water of the estuary. Gibbsite reacted with silica to form kaolinite and resulted in the formation of the transitional (bauxitic) clays overlying the bauxite. Kaolinitic sediments transported by streams again spread over the altered and redeposited material. At the close of the kaolin depositional period movement along the Andersonville Fault Zone and related faults changed the basinal configuration, and the area of the uplifted (southern) block of the fault was exposed to weathering and bauxitization for a limited period of time. General submergence again occurred and much of the district was covered by marine and brackish water, ending the period of commercial kaolin deposition.

The kaolin and bauxite deposits in the Andersonville district form a broad belt 15 kilometers wide and 22 kilometers long trending in a northwest-southeastward direction. Most of the kaolin and bauxite of commercial value occur within a narrow 10-kilometer-wide zone in the belt. The reserves of kaolin suitable for refractory and chemical use are approximately 290 million tonnes. Paramarginal resources of sandy kaolin suitable for refractory, chemical, or aluminum manufacture after beneficiation are approximately 240 million tonnes. Indicated and inferred reserves of bauxite and bauxitic clay are 1.8 million tonnes and 7.3 million tonnes respectively.

INTRODUCTION

Purpose and Scope

The present investigation was undertaken as a re-evaluation of kaolin and bauxite resources of the Andersonville District, Georgia. It consists of: (1)a study of the mineralogy, sedimentology, and paleoenvironmental aspects of the kaolin and bauxite deposits, and (2) a computer-assisted resources evaluation of data derived from approximately 600 exploration holes drilled by mining companies between 1960 and 1975.

Location and Geography

The Andersonville District lies within the Coastal Plain of Georgia approximately 40 kilometers south of the Fall Line which marks the boundary between the unconsolidated sediments of Cenozoic and Mesozoic age and the older crystalline rocks of the Piedmont. The district occupies an area of about 300 square kilometers in Sumter, Schley, and Macon Counties in the vicinity of Andersonville, Georgia (Figure 1).

The terrain of the district is characterized by broad, flat-topped divides separated by shallow valleys of eastwardly flowing tributaries of the Flint River. Tributary valleys have assymetrical cross-sections with steep north-facing walls and gentle south-facing slopes. Valley bottoms are narrow and occupied by swamps produced by natural damming of tributaries due to dead falls, tangled vegetation, and beaver dams. Buck, Camp, and Sweetwater Creeks (Plate 1) provide the drainage for the district and have gradients of 1.3 to 1.9 meters per kilometer in their lower courses. Average relief between the divides and valley floors is 46 meters although the maximum elevations vary from 162 meters in the northwestern part of the district to 76 meters in the southeast adjacent to the Flint River. Two terraces veneered with alluvium occur at elevations of 90 meters and 105 meters atop the prominent

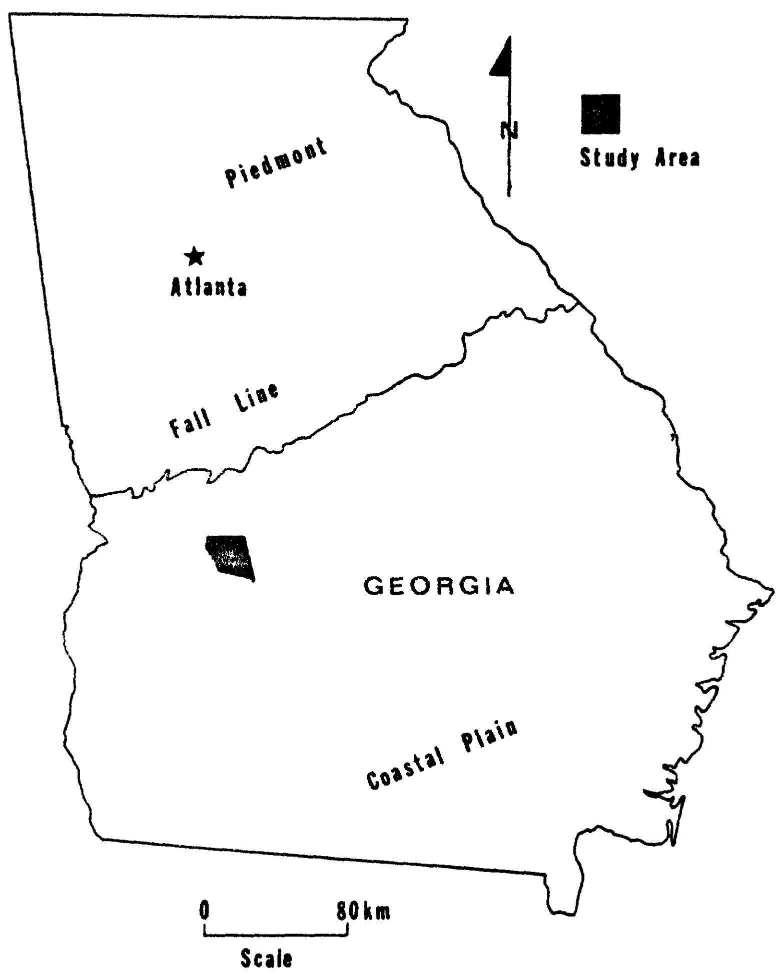

Figure 1. Location of study area

bluffs that form the west wall of the Flint River valley which bounds the district on the east.

Mining History

Veatch (1909) first noted a "peculiar nodular clay"(i.e., kaolin) out-cropping at Kelley's Mill on lower Sweetwater Creek in Sumter County (Plate 1), and in 1912 bauxite was discovered a few hundred yards upstream from this locality (Richards, 1913). Two years later, the Sweetwater Mine was opened at this site by the Republic Mining and Manufacturing Company (later to become the Aluminum Company of America). The bauxite was used mainly for manufacturing of aluminum metal and to a lesser extent for commercial alum.

By 1926, mining of bauxite in Andersonville for metal had ceased (Smith, 1929). In 1930, the American Cyanamid Company acquired the mining properties and production facilities of the Republic Mining and Manufacturing Company and was the only active mining concern in the district from 1930 to 1969. During that interval, an estimated 500,000 dry tonnes of bauxite (53.5% Al_2O_3 dry basis) was produced. Almost one-third of this was mined during World War II. From 1958 to 1959, a moderate amount of kaolin was also produced for use in fire brick, face brick, and cement manufacture.

In 1969 the Mullite Corporation of America (Division of C-E Minerals) completed the first plant in the district for production of calcined bauxite and kaolin. A second plant was added by the same company in 1972. The American Cyanamid Company completed a facility for processing kaolin and bauxitic clay for use in alum manufacture in 1973. All bauxite produced in the district since 1973 has been used in refractory manufacture. Virtually all kaolin production at the present time is in the form of partially calcined clay for alum plant feed or dead-burned clay for refractory manufacture.

Previous Work

The first published report concerning the clays and bauxite of the Andersonville District was by Veatch (1909) in which extensive outcrops of "white clay" occurring in the Midway Formation in Sumter, Macon, and Schley Counties are mentioned. Veatch further described outcrops of nodular clay at Copperas Bluff on the Flint River and at Kelley's Mill on Sweetwater Creek in Sumter County. Veatch and Stephenson (1911) discussed the stratigraphic position of kaolin and bauxite deposits relative to the other formations of the Coastal Plain of Georgia. Shearer (1917) also dealt with the stratigraphy of these commercial deposits and included the first detailed description of the bauxite deposits along with chemical and mineralogical analyses of the kaolin and bauxite. Smith (1929) discussed numerous outcrops of kaolin and bauxite in the Andersonville District and provided additional descriptions of mines and chemical analyses of bauxite and kaolin. Munyan (1938) presented further descriptive data concerning the deposits.

An extensive geologic mapping and drilling program in the district was carried out during World War II by the United States Geologic Survey and the United States Bureau of Mines as part of the Strategic Minerals Investigation Program. The results were reported by Zapp (1948, 1965) and Beck (1949). These works provided a comprehensive evaluation of the distribution and an estimate of the resources of kaolin and bauxite deposits in the district.

Several publications have described the general characteristics of commercial deposits within the Andersonville District. Papers by Harder (1949), Bridge (1950), Allen (1952), Overstreet (1964), and Burst (1974) are examples of these. Grumbles (1957) also described the general nature of the deposits but included ideas concerning the origin of the kaolin and bauxite. Flock (1966) studied the stratigraphic variations in mineral and chemical compositions and in physical properties of kaolin and bauxite cores from drill holes in the

Sweetwater and Boggy Branch area. Cofer and others (1976) reported on the aluminous resources of the district, and some of these results have been incorporated in this report.

Acknowledgments

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The authors would like to express their appreciation for the assistance rendered by the members of the professional staff of the U.S. Geological Survey, Reston, Virginia. These include: Nancy A. Wright and Mary A. Carey for their aid in preparation of the computer-assisted resources evaluation; Norman Fredericksen for his invaluable service in sporomorph identification and dating of lower Tertiary sediments; and Myer Rubin for determining the ^{14}C dates. Sam H. Patterson provided supervision of the project and patient assistance during manuscript preparation.

The project could not have been undertaken without the cooperation of the exploration departments of American Cyanamid Company and A.P. Greene Refractory Company who provided mine access, drill-hole data and cores. C-E Minerals provided access to their mining properties and assistance in obtaining chemical analyses. Students at Georgia Southwestern College logged thousands of feet of core and measured numerous mine sections and gathered field data; Roy Rountree, Wayne Johnson, Buck Buchanan, Linda Holland, and Gail Detamore were particularly helpful. Special thanks is extended to Debbie Standridge and Kathy Johnson, secretaries of the Division of Science and Mathematics, who labored long and hard to convert the authors' handwritten manuscript to typed copy.

STRATIGRAPHY

The Andersonville District is underlain by unconsolidated sediments that range in age from Mesozoic to Quaternary. A generalized stratigraphic section as measured in open pit mines and delineated from subsurface cores is shown in Figure 2. A correlation chart for the Eastern Gulf States and Georgia is provided to clarify provincial stages/formational relationships (Figure 3).

UPPER CRETACEOUS

Providence Formation

The oldest rocks exposed in the district are the non-fossiliferous sands of the Providence Formation which underlie lower Paleocene beds in the study area. The Providence Formation crops out along the lower slopes of Buck Creek Valley (Plate 1). As seen in weathered outcrops the section consists of approximately 6 meters of light red-to-tan colored micaceous sand that is coarse-grained, cross-bedded, and slightly arkosic. To the northeast of the mapped area, exposed sections also contain angular and rounded clasts of kaolin up to 2 centimeters in diameter and a few thin lenticular kaolin beds. In relatively unweathered outcrops along Buck Creek, and in river bluffs north of Oglethorpe, which are 3 to 6 kilometers north of the Andersonville district, the upper portion of the Providence Formation is a poorly sorted lignitic, pyritic sand. Logs of wells at Montezuma, located 6 kilometers northeast of the district, show the upper lignitic sand grading downward into marine sands, clays, and limestones. The maximum thickness of the Providence as determined from wells is 48.8 meters (Herrick, 1961).

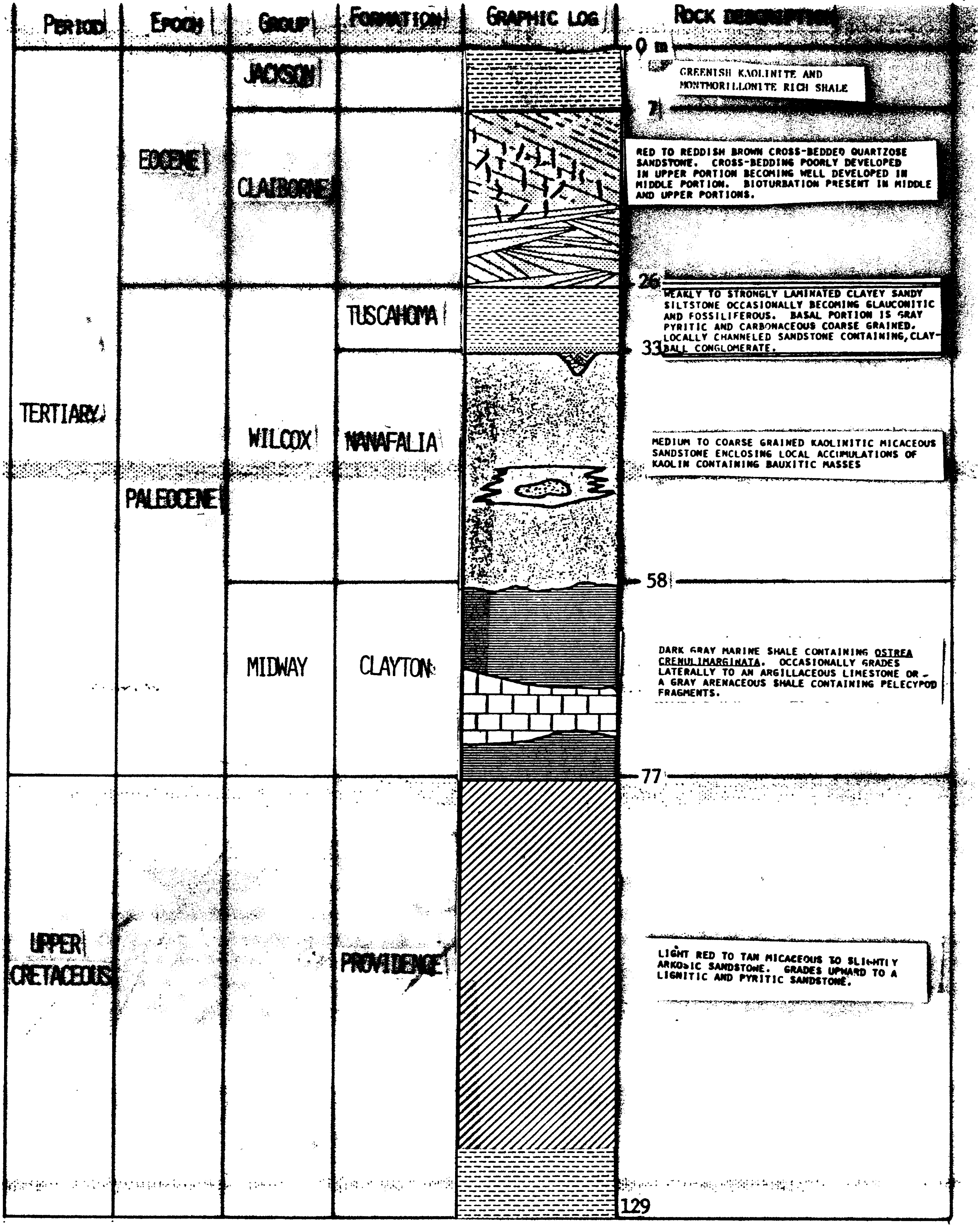


Figure 2. - Generalized stratigraphic section of the Andersonville District

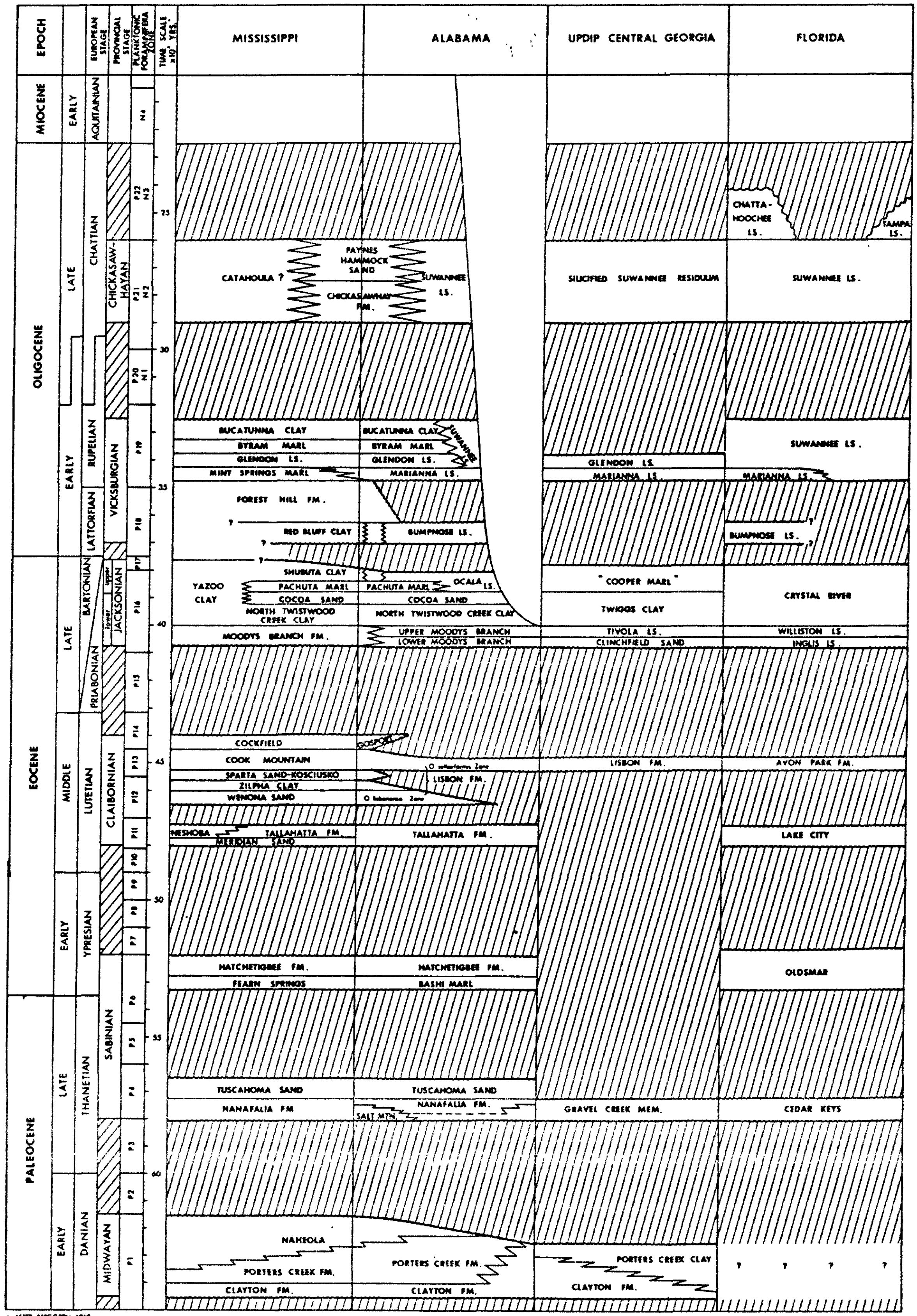


Figure 3. - Regional stratigraphic correlation chart (after Huddlestun, et al, 1974).

