# SOUTHEASTERN

# GEOLOGY

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# SOUTHEASTERN GEOLOGY

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# A CRETACEOUS-TERTIARY DEPOSITIONAL SEQUENCE

# IN THE SUBMERGED COASTAL PLAIN OFF NORTH CAROLINA

By

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## ABSTRACT

Seismic reflection records and cores from the inner continental shelf off Long Beach, North Carolina show that the shelf floor is underlain by a thick section of silty fine quartz sand disposed in a sequence of forset type beds prograding southward. The top of this deposit is truncated by an erosion surface that lies either at or very near the shelf floor. Foraminifera from cores that penetrated the upper part of the deposit indicate that the part closest to shore is of Late Cretaceous age while farther seaward the deposit is Early Paleocene. The ready accessibility to these deposits by relatively short cores and good to excellent preservation of the fauna suggest that more detailed coring would yield useful stratigraphic information of the Cape Fear Region.

## INTRODUCTION

### Purpose

A geological survey of the inner continental shelf off North Carolina from Cape Lookout to the South Carolina border was carried out by the Coastal Engineering Research Center in 1970 and 1971 (Fig. 1). The principal purpose of this survey was to obtain information on offshore sand resources and aspects of the engineering geology for application to Corps of Engineers planning and project data requirements. Results of analysis and interpretation of these data have been compiled into two reports by the Coastal Engineering Research Center (CERC) (Meisburger, 1977a, and Meisburger, 1979). The purpose of this paper is to briefly outline stratigraphic information obtained on extensive deposits of Cretaceous and Paleocene age which occurs on the inner shelf between the Cape Fear River entrance and the South Carolina Border.

Data obtained in the Long Bay section consist of 482 trackline kilometers (260 n. mi) of seismic reflection profiles obtained with a 50 to 200 joule sparker source and 43 sediment cores having a diameter of 10.2 cm (4 in.) and lengths ranging from 0.75 to 6.1 m (2.5 to 20 ft). These cores were obtained with a pneumatic vibrator-hammer coring assembly.

### Setting

Long Bay is a relatively shallow bight in the Carolina coast extending from Cape Fear, North Carolina to Cape Romain, South Carolina (Fig. 1). The North Carolina portion of the bay overlies a major positive feature in the basement rocks known as the Cape Fear Arch or Carolina Ridge, which trends northwest - southeast beaneath the coastal plain and adjacent continental shelf (Hersey et al., 1959; Murray, 1961; Brown, Miller, and Swain, 1972).

Stratigraphy of the Cretaceous, Tertiary and Pleistocene deposits underlying the North Carolina coastal plain region adjacent to Long Bay have been described from outcrop and core-hole samples by numerous workers. Much of the older data have been summarized in Brown, Miller and Swain (1972). More recent studies containing significant stratigraphic findings have been presented in abstracts by Baum, Harris and
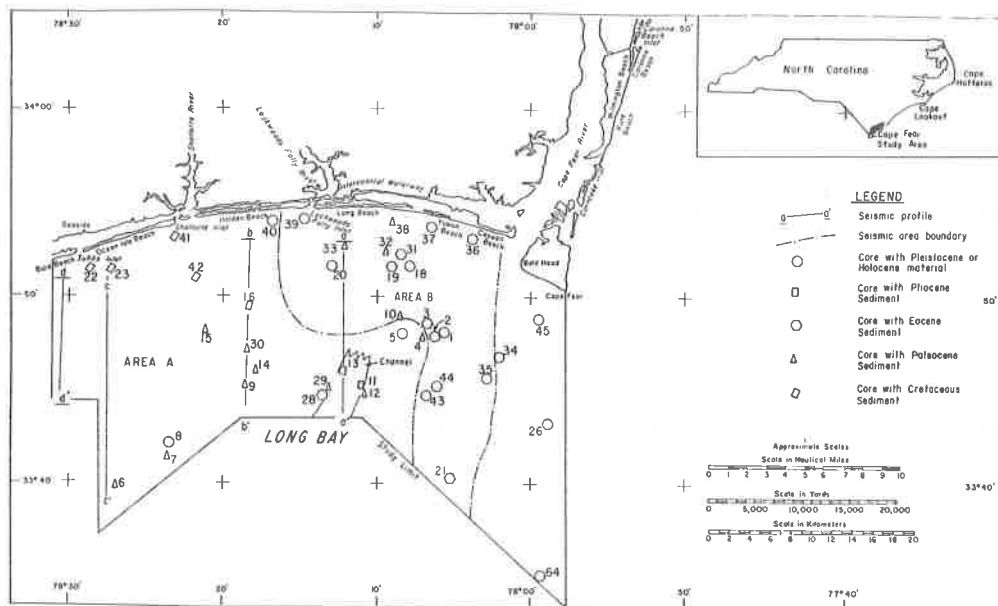
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*Figure 1. Map of eastern Long Bay showing profile and core locations and the age of the oldest sediments recovered by each core.*

Zullo, 1978; Harris, Baum, Wheeler, and Textoris, 1977; Meisburger 1977b; and Zullo and Harris, 1978; in theses by Baum, 1977; Harris, 1975; and Upchurch, 1973; and in scientific publications by Baum, Harris, and Zullo, 1978; Harris, 1976, 1978; Harris and Baum, 1977; Harris and Bottino, 1974; Lawrence, 1975, Wheeler and Curran, 1974. The marine geology of Long Bay has been described in a thesis by Pratt, 1970.

## SEISMIC REFLECTION CHARACTERISTICS

The sixteen seismic reflection profiles available for Long Bay show two principal patterns of reflectors (see Fig. 2 for selected profiles). In the area off the Cape Fear River entrance (Area B, Fig. 1) there was little sub-bottom penetration beyond a strong reflector that in most places lies close to the shelf floor and crops out locally (Profile a-a', Fig. 2).

Area A (Fig. 1) lying to the west of Area B is underlain by a reflection unit that exceeds 30 m (98 ft) thickness and that contains a series of southward dipping reflectors. The top of this unit, here called Unit 1, appears to be truncated by an erosion surface that lies very close to the inner shelf floor and frequently crops out (Profiles b-b', c-c' and d-d', Fig. 2).

The base of Unit 1 is generally beyond penetration range of the seismic system but can be distinguished close inshore (Profile b-b', Fig. 2). The pattern of dipping reflectors in Unit 1 suggests that they arise from a series of forset beds that prograde southward from some source inland of the present shoreline.

An additional feature of some prominence is a large filled stream channel (Fig. 1) which trends south from the southern edge of Area A and presumably extends northward beneath the acoustically impenetrable layer in that area.

## SEDIMENT CHARACTERISTICS

The oldest sediments encountered in the Long Bay area cores are of Late Cretaceous age and come from the inshore part of Unit 1 within 10 kilometers (6.2 mi) of the shore. Cores which penetrated to a maximum of 4.6 m (15 ft.) into the unit indicate that the upper part of the deposit is mostly composed of silty fine sand, that

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is dark grayish brown (10 YR 4/2 Munsell Code) in color. Grain counts of washed residues show 1 to 5 percent of the grains are glauconite and phosphorite and up to 20 percent are well preserved Foraminifera. There are lesser amounts of echinoid fragments, ostracods and small pieces of mollusk shell.

The foraminiferal fauna in most samples is about 95 percent benthonic, 5 percent planktonic. The most common benthonic species are *Anomalinoides carolinensis* Curran and *Cibicides harperi* Sandidge, which together consist of up to 50 percent of the specimens. Other common benthonic species are *Anomalinoides pseudopapillosa* (Carsey), *Cibicides coonensis* (Berry) *Dorothia bulletta* (Carsey) *Gaudryina bulloides* Olsson, *G. rudita* Sandidge, *Guembelitria cretacea* Cushman, *Gyroidinoides imitata* and *Tappanina selmaensis* (Cushman). The most common planktonic species are *Globotruncana sp., Heterohelix carinata* (Cushman),*H. globulosa* (Ehrenberg), *H. striata* (Ehrenberg), *Rugoglobigerina macrocephala* Bronnimann and *R. rugosa* (Plummer).

Sediments recovered from the seaward part of Unit 1 in cores 6, 7, 10, 12, 15, 29 and 30 (Fig. 1) consist of fine to very fine quartz sand similar in size and general appearance to the Upper Cretaceous deposits nearer shore. However, there is substantial difference in assessory minerals; little or no glauconite and phosphorite occur in the deposit, ostracods, echinoids and mollusk fragments are rare, and Foraminifera make up less than 3 percent of the grains.

The foraminiferal fauna of these deposits indicate an early Paleocene age. The fauna contains more than 95 percent benthonic species dominated by *Anomalinoides* newmanae Cushman, *Cibicides cf C. howelli* Toulmin and *Gyroidinoides octocamerate* (Cushman and Hanna) which collectively make up about 70 percent of the specimens. Other common benthonic species are: *Alabamina wilcoxensis* Toulmin, *Eponides pygmeus* Page, *Lenticulina midwayensis* (Plummer) *Pseudouvigerina triangularis* Jennings, *Siphogenerina eleganta* (Plummer) and *Spiroplectaminia cf S. plummerae* Cushman. The most common planktonic species are: *Globoconusa daubjergensis* (Bronnimann), *Planorotalites compressa* (Plummer) and *Subbotina pseudobulloides* (Plummer).

Six other cores (4, 9, 14, 32, 33, 38) from both areas A and B also contain Paleocene age sediments but unlike the fine Paleocene sand discussed above, this material consists of fine to coarse glauconitic sand (cores 9, 14) and sandy limestone (14, 32, 33, 38) containing sparse to abundant glauconite and phosphorite. Of this group only core 14 contains a sufficiently abundant and well preserved foraminiferal fauna to characterize the assemblage. The relatively sparse and poorly preserved Foraminifera in the other cores, or lithologic similarities, suggest correlation wth the core 14 material.

In core 14 benthonic species comprise over 95 percent of the foraminiferal fauna. The dominant species are *Anomalinoides umboniferous* (Schwager) and *Gyroidinoides octocamerata* (Cushman and Hanna) together comprising 60 percent of the specimens. Other common species are *Cibicides cf C. howelli* Toulmin, *Dentalina basiplanata* Cushman, *Fursenkoina cf F. wilcoxensis* (Cushman and Ponton) *Lenticulina midwayensis* (Plummer) and *Pseudouvigerina triangularis* Jennings. The only common planktonic species is *Subbotina pseudobulloides* (Plummer).

## DISCUSSION

The proximity of mapped outcrops of the Peedee Formation to the shoreline of Long Bay and similar elevations suggest continuity between Unit 1 and the Peedee Formation. Faunal and lithologic characteristics are also consistent with this interpretation. None of the cores in Unit 1 recovered rocks resembling the Rocky Point Member which forms the uppermost part of the formation in places (Wheeler and Curran, 1974; Harris, 1978).

The differences between the lithology and fauna of the two groups of Paleocene sediments recovered in Long Bay suggest that they were deposited under different environmental conditions and probably at different times. It seems unlikely therefore that the deposits sampled by cores 4, 9, 14, 32, 33 and 38 are part of the forset series of Unit 1. Only three of these cores (9, 14 and 15) are from the area where Unit 1 is visible on the seismic reflection profiles. In all three cases the seismic records
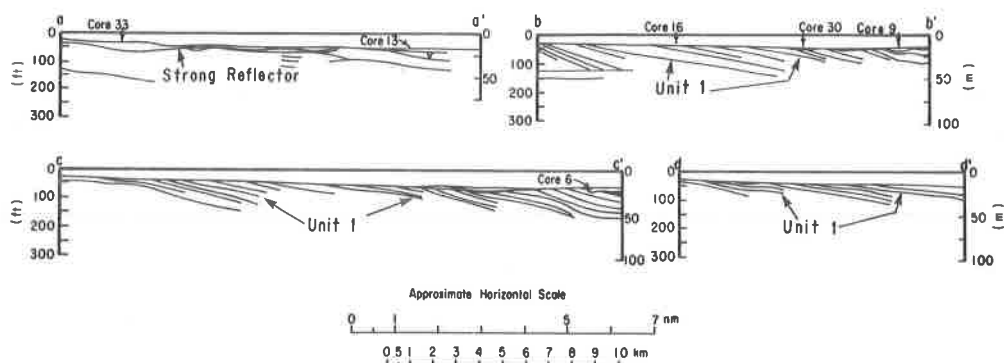
Figure 2. *Line profiles reduced from seismic reflection records showing the reflector patterns in eastern Long Bay. See Figure 1 for profile locations.*

indicate that these cores probably bottomed in deposits overlying Unit 1, though resolution is not good enough to be certain of this. The seismic reflection profiles and available cores indicate that the surface of Unit 1 is covered by a thin and discontinuous overburden which can be penetrated in most places by standard vibratory coring devices having a core tube length of 3 meters or more. The upper part of the Cretaceous and Paleocene deposits in Unit 1 could therefore be sampled in detail at a relatively modest cost. The accessibility of these deposits, their range in age and the good preservation of included faunal remains suggests that further detailed exploration might yield valuable stratgraphic information.

## ACKNOWLEDGEMENTS

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# ALTERED ROCKS IN A FAULT ZONE

## NEAR PAGELAND, SOUTH CAROLINA

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## ABSTRACT

A study of the mineralogy, petrography, and chemical composition of a series of samples taken across a conspicuous fault zone near Pageland, S.C., shows that the rocks, which are part of the Carolina slate belt, have been subjected to hydrothermal and weathering alteration as well as greenschist-facies metamorphism. Five visually distinctive alteration zones which have subtle mineralogical and chemical differences have been characterized. Meta-argillite in the hanging wall above a meta-lithic lapillistone has lost chlorite and mixed-layer clay of chlorite-brucite and the elements Fe, K, Mn, Ba, Cr, and Cu when compared with meta-argillite country rock 0.8 km to the northwest. The fault zone has gained silica, coarse-grained muscovite, and sulfide minerals from hydrothermal processes. The quartz-muscovite-kaolinite mineral assemblage in the altered area at the roadcut resembles gold-bearing rocks at the nearby Haile mine, although no gold was found in the fault zone. The fault zone shows features characteristic of hydrothermal activity elsewhere in the southeastern Piedmont.