PALEOCENE

Midway Group

Clayton Formation

McCallie (1908) included the Midway Group (as now used in the Andersonville District) as part of his Midway Formation on the first geologic map of Georgia. Cooke (1943) described and mapped the Midway-age rocks in Macon, Schley, and Sumter Counties and first applied the name Clayton Formation to the unit and assigned the Midway sediments to the Paleocene. In the Andersonville District, Zapp (1948, 1965) mapped a series of dark shales, calcareous sands, and clays and sandy limestones occurring between the Providence and Nanafalia Formations as the Clayton Formation but used the term Midway Group for the unit in his text. He estimated a thickness of 13.7 to 15.2 meters where sediments had not been leached of their carbonate content. Zapp (1965) believed that thinning of the section due to decalcification is significant only in up-dip outcrops along the slopes of Buck Creek Valley. Grumbles (1957) divided the Clayton in the district into an upper dark-gray shale member and a lower sandy fossiliferous limestone unit. Huddlestun and others (1974) considered the dark shaley clays of the Andersonville area to be the Porters Creek Formation and believed it to conformably overlie and grade into the Clayton in the river bluff northwest of Montezuma.

The Clayton Formation in the Andersonville District, based on examination of outcrops and drill hole data during this investigation, has a thickness of 18.3 to 21.3 meters and is variable in lithology over short distances. The dark-gray, shaley, marine clay generally overlies, but may locally underlie or be the lateral equivalent of the argillaceous, arenaceous limestone and gray clayey sand that contains biostromes of oysters and detrital accumulations of shell fragments. In some areas the Clayton Formation consists almost entirely of dark shaley clay as observed in beds penetrated by drill hole BF 1 (Plate 1) near Sweetwater Creek and Highway 49. In other areas it consists of 1 to 1.2 meters of marine clay overlying gray sands and clays containing abundant Ostrea crenulimarginata (Gabb), as at English Mill north of Camp Creek near Highway 195 (Plate 1).

A thin 2.1 to 2.4 meter thick, persistent, indurated, coquinoid, sandy limestone was encountered 7.6 to 9.1 meters below the top of the formation in all holes penetrating the formation. Locally, biostromes and detrital shell material overlie or underlie this limestone so that the total thickness of predominantly calcareous sediments may reach 6 to 9 meters.

Sporomorph assemblages obtained from the upper clay unit of the formation confirms that the Clayton is Paleocene in age and not younger than Middle Midwayan in age (Cofer and Fredericksen, in press).

Wilcox Group

Veatch and Stephenson (1911) applied the name Wilcox Formation to the upper portion of Veatch's (1909) Midway Formation including the kaolin and bauxite-bearing sediments of western Georgia. In the Andersonville district the term Wilcox Group is now applied to those rocks that are overlain by the Claiborne Group and consists of the Nanafalia and Tuscahoma Formations (MacNeil, 1947; Zapp, 1948, 1965).

Nanafalia Formation

In this report the name Nanafalia Formation will be applied as by Zapp (1948, 1965) who used the name for all sands and clays overlying the Clayton Formation and underlying the laminated silts and sands of the Tuscahoma Formation. Geologists of the Georgia Geological Survey (Huddlestun and others, 1974) also recognize the Nanafalia Formation in the Andersonville district; however, they conclude that only its Gravel Creek Member is present in the region. The authors of this report agree with this stratigraphy but will not use the name Gravel Creek Member because it would apply to the same beds as the formational name in the Andersonville district.

The unconformable contact between the lowermost formation of the Wilcox (i.e., the Nanafalia) and the Clayton Formation is well exposed only in two locations within the district. At the railroad cut west of Sweetwater Creek bridge on Highway 49 (Plate 1) light gray, coarse grained, micaceous sands of the Nanafalia rest on the broad undulating surface of the slightly kaolinized, leached, yellow stained upper portion of the dark shales of the Clayton Formation. At English Mill (Plate 1) the contact between the Clayton and Nanafalia Formations is poorly exposed with the Clayton showing no evidence of alteration or leaching. The unconformable contact between the Nanafalia and Clayton Formation can also be traced in the subsurface north and south of Sweetwater Creek. At the contact between formations, as seen in surface exposures and in cores, clasts of Clayton appear as ovoid or irregular patches of montmorillonite clay embedded in the overlying sandy kaolins of the Nanafalia Formation. In a few localities subsurface cores show unweathered Clayton overlain by a dark-gray lignitic, kaolinitic sand which grades upward into kaolin within less than a meter.

The Nanafalia Formation is predominantly a thick series of light-colored, medium to coarse-grained, kaolinitic, micaceous sand and lenticular beds of kaolin and sandy kaolin. In the vicinity of Andersonville, thick, nearly pure kaolin and sandy kaolin frequently occupy almost the entire section. Often the presence of secondary pyrite and hematite gives rise to reddish-purple splotches which create a mottled appearance in the kaolins. Bauxite occurs as irregular masses enclosed within some of the kaolin lenses. In the southern part of the district, south of Mountain Creek and near the confluence of Lightwood and Sweetwater Creeks (Plate 1), the kaolin and bauxite units thin and interfinger with dark-gray, lignitic, micaceous, clayey sands. South of Toteover Creek (Plate 1) and west of Andersonville, the lower part of the Nanafalia contains interbedded glauconite, sandy kaolin and lignitic, micaceous, kaolinitic sand. At the sites of several drill holes south and west of the Andersonville district, the Nanafalia consists of dark-gray, lignitic silty sands with little or no kaolin.

Formation thickness reaches a maximum of approximately 24 meters in the central portion of the district near Sweetwater Creek and Boggy Branch (Plate 1), and the kaolin and sandy kaolins are as much as 18.3 meters thick in this area. Northeast of the confluence of Tripple and Camp Creeks (Plate 1) the Nanafalia Formation thins gradually and is 9.2 meters thick where penetrated by drill hole RN 1 (Plate 1) south of the intersection of Highways 49 and 26. In the extreme northwestern part of the area between upper Camp Creek and Buck Creek (Plate 1), the upper part of the Nanafalia has been removed by erosion over part of this area.

Sporomorph assemblages extracted from lower and Middle parts of the Nanafalia indicate an early Wilcox age (Cofer and Fredericksen, in press).

Tuscahoma Formation

The name Tuscahoma was first used by Smith (1886) for sands outcropping on the Tombigbee River near Tuscahoma, Alabama. Cooke (1943) recognized the presence of Tuscahoma equivalent in Georgia, and Owen (1963) included as Tuscahoma in Sumter County all those beds overlying undifferentiated Midway (including kaolin-bearing sands) and underlying the Claiborne Group.

Where the laminated sands and silts of the overlying Tuscahoma Formation are in contact with the Nanafalia clays, the boundary between the two formations appears generally conformable. However, in some localities channels originate within the Tuscahoma which cut through the lower beds of the formation and extend well into the underlying kaolin deposits (Figure 4a). The channels are commonly filled with massively bedded or cross-bedded sands 0.3 meters to 1 meter thick, which alternate with thinner, nearly sand-free silt and clay beds (Figure 4b). Clasts of kaolin are common in the channel sands. An excellent example of channeling occurs in the Wilburn Mine on Sweetwater Creek (Plate 1, Site WL), where a steep walled, channel fill 40 meters long, 11.6 meters wide, and 4.3 meters thick extends across the eastern wall and cuts into the underlying kaolin. The channel fill consists of dark gray, glauconitic, sandy clayball conglomerate 0.3 meters thick (Figure 5) which contains lignitic plant debris, abundant siliceous dinoflagellate tests and acritarchs. This portion of the fill is overlain by 4 meters of white, slightly kaolinitic, coarse, gravelly

Figure 4a.
Lower beds of Tuscahoma Formation filling channel cut in the Nanafalia Formation, in wall of pit WE (Plate 1).

Figure 4b.
Clay lenses and cross-bedded channel sands of the Tuscahoma Formation.

Figure 5.
Clayball conglomerate at the base of channel deposits in the Tuscahoma Formation, in wall of pit WL (Plate 1).

sand beds that are 15 to 20 centimeters thick and separated by dark shale layers 1 to 3 centimeters thick. The top of the channel is 60 centimeters above the lowermost beds of the Tuscahoma Formation and is continuous with the adjacent Tuscahoma strata.

In the district the Tuscahoma Formation is represented by a series of laminated sands and silts that are sometimes glauconitic and contain foraminifera and fish teeth 4 to 8 millimeters long. The glauconite occurs as lobate pellets and as internal molds of foraminiferal tests. The basal portion of the formation is often carbonaceous and coarser grained with gravel and pebble-sized quartz being observed at a few sites (e.g., at open pits 58B, E, AWW, and DWW; Plate 1). The dominant clay mineral in the Tuscahoma is kaolinite except in the marine beds; here mixed layer illite-montmorillonite is the most abundant clay phase.

Where the Tuscahoma Formation pinches out it commonly grades from a laminated silt to a dark-gray, silty, pyritic, kaolinitic clay containing abundant wood fragments. Such a facies change was observed in the north wall of the Wilburn Mine (Plate 1, Site WL) where the transition takes place within a distance of approximately 76 meters.

In the extreme southern parts of the district drill holes penetrated as much as 9 meters of Tuscahoma, but the formation thins rapidly and pinches out south of Sweetwater Creek. Near the Andersonville Prison Park (Plate 1) the Tuscahoma is 3.7 meters thick but it is much thinner farther east and north. The formation is absent in all areas north of Camp Creek from its mouth westward to the Schley County line, except for a small area near Fountainville (Plate 1). West and southwest of upper Camp Creek the formation thickens irregularly and is approximately 6 meters thick along the southeastern edge of the study area.

Eocene

Claiborne Group

The Claiborne Group is a series of nearly pure quartz sand beds that unconformably overlies or overlaps the Tuscahoma Formation in the Andersonville district. The unconsolidated nature of the sands restricts the outcrop to a few steep-walled erosion gullies and recent mine exposures.

As seen in mine exposures in this study, the lowermost units of the Claiborne Group consists of cross-bedded, cross-laminated, fine-to coarse-grained sand that may be locally pebbley and gravelly at the base. Sands in the lower part of the formation are slightly micaceous and kaolinitic (i.e., 10 percent by weight) but may contain local concentrations of clay clasts and thin lenticular beds of clay composed almost entirely of kaolinite.

The uppermost unit of the Claiborne Group as exposed in mine walls is mainly a weakly cross-bedded, locally bioturbated and glauconitic red or red-brown silty sand. At Site H 316 (Plate 1) irregular concentrations of fossiliferous, glauconitic silts are observed in the upper unit. In the northwest part of the district the upper unit can be traced in the subsurface as a yellowish-brown, clayey, silty sand, but in outcrop it is chiefly a weathered brick red or brownish red, silty clayey sand that is difficult to recognize. In the southeastern part of the district the unit can be traced in the subsurface as a red or yellow, silty, clayey sand overlying the typically unconsolidated, slightly kaolinitic sands of the lower part of the Claiborne Group.

The maximum thickness of the Claiborne Group is approximately 18 meters near the Hatton Mine (Site HW, Plate 1); the Group is only slightly thicker southward from this point. The Group is approximately 6 meters thick east of Fountainville, and it is absent northeast of the junction of Highways 26 and 49 (Plate 1).

Claiborne and Jackson Groups Undifferentiated

Along the crest of divides in the district Zapp (1948, 1965) mapped greenish clays (composed of montmorillonite and kaolinite) associated with yellowish clayey sands that contain carbonaceous layers; this material was considered to be residuum derived from dissolution of Jackson Age (late Eocene Age) limestone. In addition, Zapp (1948, 1965) found yellow and red-brown clayey sand containing chert boulders locally overlying and merging with this unit. He considered this to be residuum derived from Oligocene limestone.

In the present investigation the two units described above were penetrated by several drill holes. Holes FN 1 0.8 kilometers northwest and JH 1 4.8 kilometers southeast of Andersonville (Plate 1) penetrated 7.3 meters of the combined units. They are underlain by and grade into the yellow clayey silts and red clayey sands of the upper Claiborne. The residual material in the district was probably derived from the Lisbon and Ocala limestones, of Claiborne and Jackson Ages respectively. Both formations weather to produce a cherty residuum and both outcrop south and east of the district.

Quaternary

The Quaternary in the district is represented mainly by alluvial terraces along the Flint River which are veneered with a heterogeneous mixture of gravel, sand and clay. The thickness of these deposits varies from a few centimeters to a maximum of 9.2 meters.

Quaternary peat deposits are exposed in the south wall of the Wilburn Mine (Site WL, Plate 1) located in the Andersonville Fault Zone (Plate 1) at an elevation of 88 meters. A 1.8 meter bed of sandy clayey peat is overlain by 0.8 meters of fine-grained, well-sorted sand which is in turn overlain by 1.5 meters of sandy peat (Figure 6). The upper peat accumulation lies immediately

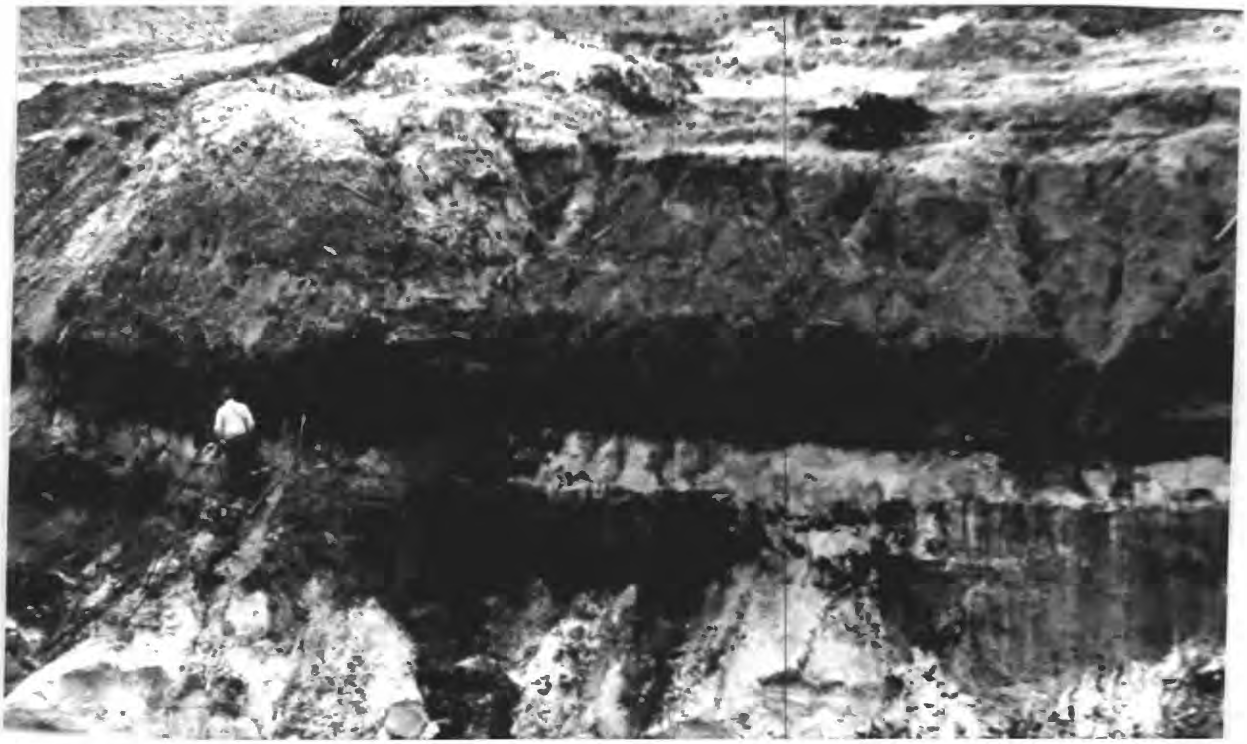


Figure 6.
Peat deposits in south wall of Wilburn Mine
(Pit WL, Plate 1).

below the thin soil layer (0.6 to 0.9 meters thick) which supports the present plant cover of the flood plain of Sweetwater Creek. Roots of living plants penetrate into the peat beds. The lower peat overlies well-sorted sand of undetermined age which rests on coarse gravelly sand of a channel-fill in the Tuscahoma.

Carbon-14 age determinations on the peat samples were made by the U.S. Geological Survey Radiological Laboratories at Reston, Virginia. A sample collected 10 centimeters above the bottom of the lower peat and associated with northern-spruce seed-cones (W3944) gave a date of 21,300 ± 400 yBP. Wood fragments (W4104) from the upper portion of the same layer gave a date of 15,840 ± 300 yBP, and a sample (W4113) from the basal portion of the upper peat layer indicated a date of 10,570 ± 250 yBP (Rubin, 1978). The elevation of the peat and underlying sands is below the present valley floor. It is believed that peat accumulation and associated sediments resulted from fault-damming related to recent movements along the Andersonville fault zone.

STRUCTURAL FEATURES

General Relationships

The regional dip of the sedimentary formations is toward the southeast and ranges from 4.0 meters per kilometer for the Midway Group to 2.6 meters per kilometer for the Claiborne Group, except where it is interrupted by faulting which causes a dip reversal of strata. Reversal can be observed only in a few outcrops, for example in an open-pit mine west of Highway 49 just north of Sweetwater Creek (Location MLX) and in the roadcut on the south side of Viney Branch on this highway (Plate 1). The strike of sedimentary units in the district is N50E except in the vicinity of the Andersonville Fault Zone (Plate 1) where the strike is nearly east-west.

The Andersonville Fault Zone

During this investigation the Andersonville fault was found to be a structurally complex zone rather than a single feature and therefore the name is modified to project this idea.

The presence of faulting in the district was first detected by Zapp (1948). He reported a displacement of kaolin-bearing strata of approximately 26 meters between drill holes located at site MLX and in the floor of Prison Branch directly to the north (Plate 1). Although drill logs available indicated variable displacement along the strike, Zapp (1965) extended the fault trace eastward to the Flint River, but was unable to verify the westward extension of faulting beyond Andersonville. Owen (1963) extended the Andersonville fault as defined by Zapp, west into Schley County for a distance of 9.6 kilometers. Subsurface data from wells in Dooly County support an extension of the faulting to a point 8.1 kilometers east of the Flint River. Vohris' (1972) map indicated that the total traceable length of the Andersonville fault is 32.3 kilometers. These observations indicate that the Andersonville Fault Zone is a major structural feature of the Georgia Coastal Plain.

Stratigraphic relationships observed in drill cores, outcrop and mine exposures during this investigation indicate that the sediments were deformed and displaced over a broad zone in excess of a kilometer in width. Most of the displacement occurred within a 0.4 kilometer zone accompanied by flowage of unconsolidated sediments and flexure and rupture of more indurated beds. Reversal of dip occurs well south of the fault zone as mapped. North of the zone the Clayton Formation marker horizons which were penetrated by drill holes 100 to 300 meters apart, are displaced vertically several meters.

The amount of displacement in the fault-zone varies along the strike and apparently increases with depth. Most drill holes in the area bottomed within the Clayton Formation and little is known about the amount of displacement of older beds. The dense carbonaceous silty claystones and limestone of the Clayton and the glauconitic sand and the laminated sand and silts of the Tuscahoma formations served as the most reliable reference horizons. The maximum displacement measured on the top at the Clayton was 28 meters between the outcrop on GA 49 located adjacent to site BF1 and drill hole location FN1 and also between FN1 and a drill hole at site PCE-3 (Plate 1). Displacement as measured on the top of the Tuscahoma at the latter two sites is 19.5 meters but the difference in elevation as determined on the top of the Claiborne group is slightly over 6 meters. Between map site CL-9 and the Tuscahoma outcrop south of the fault-zone on Triple Creek the apparent displacement is 9 meters. On the western edge of the mapped area the difference in elevation on the Tuscahoma is 7 meters on either side of the fault zone. At the Flint River, seismic data and drill hole information indicates a displacement of the Clayton Formation of approximately 28 meters and a somewhat greater displacement of older beds.

The apparent decrease in displacement in successively younger sediments is thought to be largely due to intermittent movement on the fault from pre-Clayton to recent time. Differential rates of erosion and deposition on each side of the faulted area has resulted in thinning of beds on the upthrown side and thickening on the downdropped side. Sediments of both the Clayton and Nanafalia formations are significantly thicker on the downthrown side of the fault zone immediately adjacent to the zone and the Tuscahoma Formation pinches out against the uplifted block in the central and eastern part of the area.

A structural contour map (Figure 7) of the top of the Clayton Formation prepared from drill hole data shows the influence of faulting on strike and dip of the Clayton and the extent of deformation. The strike of the Clayton on the upthrown southern fault-block is nearly east-west and the gentle southward dip reverses and steepens abruptly near the fault zone; in the fault zone the dip reaches a maximum of approximately 60°. Relief on the Clayton surface south of the fault zone is variable with two prominent highs and an intervening saddle (Figure 7). One high is located south of the town of Andersonville, the other is eastward near the Flint River. Southward from these highs the dip steepens to 5.6 meters per kilometer. Immediately north of the fault zone the formation is nearly horizontal, but further to the north drill hole data indicate that the strike turns to the northeast and the dip gradually steepens to approximately 3.8 meters per kilometer about 1.6 kilometers north of the fault zone (Figure 7).

Further evidence of faulting in the district is seen in mine exposures and drill cores. At several localities flowage of plastic clays and unconsolidated sands and fragmentation and slickensiding in some kaolins and bauxite was observed. Large scale flowage of clays and sand intrusions in kaolin occur in the Wilburn Mine which is located in the fault zone (Site WL, Plate 1). The distribution of sand intrusions suggest that they resulted from seismic shaking of water-saturated sediments. Sand dikes and dome-shaped bodies with distinct boundaries, which penetrate well into overlying kaolin beds south of the fault zone, were observed at locations L278 and WE (Plate 1).

Concomitantly with the present study, two other investigations were made

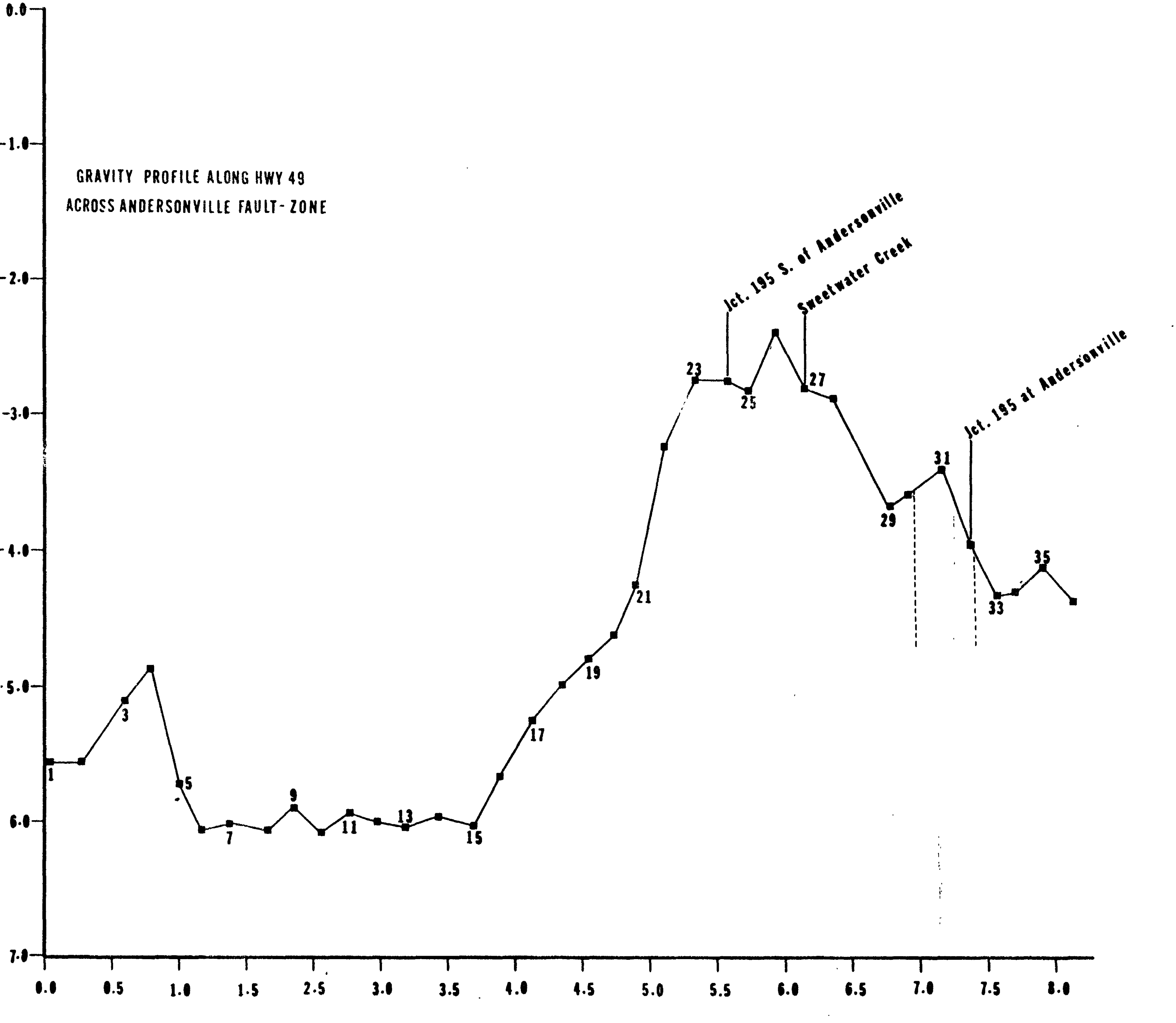


FIGURE 8. GRAVITY PROFILE ACROSS ANDERSONVILLE FAULT ZONE

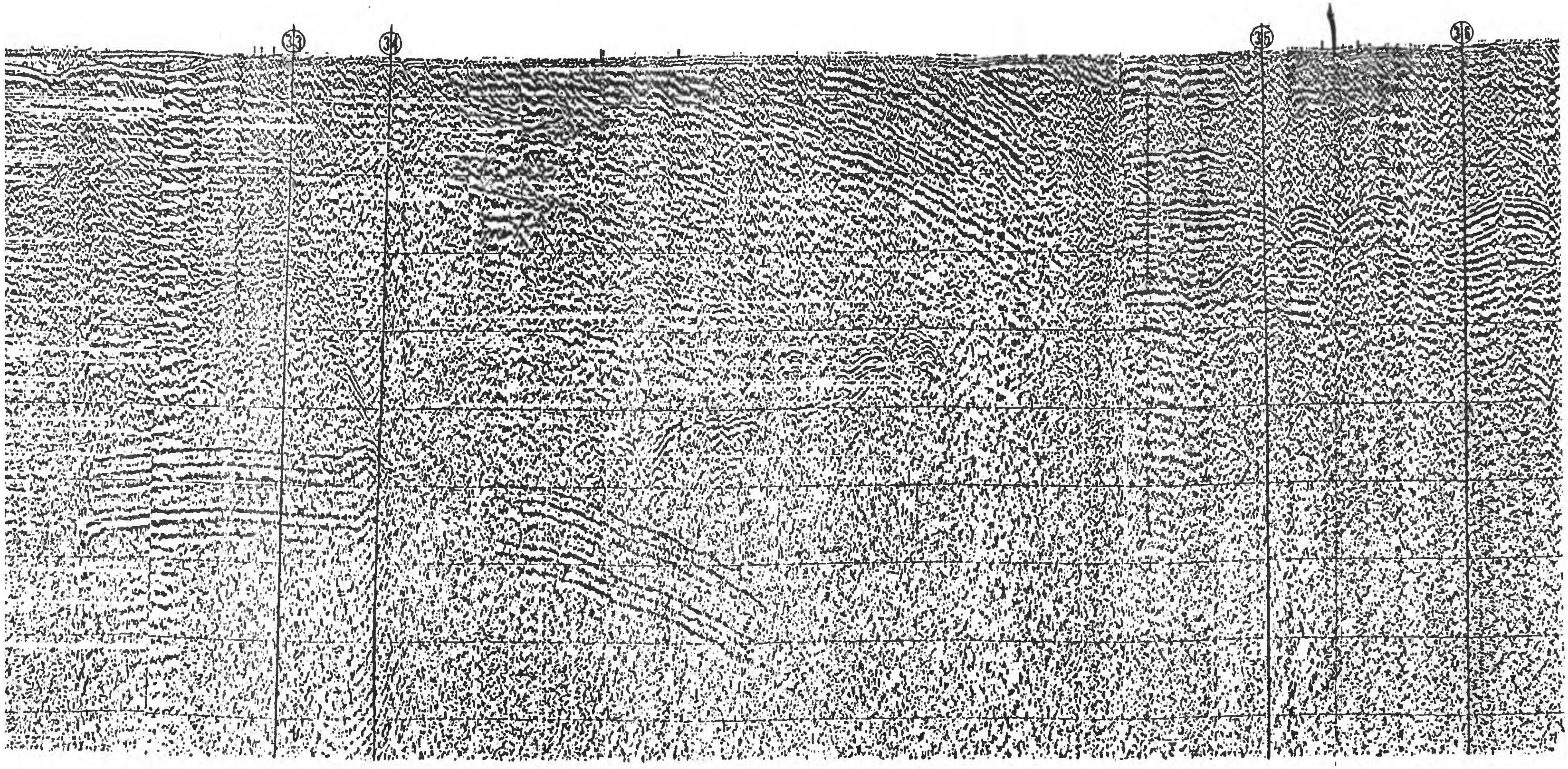


Figure 9. Seismic profile across Andersonville Fault Zone on Flint River

which contributed to a better understanding of the nature of faulting and its influence on structural features of the district. One was preparation of a regional gravity survey of twelve southwest Georgia counties by staff members of Georgia Southwestern College during which a gravity line was run along Highway 49 across the Andersonville Fault Zone (Figure 7). The other investigation by the Georgia Geological Survey produced a seismic profile along the Flint River from Reeves Landing to a point just opposite the mouth of Camp Creek (Plate 1).

The gravity profile (Figure 8) shows clear evidence for upward displacement of the block south of the Andersonville Fault Zone. In addition, estimated depth to compensation of gravity data (Jones, 1978) suggests that denser rock below the unconsolidated sediments of the Coastal Plain is involved in that movement.

The seismic profile along the Flint River (Figure 9) which crosses the Andersonville Fault Zone shows an upper prominent seismic reflector visible from just to the left of Station 35 to the right hand edge of the profile; this is the moderately indurated sandy limestone of the Clayton Formation. The lower reflector visible from just to the left of Station 35 to the left edge of the profile is a siliceous limestone in the Ripley Formation which underlies the Providence sand. The profile reveals that much of the displacement within the zone is accomplished by flexure and attenuation in the poorly consolidated sedimentary beds. Rupture, vertical displacement, and deformation of indurated layers (lower reflector) can be seen in the profile just to the right of Station 34 and in the vicinity of Station 35 (upper reflector). Deformation and tilting of indurated layers over a wide area north of the fault zone (i.e., on the downthrown block) is exhibited in the profile. The zone of dip reversal and flexure is approximately one kilometer in width; however, most of the displacement by fracture is restricted to a zone 0.4 kilometers wide (Plate 1).

Other Structural Features

Previous investigators have suggested faulting in areas of Sumter County bordering the Andersonville district on the south. Owen (1963) using subsurface data proposed the existence of a "structural belt" (presumably a zone of faulting) trending N55E located about 3 kilometers south of the present study area. Rountree and others (1978) presented gravity data suggesting a major fault trending southwest in the same general area. Their data suggests that the upthrown block is to the south.

During this investigation it has been noted that drainage patterns of the major streams (i.e., Buck, Camp, and Sweetwater Creeks) are characterized by long linear trends with sharp changes in direction (Plate 1) suggesting that structural and stratigraphic controls shape their courses. Two of the main linear trends of streams coincide with the (N60W and N55E) principal joint directions observed in outcrops in the clay pits. The straight segments of major stream courses that parallel a principal joint set have tributaries whose courses correspond approximately to the complimentary joint set of that system. The Andersonville Fault Zone apparently determines the course of Sweetwater Creek and its tributaries for a short distance along the middle one-third of its course (Plate 1). The upper reaches of Mountain Creek (Plate 1) also parallels a possible fault. In this area dip reversals on the Clayton Formation create an elongated structural depression parallel with the creek (Figure 7). The origin of the depression is unclear, but it is similar in many ways to the structural low along the Andersonville Fault Zone and has been interpreted as resulting from a near vertical fault (Plate 1). Other evidence for faulting is seen in apparent displacement of cherty layers of the Claiborn/Jackson age sediments and in Flint River terrace deposits which support a nearly vertical escarpment for a distance of approximately one kilometer along the southeastern end of the proposed Mountain Creek Fault (Plate 1). Displacement along the escarpment reaches a maximum of approximately 8 meters.

Timing of Tectonic Events

Movement along the Andersonville Fault Zone prior to and during deposition of Tuscahoma sediments is indicated by the thinning of the formation over structural highs created by faulting. A lithologic change in the lower sandy portion of the formation, from a glauconitic fossiliferous sand to a carbonaceous lignitic sandy clay, takes place where thinning occurs. In addition, evidence from mine exposures and drill hole logs shows that most of the channeling that penetrates into the Nanfalia sediments occurred during deposition of the lower part of the Tuscahoma and is a direct result of faulting activity. For example, north of the Andersonville Fault Zone the direction of channeling is southward toward the fault zone and channels which developed on the saddle south of the zone have trends toward the north (i.e., also in the direction of the fault zone). This indicates that both the upthrown (southern) block and the downthrown (northern) block were tilted toward the fault zone and channeling developed on these sloping surfaces.

Features suggesting intermittent movement on the faults of the area as late as Holocene time have been observed at two localities. At Site WL (Plate 1) peat accumulations, which lie below the level of the present surface and occur within the Andersonville Fault Zone, are thought to have formed as a result of fault damming of a Holocene stream. The escarpment in Flint River terrace deposits near the southeast end of the proposed Mountain Creek Fault suggests recent movement along this fault.

MINERALOGY

Analytical Procedure

Coarse-grained material (i.e., > 0.0625 mm) was identified by petrographic and optical microscope methods. Microscopic identification was augmented by X-ray diffraction analysis and flame spectrometry where applicable. Heavy mineral fractions were obtained by heavy liquid and magnetic separation.

Clay mineral identification was made with a Philips X-ray diffractometer equipped with a curved graphite-crystal focusing monochrometer using nickel-filtered $CuK_{\alpha 1}$ radiation. Oriented samples were prepared by slurrying the clay in distilled water with ultrasonic agitation. The slurry was placed on a glass slide to dry at room temperature or in an oven at 60°C. Oriented samples were also prepared by elutriation of clays and sedimentation to produce limited particle-size range mounts (20μm to 2μm, <2μm, 1μm, <0.5μm, and <0.2μm). Unoriented samples were prepared by shaving the fragments with a razor blade for insertion into a diffraction sample holder or by lightly packing disaggregated and sized samples into a sample holder by rolling with a glass rod. Oriented samples were analyzed in an untreated state after glycol solution and after heat treatment at 450°C and 600°C. Unoriented samples were heated to 600°C and 1050°C as necessary for confirmation of identification. Approximately 20 clay samples were examined by scanning electron microscope techniques to determine and verify certain textural/compositional variations detected during X-ray analysis.

Clay Minerals Detected

Kaolinite was identified by its 7.15 and 3.56Å reflection which collapsed on heating to 600°C. The crystallinity was determined on unoriented samples using the method of Hinckley (1963). SEM examination confirmed that samples containing well-formed crystalline particles had the highest crystallinity index. Even in oriented samples coarse-well-crystallized kaolin produced relatively sharp reflections, in the 19° to 22° 2θ range.

Gibbsite is associated with kaolin and the two minerals have many overlapping peaks. The presence of gibbsite was determined by the appearance of its d_{002} spacing at 4.85 Å. Small amounts (<2%) of gibbsite in the kaolins were not detected by X-ray analysis.

The term illite is referred to in this study as a clay-size mica which probably includes 2M, 1M and Md polytypes. This mineral was identified by prominent reflections at 10.0, 5.0, 3.3, and 2.5 Å. Neither glycolation nor heating to 600°C caused any changes in the d-spacings. Some samples have broad d_{001} reflections slightly asymmetrical toward low 2θ angles and undergo some shape change on glycolation but without measurable expansion.

Montmorillonite was identified by its 14.0 Å spacing for d_{001}, which expands to 17.0 Å on glycol solvation and collapses to approximately 9.6 Å on heating to 450°C; d_{006} varied from 1.49 Å to 1.50 Å. The threshold of montmorillonite detection in kaolin was about 3 percent for elutriated samples mounted on glass slides. In packed and slurried samples, the threshold was about 10 and 5 percent respectively.

Mixed layer illite-montmorillonite is characterized by a broad asymmetrical or ill-defined maxima of d_{001} between 11 Å and 13 Å which displays variable expansion (i.e., 13 Å to 16 Å) upon glycolation. Potassium saturation or heating to 450°C shifts the peak to approximately 10 Å.