## INTRODUCTION

A series of bleached and colorfully stained rocks bordering a silicified breccia in a fault zone is conspicuous along State Route 207 1.85 km northwest from the center of Pageland, South Carolina. The Universal Transverse Mercator coordinates are 3,848,800 N; 554,180 E. These altered rocks are very different from the saprolite of the surrounding metamorphic rocks in the Carolina slate belt indicating that some local alteration process such as hydrothermal leaching, in addition to deep weathering and low-grade metamorphism, must have been operative there.

In order to recognize and differentiate the products of superimposed alteration processes, we studied surface samples collected mostly from the roadcut where the rocks are well exposed. We anticipated that the results would contribute to our understanding of the same processes in similar-appearing rocks at the nearby and formerly very productive Haile mine where, in addition to faulting and alteration, gold-bearing rocks and massive sulfide deposits complicate the geologic setting.

We thank Leung Mei and Anthony Dorrzapf for the spectrochemical analyses, Roosevelt Moore for the gold analyses, Robert D. Perantoni for the dry-density measurements, and James R. Estabrook, Patricia J. Loferski, and Dwight E. Wallace for specimen preparation assistance in the laboratory.

## GEOLOGICAL SETTING

The Pageland fault is a northeast-trending normal fault cutting Carolina slate-belt rocks in northeastern South Carolina (Figure 1). The fault extends to the southern and eastern boundaries of the Upper Triassic and Lower Jurassic(?) Wadesboro basin in
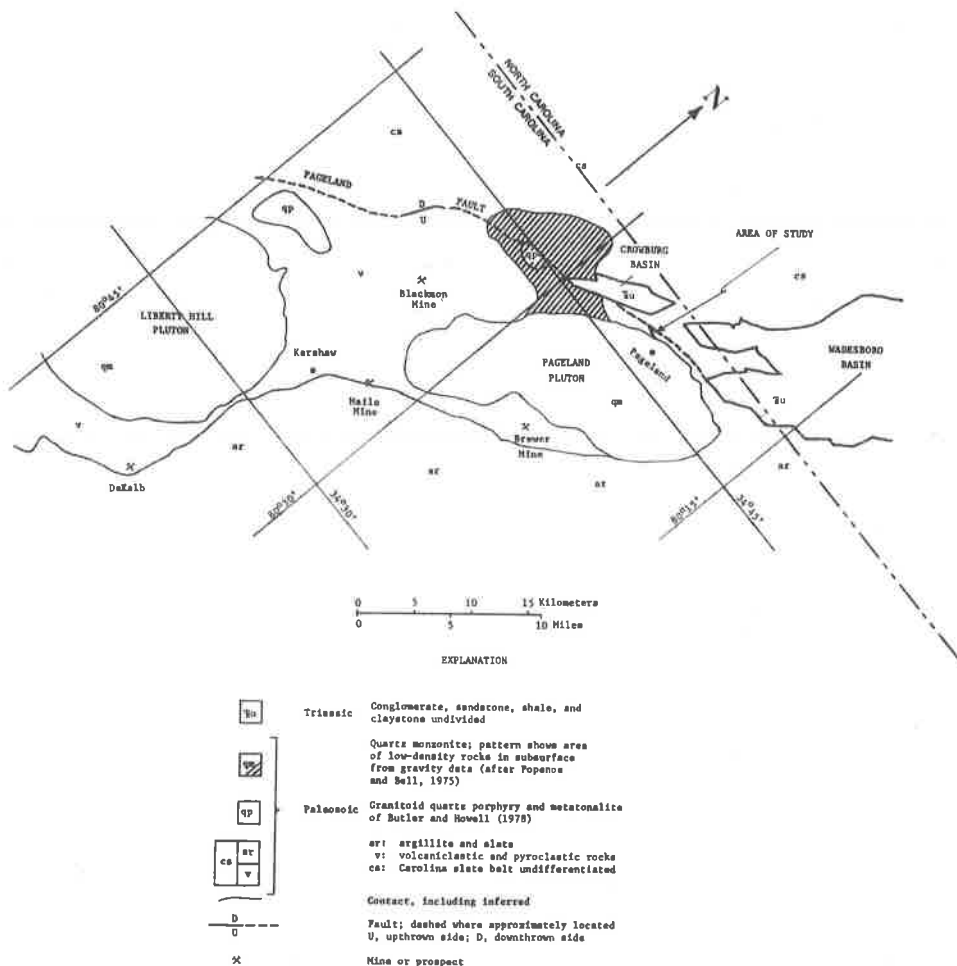
*Figure 1.* Geological map of the region along the Pageland fault. Compiled and simplified from Bell and others (1974), Butler and Howell (1976), Randazzo and others (1970), and Bell (unpub. data).

southern North Carolina (Bell and others, 1974). It bounds part of the Crowburg basin, containing similar rocks, in South Carolina, and extends southwest through the Taxahaw quadrangle, Lancaster County, S.C. where at least several hundred meters of dip-slip movement are inferred (Butler and Howell, 1978). The fault is near the north and northwest contact of slate-belt rocks with a quartz monzonite pluton informally called the Pageland pluton. Gravity data (Popenoe and Bell, 1975) indicates that part of an amoeboid-shaped Bouguer anomaly associated with the Pageland pluton extends northwest from the outcrop area of the quartz monzonite and underlies an area near Taxahaw through which the Pageland fault extends. The northwest lobe of this gravity anomaly seems to be due to a steep-sided mass of low-density rock which Bell and Popenoe (1976) thought did not crop out but which may be related to a small body of much altered metatonalite apparently cut by the Pageland fault (Butler and Howell, 1978). The metatonalite is related by Butler and Howell (1976) to felsic volcanic rocks in the adjacent volcanic units of the Carolina slate belt because it is of similar composition.

Although the fault displaces Upper Triassic and Lower Jurassic(?) rocks in the Wadesboro and Crowburg basins and is at least partly younger than these rocks, it is cut by younger diabase dikes apparently without off-set or brecciation. Movement on the Pageland fault earlier than the Triassic or Jurassic Periods is indicated by the silicified breccia, silicified rock, and abundant quartz veins in the area between the

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Wadesboro and Crowburg basins where the fault cuts argillites and metavolcanic rocks of the slate belt.

In contrast, no such associated silicified rocks or quartz veins have been recognized where the fault cuts Mesozoic rocks. Butler and Howell (1976, p. 141-141) suggest that, "the most logical time for such extensive mobility of silica is during either volcanism or metamorphism."

The metavolcanic rocks in this part of the Carolina slate belt have yielded isotopic ages by rubidium-strontium methods that, in spite of scattered data, define an isochron of 522 ± 24 m.y. indicating that the rocks are Late Cambrian or Early Ordovician (Butler and Fullagar, 1975; Black, 1978). The volcanism and metamorphism also occurred before emplacement of the Pageland pluton which has not been metamorphosed and which is about 296 m.y. old on the basis of Rb-Sr isotopic data reported by Fullagar and Butler (1979).

It is possible that alteration on the Pageland fault occurred at approximately the same time as mineralization at the Brewer mine where intensely silicified and hydrothermally altered rocks are gold-bearing.

Muscovite samples from auriferous rocks representing hydrothermal alteration at the Brewer mine have been dated by the potassium-argon method. The apparent ages average about 415 m.y. (Bell and others, 1972) and were thought to relate the mineralization to early Paleozoic volcanic events, rather than to the Pageland pluton.

Gold-bearing rocks have been prospected or mined at numerous localities in the vicinity of the Pageland fault most notably at the Haile mine and Brewer mine. Except for those two mines, gold mostly occurs in thin quartz veins. In parts of Fairfield Co., S.C., the presence of thin gold-bearing quartz veins and veinlets has been suggested as a criterion for hydrothermal alteration in areas where extensive quartz-sericite schists might other wise be a residium from deep and prolonged weathering of a metamorphic terrain (Bell, 1976).


## ROCK UNITS

Figure 2 shows a cross section and a surface projection of the fault zone made by plane table and alidade. A nearly vertical fault in this zone is probably represented by the centrally located breccia area. Meta-argillite is in the hanging wall above a coarser grained meta-volcaniclastic unit. The division of the rocks into five zones of alteration, A to E in Figure 2, was made in the field on the bases of rock types and color variations caused by alteration processes. This division was later confirmed by petrographic examination.

The meta-argillite hanging wall represented by alteration zones A, B, and C is in sharp contact with the metamorphosed lithic lapillistone footwall unit represented by alteration zones D and E (Figure 2). The contacts between the alteration zones are gradational into one another. Brecciated and silicified rocks are found throughout in varied amounts, but are most prominent in a 30 m-wide zone in the lapillistone unit. The higher topography near the contact of zones D and E is a reflection of this increased silica concentration. Bedding was found only in the meta-argillite of zone A. There the strike, perhaps as a result of the faulting, is north and the dip is from 13° to 30° west. Surface exposures are very poor in the area. At the southeast end of the roadcut there is another contact of lapillistone with meta-argillite but because the outcrop is so small and obscure the significance of the contact is unknown.


## META-ARGILLITE

Alteration zones A, B, and C are in the meta-argillite hanging wall of the fault zone. Outside the fault zone, 0.8 km northwest of the roadcut, the meta-argillite ranges from pale olive to dark yellowish brown and is drab in comparison to rocks of the fault zone. Rhythmic laminations consist of 1-4 mm-thick layers of fine grains alternating with layers of coarse silt-size grains in a very fine-grained matrix. Microscopically, schistosity can be seen to cut bedding. The mineralogical composition, which conforms to the definition of Flawn (1953) for meta-argillite, is, in decreasing

Alteration zones in meta-argillite unit
Query where unit and zone identification
is questionable

Alteration zones in lapillistone unit

Area of intense brecciation and silicification

Quartz vein

Individual fault; dashed where approximately
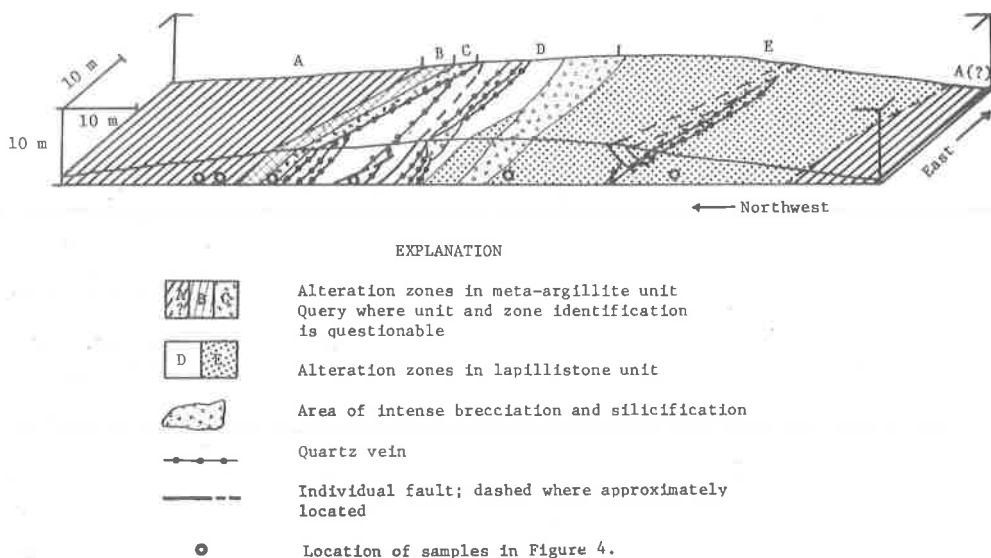located

Location of samples in Figure 4.

*Figure 2. Isometric diagram of the fault zone near Pageland, South Carolina, showing alteration zones described in the text and in Figure 4. (Plan view constructed from projections of attitudes measured on the outcrop face.) Surficial deposits not shown.*

abundance: quartz, chlorite and mixed-layer chlorite-brucite, muscovite, kaolinite, and hematite surrounded by goethite.

At the roadcut zone A, the least altered meta-argillite, is about 25 m wide. The rock is pale to dark yellowish orange and pale yellowish brown and contains Liesegang bands of iron oxides and black veinlets of lithiophorite [Al, Li) $MnO_2(OH)_2$]. The bedding laminations and sparse, concordant, very thin quartz veinlets have been folded together on a small scale. Schistosity intersects these structures at a high angle. In places, there is a 1-3 cm meta-argillite breccia produced by faulting. The mineralogical composition is in decreasing abundance: quartz, kaolinite, muscovite, goethite, hematite, lithiophorite, and a trace of chlorite and mixed-layer chlorite-brucite.

Zone B is a 2 m-wide zone of moderately altered meta-argillite. It is reddish orange mottled with white clay and grayish orange, 2-3 mm meta-argillite breccia fragments. The micaceous fabric is contorted and there are many quartz veinlets. The mineralogical compositon is the same as that in zone A.

In zone C, 1 m wide, the meta-argillite appears most altered. The rock is a pale, red-purple, fault breccia containing 1 cm sized clasts. Hematite stains and Liesegang bands are conspicuous features. The mineralogical composition is the same as zones A and B except that chlorite and mixed layer chlorite-brucite are missing.

## LITHIC LAPILLISTONE

Metamorphosed lithic lapillistone, following the terminology of Fisher (1961), seems the most appropriate name for the rock unit in alteration zones D and E. The rock appears to be pyroclastic admixed with clastic material of nonvolcanic origin.

The lapillistone has a massive texture and is mostly composed of medium sand-sized angular clasts of quartz and of what were originally lithic fragments, now replaced by quartz, mica, and kaolinite. The matrix of the rock is a very fine-grained mixture of kaolinite and mica. Angular blocks of argillite and lapillistone representing fault breccia are also present. There is an irregular metamorphic fabric of the mica crystals which average 25 µm, in length. Some clasts are completely replaced by clusters of larger, 75 µm, mica crystals. The mineralogical composition of the D and E zones is in decreasing order: quartz, kaolinite, muscovite, goethite, and hematite.
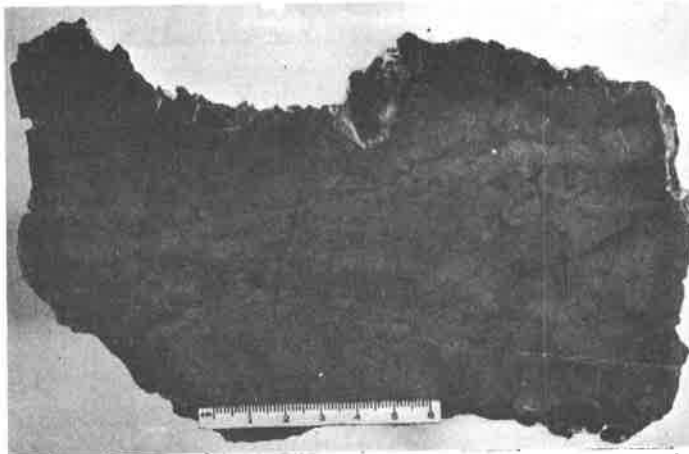
*Figure 3. Photograph of a slab taken from the central breccia zone showing complete silica replacement of breecia and minor quartz veining. Weathering has removed the matrix around silicified angular clasts of meta-argillite at top of slab.*

Zone D, which is 23 m wide, is mottled grayish yellow and white and zone E, which is 50 m wide, is white to very light gray with minor grayish orange mottling. The color difference reflects the greater iron staining in zone D. Also, in zone D traces of pyrite pseudomorphs are retained.