Glauconite, which was identified primarily by its occurrence in dark green lobate pelletal form, appears to be a mixed layer clay with illite being the dominant phase. Pellets ground in water, dispersed, and sedimented on glass slides give a broad asymmetrical peak at 10 Å; other peaks occur at 4.53 Å, 3.33 Å, and

2.59 Å. Glycol treatment enhances the d_{100} reflection and expansion varies from 10.3 Å to 11.5 Å.

Chlorite was identified by its 14 Å reflection and its lack of expansion on solvation with glycol. The position of its major diffraction peaks were unaffected on heating to 600°C.

Berthierine was identified by reflections at 7.05, 3.52, 2.68, 2.52, 2.40, and 1.55 Å. In the presence of kaolinite, the 3.52 Å reflection is most useful for recognition. Upon heating this clay mineral to 1050°C the predicted high temperature products (i.e., mullite, spinel, cristobalite and hematite) were detected by X-ray diffraction. The presence of berthierine is suggested in kaolin by the greenish cast it imparts to the clay. This mineral also rarely occurs in pelletal form intergrown with siderite.

Mineral Occurrence and Character

Quartz and muscovite are the most abundant non-clay minerals in the rocks of the Andersonville district. Of these, quartz is the most abundant sand or silt-sized mineral observed in study area sediments. Muscovite is present in all sedimentary units and is particularly abundant in the Nanafalia and Tuscahoma Formations. It occurs in relatively unaltered compact books, altered expanded books and stacks, ragged flakes and partially kaolinized fragments which range in size from 1 mm to 0.2 mm.

Potash feldspar or clay pseudomorphs after feldspar were only rarely observed in the uppermost sandy-kaolin of the Nanafalia Formation, but are moderately abundant (>1%) in the lower part of Clayton and upper part of the Providence and Tuscahoma Formations.

Hematite and goethite are ubiquitous minerals in the weathered portion of all sediments within the district. They commonly occur as oxidation products of iron sulfides well below the vadose zone of the present watertable. Pyrite and marcasite, which also occur as secondary minerals, are relatively abundant in all the sediments containing appreciable organic debris.

The heavy mineral assemblages of the Nanafalia and Tuscahoma Formations and the Claiborne Group are given in Table 1. The relative abundance of these minerals (exclusive of muscovite and glauconite) are on the order of one-half of one percent in sand units and lesser amounts in clays and silts. Large amounts of secondary hematite, pyrite, and siderite in the kaolins made the estimation of heavy mineral abundance difficult. Ilmenite, tourmaline, staurolite, kyanite, rutile, and zircon are common to the Nanafalia, Tuscahoma, and Claiborne. Sillimanite, diopside, xenotime, and monzonite are present only in the Nanafalia and Tuscahoma. The heavy mineral suite occurring in several formations is discussed in relation to provenance and post-depositional alteration of the sediments in a later section.

Clay mineral content of the sediments varies widely between and within formational units. Kaolinite is the principal clay mineral of the Claiborne sands and the Tuscahoma and Nanafalia Formations over most of the district. It is also a significant component in paleosoils developed on the Clayton and Tuscahoma surfaces and is the principal clay mineral in the modern surface soils in the district. Gibbsite is associated with kaolin and goethite in surficial materials formed in the present weathering environment. It is the principal mineral in the bauxite where it occurs as crystalline aggregates with kaolinite to form oolitic and pisolitic structures and crystalline vein fillings. Gibbsite also occurs as widely disseminated grains in many kaolin lenses of the Nanafalia. Illite occurs in all sedimentary units of the district where it becomes a significant component (up to 20%) in some kaolin lenses. It is also a major component in the subsurface in the Nanafalia in the southeastern part of the district. Montmorillonite is the principal clay

Table 1

Heavy mineral abundances and species in Claiborne Group and Nanafalia and Tuscahoma Formations.

Claiborne Group		Nanafalia Formation		Tuscahoma Formation	
Mineral	Abundance*	Mineral	Abundance	Mineral	Abundance
Muscovite	Ab	Muscovite	Ab	Glauconite	Ab
Ilmenite	Ab	Ilmenite	Ab	Muscovite	Ab
Tourmaline	C	Tourmaline	C	Ilmenite	C
Staurolite	C	Staurolite	C	Tourmaline	C
Rutile	C	Zircon	C	Staurolite	C
Zircon	C	Kyanite	R	Zircon	C
Kyanite	C	Rutile	R	Biotite	R
Sillimanite	C	Biotite	R	Kyanite	R
Diopside	R			Rutile	R
Xenotime	R			Hornblende	R
Monazite	R				
Average % heavy minerals in sand units = 0.43% exclusive of muscovite		Average % heavy minerals in clay/kaolin units = 0.09% exclusive of muscovite		1.6% heavy minerals in sandy silt exclusive of glauconite	

* Ab = abundant.

C = common.

R = rare.

mineral of the Clayton Formation and is abundant in the marine facies of the Tuscahoma Formation. It is locally abundant in kaolin lenses within the Nanafalia and is present in the upper calcareous and glauconitic Claiborne Group sediments. Mixed-layer illite-montmorillonite is common in the clay fraction of sediments containing pelletal glauconite (Clayton and Tuscahoma). Glauconite occurs as dark green pellets and fragments ranging in size from fine gravel to coarse silt-size particles. Some pellets appear to be formed from fecal matter and as casts of foraminifera tests. It is sparse in the Clayton Formation and Claiborne Group, and abundant in the marine facies of the Tuscahoma where locally it may compose 35 percent of the sediment. Fragmented and abraded pellets of glauconite occur in fine sand-sized particles in a Nanafalia kaolin lens at the western edge of the district. Chlorite occurs only in small quantities in the uppermost sand and calcareous silty sands of the Claiborne Group. Berthierine occurs as pellets and fine-grained intergrowths with kaolinite at several localities within kaolin beds in the Nanafalia.

SEDIMENTOLOGY AND DEPOSITIONAL ENVIRONMENT OF THE CLAIBORNE AND WILCOX GROUPS

Field and Laboratory Methods

Data were obtained from 35 stratigraphic sections in 13 open-pit mines located within the study area (Plate 1). Each unit in the sections was described in terms of texture, gross mineralogy, biogenic structures, and sedimentary features produced by current action, deformation, and chemical processes. Additional data were collected from the subsurface in geologic drill logs and cored sections. The latter were limited primarily to the Tuscahoma, Nanafalia, and to a lesser extent, the Clayton Formation.

In addition to field observations, 360 sediment samples were collected from various horizons within measured sections for detailed laboratory and mineralogical analysis. A total of 133 sediment samples were analyzed for grain size. The greater than 0.063 millimeter size fraction was sized by pipette analysis. Because of the extremely fine-grained textures encountered in relatively pure kaolins, pipette analysis and centrifugation was employed to achieve a size analysis with cumulative totals of at least 95 percent; centrifugation procedures outlined by Jackson (1956) were followed. Grain size data of each sample obtained by sieve and pipette analysis were combined to construct a cumulative frequency curve. Data were taken from this curve to calculate the Folk parameters of graphic mean (M_z) and inclusive graphic standard deviation (σ_I).

A total of 60 sediment samples were selected for grain shape analysis. Using a binocular microscope, roundness and sphericity were estimated for 25 grains from each sand-size fraction (from approximately 2.00 millimeters to 0.063 millimeters) thus giving a total of approximately 250 grains examined per sample. Quantification of shape data was carried out using Powers' chart (1953) for visual estimation of roundness and sphericity as modified by Folk (1955).

In order to characterize the stratigraphic units, mineralogical analyses were completed on more than 400 samples collected from mine faces, surface exposures, and subsurface cores. Oriented slides were prepared from clay-size fraction of all lithologic units and for each subsize taken during pipette/centrifuge analysis (i.e., from $\leq$ 0.063 to 0.2 millimeters); X-ray analysis was carried out on these samples. Approximately 50 samples collected from all units were subjected to heavy mineral analysis. A detailed description of procedures employed in mineralogical analyses was given in the previous section concerning mineralogy.

Field measurements of about 150 dip directions were made on cross-beds at different stratigraphic horizons. Where sufficient measurements were available at the same stratigraphic level across the district, those data were subjected to vector analysis.

Basis for Interpretation of Sedimentological Data

Size analysis parameters and grain shape data can be used to provide information concerning energy of the depositional environment of sediments. For example, mean grain size (M_z) is an indicator of average kinetic energy (velocity) of a depositional regime. Beach, dune, and fluvial environments have widely varying grain size ranges, as found in studies done by Moiola and Weiser (1968), Friedman (1961), and Mason and Folk (1958). Mean grain sizes (M_z values) reported for sand units (i.e., the Claiborne Group) in this investigation fall into any of these three environments (Table 2).

An effective indicator of depositional environment is sorting (σ_I) which is more sensitive to depositional energies (and energy fluctuations) than M_z values. Generally, better sorting is found in high energy environments and poorer sorting is found in low energy depositional environments. According to

Table 2. Grain size analysis parameters of lithologic units described in open-pit kaolin mines.

	Number of Samples	Mean Grain Size (M_z) ϕ	Mean Grain Size (M_z) mm	Sorting Coefficient σ_I	% Silt & Clay
Upper sandy clay of Nanafalia Formation	8	8.64	0.0025	3.40ϕ	79.72
Lower portion of silt units of Tuscahoma Formation	16	2.48	0.18	2.41ϕ	18.26
Upper silt units of Tuscahoma Formation	28	7.16	0.007	3.04ϕ	75.39
Sands of Claiborne Formation	35	2.88	0.14	1.91ϕ	14.44
Clay/kaolin of Nanafalia Formation	14	10.18	0.00097	1.72ϕ	99.39

Folk (1966), well sorted sediments should display σ_I values of 0.35ϕ, whereas those that are extremely poorly sorted give values of 4.00ϕ. It has been shown that dune sands display sorting values ranging from 0.25ϕ to 0.35ϕ (Mason and Folk, 1958), beach sands from 0.33ϕ to 0.73ϕ (Friedman, 1961), fluvial sediments from 0.30ϕ to 1.40ϕ (Friedman, 1961), floodplain and neritic sediments from 2.00ϕ to 3.50ϕ (Folk, 1968)

Further, it is expected that high energy environments will contain small amounts of silt and clay while low energy environments contain large amounts. Data reported by Visher (1969) shows that beach and dune environments have silt and clay contents ranging from 0.01 to 7.0 percent, river estuaries from approximately 1.3 to 5.0 percent, fluvial environments from 1.3 to 30.0 percent and deltas from approximately 10.0 to 53.0 percent. Constructing a log-probability plot from size analysis data as done by Reed, LeFever, and Moir (1975), Visher (1969), and Sindowski (1958) provide more specific information as to depositional environments. This technique of examining grain-size distribution curves in light of their overall shapes, truncation points, and percent silt and clay content has been used successfully in differentiating between many overlapping sedimentary environments.

Wilcox Group

Nanafalia Formation

Description of Sedimentary Features

A modified computer-generated isopachous map of kaolin containing less than 15 percent sand and silt, produced for the resource evaluation portion of this study, gives the aggregate thickness of relatively pure kaolin bodies and illustrates their distribution as controlled by the depositional basin configuration (Figure 10). Thickest deposits lie in a broad belt adjacent to lower Sweetwater Creek, and other thick accumulations occur in the Mountain Creek area and between Boggy Branch and Camp Creek. The dominant trend of kaolin deposition is southeastward. A comparison of kaolin distributions (Figure 10) with that of the subsurface contour map of the top of the Clayton Formation (Figure 7) suggests that the distribution of kaolin may be related to the topography of the floor of the depositional basin. Although part of the structural relief of the Clayton surface was developed after the deposition of the Nanafalia, the topography of the floor of the basin was probably very similar to that of the Clayton surface with the downthrown blocks of the Andersonville Fault Zone and the Mountain Creek fault area restored to the level of the adjacent surface.

Clay mineral distributions also provide an indication as to depositional environment. Montmorillonite and illite are significant components in the Nanafalia in the southern (seaward) part of the district with kaolinite being dominant in the central and northern (shoreward) areas. Glauconite occurs in sandy kaolins west of Andersonville and berthierine occurs in the southern part of the district and on the downthrown fault block near Andersonville. In the northern and central parts of the district the presence of at least two bauxite horizons are noted within the Nanafalia.

Current-generated structures are generally absent in the massive kaolin units except for rare occurrences of cross-bedding associated with the upper sandy portions of the clay. A few laminations are also present in the kaolin as silt and fine sand-sized grains of quartz and muscovite. In some instances, bedding has been accentuated by deposition of iron oxides, sulfides, or carbonates by percolating ground water.

Locally, carbonized and pyritized plant remains in the form of root-like structures, twig-sized fragments, and grass impressions several centimeters long and a few millimeters across occur in otherwise pure kaolin (Figure 11). Although these plant remains are rarely observed, they are widely distributed. They have been found at eight localities as far south as THK32 and as far north as LF8 (Plate 1). Because preservation of cell structure in these remains is poor it cannot be determined whether they are relicts of a paleosoil, freshwater swamp or tidal/estuarine swamp. However, root distribution and size indicates that these remains represent a grass-like plant. The plant remains are commonly associated with casts or molds that have been termed by others as bryozoan casts or filled burrows (Buie, 1978). They commonly are several centimeters in length and occur in branching, curved, straight or anastomosing forms (Figure 12a). It should be noted that burrows are also found in the absence of plant remains perhaps indicating that oxidation of these organic remains took place thereby leaving only the burrow structures created by animals that inhabited the upper few centimeters of an organic-rich layer.

At a few localities kaolin lenses contain an organic-rich layer a meter or so thick. The transition from pure (or slightly sandy) kaolin to organic-rich kaolin takes place within a few centimeters. The lignitic clay deposits tend to be elongated, somewhat sinuous, and cover less than a hectare in area. The organic-rich clays sometimes contain large wood fragments, but no stumps or roots were observed. At locations LS95 and 58B (Plate 1) (i.e., northern and central areas respectively), the lignitic clay contains palynomorphs suggestive of a freshwater environment, have a high abundance of fungal spores and contain no marine to brackish water dinoflagellates or acritarchs, and hence represent freshwater deposits developed on a surface exposed to weathering (Cofer and Fredericksen, in press).

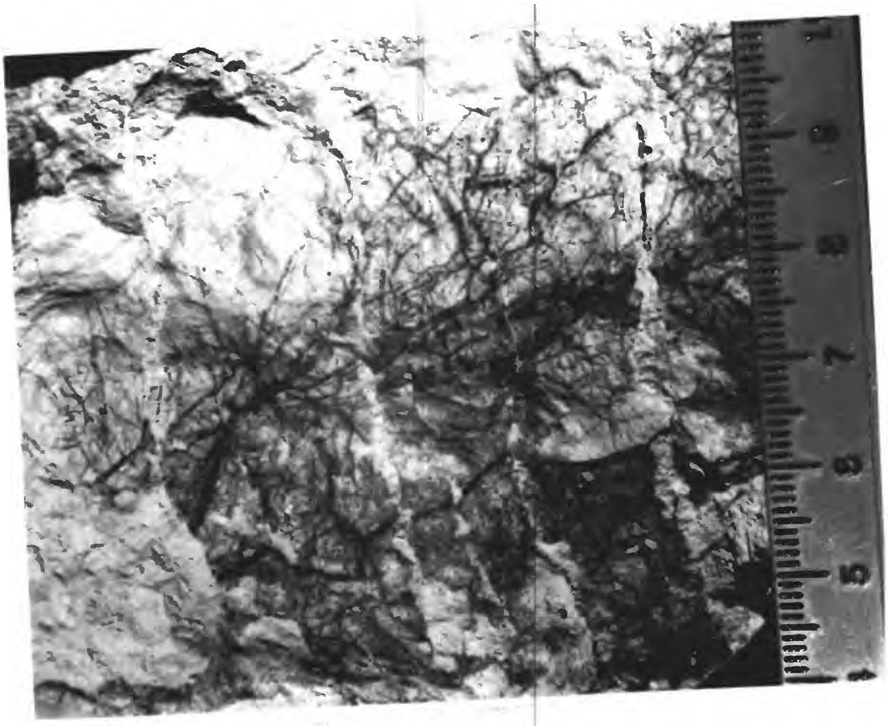


Figure 11.
Root-like structures in massive kaolin,
Nanafalia Formation, Location WLF 8 (Plate 1).

12a. Burrow casts or molds in massive kaolin, Nanafalia Formation .

In most cores and mine exposures, the top of the kaolin beds contain dessication cracks that extend downward for a few centimeters and are filled with sandy, organic-rich silts from the overlying Tuscahoma Formation. Near the top of some kaolin beds, large, filled, chambered burrows closely resembling structures produced by some species of modern bees have been identified (Tietjen, 1978). These burrows extend 25 or more centimeters into the clay (Figure 12b).

Average values for M_z, σ_I, and percent silt and clay of the upper sandy clays are given in Table 2. Results of grain shape analysis of quartz grains taken from the Nanafalia Formation are given in Table 3. Grains display a low degree of sphericity but are slightly more rounded than the quartz grains in the Tuscahoma Formation and Claiborne Group. Heavy mineral variety and abundances in the Nanafalia is less than that observed in the Tuscahoma and Claiborne (Table 1), but the condition of the mineral surfaces and variety of mineral species is similar in the Nanafalia and Tuscahoma Formations and the Claiborne Group.

Depositional Environment of the Nanafalia Formation

Sedimentological data collected for kaolin beds in mine exposures and cores suggest that these immature sediments (i.e., having up to 99% clay and silt size particles and a high percentage of angular quartz grains, Tables 2 and 3) were deposited in a low energy environment.

The presence of montmorillonite and illite in the southern part of the district indicates marine influence in that portion of the depositional basin, and glauconite, which was observed west of Andersonville, provides support for a marine environment. In addition, the occurrence of berthierine also points to a marine or estuarine influence in the depositional basin. Berthierine is reported as forming in modern marine sediments off the Niger

Figure 12b.
Insect burrows in upper portion of kaolin, Nanafalia Formation, infilled with organic rich silt of Tuscahoma Formation, in wall of pit 58B (Plate 1).

Delta (Porrenga, 1967) and at Loch Etive, Scotland, a basin with restricted circulation and moderate to low salinity (Rohrlich, and others, 1969).

Burrow casts, root structures, dessication cracks, etc. suggest that the clays of the Nanafalia Formation were deposited in very shallow water environment that was at or above sea level and subjected to non-marine conditions during part of the depositional cycle. The occurrence of bauxite within the Nanafalia also demonstrates that the formation was exposed subaerially, at least on a local scale.