Silicification in the fault zone was most intense in a 4 m-wide brecciated area in zone D; smaller areas of intense silicification were found elsewhere in zones D and E. The intense silicification nearly completely replaced the brecciated lapillistone and minor argillite clasts with dull gray quartz (Figure 3). This type of brecciated and silicified rock was observed by Butler and Howell (1976) in the fault zone 25 km to the southeast. Also late-stage veinlets of clear quartz locally show coxcomb and vuggy structures. Weathered-out pyrite pseudomorphs are common in the silicified breccia. The meta-argillite clasts have extremely sharp, straight boundaries indicating that this material was indurated and perhaps silicified before fracturing and a later silicification. Some clasts of the lapillistone contain mica which has resisted silica replacement.

## SAMPLES AND METHODS OF STUDY

Twenty-one representative grab samples of rock and quartz veins were taken from the roadcut. For comparison, an additional sample of the meta-argillite country rock from 0.8 km northwest of the roadcut was also collected. Thin sections for study by petrographic microscope were made of most of these samples; all were friable and had to be impregnated before thin sectioning. To supplement thin-section study, x-ray diffraction analyses were made of randomly mounted whole-rock powders for mineral identification and qualitative estimation of mineral proportions. Clay-mineral identification by x-ray diffraction was done on oriented mounts of the less than 2 μm-size fraction, supplemented by standard clay sample treatments of glycolation, potassium (K) saturation, and 550°C heating.

The densities of 13 samples were measured after coating them with a plastic film following air drying.

Eight large samples, about 390 cubic inches each, were collected, and the contained minerals, mostly heavier than quartz and coarser than clay, were concentrated by means of a 16-inch gold pan. These concentrates were further refined, using bromoform and a Frantz magnetic separator, before they were examined microscopically.

Eight other samples were split and analyzed for gold by colorimetry and analyzed for 63 elements by emission spectrography.

ALTERATION ZONES

A — B C — D — E

Fe%
K%
Mn%
B ppm
Ba ppm
Cr ppm
Cu ppm
Rock Density

0   10   20   30 Meters
0        50        100 Feet
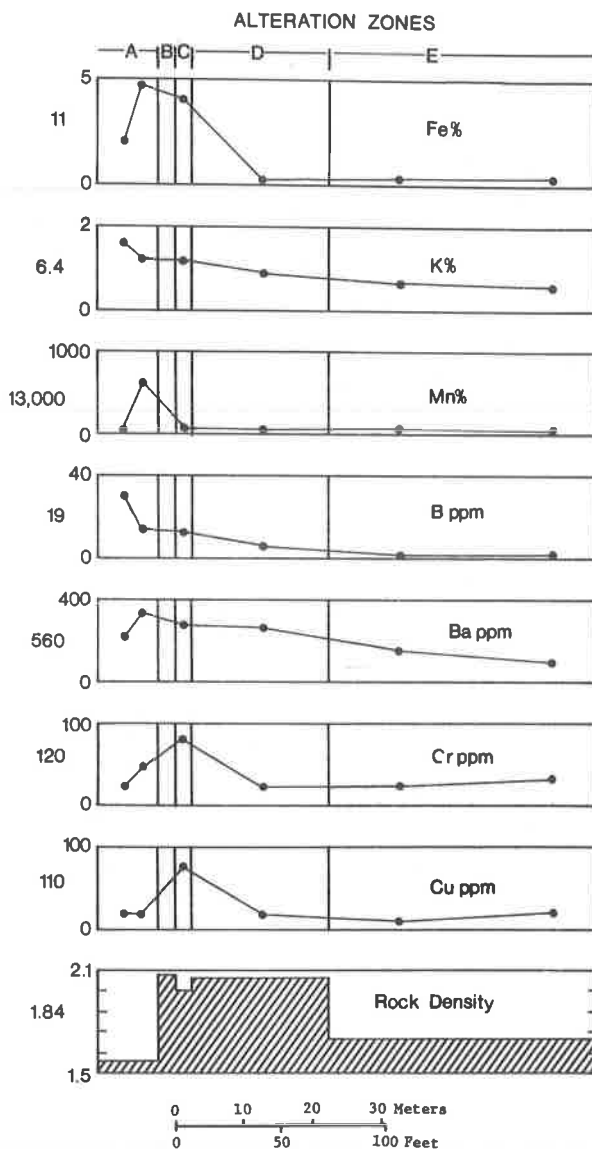
*Figure 4. Selected minor and trace element concentrations and rock densities for the alteration zones shown in Figure 2. Numerical values to the left of the plots refer to the corresponding concentration (or rock density) of the meta-argillite country rock.*

## RESULTS

Thin-section study of the soft and friable samples from the Pageland fault zone and nearby meta-argillite indicate that rock structure and mineral textures are preserved. According to the definition of Becker (1895, p. 289-291) saprolite is "...a general name for thoroughly decomposed, earthy, but untransported rock. When the exact character of the original rock is known, it is easy to qualify this term and to speak of 'granitic saprolite,' and the like." The rocks in the Pageland fault zone, therefore, are hydrothermally altered fault-zone saprolite according to this definition.

Kaolinite and muscovite observed in thin section and identified by x-ray diffraction have sharp, symmetrical x-ray diffraction peaks showing that they are well crystallized. Kaolinite can form in both hydrothermal and weathering environments,

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which only isotopic study could distinguish. The muscovite, however, is the $2M_1$ polytype which is thought to be a high-temperature polytype by Yoder and Eugster (1955). Therefore, mica in these samples does not have a weathering origin. The mica with schistose fabric is ascribed to regional metamorphism whereas the larger mica clusters, found only in zones D and E, appear to have formed by hydrothermal means.

Chlorite is abundant in the meta-argillite country rock but occurs rarely in zones A and B and is absent in zone C. The chlorite was probably of metamorphic origin but has been modified or destroyed by weathering and possibly by acid hydrothermal alteration near the center of the fault zone. The 14A clay mineral was determined to be chlorite rather than vermiculite because K saturation did not decrease the basal spacing. Approximately equal peak heights for the first three basal x-ray diffraction peaks show the chlorite to be magnesium-rich rather than iron-rich. The main 14A chlorite peak is sharp but it is asymmetric toward higher d-spacings and there are small peaks at 28A and 32A. These characteristics are due to a regularly interstratified mixed-layer clay of chlorite and brucite which probably formed during weathering. Heating the samples containing chlorite to $550^{\circ}C$ caused the loss of the 7A and 3.5A peaks and replacement of the 14A peak with a broad one at 12A; this is typical of chlorites in soil (Thorez, 1976).

Feldspar was not detected by petrographic or by x-ray diffraction means in either the country rock or rocks in the alteration zones. Very low values for Na and Ca by emission spectrographic analysis support this observation. This contrasts with the results of Butler and Daniel (1964) who found albite persisting in similar greenschist facies rocks of the slate belt in Albemarle County, N.C.

No zeolites were found although these minerals are widespread in the Piedmont of the Carolinas (Butler, 1977). The absence of zeolites is consistent with an acid environment rather than a basic environment required for zeolites (Meyer and Hemley, 1967).

The bulk densities of all the samples from the Pageland fault zone and the nearby meta-argillite were measured and the average for each of the units is shown on Figure 4. The densities recorded are low compared with the range of 2.38-2.99 (Bell and Popenoe, 1976, p. 676-677, table 1) for similar rocks in South Carolina which have not been exposed to subaerial weathering. Figure 4 shows relatively higher densities in zones B, C, and D reflecting veins of quartz introduced at the contact of the hanging wall and the foot wall of the fault zone. A bulk density of 2.48 measured for a sample of the silicified breccia is 94 percent of the ideal density of quartz and results from extensive silica replacement. Hematite casts pseudomorphous after sulfide crystals in quartz veins indicate that there is hydrothermal introduction of sulfides as well in this central area.

A weathering or hydrothermal origin is possible for lithiophorite (Fleisher and Faust, 1963; Hewett and others, 1968), goethite, and hematite. These minerals appear in the Pageland fault zone as crusts, diffusion bands, and as sulfide replacements rather than as continuous veins, strongly suggesting a weathering origin. The lithiophorite contains only 0.3 percent lithium, an amount comparable with that found for the same mineral from Charlottesville, Va., by Mitchell and Meintzer (1967). The lithiophorite scavenges heavy metals. A sample from zone A contained 1 ppm silver, 510 ppm lead and several thousand ppm copper, zinc, nickel, and cobalt. However, the total amount of lithiophorite is exceedingly small.

Heavy minerals are sparse in the country rock and alteration zones. Samples from zone A contained 0.13 weight percent minerals that were heavy and coarse enough to be concentrated in a gold pan, including a relatively large quantity of lithiophorite. The other zones and the country rock had very much lower concentrations of these minerals. Table 1 lists the minerals identified in concentrates made from rocks in zones A to E and from the meta-argillite country rock. Lithiophorite, hematite, and goethite are products of recrystallization after local chemical migration. Pyrite and pyrophyllite appear authigenic; the remaining minerals are rounded or subrounded and presumably are original detrital constituents of the rocks.

Emission spectrographic analysis of a sample from alteration zone D shows that alkali and alkaline earth oxides are very low and approach the limits of detection by the method. The major elements recalculated as oxides from the spectrographic results are shown in Table 2. Using this analysis and the results of x-ray mineral

Table 1. *Minerals identified in concentrates made from altered rocks in the Pageland fault zone using a gold-pan.*

[An x indicates the mineral is present whereas an X indicates the mineral is especially abundant in the concentrate.]

| | Meta-argillite country rock | A | B | C | D | E |
|---|---|---|---|---|---|---|
| Lithiophorite | | X | | | | |
| Hematite | | | x | X | | |
| Goethite | X | x | | x | x | X |
| Anatase | x | | x | x | X | |
| Magnetite | x | x | x | | x | x |
| Zircon | x | | x | X | x | x |
| Epidote | x | | x | | x | x |
| Tourmaline | x | | x | | | x |
| Pyrophyllite | | | x | X | x | |
| Garnet | | | | | x | x |
| Leucoxene | | | | x | | |
| Kyanite | | | x | X | | |
| Staurolite | | | x | | | |
| Rutile | x | | | | | |
| Gahnite | x | | | | | |
| Chrysoberyl | x | | | | | |
| Pyrite | x | | | | | |

Table 2. *Major oxides of rock from Pageland fault, alteration zone D, calculated from emission spectrographic analysis.*

[Analyst: L. Mei]

| | |
|---|---|
| $SiO_2$ | 73 |
| $Al_2O_3$ | 13 |
| $Fe_2O_3$ | .73 |
| $MgO$ | .25 |
| $CaO$ | .031 |
| $Na_2O$ | .085 |
| $K_2O$ | 1.1 |
| $TiO_2$ | .37 |
| $P_2O_5$ | < .17 |
| $MnO$ | .0061 |

identifications, calculations show that approximately 23 percent kaolin, 10 percent muscovite, and possibly 1 percent chlorite may be present in the sample, with about 65 percent quartz.

Emission spectrographic analyses of samples from the alteration zones and the meta-argillite country rock showed no unusually high concentrations of trace elements (those measured in ppm). The five trace elements which showed systematic variation--Mn, B, Ba, Cr, and Cu as well as Fe--are plotted on Figure 4. The trends for Fe, Mn, Ba, Cr, and Cu show a slight enrichment within the fault zone near the contact of meta-argillite and the brecciated pyroclastic unit. However, there is a lower concentration of these elements plus K within the fault zone as compared with the meta-argillite country rock. The trends in Figure 4 yield patterns which resemble those expected from secondary dispersion of ore metals by supergene leaching and redistribution along a permeable fault zone.

Gold was not found by colorimetric analysis in six samples from the alteration zones or in the sample from nearby country rock above a lower detection limit of 0.3 ppm nor was it found in quartz veins in the silicified breccia zone above a detection limit of 0.05 ppm. No gold was visible in the heavy-mineral concentrates. Possibly gold was introduced hydrothermally but then removed from the permeable fault zone by prolonged weathering. Kinkel and Lesure (1968) found evidence for gold migration

by supergene processes in the Carolina slate belt. Gold could have been locally solubilized as Au Cl$\bar{4}$, an ion which forms in the presence of MnO$_2$ and moderate concentrations of chloride and hydrogen ions (Krauskopf, 1967). Humic acid from soils has also been shown capable of complexing and transporting gold under fairly normal Eh and pH conditions (Baker, 1978).

## CONCLUSIONS

The metamorphosed rocks in the Pageland fault zone have been altered into a series of colorful zones by a combination of weathering and hydrothermal processes. Silica and some sulfides have been introduced, as indicated by quartz veins and sulfide crystals. These veins, together with the extensive silica replacement of breccia, the large mica clusters in parts of the fault zone, the widespread 2M$_1$ polytype muscovite and the loss of chlorite, indicate the effects of acid hydrothermal activity in the fault zone.

The hydrothermal activity introduced some material but the fault zone is primarily the site of mineralogical and chemical loss. The locally preserved schistose texture and chlorite is evidence for greenschist facies metamorphism. Albite is stable under such metamorphism so its loss in the Pageland fault zone and nearby meta-argillite country rock can be attributed to very thorough surficial weathering or to acid hydrothermal alteration that perhaps took place before metamorphism. This latter sequence of events has been suggested to explain the origin of high aluminum-bearing deposits containing kyanite and pyrophyllite in similar rocks of the slate belt in North Carolina (Espenshade and Potter, 1960, Sykes and Moody, 1978).

Although the formation or modification of certain minerals can be identified with a particular geologic process, the distinction between weathering and hydrothermal alteration in the Pageland fault zone is equivocal. The proper proportion of the two processes is not clear. The bright colors of the alteration zones, the Liesegang banding of iron oxides, the clots of hematite surrounded by goethite, the veinlets of lithiophorite, and soil-formed chlorite are all evidence that weathering processes and recrystallization after local chemical migration have been active.

Nevertheless, the rocks in the Pageland fault zone show features similar to some commonly attributed to hydrothermal activity elsewhere in the Carolina Piedmont and discussed recently by Sykes and Moody (1978), Kesler (1972), Spence and others (1978), and Bell (1976). Hot springs, fumerolic and solfataric activity have been called upon by these authors as originating phenomena for the hydrothermal process for areas of different alteration intensities and areal extents. The alteration of the Pageland fault zone may have resulted from similar phenomena which acted over a short time in a restricted area.

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# PROBLEMS WITH THE EOCENE STRATIGRAPHY IN PANOLA COUNTY,

## NORTHERN MISSISSIPPI

By

E. H. Grissinger, J. B. Murphey, and W. C. Little

## ABSTRACT

Eighty-five exploratory holes were drilled and logged in Hotophia, Johnson, Goodwin, and Long Creek watersheds, Panola County, northern Mississippi. All but four of these holes were cased to minimize sample contamination. Continuous undisturbed 1.5- or 3-inch diameter samples were obtained except for several of the deeper holes which were skip drilled. A total of 6173 feet of material was sampled. The maximum sampling depth was 211 feet. Units lithologically equivalent with the Citronelle, Tallahatta, Zilpha, Winona, and Kosciusko formations were observed. The relative position and distribution of these units, however, is incongruent with their present stratigraphic classification. Coarse to fine alluvium overlies a paleosurface developed on the Zilpha-Winona materials. This paleosurface, which controls groundwater, is not congruent with surface watershed configurations. As an alternative to the present stratigraphic classification, we suggest that these surficial units, superjacent to the paleosurface, are terrestrial post-Eocene units deposited in response to sea-level elevation changes.

## INTRODUCTION

The U.S. Department of Agriculture Sedimentation Laboratory is presently involved in a comprehensive stream channel stability study. The design of this study is based on the premise that the channel network is one element of the total watershed and must be studied as a part of the watershed system. The study has been implemented to evaluate both within-channel stability relations and watershed conditions that influence sediment and water delivery to the channels. The system has three dimensions, the length and width defined as the surface topography and the depth defined as that necessary for evaluating the subsurface hydrologic controls that are pertinent to this study. As one part of our comprehensive study, we have investigated the lithology of near-surface units in four study watersheds in Panola County, Mississippi. In this initial report, we have described the distribution of the lithologic units and discussed (a) the agreement of our findings with the generalized section of stratigraphic units for Panola County, and (b) the significance of these lithologic units with respect to ground-water conditions.

## GEOLOGIC SETTING

The study area includes four watersheds in the southeast quarter of Panola County, northern Mississippi. This area is within the Coastal Plain Physiographic Province, with the western two-thirds in the Loess or Bluff Hills Subprovince and the eastern one-third in the North Central Hills Subprovince. Loess caps all interfluves but thins rapidly from west to east and Holocene alluvial deposits are present in all valleys. Drainage is westerly to the Mississippi alluvial valley via the Tallahatchie River for Hotophia Creek and via the Yocona River for Johnson, Goodwin, and Long Creeks (Figure 1).

The generalized section of stratigraphic units for Panola County is summarized in Table 1 (Vestal, 1956). This generalized section agrees with those of surrounding counties. The Meridian formation (basal Claiborne) and the Ackerman formation (upper Wilcox) were both included in the sections for Lafayette (Attaya, 1951) and Yalobusha (Turner, 1952) Counties, east and southeast of Panola County, respectively. However,
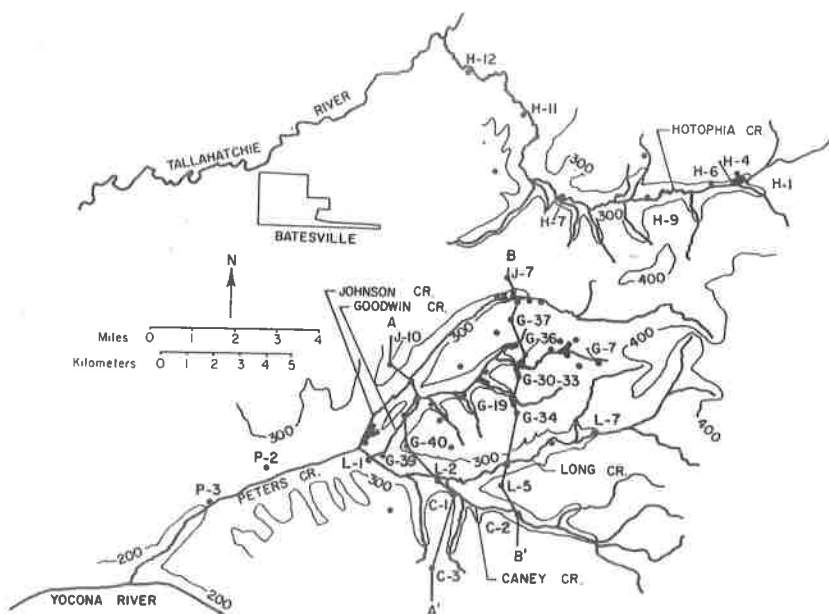
Figure 1. Location of exploratory holes in study area, Panola County, Mississippi.

Brown (1947) and Lang and Boswell (1960) considered the Meridian to be a member of the Tallahatta formation. Additionally, Priddy (1942) divided both the Zilpha and Winona formations into upper and lower divisions. The age of the Citronelle formation is the source of some disagreement in that Fisk (1944) and Kolb et al. (1968) both identified the gravel units as basal terrace deposits of Pleistocene age whereas a Pliocene age was accepted by Vestal (1956).

Field identification of individual formations in northern Mississippi has been a major problem due to (a) the loess veneer, (b) the absence of diagnostic marker beds, and (c) the similar nature of the numerous sand exposures which either directly underlie the loess cap or are exposed at the surface. These sand units are presently mapped as Eocene formations but were originally considered by Hilgard (1860) to be Quaternary in age. He named these materials the Orange Sand formation. Logan (1907) renamed these sands Lafayette and included surficial gravels, conglomerates, ironstones, plastic clays and silts within this formation. He also considered this unit to be Quaternary in age. Since Logan's report, however, these surficial materials have been considered to be Eocene formations (Lowe, 1913; Attaya, 1951; Turner, 1952; Vestal, 1956).

Five of these formations concern this report--the Citronelle, Kosciusko, Zilpha, Winona, and Tallahatta. Characteristic properties as reported by Vestal (1956) are:

Citronelle formation--sand, sandstone, gravel, and clay.

The sand is coarse to fine, cross-bedded to the southeast, and cemented in places. Gravel is sparse and occurs as stringers to thin beds. Clay is present as lenses or is disseminated in the sand phase as a minor component.

Kosciusko formation--sand, sandstone and reworked clay.

Sand is fine to coarse and has variable colors ranging from light gray to chocolate or red brown. Clays are pink, yellowish or white and occur as balls, nodules, stringers, or as matrix within the sands.

Zilpha formation--clay, sandy silt, lignite, sandstone and siltstone.

The fine sediments are shalelike, carbonaceous and brown to black when moist but dry to a gray color. They contain marcasite concretions and have a sulfide smell. They are layered and have laminae of micaceous silt to fine sand. The sands are fine, carbonaceous, gray to black, micaceous and have a sulfide smell.

Tallahatta formation--shale, clay, sand, silt, sandstone and siltstone.

The Neshoba member is composed of clean to argillaceous fine sand and is

usually yellow to gray with some red to brown staining. Clay is present as matrix material, laminae, stringers or thin beds. This member is frequently micaceous and occasionally cemented. The Basic City member is shalelike to clayey, usually light colored but occasionally brown to red, micaceous, and has scattered thin seams of organic material. Outcrops of this member are frequently cemented.

The Winona formation was not positively identified or described by Vestal for Panola County. Priddy (1942) described it in Tallahatchie County as follows:

Winona formation--sand, silt, clay, and claystone.

This formation is slightly to very glauconitic, micaceous to very micaceous, carbonaceous, and has variable colors ranging from grayish-tan to greenish-brown to brownish-black. Clay is frequently present as thin stringers, laminae or beds. Outcrops oxidize rapidly to bright red to brown colors.

## METHODS AND MATERIALS

Eighty-five test holes were drilled in the study area (Figure 1). Most of the holes were cased to minimize sample contamination, and relatively undisturbed cores were collected using either 1.5- or 3-inch diameter split spoons or 3-inch diameter spoons. Cemented materials were sampled using diamond core barrels. Most holes were sample continuously but several of the deeper holes were skip drilled. Maximum sampling depth was 211 feet. The ground surface elevations of test holes were established by surveying.

A total of 6173 feet of material was drilled and several thousand samples were collected and described at the drill site. This field description included color, texture, depositional and weathering features, the nature of the contacts, and other distinguishing characteristics. Blow counts were also recorded for split spoon samples. Color was described using the Munsell system. In addition, chemical characterization has been initiated for selected samples, including: pH; water soluble calcium, magnesium, sodium and potassium; exchangeable calcium, magnesium and potassium; and extractable hydrogen, aluminum and iron. Chemical analyses followed the procedures of the Soil Conservation Service (1972).

We have examined formation exposures identified by Vestal (1956) and concur with his description of lithology. For purposes of continuity we have continued to use the formation names as proposed by Vestal (1956). However, we use these names only as lithologic unit names in reporting our results and identify such lithologic units by
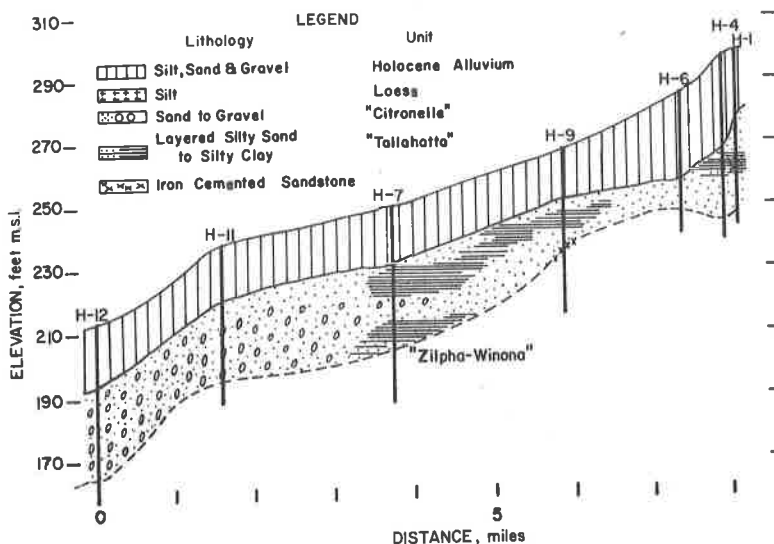


Figure 2. Profile section along Hotophia Creek valley.

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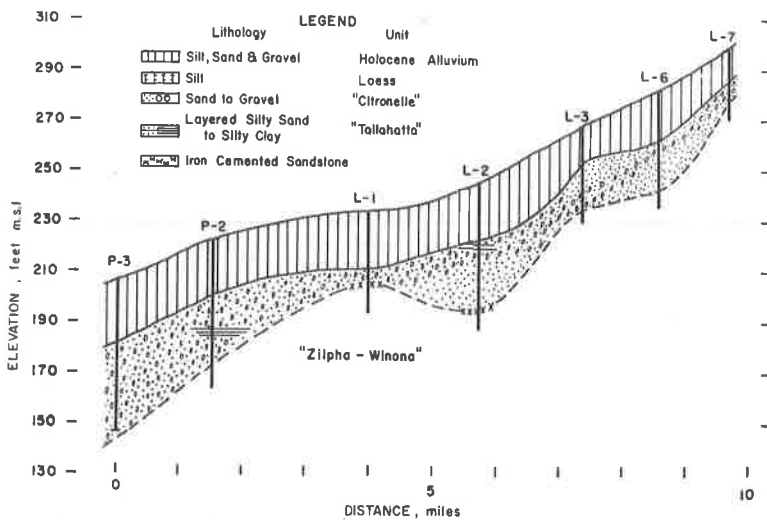
Figure 3. *Profile section along Peters and Long Creek valleys.*
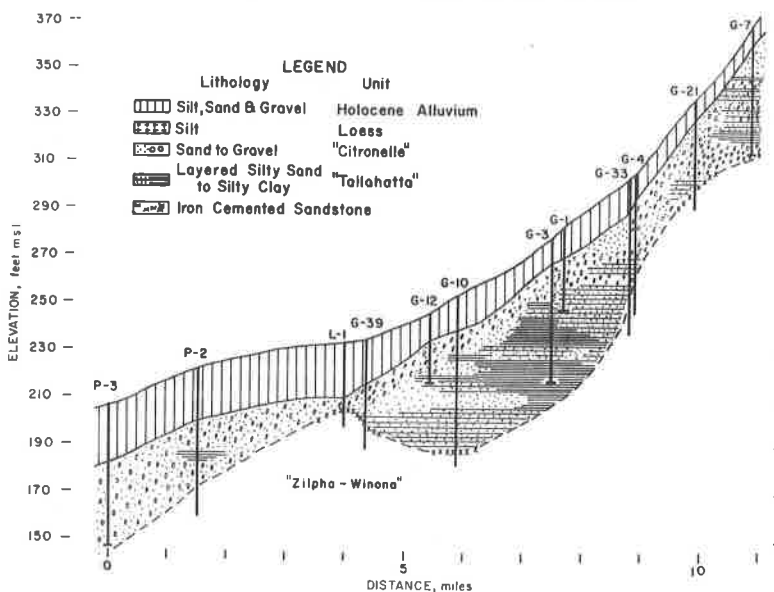


Figure 4. *Profile section along Peters and Goodwin Creek valleys.*

quotation marks. We disclaim any implication of relative position within the generalized section for these lithologic units.