Tuscahoma Formation

Description of Sedimentary Features

Except for fine laminae, sedimentary structures indicative of current action are absent in the upper portions of this formation. However, low-angle current cross-bedding was noted in pits WE and 58B (Plate 1) in the basal, coarse-grained portion of the Tuscahoma. The scarcity of these structures did not permit collection of sufficient dip direction data to construct a current rose. Cut and fill channels which originate in the lower coarse-grained portion of the formation and dissect underlying clays was noted in pits WE and WL; these features were described in more detail in the section concerning stratigraphy. No bioturbation was observed in any portion of the Tuscahoma.

The mineralogy of the greater than 0.063 millimeter size fractions of the Tuscahoma Formation is predominantly quartz, whereas silt and clay fractions are dominated by kaolinite with subordinate amounts of muscovite being present toward the top of this unit. Heavy mineral analyses of the lower portion of the formation at Site P34, THJ24, FN1, and WL (Plate 1) indicates an average of about 20 percent glauconite in the sand-size fraction. Exclusive of glauconite, the heavy mineral assemblage is similar to that observed in the Claiborne Group and the underlying Nanafalia Formation (Table 1).

Various size analysis parameters pertaining to the Tuscahoma Formation and the coarser grained basal portions of the unit are given in Table 2. Log-probability plots constructed from size analysis data are shown in Figures 13 and 14. Results of shape analysis carried out on sand-size quartz grains from the formation are given in Table 3.

Depositional Environment of the Tuscahoma Formation

It is believed that this immature sediment was deposited under very low energy conditions; this is suggested by the poorly sorted character, high percentage of silt and clay fractions, angularity of quartz grains, and the lack of current structures in the upper portions of silt units. The log-probability plots (Figure 13) for the upper portions of silt units display the characteristic curves established by Visher (1969) for a modern deltaic environment. Lack of bioturbation in the Tuscahoma implies that non-marine conditions prevailed, but stagnant low-oxygen conditions create an unfavorable environment for establishment of benthonic communities in either fresh or marine waters. Reducing conditions are indicated by the presence of great amounts of organic material in the bottom portion of silt units at some locations. The occurrence of an abundance of siliceous dinoflagellate tests in these sediments in seaward (down-dip) areas and fern spores in the clayey silts of the central and northern (shoreward) areas of the district indicate a transitional environment.

Prior to sedimentation of the upper silts, a higher energy depositional regime may have existed in some localities (i.e., pits WE, WL, 58B, E, DWW, and AWW; Plate 1) where sediments are coarser with occasional cross-bedding and

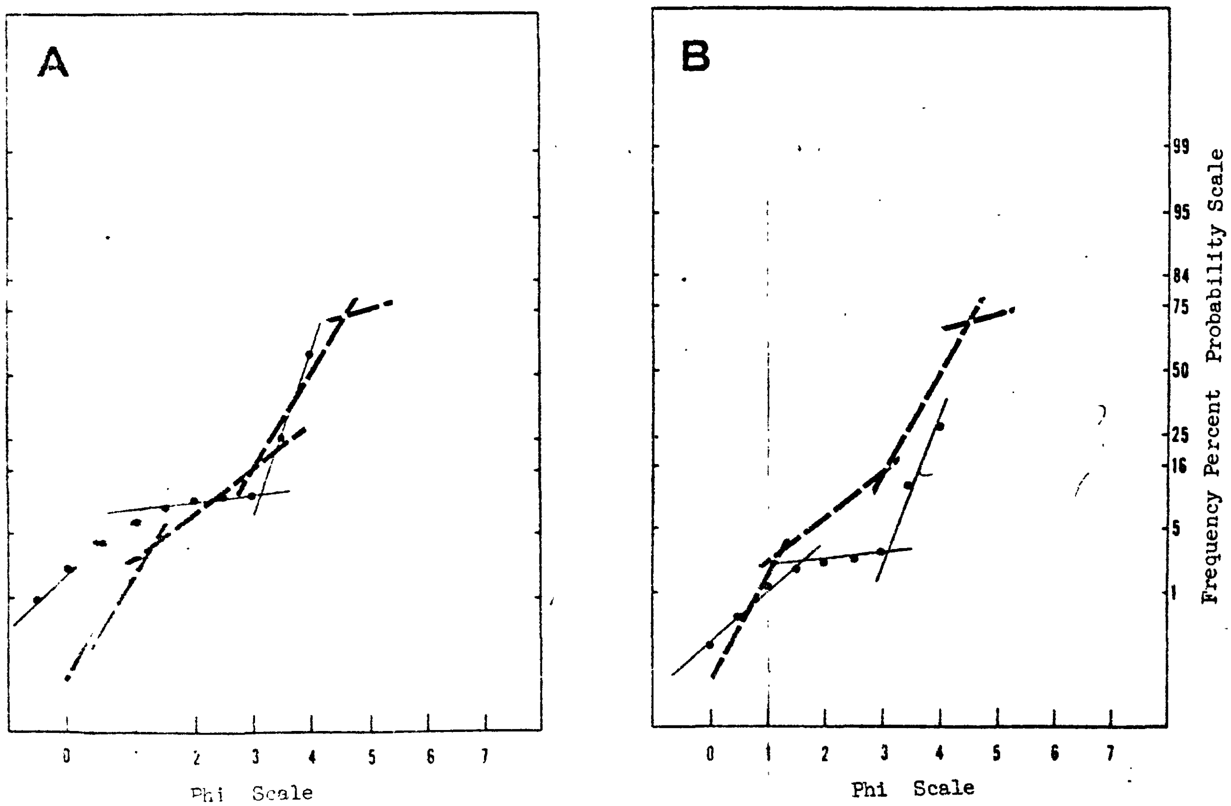


Figure 13.
Log probability plot of Tuscahoma silts. Curves A and B display grain size distributions similar to Visher's (1969) plots for deltaic environments. Visher's data shown by dashed line. Curves A and B are plotted from samples collected in Pits 58B and WE respectively.

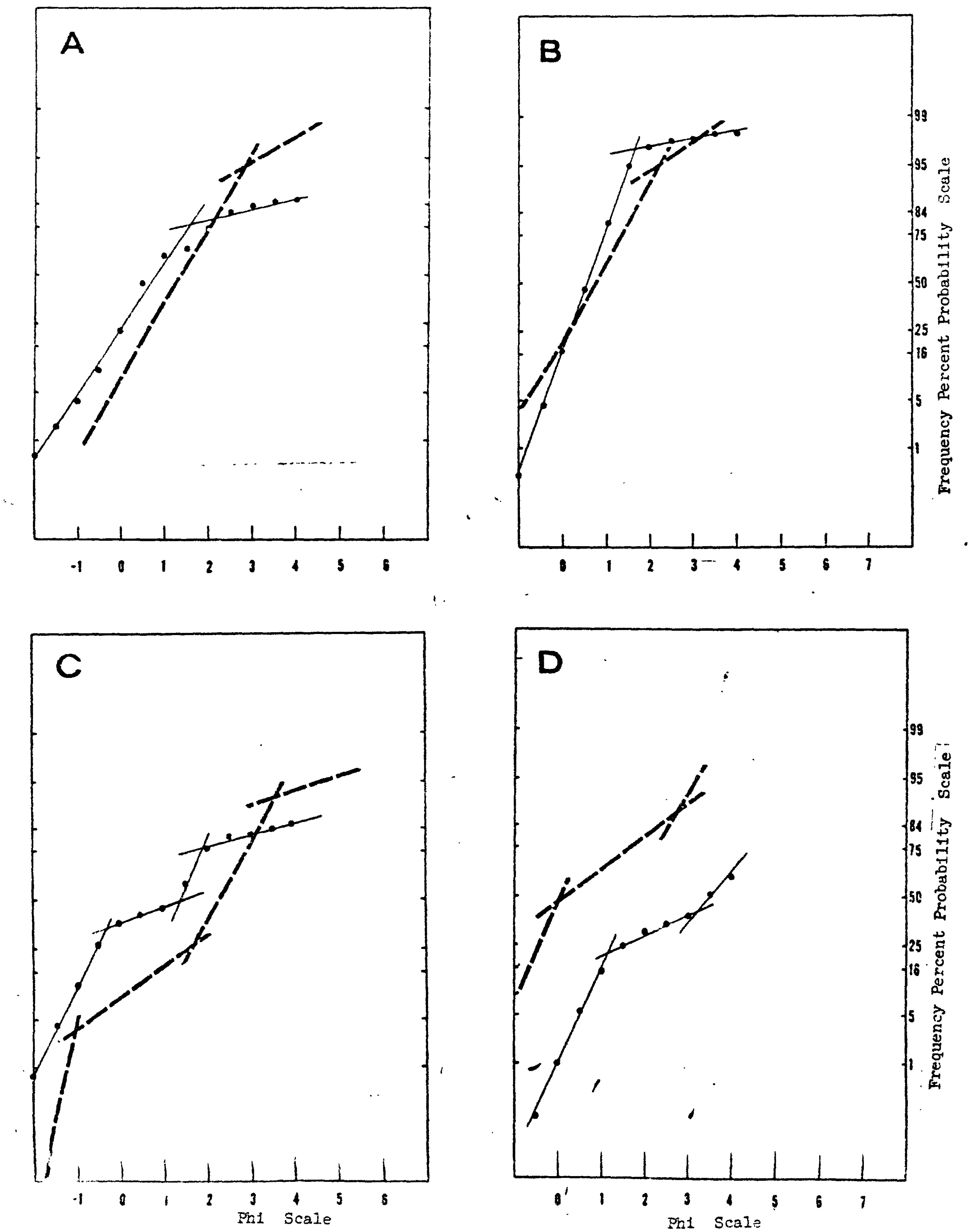


Figure 14.
Log probability plots of lower coarse grained portion of Tuscahoma silts. Curves A and B display shapes similar to those described by Visher (1969) for fluvial systems; plots C and D resemble curves plotted from deltaic environments. Visher's data shown by dashed line. Curves A and C are plotted from size analysis data from samples collected in Pits 58B; curves B and D are plotted from samples collected in Pit WE.

Table 3

Shape analysis data from lithologic units of the Andersonville district. Given is percent of grains per sample falling into roundness categories of Powers (1953) as modified by Folk (1955).

	Number of Samples	Very Angular	Angular	Sub-angular	Sub-rounded	Rounded	Well-rounded	Sphericity
Claiborne Group	12	5.3	43.1	43.9	6.9	0.6	0.2	Low
Tuscahoma Formation	14	3.3	53.1	40.2	3.0	0.4	-	Low
Nanafalia Formation	9	4.5	30.3	56.3	9.3	2.4	-	Low

channel structures. Grain-size distribution plots shown in Figure 14 indicate a combined fluvial/deltaic-type environment may have been operating to deposit coarse-grained basal portions of the Tuscahoma Formation in the central part of the district. Curves A and B display shapes similar to those described by Visher (1969) for fluvial systems; plots C and D resemble curves plotted from deltaic environments. A marine influence for the central and southern part of the district is indicated by the presence of glauconite in the coarse-grained basal portion of the formation as seen in drill cores P34, THJ24, FN1, and mine location WL (Plate 1).

Claiborne Group

Description of Sedimentary Features

The uppermost portions of the Claiborne Group (i.e., the top 4 meters below the surface) display extremely faint planar cross-bedding. This structure is masked by the presence of secondary iron oxides within the unit. Directly below this level in pits HW, WE, E, and 58B (Plate 1) is a 1 to 2 meter zone of bioturbated/cross-bedded sands. These biogenic structures consist of single, sand-filled, vertical to "L"-shaped burrows approximately 10 to 20 millimeters in diameter. Beneath this zone and down to the upper boundary of the Tuscahoma Formation, sediment coarsens to a medium-grained sand and displays planar, herringbone current cross-bedding. Dip directions of cross-bedding foresets were measured in the bioturbated portion of the Claiborne and a current rose was constructed (Figure 15).

Mean grain size (M_z) and sorting values (σ_I) for the Claiborne Group are given in Table 2. The values of M_z and σ_I show these sediments to be medium to fine-grained and poorly sorted with an average silt and clay content of approximately 14 percent. A log-probability plot was constructed

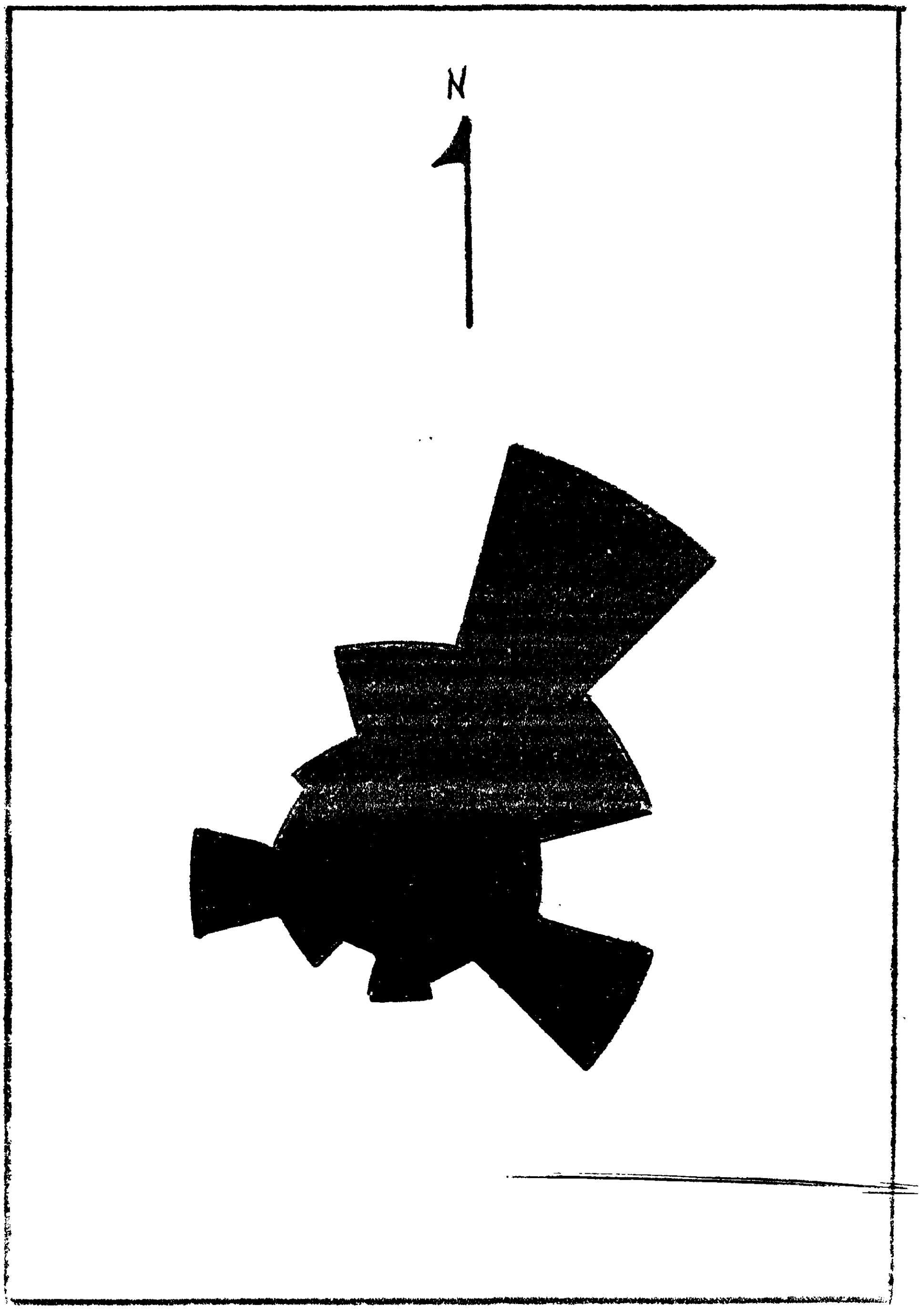


Figure 15.
Rose diagram of cross-bedding dip directions in the Claiborne Group. Diagram is based on approximately 150 measurements in two kaolin pits (AWW and E) in the northwestern part of the Andersonville district and one pit (HW) in the southeastern part of the district. Pit locations are shown on Plate 1.

from size analysis data (Figure 16). Shape analysis of individual quartz grains from the Claiborne reveal that most are angular to subangular with a low degree of sphericity.

The mineralogy of the coarse-grained fraction (i.e., sand size and greater) of the Claiborne Group is dominated by quartz with minor amounts of secondary hematite or limonite particles being present in the upper portion of the group. Silt and clay fractions are composed principally of kaolin, with lesser amounts of quartz. Subordinate amounts of chlorite are also observed in the upper 3 to 5 meters of the Claiborne and is traceable throughout the study area. Down section, toward the Tuscahoma Formation, chlorite content decreases and small amounts of illite become detectable.

The Claiborne Group contains a wide variety of heavy minerals (Table 1). Staurolite and coarse silt-sized tourmaline is present in almost perfect euhedral crystals (i.e., striated crystal faces and doubly terminated). Kyanite and sillimanite occur as cleaved portions of euhedral crystals. The remaining species were present as rounded to subrounded anhedral grains. Garnet, which is also present in Piedmont source areas and has approximately the same chemical stability as kyanite, staurolite, and sillimanite, was not observed. Lack of this mineral has been noted by other investigators (Davis, 1974) working in this area of the Coastal Plain.