## RESULTS AND DISCUSSION

The three lithologic units relevant to a discussion of the stratigraphic column for the study area include the "Citronelle," "Tallahatta" including both the sandy phase "Neshoba" and clayey "Basic City" members, and the "Zilpha-Winona" facies complex. The "Zilpha" and "Winona" units are considered a facies complex due to their alternating occurrence (interfingering) with depth in most cores. Figures 2 through 6 illustrate typical distributions of these units. Figures 2 through 4 are profile sections along the long axes of Hotophia, Long, and Goodwin valleys respectively, whereas Figures 5 and 6 are cross sections of the valleys. The hole spacings shown in these
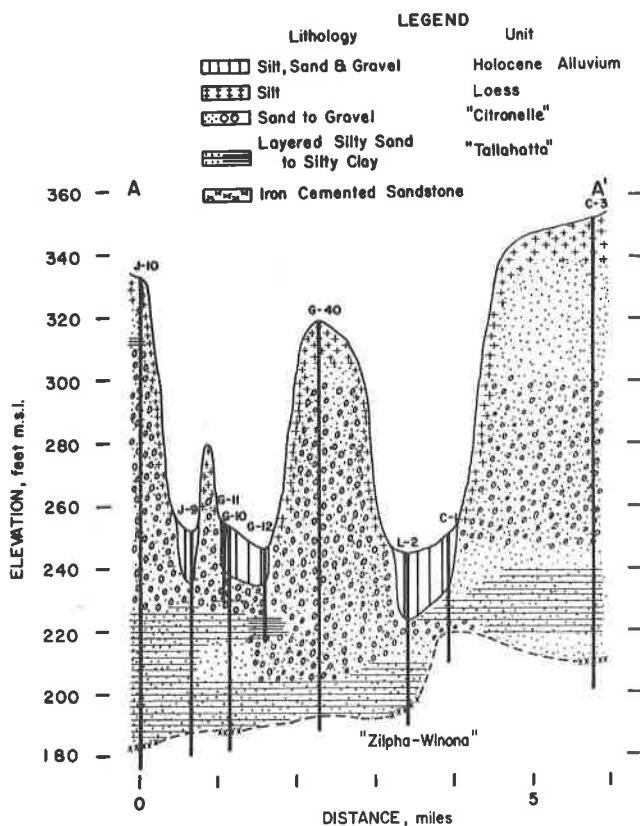
Figure 5. Cross section from hole J-10 to hole C-3 (A to A', Figure 1).

Table 1. Generalized section of stratigraphic units, Panola County, Mississippi (after Vestal, 1956).

| SYSTEM | SERIES | FORMATION | MEMBER |
|--------|--------|-----------|--------|
| QUATERNARY | HOLOCENE | RECENT ALLUVIUM | |
| | PLEISTOCENE | LOESS | |
| | PLIOCENE | CITRONELLE | |
| TERTIARY | EOCENE–CLAIBORNE | KOSCIUSKO | |
| | | ZILPHA | |
| | | WINONA | |
| | | TALLAHATTA | NESHOBA |
| | | | BASIC CITY |

figures are straight-line distances between adjacent holes.

The typical sequence observed in these valleys, as illustrated in Figures 2-4, is Holocene valley fill overlying either gravels or "Tallahatta" materials which in turn unconformably overlie the "Zilpha-Winona" facies complex. Iron-cemented sandstones frequently occur at the contact between the "Zilpha-Winona" complex and overlying materials. These sandstones are associated with abrupt textural changes. In several locations valley fill deposits directly overlie "Tallahatta" materials whereas at other locations typical "Tallahatta" materials occur as scattered bodies within or below the

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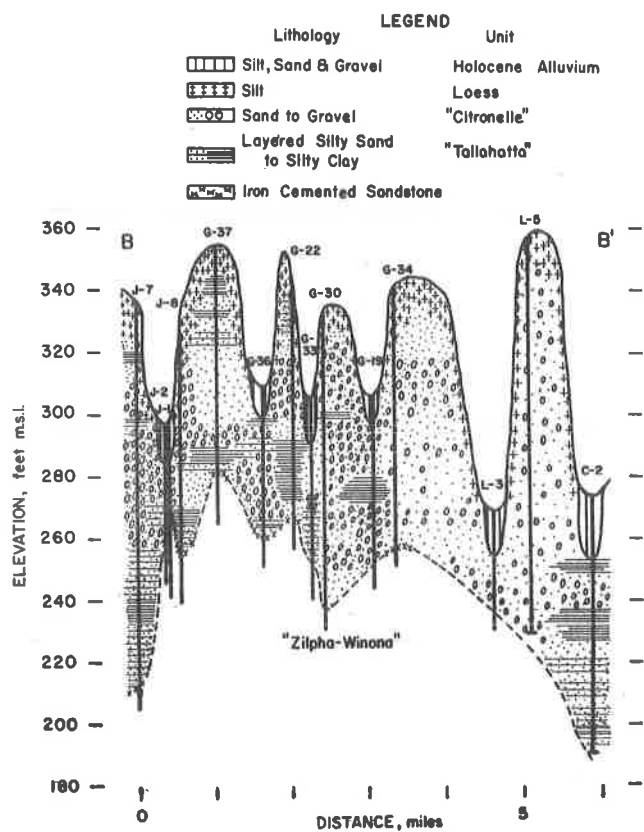
Figure 6. *Cross section from hole J-7 to hole C-2 (B to B', Figure 1).*
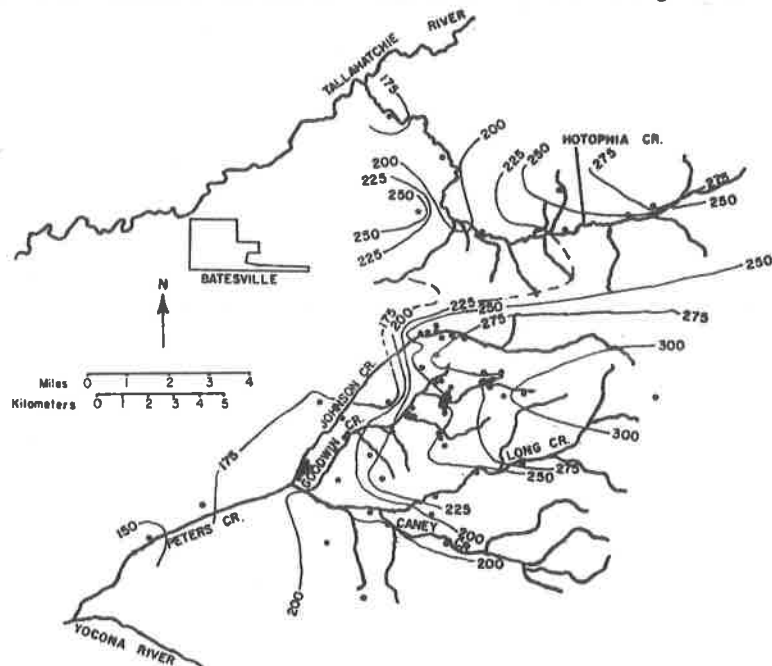


Figure 7. *Surface of "Zilpha-Winona" complex, elevations in feet mean sea level.*

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Table 2. Average[1] chemical data for "Tallahatta" and "Zilpha-Winona" materials.

| Analysis | "Tallahatta" | "Zilpha-Winona" |
|---|---|---|
| Extractable | | |
| Iron | 37 ppm | 3,100 ppm |
| Aluminum | 0.05 meq/100 g | 4.19 meq/100 g |
| Hydrogen | 0.06 meq/100 g | 18.9 meq/100 g |
| Exchangeable | | |
| Sodium | 0.23 meq/100g | 0.04 meq/100 g |
| Potassium | 0.21 meq/100 g | 0.11 meq/100 g |
| Calcium | 3.86 meq/100 g | 3.60 meq/100 g |
| Magnesium | 2.41 meq/100 g | 0.44 meq/100 g |
| Water Soluble | | |
| Sodium | <0.01 meq/100 g | 0.02 meq/100 g |
| Potassium | <0.01 meq/100 g | <0.01 meq/100 g |
| Calcium | <0.01 meq/100 g | 1.64 meq/100 g |
| Magnesium | <0.01 meq/100 g | 4.66 meq/100 g |
| pH | 5.50 | 2.00 |

1    Average values for 10 samples each.

gravels and/or sands. These gravels may have been reworked following initial deposition and may thus be atypical "Citronelle." No gravels were observed at Hotophia Creek sites east of hole H-7 (Figure 2). The presence of "Zilpha" material in the subsurface in the western part of the study area was expected since Vestal (1956) reported an exposure of this unit north of our study area and Kolb et al. (1968) reported its presence in the subsurface to the west. The presence of "Zilpha" material in the subsurface in the eastern part of our study area (east of hole H-7) was totally unexpected since Vestal (1956) identified outcrops in this area as Tallahatta.

Similar but more definitive sequences are presented in Figures 5 and 6 for cross sections across Johnson, Goodwin and Long Creek valleys. Again "Tallahatta" materials occur as scattered bodies overlying the gravels, or in some cases within or below the gravels; both unconformably overlie the "Zilpha-Winona" facies complex. The gravels are typical "Citronelle," and the "Tallahatta" materials fit Vestal's (1956) description of this unit. The contact between the "Tallahatta" and the "Zilpha-Winona" complex materials, where present, is sharp with little or no weathering. This contact is characterized by an abrupt change of pH from 5 to 6 for the overlying "Tallahatta" to 3.5 or less for the underlying "Zilpha-Winona" complex. Similar abrupt changes at this contact characterize water soluble and extractable base data. Average chemical data for these two units are presented in Table 2. The single exception to the preceding chemical data concerns the few thin lignitic seams within the "Tallahatta." This ligntic material has chemical properties intermediate with or approaching "Zilpha-Winona" type materials.

The relief on the "Zilpha-Winona" surface (Figure 7) is enhanced by two dominant troughs, one conformable with Caney Creek valley and a second generally conformable with the Hotophia-Johnson divide. A third incision is evident in Hotophia Valley near the Hotophia Creek-Tallahatchie River confluence. This incision generally follows the eastern edge of the gravel deposits and may have formed in response to gravel plugging of the original drainage. The dissimilarity of the surface watershed and the top of the "Zilpha-Winona" complex is directly pertinent to ground-water conditions and water budgets for surface watersheds. From field observations, typical "Zilpha-Winona" samples were only slightly moist and "Zilpha-type" clayey materials were effectively dry. The overlying more permeable materials were generally saturated. This "Zilpha-Winona" surface functions as an aquiclude, perching ground-water and controlling subsurface hydrology.

The relative distributions of these lithologic units conflict with the presently accepted generalized section for Panola County. "Tallahatta" material was found to occur in association with the "Citronelle" gravels overlying "Zilpha-Winona" materials throughout the gravel-laden (western) part of our study area. In the gravel-free easternmost part, "Tallahatta" material was found superjacent to the "Zilpha-Winona" materials. This "Tallahatta" material is not in the proper position relative to either the

"Citronelle" or the "Zilpha-Winona" complex. Similarly, in the western half (approximately) of the study area, materials lithologically equivalent to the Koscuisko overlie "Citronelle" gravels which makes these materials out of place.

We do not yet have enough data to justify an attempt at revising the standard section for this area of interest. Such a revision will evolve from a complete definition of the nature and distribution of the lithologic units and the configuration of the erosional surface, i.e., in our study area the erosional surface on the "Zilpha-Winona" complex. The relief on this surface (Figure 7), the abrupt change in chemical properties of the materials at this contact (Table 2) and the occurrence of this surface east of the gravel deposits all suggest that this erosion surface has regional significance.

Complementary evidence for such a surface in the southern Mississippi Valley, however, is not well documented. Doering (1956) has reported one such surface underlying the coastal plain Citronelle (which may differ from the Mississippi Valley Citronelle). He reported that the Citronelle "is separated by an unconformity of regional importance from underlying beds which are generally lithologically different." Similar observations have been made by Hilgard (1860), Shaw (1918), Fisk (1944), Wright (1951) and Kolb et al. (1968). Several unconformities have been identified between Eocene formations in surrounding counties. These unconformities may possibly be an easterly continuation of the single erosion surface identified in our study area. Such unconformities between Eocene formations have been reported by Vestal(1954) in Marshall County, by Turner (1952) in Yalobusha County and by Attaya (1951) in Lafayette County. These unconformities include surficial sands identified as the Kosciusko formation unconformably overlying the Zilpha formation and surficial sands identified as the Meridian formation unconformably overlying the Ackerman (Wilcox) formation. As noted previously, Hilgard (1860) considered these surface materials to be Quaternary in age. We believe that any such age definition is questionable at this time.


SPECULATION

Several erosional surfaces have been reported in the upper Mississippi River drainage area. As examples, Willman and Frye (1969) reported extensive dissection of a late-Tertiary surface developed on Galena Dolomite in the Driftless Area of Illinois; Horberg (1950) observed gravels disconformably overlying an erosion surface which developed on Eocene sediments and Frye and Leonard (1952) described a severely eroded late-Tertiary surface in Kansas overlain by gravels at elevations as much as 300 feet above present flood plain level. Thornbury (1965) noted various opinions concerning these midwestern erosion surfaces but concluded that they are time equivalent, resulting from a major mid-Tertiary erosion cycle. He assumed that these surfaces developed contemporaneously with the Harrisburg peneplain in the Appalachians. Gravel deposits of similar lithology, variously identified as Lafayette, Citronelle or Grover, typically overlie such midwestern erosion surfaces.

The similarities between the observed erosion surface in northern Mississippi and those reported in the midwest suggests that these surfaces may be comparable and that all may have formed in response to Tertiary sea-level control. According to Worsley and Davies (1979), sea levels were approximately 600 feet above present from about 45 to 30 million years ago, and then regressed to about 300 feet below present during the next several million years. Gradual sea transgression began prior to 25 million years ago and continued until about 15 million years ago, attaining a maximum elevation of about 250 feet above present sea level. After a relatively short stillstand, the sea levels regressed to about 200 feet below present. This condition persisted into the Pleistocene. Worsley and Davies (1979) described these sea level changes as eustatic. Similar sea level regressions and transgressions have been described by Melhorn and Edgar (1975) with only a slight time scale variation from the preceding and are being used by Exxon as an aid to their oil exploration (Kerr, 1980). Miocene and younger sea level changes have been reported by Hack (1975) and Hsü (1978) and are again in general agreement with the preceding scenario. As discussed by Worsley and Davies (1979), changes in eustatic sea levels would be associated with concurrent climatic

changes. Such climatic changes have been reported. Smith (1976) reported two times of major ocean-water cooling, the first from late-Eocene to middle-Oligocene and the second from middle-Miocene to Pleistocene. These two times of cooling were separated by a warming trend. Late-Miocene cooling has also been reported by Loutit and Kennett (1979) and by Imbrie and Imbrie (1979). The latter consider late-Miocene to be the intial phase of Cenozoic glaciation. Clearly, such eustatic sea level and concurrent climatic changes imply massive and widespread denudation and sediment movement, particularly for sediments temporarily stored near shore during high ocean stands.

We speculate that the erosion surface on the "Zilpha-Winona" material in Panola County formed in response to sea-level controls as described by Worsley and Davies (1979). According to this scenario, the near-surface materials must be post-Eocene and are present as a veneer superjacent to the erosion surface. We have established that one exposure of the "Tallahatta" layered clay (superjacent to gravel deposits) shows magnetic reversal and is thus older than 700,000 years. An early glacial-age origin for these deposits superjacent to the erosion surface is suggested by (a) the large size of several erratics and (b) the paleocurrent direction recorded by fore-set bedding angles. A 36- and a 62.5-pound erratic were exposed in cut banks in the study area and a third chert erratic of approximately 20 cubic feet was observed in the bed of Long Creek. The large size and minimum roundness of these erratics suggests ice-rafting. Sand lenses within the gravel deposits are typically cross-bedded and Autin (1978) has shown that these bedding angles have a bimodal distribution, with one mode aligned to the southwest and a second mode aligned to the east-southeast. This latter bedding direction, together with the southeastern cross-bedding angles reported by Vestal (1956), suggests that some of the gravels were deposited from the ancestral Mississippi River system, possibly as tributary-valley backfills.

## CONCLUSIONS

We have investigated the surficial stratigraphy in Hotophia, Johnson, Goodwin, and Long Creek watersheds, Panola County, northern Mississippi. As previously described by Vestal (1956), the surficial units include Citronelle, Kosciusko, Tallahatta, Zilpha, and possibly Winona formations. We have observed units that are lithologically equivalent to these formations, but the distribution of the "Kosciusko" and "Tallahatta" materials is incongruent with their present stratigraphic position in the generalized section. "Kosciusko" materials occur superjacent to the "Citronelle" gravels. "Tallahatta" materials occur within the "Citronelle" gravel deposits and superjacent to the "Zilpha-Winona" materials.

The "Zilpha-Winona" materials are subjacent to an erosional surface that is an aquiclude and controls subsurface hydrology. It underlies the entire study area and has high relief that is not conformable with present surface relief. We interpret this surface as one of regional significance and speculate that it is continuous to the east in Mississippi. We additionally speculate that it may be equivalent to the erosional surface widespread in the upper Mississippi Valley. This speculation is based on the premise that post-Eocene sea level changes were the dominant control of late-Tertiary degradation. If this scenario is correct, the surface materials must be post-Eocene in age, deposited as a veneer superjacent to the erosion surface.

The distributions of this surface and superjacent deposits are both pertinent to our continuing study of the geomorphic surface and its influence on channel stability. The paleosurface controls subsurface hydrology and is directly pertinent to any watershed study. In addition, a thorough definition of the surficial stratigraphy is required in order to (a) develop possible relations between the Holocene valley-fill materials and local, surficial sources of these materials, and (b) establish pertinent geologic controls for extrapolating the results of our intensive watershed study to adjacent areas. We hope that our results, interpretations and speculations will stimulate interest in this complex area of investigation.

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# STRUCTURE CONTOUR MAP OF BASEMENT BELOW

# NORTH CAROLINA COASTAL PLAIN

# AND CONTINENTAL SHELF

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## ABSTRACT

A structure contour map of the basement surface below the North Carolina Coastal Plain and continental shelf has been prepared from existing basement well and seismic data. This map results from work performed as part of a U.S. Department of Energy-funded project to evaluate geothermal energy potential in the Atlantic Coastal Plain.

As shown by the structure contours, the basement surface is not simple. Large scale features, including the Cape Fear Arch, a major northwest-trending basement flexure in southern North Carolina, and a sharp increase in the dip of the basement surface along a north-northeast trend at approximately the -1500 foot contour northeast of the Cape Fear Arch are defined. The basement structure contour map was used to predict basement depths for eight holes drilled as part of the Virginia Polytechnic Institute and State University (VPI&SU) - Department of Energy (DOE) project; predictions were accurate to within 2 per cent of true depths.

## INTRODUCTION

For the past several years, a DOE-funded program exploring the potential for low-temperature geothermal resources in the Atlantic Coastal Plain has been underway at VPI&SU (Costain, 1979; Glover, 1979). Exploration is based upon a model predicting high heat flow from granitic plutons in the crystalline basement below the Atlantic Coastal Plain. According to the model, such plutons would contain anomalously high amounts of radioactive elements relative to surrounding country rock; radioactive decay would produce heat which would be retained in deep acquifers due to the insulating capability of the overlying Coastal Plain sediments. Analysis of this model requires a knowledge of both the thickness of the Coastal Plain sequence and the lithology of the basement below the Coastal Plain. Therefore, an attempt was made to compile all available information regarding these two parameters. For this compilation, "basement" has been defined to include all crystalline rocks of the buried Piedmont as well as volcanic and sedimentary rocks confined to buried Triassic/Jurassic basins. Overlying Coastal Plain sediments are of Cretaceous and younger age, with the exception of deep Coastal Plain sediments of possibly Upper Jurassic age near Cape Hatteras (Mattick et.al., 1974).

Information regarding the Coastal Plain basement was obtained primarily through a review of professional journals, oil and gas drilling reports, U.S.G.S. publications, and state geological survey publications. State survey geologists also provided supplemental data, and additional data were obtained from several test holes drilled to basement as part of the VPI & SU-DOE geothermal project.

## NORTH CAROLINA BASEMENT DATA

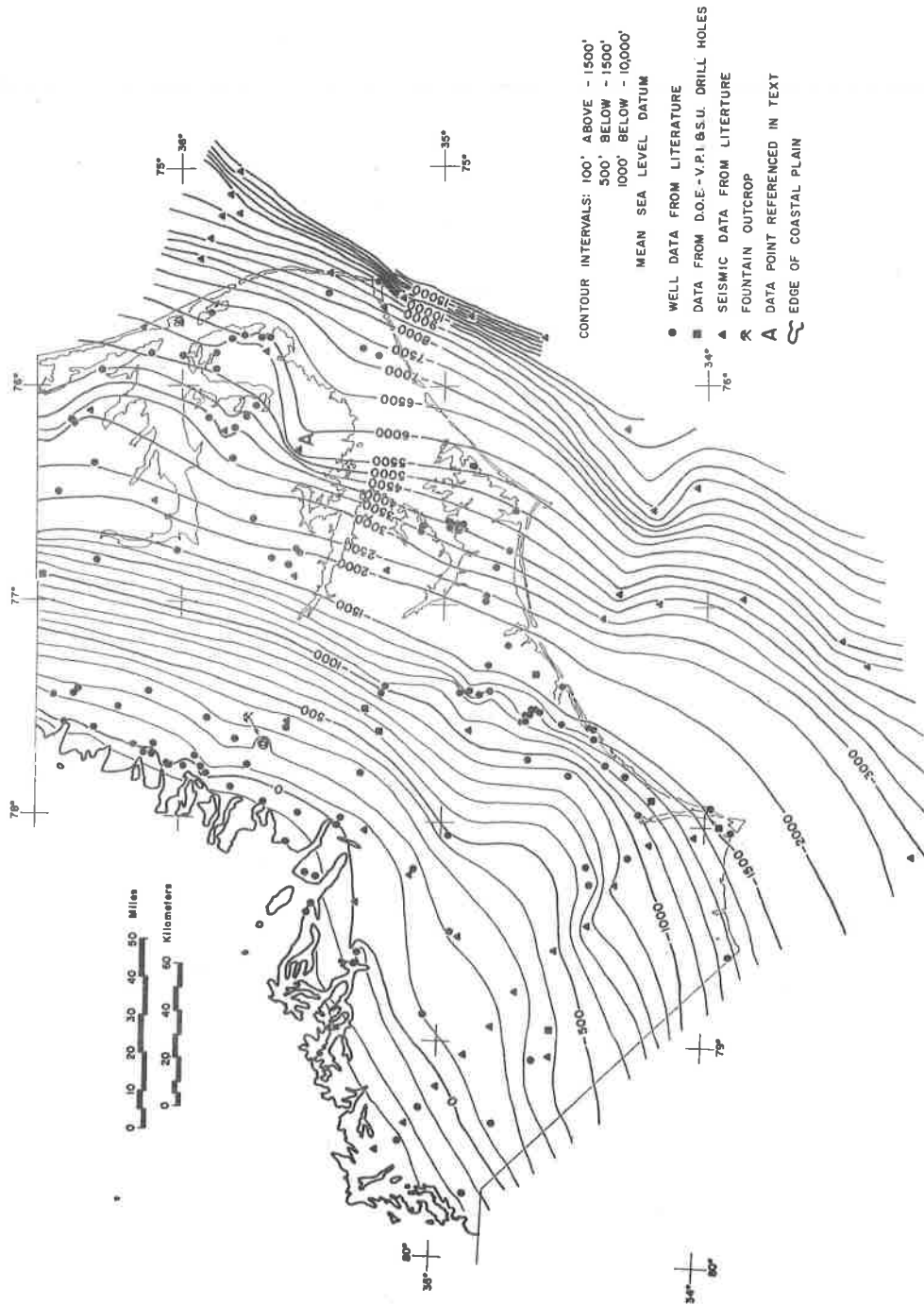The compilation of basement data includes four hundred fifty wells drilled to

*Figure 1. Structure Contour Map of the Basement Surface Below North Carolina Coastal Plain and Continental Shelf.*

basement in North Carolina, mostly near the thin western edge of the Coastal Plain. Depth to the top of basement was obtained for one hundred fifty of the wells. Appendix I summarizes pertinent information regarding these wells. Additionally, data regarding depths to basement in the North Carolina Coastal Plain are available from published reports of seismic refraction investigations in North Carolina (Skeels, 1950; Bonini and Woollard, 1960). Appendix II lists data on thirty-two seismic refraction lines obtained during these investigations. Information on depth to basement on the continental shelf is available from several sources (Hersey, et. al., 1959; Dowling, 1968; Klitgord and Behrendt, 1979; Grow and Markl, 1977; King, 1980). Data points obtained from these sources are also listed in Appendix II.

Figure 1 is a structure contour map constructed from the data included in Appendix I and Appendix II. Because most of the data in the tables were derived from reports listing English measure units, data in the appendices and figure are presented in such units. The map presented here updates earlier maps by Spangler (1950); Bonini and Woollard, (1960); Dennison et al., (1967); Flawn, (1967); Maher, (1971); Brown et al., (1972).

Several features of the North Carolina basement surface are apparent from Figure 1. The Cape Fear Arch, a subsurface topographic high which has been recognized for nearly a century (Dall and Harris, 1892; Stephenson, 1926; Mansfield, 1927; Prouty, 1936; Cooke, 1936; Richards, 1945, 1947, 1948; Straley and Richards, 1950; Berry, 1951; LeGrand, 1955; Ferenczi, 1960), is well defined, as is a sharp increase in basement slope which occurs at approximately -1500' on the basement northeast of the Cape Fear Arch. This change in basement slope occurs along a north-northeast trend, parallel to Appalachian structural trends west of the Coastal Plain. To the west of this break, the basement slope is approximately 30'/mile (5.7m/km or .3°), increasing abruptly to approximately 100'/mile (18.9 m/km or 1.1°) at the break in slope. This break in basement slope was previously recognized by Prouty (1946) and by Berry, (1948). A greater steepening of the basement slope is apparent at the -10,000' contour below the continental shelf off Cape Hatteras. The basement slope here assumes a gradient of approximately 850'/mile (160 m/km or 9.1°). Figure 1 also indicates an embayment on the basement surface west of Cape Hatteras. It should be noted that seismic point A (Figure 1) is the sole control point for this embayment. This configuration was noted by Bonini and Woollard (1960) who felt that such a basement structure was real.

The basement surface appears to be a somewhat irregular surface, with local relief of 50-100', as evidenced by sharp jogs in contours, particularly where data points are clustered. An outcrop of basement rocks near Fountain in Pitt County (Figure 1), approximately twenty miles from the western edge of the Coastal Plain, indicates local basement relief in excess of 200'.

The contour map was constructed to aid in estimating basement depths for VPI & SU geothermal drill holes in the Coastal Plain of North Carolina. Estimates derived from this map proved reasonably accurate for eight holes drilled between late 1978 and early 1980 (Figure 1). Depths to basement at these locations were all within 1-2' of predicted depths. These drill holes were all less than 2000' deep; somewhat less accuracy might be expected in areas where the Coastal Plain sediments are thicker and the basement dip is correspondingly steeper or in areas where control data are sparse.


## APPLICATIONS

The revised structure contour map presented here is a valuable tool for those who require reliable estimates of the thickness of the Coastal Plain sediments in North Carolina. Such estimates are a necessary prerequisite to the evaluation of the geothermal resource potential of deep Coastal Plain aquifers as well as the evaluation of basement "hot dry rock" prospects, a geothermal technique presently being developed by the Los Alamos Scientific Laboratory (Energy Research and Development Authority, 1977). The map may also aid in evaluating oil and gas potential in deeper parts of the Coastal Plain and continental shelf and may also be of use in hydrologic and water resources studies of the North Carolina Coastal Plain.