Depositional Environment of the Claiborne Group

Using the sedimentological parameters derived from grain-shape and grain-size distributions an assessment of probable energy of the depositional regime can be made. Applying the average σ_I value determined from the Claiborne Group ($\sigma_I = 1.91\phi$) the sands fall between those values obtained for floodplain/neritic sediments (Folk, 1968) and those obtained from the fluvial environment (Friedman, 1961). The log-probability plots (Figure 16)

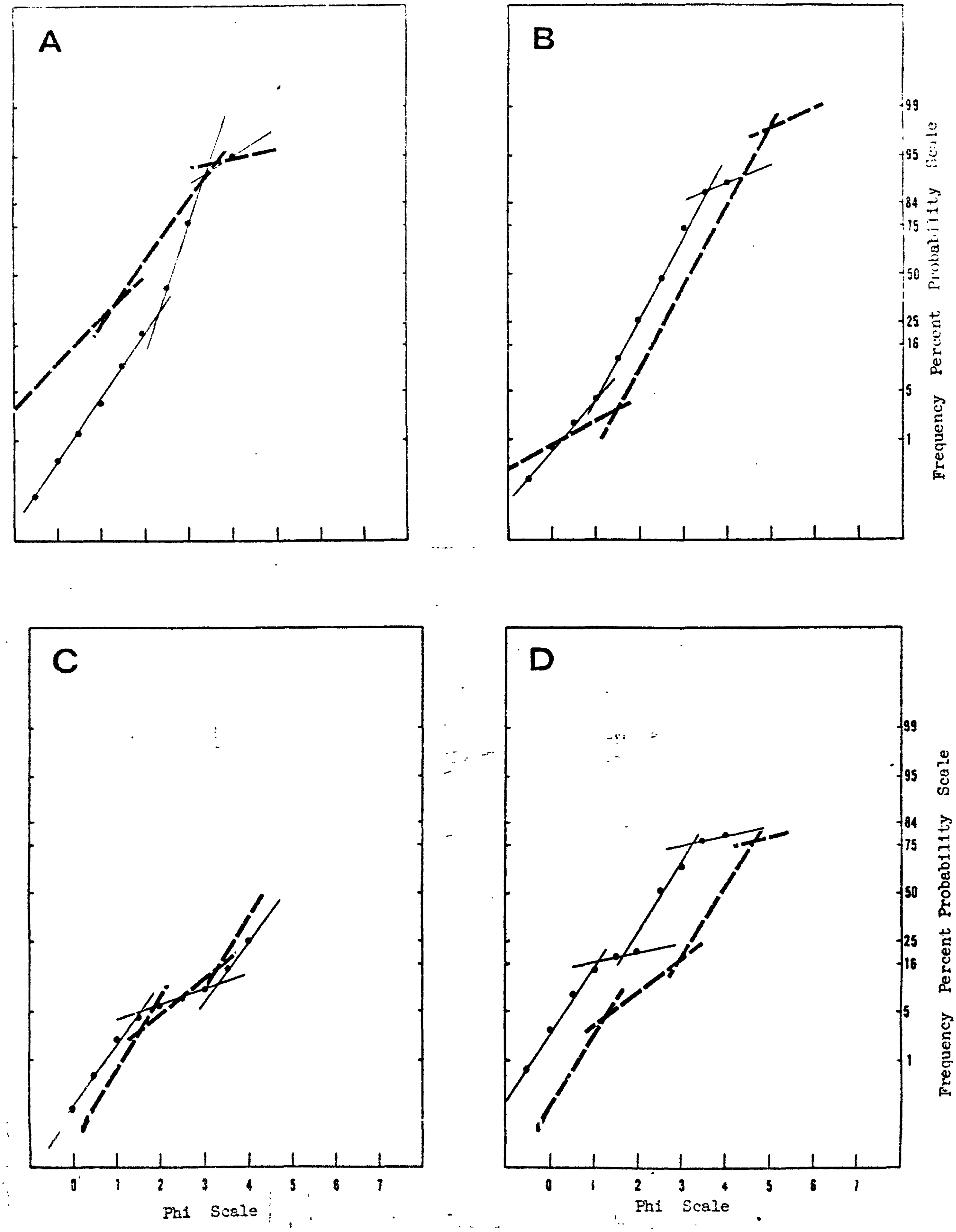


Figure 16.
Log probability plots of Claiborne Group sands. A and C - channel sample of beds 10 meters thick, pit 58B (Plate 1); B and D - channel sample of beds 10 meters thick, pit WE (Plate 1). Source of data: . ________., this study; . -------., Visher (1969).

indicate by the shape and truncation points of the curves that these sediments are similar to those occurring in modern estuary (curves A and B) and deltaic depositional environments (curves C and D) as described by Visher (1969). Silt and clay content of the Claiborne Group sediments (14.4%) places them in the range of silt and clay content observed in fluvial or deltaic environments (Visher, 1969). Considering grain-shape and clay content, the sands can be classified as immature sediments and would accumulate in low energy environments where current action is so weak or deposition so rapid that neither the sediments are winnowed nor the grains rounded.

Evidence that these sands were deposited under marine influence is seen in the mineralogy and sedimentary and biogenic structures that they display. Bioturbation similar to that described above is common in both recent and ancient shallow-water marine environments (Heckel, 1972; Howard, and others, 1973). A rose diagram (Figure 15), constructed from cross-bed data, has a slight bimodality toward the west and southeast which suggests tidal influence in the deposition of Claiborne sands. The dominant orientation of the current rose (i.e., the longest petal) may indicate a dominant longshore current moving toward the northeast. In addition, the sands of this unit are irregularly glauconitic and fossiliferous just south of the Andersonville fault thereby indicating deposition under marine conditions.

Based on sedimentological evidence cited above, the sediments of the Claiborne Group were probably deposited under relatively quite, shallow-water marine conditions in a deltaic or neritic environment. The angularity and condition of the surface of silt and fine sand-size heavy minerals suggest that the sediments have not been extensively altered by weathering since deposition.

KAOLIN AND BAUXITE DEPOSITS

Physical Characteristics

Thick kaolin deposits are generally massively bedded, uniformly colored grayish to yellowish white clay composed almost entirely of clay-sized kaolinite crystallites. In areas where kaolin beds are overlain by carbonaceous, pyritic, sandy silt or silty sands, the upper meter or two of the clay is commonly dark. Sandy portions of kaolin bodies are frequently mottled red, yellow, and purple due to staining by iron oxides; this is more common in the upper portion of clay bodies and particularly where the overburden is thin and composed of permeable sediments which are considerably altered by weathering. In addition, the upper iron stained portion of the clays may enclose hollow goethite concretions which often contain small quantities of well crystallized kaolin.

Bauxite occurs in grossly tabular layers within kaolin lenses. Bauxite and bauxitic clay "horizons" appear to parallel the dip of the Nanafalia Formation only in a general sense, and the elevation in adjacent kaolin bodies may or may not be equivalent. Bauxite lenses are usually 1 to 3 meters thick and are overlain and underlain by 3 to 6 meters of bauxitic clay. In plan view, the bauxite layers are irregular in outline and are between 1 and 5 hectares in areal extent, but may rarely reach 10 hectares. The greatest occurrence of bauxite is found south of the Andersonville Fault Zone in the saddle area between structural highs at either end of the zone (Figure 10). Other large commercial deposits occur in the vicinity of Boggy Branch and Camp Creek. Bauxite is generally absent in down-dip (southern) parts of the district, where the enclosing sediments have a more marine character.

Bauxite and bauxitic clays are typically composed of pisolitic-structured intergrowths of kaolinite and gibbsite, but locally the concretionary structure is not well developed and difficult to recognize in hand sample. In a typical bauxite layer the central portion is usually well indurated with firm pisoliths and/or ooliths embedded in a coherent matrix. Laterally, along the outer boundary of the layer the matrix tends to be less coherent and pisoliths less abundant. The outer (lateral) boundary of the bauxite is usually indistinct, and small patches of indurated bauxite gradually merge with the surrounding clay which may display a pisolitic texture over a short distance. The lower contact is always gradational and irregular. The upper contact is usually irregular and gradational (Figure 17), but occassionally the bauxite is in sharp contact with overlying kaolin and rarely, sandy kaolin.

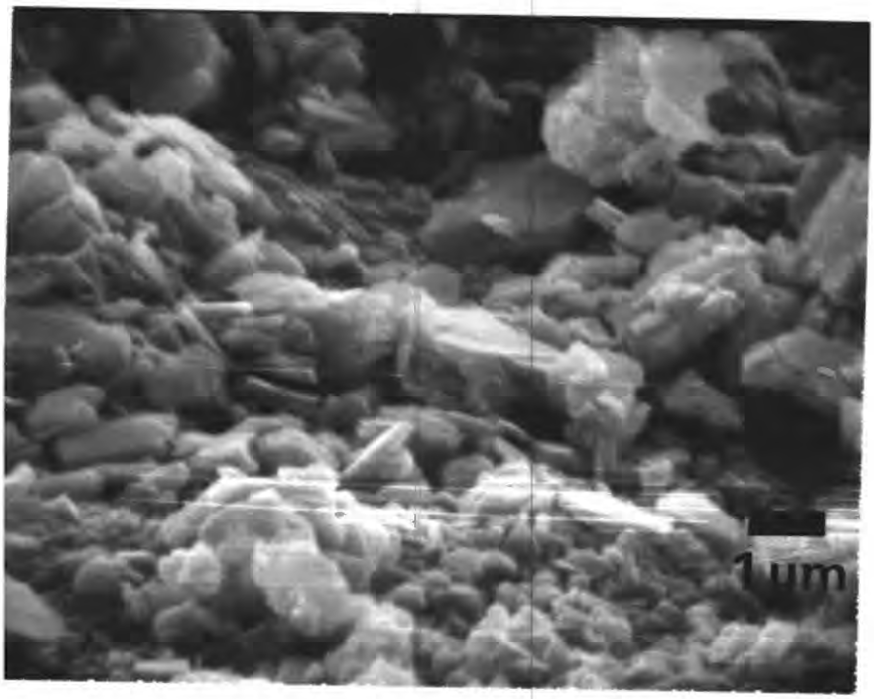
Occurrence and Distribution of Minerals

A detailed description of the variation in the mineral content of the kaolins vertically, horizontally, and geographically is necessary in order to adequately characterize the deposits as sediments and products of diagenetic and postdiagenetic changes.

Kaolin

Kaolinite is the dominant clay mineral in the kaolin-bauxite deposits. The average kaolinite particle size is less than 1 μm; stacks and vermicular crystals were rarely observed and only occassionally exceeded 0.5 mm in length. The crystallinity was found to vary from moderately good to poor (1.4 to 0.25). In the lower part of the kaolin lenses, kaolinite is somewhat less well crystallized than in the upper portion. Kaolinite with a relatively high crystallinity (1.2) occurs interstitially with pisoliths and ooliths in low-grade bauxite and bauxitic clays. Scanning electron microscopy indicates a correlation between a high crystallinity index and crystal size and degree of perfection of external form (Figure 18). Kaolinite occurring in bauxitic material has a greater particle size range than that observed in adjacent kaolins. Books, laths, and

17. Pisolitic bauxite grading vertically into massive kaolin



18. SEM photomicrograph of well crystallized kaolin in bauxitic clay . . . .

stacks of kaolinite are more common in bauxitic clay than in kaolin layers. Crystallinity of kaolinite is often moderately good in the middle portion of lenses that have no significant gibbsite or pisolitic structure. In most deposits where the Tuscahoma Formation is absent and Claiborne Group sands overlie the kaolin, the crystallinity of kaolinite in the upper few decimeters is moderately good and the crystallite size is large (i.e., $> 1.0 \mu m$). In the subsurface in the southern part of the district the kaolins have a high percentage of illite and illite-montmorillonite and the crystallinity index of kaolinite is generally low and particle size is small (i.e., $< 1.0 \mu m$).

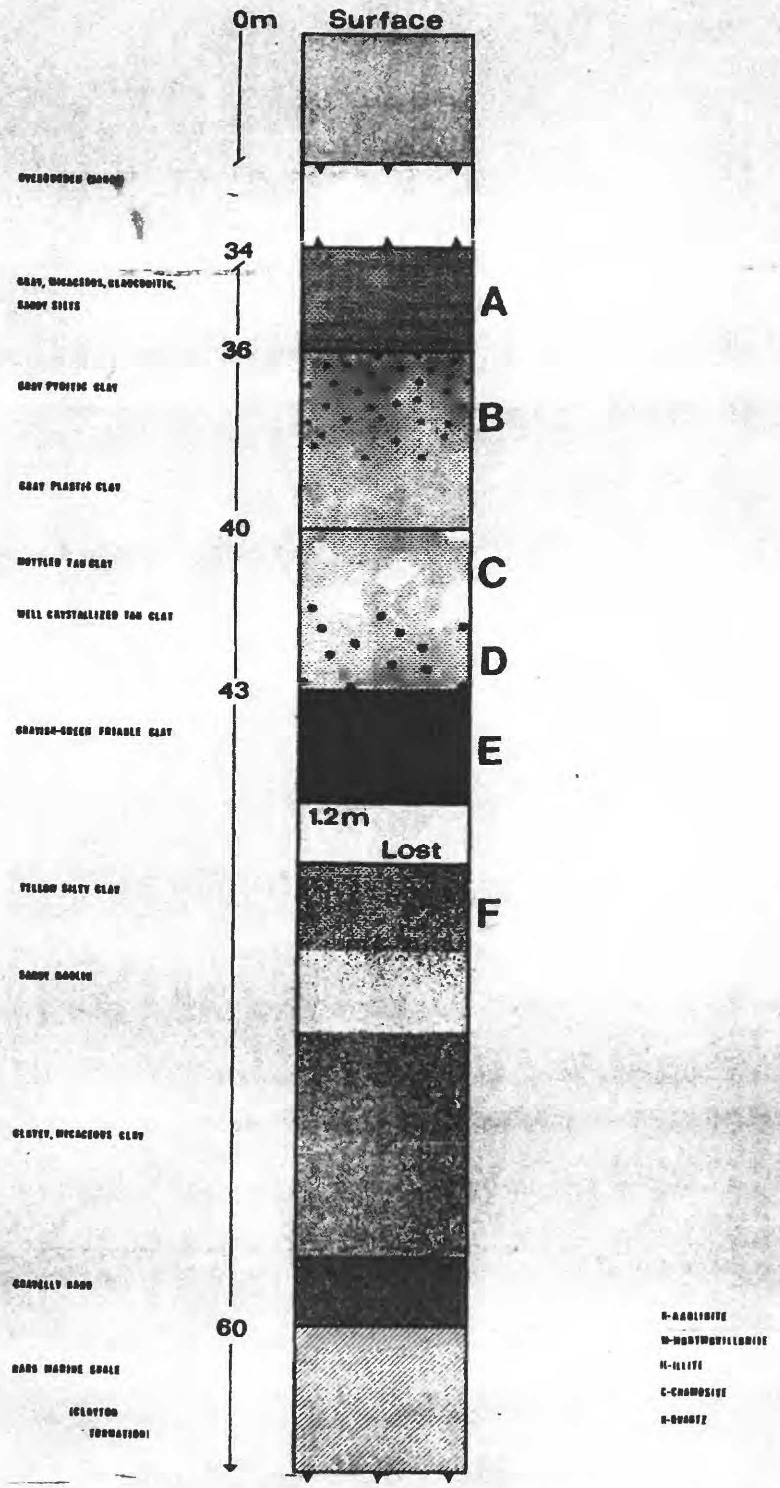
Gibbsite

The mineral varies in relative abundance in the kaolin-bauxite deposits; it makes up to 90 percent of the crystalline phases of some bauxites and occurs as a trace component in some kaolins of the Andersonville district. Gibbsite occurs as crystalline aggregates with kaolin in the soft center of some pisoliths and fills cracks and fractures in indurated matrix material and pisoliths alike. The 0.01 to 1 millimeter ooliths in clastic sedimentary bauxite or bauxitic clay are primarily gibbsite (Figure 19). Locally gibbsite occurs as finely disseminated crystals in kaolin which cannot be resolved optically. In the kaolins of the district, the gibbsite tends to be confined to the central portion of thick kaolin lenses where it and kaolinite forms the bauxite layers.

Berthierine

This mineral was identified in samples from several drill holes in the district as clay-sized particles and as rare pelletal grains, some of which were partially replaced by siderite. Berthierine in kaolin contributes to the high iron content of some clay deposits, but siderite or its oxidation products of goethite and hematite add significantly to iron enrichment in these clays. Berthierine intimately intergrown with kaolinite is found in the vicinity of locations THI-29, WLF8, and FN1 (Plate 1). At the first locality, berthierine is present with gibbsite, kaolinite, and siderite in a thin (60 centimeters) clastic sedimentary bauxite bed in the upper part of a kaolin lens; berthierine occurs in pelletal form in this bed.

The drill hole at location FN1 contains kaolin and berthierine intimately intergrown in clay size grains in the middle portion of a thick kaolin lens. The detailed stratigraphy of the core illustrates the variation in the crystallinity and mineral composition of the kaolin in the subsurface of the district. The hole is located north of the Andersonville Fault Zone (on the downthrown block) and the kaolin is directly overlain by marine sands and silts of the Tuscahoma Formation which contains muscovite, glauconite, and montmorillonite. The upper 3.6 meters of the kaolin is pyritic, micaceous, plastic, and poorly crystallized (index 0.4) and contains montmorillonite in significant quantities (≈10%). The montmorillonite content decreases with depth and is not detectable by XRD in the lower 0.5 meters of the core. Below 3.6 meters there is approximately 2 meters of illitic kaolin which is mottled red and yellow from oxidation of pyrite; its crystallinity index is 0.6. Underlying the mottled zone is a 1.2 meter zone of moderately well crystallized (index 1.2), nearly pure, soft yellowish-tan kaolinite. This clay grades imperceptively into a friable grayish-green clay 2.3 meters thick which contains intimately intergrown berthierine and kaolinite and disseminated siderite crystals 1 millimeter in diameter. The crystallinity index of the kaolin/berthierine is 0.7. Below this zone there are 2.8 meters of tan, sandy, micaceous, sideritic kaolin; quartz and muscovite content increases to the bottom of the hole. A stratigraphic section of the core and XRD patterns of oriented samples of clay appear in Figure 19.



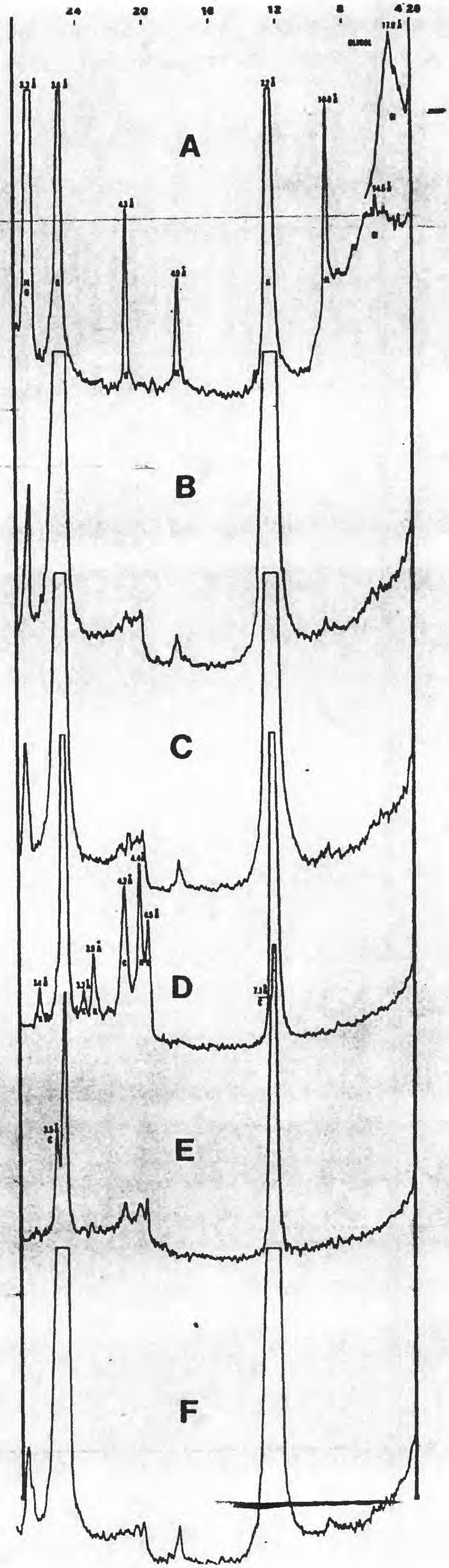


FIGURE 19. STRATIGRAPHIC SECTION OF DRILL HOLE FN-1, Å - ANGSTROM

Muscovite and Illite

Muscovite and illite occur as fine sand, silt, and clay-sized particles consisting of clear, compact books and stacks of muscovite or expanded feathery edged, cloudy to nearly opaque grains. As the particle size decreases, most of the grains take on the latter aspect. The presence of fine mica in the clay fraction tends to enhance the reflectivity of the clay resulting in the loss of its typical earthy luster. In most silty kaolins of the district, the silt is composed or predominantly quartz with slightly less abundant muscovite and rare kaolinite books and stacks.