## ACKNOWLEDGEMENTS

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Appendix I: Wells drilled to basement in North Carolina Coastal Plain for which depths to top of basement are known. Reference numbers refer to sources listed at end of text.

| COUNTY | WELL NAME (OWNER) | OPERATOR | LATITUDE | LONGITUDE | DATE DRILLED | TOTAL DEPTH (FEET) | SURFACE ELEVATION (FEET) | DEPTH TO BASEMENT (FEET) | BASEMENT ELEVATION (FEET) | REFERENCES |
|---|---|---|---|---|---|---|---|---|---|---|
| Beaufort | Rodman #1 | Coastal Plains Oil | 35°32.8' | 76°46.8' | 1963 | 2012 | 16 | 1980 | -1964 | 5,21 |
| | West Dismal #1 | Coastal Plains Oil | 35°39.0' | 76°48.2' | 1963 | 1938 | 34* | 1930 | -1896 | 5,21 |
| | Rodman #2 | Coastal Plains Oil | 35°34.0' | 76°43.3' | 1963 | 2120 | 18* | 2107 | -2089 | 5,16 |
| | Z. Ratcliff #1 | Coastal Plains Oil | 35°35.5' | 76°45.2' | 1963 | 1966 | 18* | 1963 | -1945 | 5,16 |
| Bertie | Cowand #1 | Coastal States Oil | 36°00.9' | 76°46.3' | 1969 | 1570 | 35* | 1510 | -1475 | 5,21 |
| Bladen | Corbett #1 | Am. Mining & Develop. | 34°26.1' | 78°16.5' | 1959 | 765 | 23 | 690 | - 667 | 5,16,21 |
| Brunswick | Fort Caswell | W. H. Gray Bros. | 33°53.3' | 78°02.0' | 1907 | 1563 | 10 | 1540 | -1530 | 6,16,19,24 |
| | Calabash | No. Carolina State | 33°53.6' | 78°35.3' | | 1335 | 68 | 1333 | -1285 | 6,11 |
| | Skipper #1 | Coastal States Oil | 34°17.0' | 78°09.0' | 1969 | 1010 | 47* | 1000 | - 953 | 5,21 |
| | D.O.E.-C.P. #14A | Gruy Federal | 33°56.9' | 78°00.0' | 1979 | 1864 | 25* | 1554 | -1529 | |
| Camden | DuGrandlee-Forman #1 | Urico Drill. | 36°25.2' | 76°10.0' | 1953 | 6421 | 16 | 3520 | -3504 | 5,6,16,21,26 |
| | Weyerhaeuser #1 | E. P. Blair | 36°24.7' | 76°10.5' | 1965 | 3741 | 8 | 2822 | -2814 | 1,5,6,7,21 |
| Carteret | Laughton #1 | F. L. Karston | 34°45.7' | 76°45.5' | 1945 | 4044 | 17 | 4030 | -4013 | 5,6,16,21,25 |
| | Guy M.Carraway #1 | Carolina Petroleum Co. | 34°57.1' | 76°38.5' | 1946 | 4069 | 15 | 4054 | -4039 | 5,6,16,21,25 |
| | Nita Carraway # 1 | Carolina Petroleum Co. | 34°55.8' | 76°38.1' | 1946 | 4126 | 15 | 4120 | -4105 | 5,6,16,21 |
| | D. H. Phillips #1 | Carolina Petroleum Co. | 34°58.8' | 76°39.0' | 1946 | 3964 | 13 | 3946 | -3933 | 5,6,21,25 |
| | H. H. Salter #1 | Carolina Petroleum Co. | 34°57.3' | 76°39.6' | 1946 | 3963 | 13 | 3955 | -3942 | 5,6,16,21,25 |
| | John Wallace #1 | Carolina Petroleum Co. | 34°58.8' | 76°38.0' | 1946 | 6034 | 11 | 4020 | -4009 | 5,6,16,21,25 |
| | Bayland Corp. #1 | Coastal Plains Oil | 34°53.9' | 76°22.0' | 1961 | 5609 | 18 | 5570 | -5552 | 5,6,16,21 |
| | Huntley-Davis #1 | Coastal Plains Oil | 34°43.8' | 76°34.5' | 1951 | 4965 | 17 | 4935 | -4938 | 5,6,16,21 |
| | Elliot #1 | Carr & Schmidt | 34°48.2' | 76°49.9' | 1973 | 3461 | 22* | 3396 | -3374 | 5,21 |
| | Atlantic Beach Corp #1 | Carr & Schmidt | 34°43.3' | 76°44.4' | 1974 | 4092 | 9 | 4088 | -4079 | 5,21 |
| Craven | Great Lakes #1 | Great Lakes Drill. | 34°51.0' | 76°58.9' | 1925 | 2404 | 30 | 2318 | -2288 | 5,6,10,16,17,18,21,24 |
| | C. Bryan #1 | Carolina Petroleum Co. | 34°50.9' | 76°57.9' | 1947 | 2435 | 15 | 2408 | -2393 | 5,6,16,21,25 |
| | Graham Merritt | State of No. Carolina | 35°13.4' | 77°25.4' | 1979 | 1090 | 50* | 980 | - 930 | 27 |
| | Peter Havfich | State of No. Carolina | 35°12.4' | 77°23.5' | 1979 | 1194 | 60* | 1154 | -1054 | 27 |
| Cumberland | Fayetteville Ice & Mfg. | | 35°02.9' | 78°53.3' | | 265 | 106 | 210 | - 114 | 9 |
| | | J. M. Wright | 35°02.9' | 78°53.3' | | 237 | 100 | 192 | - 92 | 9 |
| Currituck | Twiford #1 | E. P. Blair | 36°18.2' | 75°55.3' | 1965 | 4553 | -10 | 4526 | -4536 | 1,5,6,7,21 |
| | Kellog #1 | Rapp Oil Co. | 36°07.0' | 75°51.2' | 1969 | 5140 | 16 | 5071 | -5055 | 5,21 |
| Dare | Esso #1-Hatteras Light | Standard Oil of N. J. | 35°15.0' | 75°31.8' | 1946 | 10054 | 24 | 9878 | -9854 | 5,6,16,21,30,31 |
| | Mobil#1-Pamlico Sound | Socony-Mobil Oil | 35°59.9' | 75°52.0' | 1965 | 5255 | 19 | 5165 | -5146 | 1,5,6,16,21 |
| | Mobil #2-Pamlico Sound | Socony-Mobil Oil | 35°26.2' | 75°34.6' | 1965 | 8381 | 24 | 8360 | -8336 | 1,5,6,16,21 |
| | Marshall Collins #1 | E. P. Blair | 35°53.0' | 75°40.3' | 1965 | 5291 | 2 | 6268 | -6266 | 1,5,6,7,21 |
| | West Va. Pulp & Paper #1 | E. P. Blair | 35°54.6' | 75°55.5' | 1965 | 5144 | 5 | 5124 | -5119 | 1,5,6,21 |
| | Westvaco #1A | Cities Service | 35°39.6' | 75°46.7' | 1971 | 6188 | | | -6112 | 5,6,21 |
| | Westvaco #2A | Cities Service | 35°51.8' | 75°51.1' | 1971 | 5817 | | | -5509 | 5,6,21 |
| | First Colony Farms #1 | Cities Service | 35°48.3' | 75°47.8' | 1974 | 5582 | 10 | 5540 | -5530 | 5,6,21 |
| | First Colony Farms #2A | Cities Service | 35°56.6' | 75°52.3' | 1974 | 5260 | 19 | 5228 | -5209 | 5,6,21 |
| | Westvaco #2 | Gentien | 35°45.3' | 75°46.4' | 1973 | 6079 | 5* | 6062 | -6057 | 5,21 |
| | Westvaco #3 | Gentien | 35°41.4' | 75°46.8' | 1973 | 5823 | 3 | 58127 | -5809 | 5,21 |
| Duplin | Jones #1 | Coastal States Oil | 34°55.7' | 78°03.8' | 1969 | 598 | 105* | 580 | - 475 | 5,21 |
| Edgecombe | Town of Tarboro | Snyder Pump & Well | 35°53.7' | 77°32.5' | 1899 | 349 | 50 | 328 | - 278 | 6,16,19,24 |
| | Town of Pinetops | Va. Well & Machinery Co. | 35°47.3' | 77°36.5' | 1925 | 446 | 100 | 342 | - 242 | 6,19,20 |
| | Bricks Rural Life School | Va. Well & Machinery Co. | 36°08.3' | 77°42.7' | | 326 | 80* | 48 | + 32 | 20 |
| | East Carolina Training School' | Heater Well Co. | 35°59.3' | 77°46.0' | | 96 | 80* | 50 | + 30 | 20 |
| | Meadowbrook Dairy | Heater Well Co. | 35°55.2' | 77°46.3' | | 131 | 95* | 100 | - 5 | 20 |
| | G. W. Bradley | R. L. Jones | 35°56.7' | 77°43.4' | | 120 | 65* | 120 | - 55 | 20 |
| | B.C. Pitman | R. L. Jones | 36°06.1' | 77°40.1' | | 130 | 125* | 130 | - 5 | 20 |
| | Rocky Mount Ice & Fuel Co. | | 35°53.6' | 77°48.1' | | 754 | 120 | 200 | - 80 | 9 |
| | RM-1 | VPI&SU | 36°02.2' | 77°45.4' | 1990 | 413 | 90* | 112 | - 22 | |

| COUNTY | WELL NAME (OWNER) | OPERATOR | LATITUDE | LONGITUDE | DATE DRILLED | TOTAL DEPTH (FEET) | SURFACE ELEVATION (FEET) | DEPTH TO BASEMENT (FEET) | BASEMENT ELEVATION (FEET) | REFERENCES |
|---|---|---|---|---|---|---|---|---|---|---|
| Gates | Weyerhaeuser #1 | S. E. Cullinen Drill. | 36°26.0' | 76°30.0' | 1971 | 2135 | 12 | 2110 | -2088 | 5,6,21 |
| | D.O.E.-DO#1 | VPI & SU | 36°31.9' | 75°52.7' | 1979 | 1351 | 25* | 1023 | - 998 | |
| Halifax | Tillery School #1 | Heater Well Co. | 36°14.7' | 77°29.9' | | 325 | 70 | 205 | - 135 | 6,20 |
| | Town of Halifax | Carolina Drill. & Equip. Co. | 36°19.9' | 77°35.9' | | 135 | 125* | 110 | + 15 | 20 |
| | Town of Halifax | Carolina Drill. & Equip. Co. | 36°19.9' | 77°35.9' | | 285 | 125* | 110 | + 15 | 20 |
| | Town of Enfield | Va. Machine & Well Co. | 36°10.8' | 77°40.2' | | 350 | 105* | 125 | - 20 | 20 |
| | Town of Scotland Neck | Snyder Pump & Well Co. | 36°07.6' | 77°25.3' | | 507 | 100* | 349 | - 249 | 20 |
| | | | 36°19.9' | 77°35.9' | | 270 | 100 | 40 | - 60 | 9 |
| | Enfield Grade School | | 36°10.8' | 77°40.2' | | 115 | 100 | 90 | - 10 | 9 |
| | Town of Enfield | | 36°10.8' | 77°49.2' | | 200 | 100 | 109 | - 9 | 9 |
| Harnett | Erwin Cotton Mills | | 35°19.6' | 78°40.6' | | 502 | 170 | 143 | + 27 | 9,28 |
| | Town of Dunn | | 35°18.6' | 78°36.4' | | 434 | 208 | 90 | + 118 | 9,28 |
| Hertford | Edgar Baxemore #1 | Fan-seau Drill. Co. | 36°19.0' | 76°49.0' | 1949 | 1278 | | | -1235 | 5,6,16,21 |
| Hoke | No. Carolina Sanitorium #1 | Heater Well Co. | 35°03.5' | 79°19.0' | 1954 | 401 | 510 | 380 | + 130 | 4,6 |
| Hyde | Mobil #3 Palmico Sound | Mobil Oil Corp. | 35°18.4' | 75°49.8' | 1965 | 7314 | 24 | 7260 | -7236 | 1,5,6,7,21 |
| | Socony-Mobil-State #3 | Socony Mobil Oil | 35°15.0' | 75°52.0' | | 7266 | 0* | 7220 | -7220 | 7,16 |
| Johnston | W. D. Avera | | 35°28.3' | 78°16.2' | | 185 | 175 | 30 | + 145 | 9 |
| | W. D. Avera | | 35°28.3' | 78°16.2' | | 90 | 175 | 20 | + 155 | 9 |
| | W. D. Avera | | 35°28.3' | 78°16.2' | | 92 | 175 | 30 | + 145 | 9 |
| | W. D. Avera | | 35°28.3' | 78°16.2' | | 70 | 175 | 20 | + 155 | 9 |
| | W. D. Avera | | 35°28.3' | 78°16.2' | | 300 | 175 | 70 | + 105 | 9 |
| | W. D. Avera | | 35°28.3' | 78°16.2' | | 300 | 175 | 70 | + 105 | 9 |
| | W. E. Edgerton | | 35°28.3' | 78°16.2' | | 168 | 173 | 26 | + 147 | 9 |
| | Navassa Guano Co. | | 35°28.3' | 78°16.2' | | 238 | 175 | 20 | + 155 | 9 |
| | Selma Knitting Mills | | 35°28.3' | 78°16.2' | | 140 | 175 | 30 | + 145 | 9 |
| | W. B. Johnson | | 35°30.2' | 74°25.6' | | 150 | 200 | 55 | + 145 | 9 |
| | | | 35°29.2'? | 78°22.5'? | | 63 | 150 | 45 | + 105 | 9 |
| | Smithfield Cotton Mills | | 35°29.2'? | 78°22.5'? | | 150 | 150 | 20 | + 130 | 9 |
| | | | 35°29.2'? | 78°22.5'? | | 125 | 150 | 60 | + 90 | 9 |
| | Town of Smithfield | | 35°29.2'? | 78°22.5'? | | 106 | 150 | 20 | + 130 | 9 |
| | Oil Mill | | 35°30.7' | 78°14.9' | | 101 | 160 | 40 | + 120 | 9 |
| | Oliver, Godwin, & Lynch | | 35°30.7' | 78°14.9' | | 110 | 160 | 40 | + 120 | 9 |
| | Town of Pinelevel | | 35°30.7' | 78°14.9' | | 104 | 160 | 37 | + 123 | 9 |
| | Selma Cotton Mills | | 35°28.3' | 78°16.2' | | 168 | 175 | 1657 | + 107 | 9 |
| | Town of Kenley | | 35°35.4' | 78°06.4' | | 100 | 204 | 23 | + 181 | 9 |
| Jones | Hofmann Forest #2 | Peter Henderson | 34°56.3' | 77°24.5' | 1960 | 1239? | 65* | 12287 | -163 | 5,6,21 |
| Lenoir | Town of LaGrange | Layne-Atlantic Co. | 35°18.1' | 77°47.3' | 1952 | 604 | 105 | 392 | - 287 | 4,6,16 |
| | D.O.E.-C.P. #16A | Gruy Federal | 35°14.2' | 77°35.4' | 1979 | 711 | 50* | 680 | - 630 | |
| | R. Johnson, Jr. | State of No. Carolina/VPI&U | 35°17.0' | 77°29.5' | 1979-80 | 1131 | 20* | 759 | - 739 | 27 |
| Moore | Steam Pumping Plant | | 35°07.9' | 79°28.5' | | 730 | 520 | 197 | + 323 | 9,28 |
| Nash | Town of Whitakers | Heater Well Co. | 36°06.2' | 77°42.8' | | 82 | 115* | 69 | + 46 | 20 |
| | Town of Whitakers | Va. Machinery & Well Co. | 36°06.2' | 77°42.8' | | 405 | 115* | 135 | - 20 | 20 |
| | Town of Battleboro | White Well Co. | 36°03.0' | 77°45.2' | | 250 | 118* | 165 | - 47 | 20 |
| New Hanover | Fort Fisher #1 | No. Carolina Oil & Gas | 33°58.6' | 77°55.2' | 1966 | 1558 | 9 | 1543 | -1536 | 5,6,21 |
| | City of Wilmington | Clarendon Water Works | 34°15.0' | 77°57.0' | 1399 | 1330 | 9 | 1309 | -1100 | 6,16,19,21,24 |
| | J. H. Foy #1 | Coastal States Oil | 34°18.1' | 77°47.0' | 1969 | 1306 | | | -1267 | 5 |
| | D.O.E.-C.P. #14 | Gruy Federal | 34°12.0' | 77°53.4' | 1979 | 1280 | 30* | 1263 | -1233 | |
| Northampton | Seaboard School | O. L. Truby | 36°29.0' | 77°26.5' | | 265 | 130 | 230 | - 100 | 6,20 |
| | State Prison Camp | Heater Well Co. | 36°24.2' | 77°26.2' | 1912? | 296 | | | - 176 | 6,20 |
| | Thomas Gregory | | 36°26.7' | 77°33.9' | | 595 | 140* | 145 | - 5 | 22 |
| | Town of Jackson | Layne-Atlantic Co. | 36°23.3' | 77°25.9' | 1940? | 260 | 90 | 250 | - 170 | 9,19,20 |