Illite is rare in kaolins where montmorillonite is abundant. From the vicinity of THK32 east to the Flint River and north to Sweetwater Creek, illite is very abundant in the lower portions of kaolin lenses; its content increases with depth and in the lower 1 to 1.5 metere may compose 20 percent of the clay. The particle size of this clay is somewhat finer than the overlying kaolin, and the crystallinity index of the kaolinite is variable but averages 0.5.

Muscovite is present in all kaolins and is less abundant in the bauxitic clays and coarsely crystalline kaolin. It is rarely present in bauxite or where gibbsite is a principal component of the clays.

Montmorillonite

Montmorillonite content of the kaolin and bauxite of the district is variable depending on the nature of the overlying strata and the depth within the kaolin lens. In general the area from just south of Sweetwater Creek northward to Camp Creek contains less montmorillonite, and this mineral is most abundant south and southwest of this area. The upper meter or so of the kaolins tend to contain more montmorillonite regardless of the geographic location of the sampling site, and it is more abundant where the kaolins are overlain by marine strata.

Where marine beds directly overlie the kaolin or sandy kaolin, wedge-shaped dessication cracks extend into the clay and are filled with material from the overlying formation and usually contain significant amounts of montmorillonite. This is particularly true in the south-central and southwestern part of the district. In core holes of this area (locations DL10-28-3, RHJ18, CF40, CD14, P10-33, RH2-22, and RHJ26, Plate 1), montmorillonite may be about as abundant as kaolinite in the upper portion of the clay (Figure 20, P10-3M and RH2-2P). The upper 1 meter of clay is often pisolitic, may contain minor gibbsite, and resemble the bauxitic clays of the up-dip areas (Figure 20, P10-3M). The pisoliths are slightly darker than the matrix, have distinct or indistinct rims, and develop shrinkage cracks on drying. The montmorillonite content of the pisoliths usually exceeds that of the matrix as in RHJ26-3P and RHJ26-2M respectively. RHJ26-3 was collected 1 meter below RHJ26-2. The matrix and pisolites sometimes contain equal amounts of kaolinite and montmorillonite as indicated by XRD patterns for samples CF40-M and CFM40-P (Figure 20). Montmorillonite tends to decrease in abundance with depth in the hole and may be replaced by illite as the second most abundant clay mineral, as in sample CF40-2 located 1 meter below sample CF40 (Figure 20). In some areas nearby, core holes exhibit quite different mineral compositions. For example, XRD patterns of both matrix and pisoliths in the upper parts of the clay in CF40 contain appreciable montmorillonite while the similar structures in CD14 are composed of coarse-grained moderately well-crystallized kaolinite (Figure 20).

In drill hole RHJ26 (Plate 1) montmorillonite is present throughout the 2.4 meters of clay and is more abundant than kaolin in the upper meter of the core. The upper 1.2 meters is a yellowish plastic clay grading down into

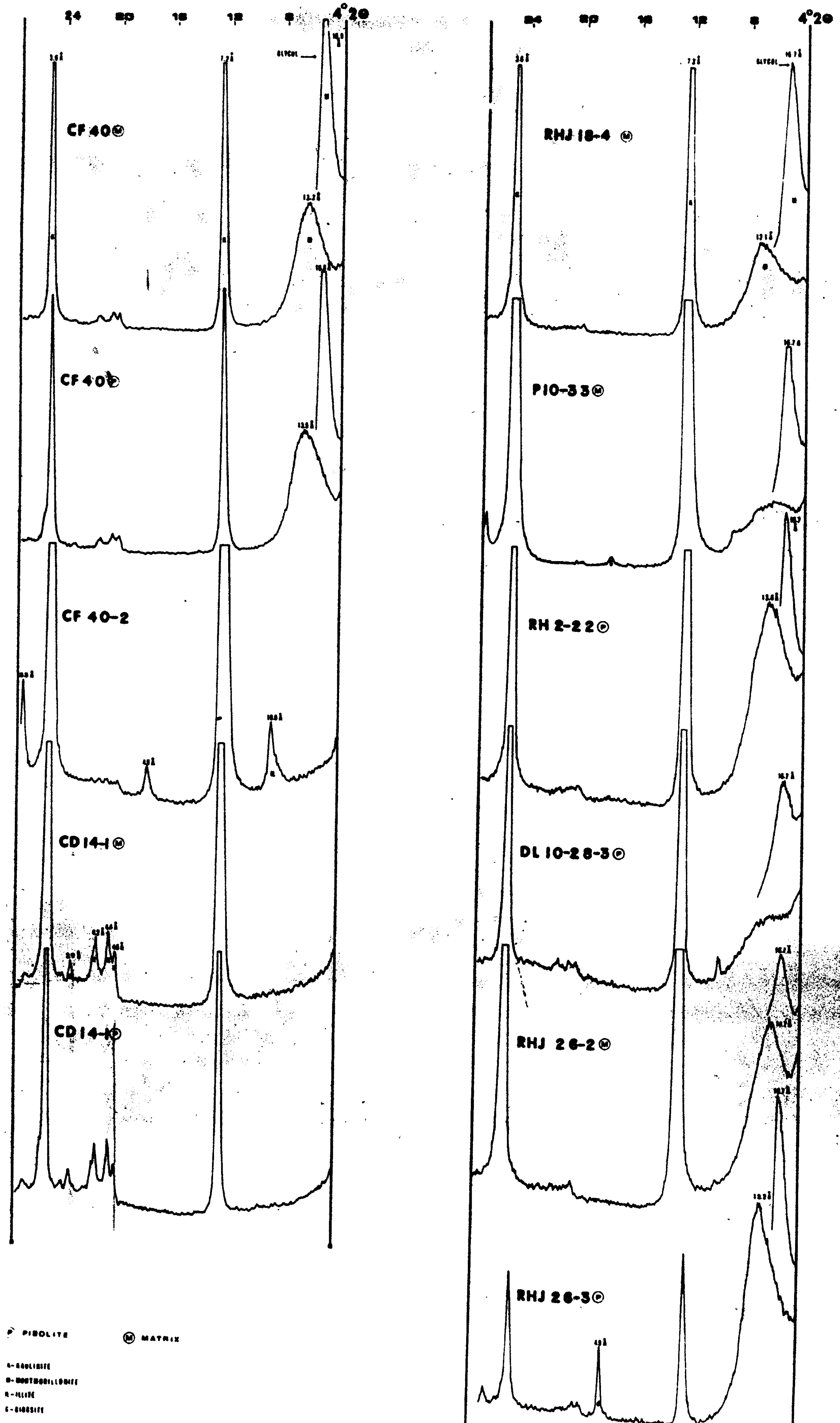


FIGURE 20. X-RAY DIFFRACTION PATTERNS OF MONTMORILLONITE AND KAOLIN MIXTURES IN PISOLITIC KAOLIN, Å - ANGSTROM.

1 meter of white, very sandy clay which overlies 0.2 meters of green friable clay. These white and green clays contain concretionary structures varying between 5 millimeters and 2 centimeters in diameter. The concretionary structures of the white sandy clay are small and most have quartz grain centers. The concentric banded rims are composed principally of montmorillonite, and examination by SEM shows this material to be lamellar with curled wispy edges. Rim materials of larger pisoliths display a globular structure (Figure 21a) and are traversed by numerous radial fractures filled with non-crystalline materials and kaolinite plates. Quartz grains from the center of the pisoliths are commonly subhedral and may exhibit evidence of extreme corrosion (Figure 21b).

Glauconite

Glauconite was detected within a kaolin lens at localities EAT2 and CL9 (Plate 1). Four meters above the bottom of the kaolin is a layer of dark gray, lignitic, clayey sand and green sandy silt approximately 1.8 meters thick. The sand size fraction of this layer contains 50% abraded, lobate, or fragmented glauconite; the remainder of this fraction (including silt size material) is composed mostly of quartz, muscovite, and wood fragments. The clay size fraction is made up of poorly crystalline kaolinite and illite.

Pyrite

Pyrite is the most abundant iron sulfide and occurs as nodules, clusters, single crystals, and fine dust-size particles which are irregularly scattered throughout the kaolin, bauxitic clays, and bauxite. In bauxite, it also fills fractures and cracks in pisolites and is sometimes totally enclosed by outer rims of composite pisolites. Pyrite is more abundant in the upper part of kaolin which is overlain by pyritic/lignitic clays and silts.

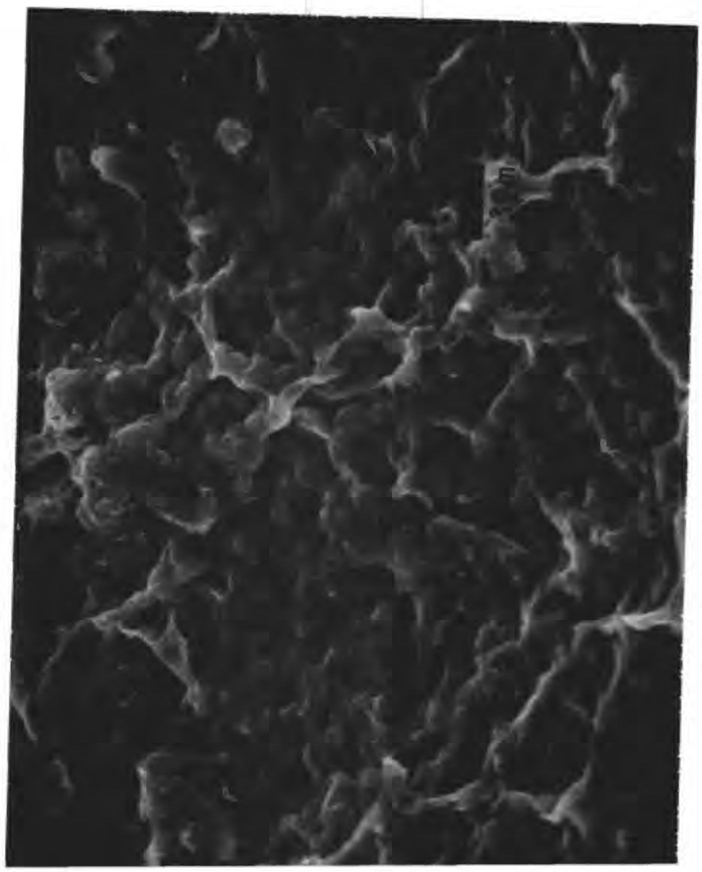


Figure 21a.
SEM photomicrograph of globular structure of rim material in montmorillonite rich pisolites from drill hole RHJ26 (Plate 1).

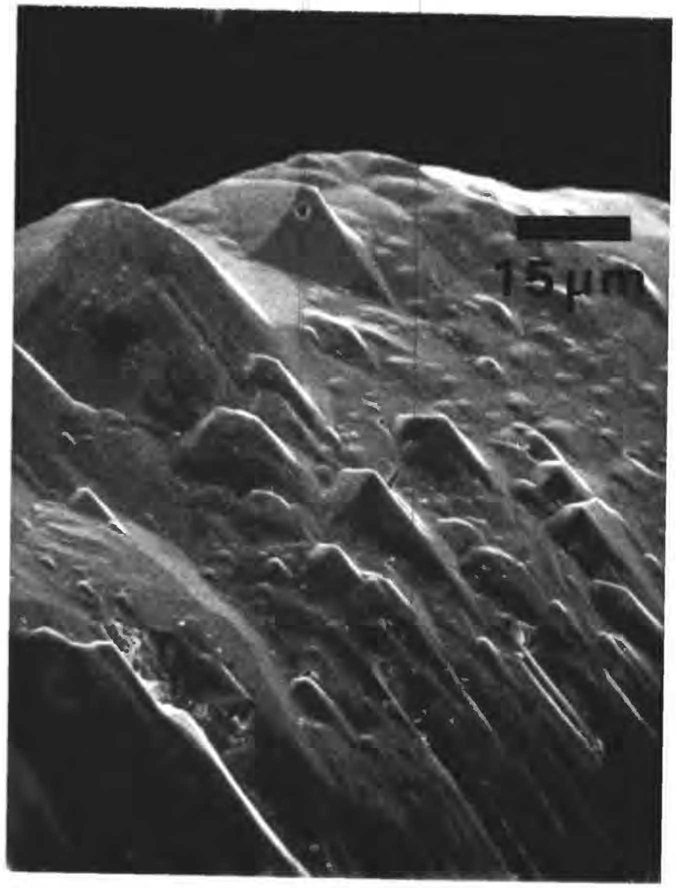


Figure 21b.
SEM photomicrograph of corroded prism faces of a quartz grain from the center of a montmorillonite rich pisolite, sample from drill hole RHJ26 (Plate 1).

Siderite

Siderite is the most abundant iron mineral in the kaolins but is generally absent where pyrite is present. It is more abundant in the kaolins of the area south of Tripple Creek/lower Camp Creek where it forms thin beds a few millimeters to a few centimeters thick in kaolin and bauxitic clay. However, it occurs most frequently as single well formed rhombohedral crystals, rosettes, or nearly spherical crystalline aggregates disseminated throughout the kaolin bodies. It varies from nearly gray-white to yellow to deep red in color. The deep red variety, which appears homogenous, has undergone partial oxidation to hematite. Siderite is frequently intergrown with pelletal berthierine and replaces it forming nearly spherical crystalline aggregates.

Heavy Minerals

The variety of heavy mineral species in kaolin and bauxite is slightly less than that observed in the Claiborne Group and Tuscahoma Formation (Table 1). All of the minerals present are relatively stable under weathering conditions except biotite. Muscovite, tourmaline, staurolite, kyanite, and biotite occur in the fine-sand to silt-sized particle range. Biotite and muscovite occur as compact, clean books and show little evidence of alteration (Figure 22a and 22b). Kyanite cleavage fragments are sharp-edged and show little alteration. Tourmaline and staurolite occur as angular fragments and as bright euhedral prisms with sharp face-edges and terminations. Zircon occurs as rounded grains and stubby euhedral tetragonal crystals. The relative abundance of heavy minerals is highest in kaolins and lowest in high grade bauxite. Muscovite is rate in bauxite and is only slightly more abundant in some of the bauxitic clays. Bauxite and bauxitic clay have a higher percentage of rounded heavy mineral grains than does the kaolin.

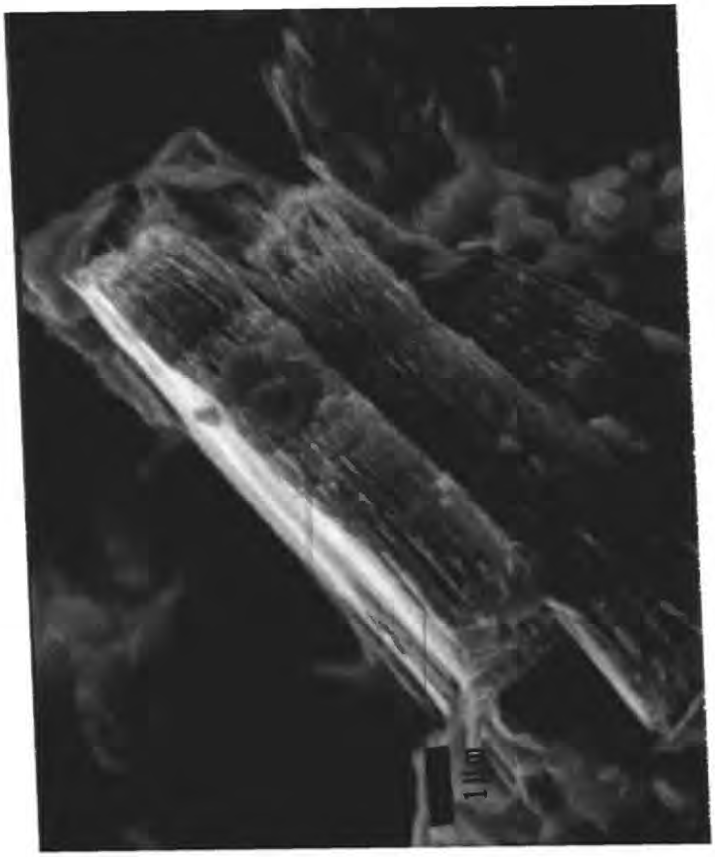


Figure 22a.
SEM photomicrograph of silt-sized muscovite books in kaolin from core hole CD-14 (Plate 1).

Figure 22b.
SEM photomicrograph of compact, fresh-appearing biotite book in kaolin, from drill hole THJ24 (Plate 1).

Diagenetic Alteration

When the kaolinitic clays were deposited they contained varying amounts of mineral impurities and carbonaceous material. Diagenetic changes effecting the impurities and the kaolin bodies were slight except locally where alteration was more extreme and extensive and bauxite was formed. The following factors tend to support the concept of moderate post-depositional alteration of original sediments.

1. The heavy mineral suite of the kaolin is much the same as that of the enclosing sediments (Table 1) and is only slightly less complex than that seen in other sediments of the region.

2. Rare but widely distributed carbonized and mineralized root and plant debris and associated burrow structures in kaolin lenses suggests that the clays were originally more carbonaceous and may have supported a prolific burrowing fauna. Thus, preservation of delicate root structures and plant debris in growth position and the preservation of the interface between clay-filled burrow-casts and the enclosing clays precludes a significant volume change due to neomineralization during post-depositional alteration.

3. The surfaces of most silt and sand-sized quartz grains show little evidence of chemical attack. Locally, some grains have been corroded and etched in coarsely crystalline or bauxitic kaolins.

4. Fine-grained mica exhibits evidence of kaolinization but abundant fine-sand to fine-silt sized muscovite and sparse biotite books in the kaolins show little evidence of alteration.

5. There is a general lack of slump and swell structures in the kaolin and bauxite that might reflect changes in volume due to extensive post-depositional neomineralization.

ORIGIN OF KAOLIN AND BAUXITE

Previous Concepts

Discussions of the origin of kaolin deposits interbedded with Cretaceous and Tertiary sedimentary strata in southeastern United States have involved more agreement than controversy. Nearly all investigators agree that the clays are sedimentary and that their source was weathered products of the crystalline rocks of the Piedmont region. The principal differences of opinion have centered around the nature of the clays at the time when they were deposited and the environment of deposition.

Veatch (1909), Shearer (1917), Neumann (1927), Smith (1929), Bridge (1950), Overstreet (1964), and Murray and Patterson (1975), to name a few, believed that the sediments were derived, transported, and deposited as clayey sediments that have undergone moderate alteration as a result of subsurface percolation and surface weathering. Kesler (1951, 1957), Grim and Wahl (1968), Flock (1966), and Austin (1972) among others, believe that the clays were derived, transported, and initially deposited as micaceous, lithic, arkosic, quartzose sands. These were weathered in situ, and the clay fraction was winnowed by stream or tidal currents or by wave action and redeposited as relatively pure kaolin in standing bodies of water. Buie (1964) and Hurst and others (1966) have suggested the source of some, if not all, of the clays was volcanic ash fall which may have been deposited on land and transported by stream to the depositional site or deposited directly in the basin.

Depositional environments are thought to be in oxbow lakes, or in fresh-water or brackish water ponds on a low lying delta (Kesler, 1957; Flock, 1966; and others). Hinckley (1961) believed that the texture of the clay indicated that some were freshwater and others were marine deposits. Buie and Fountain (1967), Scrudato and Bond (1970), and Austin (1972) indicated that some of the Tertiary clays were marine or estuarine.

Most authors believe that the bauxite associated with the clays is a product of subaerial weathering of clays. Shearer (1917), Smith (1929), and Kesler (1951) believed that mechanisms other than those associated with bauxitization of aluminous material in tropical environments were active in the formation of bauxite associated with sedimentary kaolins.

Shearer (1917), Smith (1929), Flock (1966), and Burst (1974) have proposed an origin for the deposits in the Andersonville district based on field work and/or analytical data. Shearer (1917) believed the bauxite formed from relatively pure kaolin as it was being deposited in ponds and lakes. Hydrogen sulfide gases generated by decaying vegetation in ponds provided the active agent of disolution and formation of aluminum sulfate that was reduced to form gibbsite. Smith (1929) suggested that the kaolin in the district was derived from erosion and transportation of up-dip Cretaceous kaolins. Flock (1966) believed that the kaolin was deposited in freshwater deltaic lakes after winnowing from altered arkosic sediments by migrating distributaries. He proposed that bauxite was produced in situ by bauxitization of newly deposited clay after slight uplift and weathering. The overlying clays were attributed to "silicious cap" formation during alumina accumulation and to resilification of bauxite. Burst (1974, p. 139) envisioned a tidal flat where "desilicification" progressed in meanders filled with degraded aluminosilicate lattices and essentially pure freshwater". . . . by incongruent solubilization . . . of kaolin type lattices to form gibbsite and silica." Silica then migrated outward and was stabilized as kaolinite in the outer portions of the envelope, leaving a gibbsite enriched core.

Kaolin and Bauxite Formation

Sedimentological, structural, mineralogical, and paleontological evidence gathered during this investigation indicate a complex history for the development of kaolin and bauxite deposits in the district. Palynological studies of samples from the deposits and the associated sediments provide a limited time frame for deposition of the clays and their subsequent post-depositional alteration. The following sequence of events is suggested for the formation of the deposits in light of the evidence presented elsewhere in this paper.

In the area of what is now the Andersonville district, an estuarine environment prevailed during much of the Paleocene epoch. The early Midway sediments and their fauna are typical of a protected estuarine basin environment subject to moderate tidal influence and sediment supply. Restricted circulation led to mildly hypersaline conditions which accompanied the deposition of the dark montmorillonitic clays of the upper Clayton Formation. No sediments representing the Upper Midway are present, and the Nanafalia kaolin-bearing sediments are deposited on the irregular erosional surface developed on the Lower Midway Clayton Formation.

At the beginning of Nanafalia time a turbid stream (or streams) with a large suspended load of mixed clays dominated by kaolinite flowed into the estuary. Where the slope of the estuary floor was steep, channels formed and current flow provided sufficient energy to transport and deposit mainly sand-sized particles (dominated by quartz). Between channels where bottom topography was relatively flat lateral spreading of the suspended load provided the means of concentrating the clay fraction; where the slope steepens the clay section thins. The increase in abundance of illite and montmorillonite in the seaward sediments and the predominance of kaolin shoreward is thought to be due to differential sedimentation resulting from flocculation under increased salinity in the seaward direction such as described by Ezwald and others,(1974). Minor amounts of montmorillonite and illite may have been transported by tidal currents to the estuary from the offshore marine environment. Occasional introduction of sands into interchannel areas and deposition of clay in channels contributed to the interfingering relationship of clay and sand and resulted in formation of isolated deposits. On the steepened slopes in the seaward (southward) direction newly deposited clays may have flowed down slope in gravity slides or turbidity currents. Rapid sedimentation of this type probably produced the thin, poorly sorted sandy clays common in the marine facies of the Nanafalia Formation.

The depositional cycle was interrupted by a regression which exposed the newly deposited sediments in the northern and central parts of the district to weathering and erosion. Relief was slight; fresh water swamps occurred on parts of the exposed areas while brackish or salt-water marshes probably occupied the seaward areas. Thick kaolin accumulations became the positive areas as the drainage pattern developed; the more easily eroded unconsolidated sands became the stream valleys. Because of their resistance to erosion the clays in the northern and central parts of the district were elevated above the water table. In the prevailing subtropical environment the clays were locally bauxitized. Susceptibility of the kaolinitic clays to bauxitization was enhanced by their low bulk density and high porosity. The general lack of concentration of iron during bauxitization is believed to reflect the low iron content of the original sediment; the bauxites and bauxitic clays are only slightly higher in iron than adjacent clays. If excess iron was present, it was apparently solubilized and removed from the system. Locally, iron and titanium were mobilized to become concentrated as hematite and anatase in pisolitic structures associated with bauxitization. Some solution and transportation of iron as Fe^{+2} is indicated by the occurrence of secondary pyrite and siderite in the clays and bauxite in many deposits of the district. A siliceous or ferruginous cap usually associated with bauxite formation in tropical and subtropical climates is not present; it may have been removed by subaerial or subaqueous erosion prior to deposition of the overlying kaolin. The lack of equivalence of elevation and irregular shape of bauxite deposits is thought to reflect the variation in surface relief and elevation of the groundwater table during bauxitization. In addition to the subaerial formation of bauxite, fine micas became kaolinized and relatively coarsely crystalline particles of kaolin (books and stacks) were formed elsewhere in response to weathering, while montmorillonite was destroyed.

A rise in sea level occurred and the area was submerged. Wave action and/or currents planed off the erosional surfaces, removing some of the weathering products. Redistribution of debris resulted in the formation of organic-rich sediments interbedded with kaolin and rare bedded sedimentary bauxitic material. Silica from the encroaching (brackish) water reacted with gibbsite in the porous bauxite, and reworked deposits to form kaolinite and produced the gradational upper contact between bauxite and transitional clay. The coarse particle size and higher crystallinity of kaolinite in bauxitic clay and some kaolin at this stratigraphic level within the deposits demonstrates that the coarsely crystalline kaolinite is a product of weathering or resilication of gibbsite. Where reworked materials were high in iron, resilication in a more saline environment resulted in formation of berthierine at this horizon.

During this time of submergence and reworking of surficial materials, the deposition of sandy and clayey sediment resumed. The drowned stream valleys generally became the channels where sandy sediments were deposited. The interchannel areas were again established as sites of kaolin accumulation. However, the kaolin deposited at these sites contained considerably greater quantities of montmorillonite and less illite.

At the close of the kaolin depositional period movement along the Andersonville Fault Zone resulted in uplift of the area south of the fault zone. This led to the subaerial exposure of clays and their subsequent bauxitization under intense weathering conditions. After bauxitization had ensued on the upthrown block a second withdrawal of the sea took place within the district; the mud-cracked surface of the sandy kaolins attest to this regression.

At the beginning of the Tuscahoma depositional cycle a transgression occurred that led to deposition of laminated silts and clays on the dessicated upper surface of the Nanafalia Formation; this took place to the north and west of the Andersonville Fault Zone. Because the area south of the fault zone remained subaerially exposed at this time, no typical Tuscahoma sediments were deposited; only a few scattered fresh-water swamp deposits developed on this positive area. At the southern edge of the upthrown block the porous bauxites that had developed subaerially became exposed to marine waters concentrated in Si^{4+}, Fe^{2+}, Mg^{2+}, and Na^{+}. A major portion of the gibbsite and kaolinite reacted with the water to form montmorillonite. In those areas where the water was brackish gibbsite reacted to form kaolinite. The pisolitic structure of the bauxites was preserved in both transformations.

During Eocene times, the district was blanketed with Claiborne Group sands. These sediments may have been laid down under neritic to prograding deltaic conditions.

Throughout the depositional cycle, climatic conditions were probably subtropical in the source area and at the site of deposition. The kaolin-bearing sediment was transported and deposited as relatively pure clay and kaolinitic micaceous sands which were only slightly altered after deposition except in area of bauxite formation. The source for the sediments may have been the weathered igneous and metamorphic terrain of the Piedmont to the north or kaolinitic sediments of the Coastal Plain itself. Sandy kaolins and kaolinitic sands form a significant part of Cretaceous sediments a few kilometers to the north of the district. The association of fresh and strongly altered, abraded and euhedral detrital grains suggests more than one provenance for the mineral suites. Perhaps the lower Wilcox kaolin-bearing sediments represent deposits derived from erosion of nearby kaolinitic sediments as well as a more remote Piedmont source.

RESOURCES

Because resource evaluations ultimately consider the end-use of raw (mined) materials a different set of mineralogical/descriptive terms is required; for this reason kaolin, bauxitic clay, and bauxite are defined below. Additional resource evaluation terms are also included along with computer terminology that may be unfamiliar to the reader.

Definitions

Kaolin. Kaolin applies to clay consisting mainly of kaolinite [$Al_2Si_2O_5(OH)_4$]. As a mineral resource it may contain up to 5 percent coarse clastic grains consisting principally of mica and quartz (4 to 128μm size range). Gibbsite [$Al(OH)_3$] may be present in varying amounts, and the alumina (Al_2O_3) content may vary between 38 to 41 percent. Ideal kaolinite contains 39.5 percent Al_2O_3.

Sandy kaolin. Sandy kaolin applies to clay composed chiefly of kaolinite which has a coarse clastic content (4 - 256μm size range) greater than 5 percent and up to 15 percent. Higher amounts of impurities result in an Al_2O_3 content ranging between 33 and 38 percent. Gibbsite may be present in small amounts.

Bauxitic clay. Bauxitic clay consists of pisolitic and non-pisolitic materials composed of gibbsite and kaolin in a ratio of less than 1 and greater than 0.1. The alumina content ranges from 41 to 51 percent on a dry basis.

L.O.I. Loss on ignition is the percent weight loss on firing dried kaolin or bauxite at 1000°C. This amounts to 14 percent for kaolinite and 35 percent for gibbsite.

Identified-indicated reserves. This term applies to the proportion of a resource that has the same quality as that currently produced in the district and the thickness of the deposit is sufficient for exploration. No implication as to ratio of resource to overburden is implied. The tonnage and grade are computed partly from specific measurements (U.S.G.S., 1975).

Identified-inferred reserve. These are reserves for which quantitative measurements are based on broad geologic knowledge and limited analytical data.

Identified-indicated paramarginal resource. This refers to subeconomic resources that border on being economically producible.

Hypothetical resources. These are undiscovered resources that could reasonably be expected to exist under geologic conditions prevailing in the area.

GRASP. This is an acronym for Geologic Retrieval and Synopsis Program of the United States Geologic Survey. It is a Fortran program used for storage and retrieval of alphanumeric entries in digital form (Bowen and Botbol, 1975).

Symap. Symap refers to a computer program designed to analyze data with a geographic distribution and produce the results in map form (Dougenik and Sheehan, 1975).

U.T.M. Coordinates. This refers to the universal transverse mercator coordinate system of the U.S.G.S.

Methods of Investigation

Drill logs and cores of over a thousand exploration holes were examined. The approximately 600 holes computerized form a belt trending northwest-southeast through the center of the district (Plate 1). Approximately 60 percent of the total area was covered by patterned drilling; the remainder was covered by randomly spaced holes.

Portions of drill hole data were computerized in order to generate isopach maps from which resource information would be obtained.

Each hole was located by its U.T.M. coordinates and hole collar elevation. Depth to the top of each unit sampled, geologic description, mineral composition and chemical analyses of each unit were also coded on a data sheet for computer storage. This information was stored (and retrieved upon command) via the GRASP program.

All interpretations of computer output, modification of computer generated maps and calculation and compilation of resource estimates are the sole responsibility of the senior author. A detailed description of methods, etc. appears in the form of an open file report (Cofer and others, 1976).

Computer Generated Maps

A softward package was selected that would generate an isopach map on a line printer. These maps provide a representation of the size, shape, and thickness of the deposits from which planimetric calculations of resources were made. This method of calculation is simple, rapid, and allows for application of geologic knowledge and reasoning to modify the extrapolation and interpolation built into the computer program (i.e., Symap) in areas where data points are widely spaced.

The distribution of data points over the entire map area is statistically nearly random. However, for those areas containing over 95 percent of the resource tonnage, the distribution is more uniform. In those areas where the distribution of points is unfavorable for reliable interpolation, drill hole data from other sources was applied in order to modify the contour pattern. Figure 10 serves as an example of a hand modified computer generated map.

Resource Estimates

Estimates for kaolin and sandy kaolin resources are thought to be reliable to $\pm$ 30 percent for the area in which 80 percent of the kaolin and sandy kaolin deposits occur. In areas containing the remainder of the projected resources drill hole spacing is too wide for this accuracy. Deposits containing as much as 1,000,000 tonnes may not be detected and other large tonnage may have been removed by post depositional channeling. For this portion of the resources the reliability is ± 60 percent of the projected tonnage. Estimated tonnages for kaolin and sandy kaolin are summarized in Table 4.

Resource estimates of bauxite and bauxitic clay were determined by a practical method and not from the isopach maps. Drill hole spacings suitable for kaolin resources evaluation have limited value when considering bauxite reserves. Only about 10 percent of the holes used penetrated bauxite or materials usually associated with bauxite (i.e., bauxitic clay, pisolitic kaolin, or kaolin with abnormally high L.O.I.). The indicated reserves of bauxite were calculated by assuming Zapp's (1965, p. G21) estimate of "measured" and "indicated" reserves to be correct, and modifying these by subtracting production and adding new discoveries since that date. Inferred reserves were estimated for those areas in which only widely spaced drill hole data were available. Because a typical deposit in the central part of the district contains approximately 50,000 tonnes, and one in marginal areas contain approximately 20,000 tonnes, individual drill holes encountering bauxitic materials were assumed to represent deposits of the size appropriate to their location in the district. Estimates of hypothetical resources were based on the fact that large, thick kaolin deposits usually contain bauxite. A number of such deposits probably occur where drill holes are too widely spaced to encounter all the bauxitic materials. Resource calculations of bauxitic clay were based on an average bauxitic clay to bauxite ratio of 4/1. This ratio is based on observed abundances of these two materials throughout the district. Calculated estimates for bauxite and bauxitic clay are given in Table 5.

Table 4 - Estimates of Resources of Kaolin and Sandy Kaolin

in Dry Tonnes

Resource Type	Kaolin	Sandy Kaolin	Totals
Identified indicated reserve	290,000,000		290,000,000
Identified paramarginal resource		240,000,000	240,000,000
Identified submarginal resource	50,000,000		50,000,000
Hypothetical resource	50,000,000	50,000,000	100,000,000
Total Resources	390,000,000	290,000,000	680,000,000

Table 5 - Estimates of Bauxite and Bauxitic Clay Resources in Dry Tonnes

Resources	Bauxite	Bauxitic Clay
Indicated Reserves	1,230,000	4,920,000
Inferred Reserves	600,000	2,400,000
Hypothetical Resources	1,500,000	6,000,000
Total Resources	3,330,000	13,320,000

CONCLUSION

The kaolin and kaolin-rich sediments of the Andersonville district were deposited in an estuarine environment with restricted circulation and little tidal or longshore current influence. During pre and early Clayton time the estuary probably was a typical drowned river valley with a tidal inlet open towards the southwest. Micaceous, kaolinitic clays were deposited during late Paleocene time in shallow depressions on broad, shallow-water flats between subaqueous distributary channels in the estuarine system. Kaolinitic sediments were temporarily exposed to weathering and bauxitization and further kaolinization took place. Subsequently, subaerial and/or subaqueous erosion planed off and redeposited some of the weathering products as organic-rich clays and silts, berthierine-bearing clays, and rarely as colluvial bauxite and sedimentary bauxitic clays. Upon resubmergence, gibbsite-rich, porous bauxite, and bauxitic clays were exposed to silica-saturated low salinity water of the estuary. Gibbsite reacted with silica to form kaolinite and resulted in the formation of the transitional (bauxitic) clays overlying the bauxite. Kaolinitic sediments transported by streams again spread over the altered and redeposited material.

At the close of the kaolin depositional period movement along the Andersonville Fault Zone and Mountain Creek fault changed the configuration of the basin and the area immediately south of the Andersonville Fault Zone was exposed to weathering and bauxitization for a short time. General submergence again occurred and much of the district was covered by marine and brackish water. Porous bauxitized clay enriched in gibbsite was exposed to silica-saturated saline to brackish water. Gibbsite reacted to form montmorillonite in the saline environment and formed kaolinite in areas covered by water of lower salinity.

The kaolin and bauxite deposits in the district form a broad belt 15 kilometers wide and 22 kilometers long trending in a northwest-southeastward direction. Most of the kaolin and bauxite of commercial quality and quantity occur within a narrow 10-kilometer-wide zone in the belt. The reserves of kaolin suitable for refractory and chemical use are approximately 290 million tonnes. Paramarginal resources of sandy kaolin suitable for refractory, chemical, or aluminum manufacture after beneficiation are approximately 240 million tonnes. Indicated and inferred reserves of bauxite and bauxitic clay are 1.8 million tonnes and 7.3 million tonnes respectively.

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