| COUNTY | WELL NAME (OWNER) | OPERATOR | LATITUDE | LONGITUDE | DATE DRILLED | TOTAL DEPTH (FEET) | SURFACE ELEVATION (FEET) | DEPTH TO BASEMENT (FEET) | BASEMENT ELEVATION (FEET) | REFERENCES |
|---|---|---|---|---|---|---|---|---|---|---|
| Onslow | Cadco #1 | International Paper | 34°31.8' | 77°33.0' | 1950 | 1497 | 30 | 1449 | -1419 | 5,6,16,20 |
| | Seay-Hofmann Forest #1 | Bryant Seay | 34°54.0' | 77°23.8' | 1959 | 1433 | 52 | 1420 | -1368 | 5,6,9,16,21 |
| | Hofmann Forest #3 | Peter Henderson | 34°49.5' | 77°23.9' | 1960 | 1328 | 35* | 1310? | -1275? | 5,6,16,21 |
| | International Paper #2 | No. Carolina Oil & Gas | 34°39.7' | 77°28.9' | 1967 | 1402 | 57* | 1390? | -1333? | 5,6,21 |
| | Baucom #1 | No. Carolina Oil & Gas | 34°40.3' | 77°30.3' | 1967 | 1414 | 57 | 1412 | -1355 | 5,6,21 |
| | Evans #1 | No. Carolina Oil & Gas | 34°41.5' | 77°30.5' | 1967 | 1370 | 40* | 1365 | -1325? | 5,6,21 |
| | Cadco #2 | International Paper | 34°38.0' | 77°29.9' | 1950 | 1493 | 52* | 1343 | -1291 | 5,9,16,21 |
| | Burton-Hofmann Forest #1 | E. T. Burton | 34°50.0' | 77°16.1' | 1953 | 1570 | 44 | 1560 | -1516 | 5,16,21 |
| | Seay-Hofmann Forest #2 | Bryant Seay | 34°51.9' | 77°24.5' | 1959 | 1337 | 32 | 1335 | -1303 | 5,9,16,21 |
| | James #1 | No. Carolina Oil & Gas | 34°42.0' | 77°32.0' | 1955 | 1254 | 67 | 1247 | -1200 | 5,21 |
| | International Paper #1 | No. Carolina Oil & Gas | 34°39.5' | 77°28.6' | 1966 | 1286 | 60* | 12477 | -1187? | 5,21 |
| | Sheppard #1 | No. Carolina Oil & Gas | 34°41.8' | 77°32.3' | 1965 | 1276 | 50 | 1273 | -1223 | 5,21 |
| | Justice #1 | No. Carolina Oil & Gas | 34°33.0' | 77°22.5' | 1966 | 1681 | 11 | 1669 | -1658 | 5,21 |
| | L. Parker #1 | Colonial Oil & Gas | 34°45.4' | 77°11.6' | 1970 | 2009 | 32 | 1807 | -1775 | 5,21 |
| | D.O.E.-C.P. #15 | Gruy Federal | 34°39.0' | 77°19.0' | 1979 | 1954 | ~25* | 1675 | -1650 | |
| Pamlico | B.C. Pulpwood #1 | Carolina Petroleum | 35°04.6' | 76°39.0' | 1947 | 3667 | 11 | 3658 | -3647 | 5,6,16,21,25 |
| | Atlas Plywood #1 | Carolina Petroleum | 35°05.3' | 76°40.6' | 1947 | 3425 | 8 | 3414 | -3406 | 5,6,16,21,25 |
| Pasquotank | Hoerner-Waldorf #1 | S. E. Cullinan | 36°10.0' | 76°22.0' | 1971 | 2715 | 91? | 2690? | -2599 | 5,6,21 |
| Pender | Keith #1 | Am. Mining & Develop. | 34°26.8' | 78°11.8' | 1959 | 720 | 23 | 693 | - 672 | 5,6,21 |
| | Cowan #1 | No. Carolina Oil & Gas | 34°40.3' | 77°42.5' | 1966 | 1004 | 34 | 990 | - 956 | 5,21 |
| | Batts #1 | No. Carolina Oil & Gas | 34°26.8' | 77°33.8' | 1966 | 1493 | 28 | 1480 | -1452 | 5,21 |
| | Batts #2 | No. Carolina Oil & Gas | 34°26.0' | 77°33.9' | 1966 | 1462 | 11 | 1456 | -1445 | 5,21 |
| | McMillian #1 | No. Carolina Oil & Gas | 34°25.7' | 77°37.1' | 1966 | 1431 | 15* | 1410 | -1395 | 5,21 |
| | Lea #1 | No. Carolina Oil & Gas | 34°22.6' | 77°54.0' | 1966 | 1255 | 37 | 1250 | -1213 | 5,21 |
| | G. Meeks #1 | Coastal States Oil | 34°31.0' | 77°47.0' | 1969 | 940 | 25* | 910 | - 885 | 5,21 |
| Pitt | Town of Farmville | Layne-Atlantic Co. | 35°35.5' | 77°35.0' | 1937 | 472 | 80 | 465 | - 385 | 6,9,16,19,24 |
| Richmond | W. R. Bonsal | | 34°53.0' | 79°42.0' | | 425 | 375 | 200 | + 175 | 9 |
| Robeson | Lum-1 | | 34°34.2' | 78°56.0' | 1979 | 1274 | 106* | 490 | - 384 | |
| Sampson | Town of Roseboro | VPI&SU | 34°57.5' | 78°35.5' | 1955 | 620 | 134 | 353 | - 219 | 4,6,16 |
| | Henry Vann #1 | Heater Well Co. | 35°06.0' | 78°13.3' | 1955 | 271 | 166 | 245 | - 79 | 4,6,16 |
| Scotland | U.S. Army | Va. Machinery & Well Co. | 34°46.7' | 79°22.7' | 1942 | 448 | 210 | 161 | - 153 | 6,19,24 |
| Tyrrell | Westvaco #2 | Exchange Oil & Gas | 35°53.6' | 76°09.6' | 1971 | 4198 | 26 | 3908 | -3882 | 5,6,21 |
| | Westvaco #1 | Exchange Oil & Gas | 35°47.9' | 76°12.3' | 1971 | 4242 | | | -4064 | 5,6,21 |
| | Westvaco #3 | Exchange Oil & Gas | 35°43.0' | 76°06.3' | 1971 | 4859 | 21 | 4755 | -4734 | 5,21 |
| | Whitehurst #1 | R. DeRay | 35°48.3' | 76°20.7' | 1971 | 3564 | 7* | 3547 | -3540? | 5,21 |
| | White #1 | Kit Develop. Co. | 35°46.8' | 76°08.9' | 1972 | 4315 | 3* | 4300 | -4297 | 5,21 |
| Washington | Furbee #1 | Davidson Oil | 35°43.5' | 76°37.5' | 1951 | 2693 | 17 | 2690 | -2673 | 5,21 |
| Wayne | City of Goldsboro | Layne-Atlantic Co. | 35°23.1' | 77°59.7' | 1930 | 133 | 75 | 93 | - 18 | 4,6,16 |
| | Borden Mfg. Co. | | 35°23.3' | 77°59.7' | | 907 | 110 | 268 | - 158 | 9 |
| | Goldsboro Ice Co. | | 35°23.3' | 77°59.7' | | 266 | 110 | 175 | - 75 | 9 |
| | State Hospital | | 35°23.7' | 78°01.4' | | 570 | 100 | 130 | 0 | 9 |
| | J. D. Davis | | 35°32.6' | 77°53.6' | | 140 | 144 | 90 | + 54 | 9 |
| | Fremont Oil Mill | | 35°32.6' | 77°58.6' | | 190 | 140 | 105 | + 35 | 9 |
| | Town of Fremont | | 35°32.6' | 77°53.6' | | 175 | 145 | 100 | + 45 | 9,23 |
| | W. T. Turlington | | 35°32.6' | 77°58.6' | | 126 | 144 | 100 | + 44 | 9 |
| Wilson | Dr. A. B. Williams | Heater Well Co. | 35°44.5' | 77°45.0' | 1942 | 335 | 123 | 245 | -122? | 6,15,19,20,24 |
| | Town of Elm City | Va. Machinery & Well Co. | 35°48.4' | 77°51.7' | | 187 | 130* | 74 | + 56 | 20 |
| | Wilson Country Club | C. W. Horton | 35°43.6' | 77°55.6' | | 125 | 80* | 3? | + 72 | 20 |

* Surface elevation estimated from topographic map.

Appendix II: Seismic refraction and reflection data from North Carolina Coastal Plain and continental shelf, from which depths to top of basement have been calculated. Reference numbers refer to sources listed at end of text.

| COUNTY | LATITUDE | LONGITUDE | DATE | DEPTH TO BASEMENT (FEET) | SURFACE ELEVATION (FEET) | BASEMENT ELEVATION (FEET) | REFERENCES |
|---|---|---|---|---|---|---|---|
| Beaufort | 35°34.0' | 76°53.4' | 1945 | 1930 | 36 | -1794 | 3,29 |
| Bladen | 34°26.1' | 78°28.0' | 1952-53 | 850 | 85 | -765 | 3 |
| | 34°33.7' | 78°34.9' | 1952-53 | 604 | 112 | -492 | 3 |
| | 34°42.3' | 78°46.6' | 1952-53 | 385 | 140 | -245 | 3 |
| Brunswick | 34°02.5' | 78°03.2' | 1952-53 | 1380 | 43 | -1337 | 3 |
| | 34°12.7' | 78°05.5' | 1952-53 | 1125 | 68 | -1057 | 3 |
| Columbus | 34°20.0' | 78°16.9' | 1952-53 | 1045 | 60 | -985 | 3 |
| Craven | 34°56.8' | 76°54.4' | 1945 | 2725 | 25 | -2700 | 3,29 |
| Currituck and Camden | 36°21.4' | 76°09.0' | 1945 | 3080 | 8 | -3072 | 3,29 |
| Dare | 35°13.8' | 75°38.8' | 1945 | 8578 | 6 | -8572 | 3,29 |
| | 35°26.0' | 75°30.4' | 1945 | 9000 | 0 | -9000 | 3,29 |
| | 35°49.5' | 75°50.6' | 1945 | 5460 | 8 | -5452 | 3,29 |
| | 36°00.9' | 75°42.8' | 1945 | 5720 | 9 | -5711 | 3,29 |
| | 36°09.9' | 75°44.6' | 1945 | 5260 | 4 | -5256 | 3,29 |
| Harnett | 35°25.0' | 78°58.2' | 1952-53 | 50 | 395 | + 345 | 3 |
| Hoke | 34°59.9' | 79°13.2' | 1952-53 | 170 | 216 | + 46 | 3 |
| Hyde | 35°33.3' | 76°18.1' | 1945 | 5795 | 5 | -5790 | 3,29 |
| Johnson | 35°19.2' | 78°23.2' | 1952-53 | 193 | 190 | - 3 | 3 |
| Moore | 35°06.8' | 79°23.3' | 1952-53 | 238 | 460 | + 222 | 3 |
| | 35°13.2' | 79°31.1' | 1952-53 | 190 | 565 | + 375 | 3 |
| Onslow | 34°54.4' | 77°35.0' | 1945 | 1120 | 60 | -1060 | 3,29 |
| Pamlico | 35°13.0' | 76°51.1' | 1945 | 2300 | 25 | -2275 | 3,29 |
| Perquimanns and Chowan | 36°05.9' | 76°32.7' | 1945 | 2130 | 15 | -2115 | 3,29 |
| Pitt | 35°35.6' | 77°32.8' | 1945 | 420 | 73 | - 347 | 3,29 |
| Richmond | 35°04.0' | 79°47.6' | 1952-53 | 168 | 509 | + 341 | 3 |
| Robeson | 34°47.9' | 78°56.1' | 1952-53 | 294 | 166 | - 128 | 3 |
| | 34°53.6' | 79°03.9' | 1952-53 | 360 | 203 | - 157 | 3 |
| | 34°34.3' | 79°04.0' | 1952-53 | 530 | 142 | - 388 | 3 |
| Sampson | 34°55.9' | 78°31.7' | 1952-53 | 405 | 114 | - 291 | 3 |
| | 35°06.9' | 78°14.6' | 1952-53 | 334 | 172 | - 162 | 3 |
| Tyrrell | 35°50.0' | 76°13.1' | 1945 | 4177 | 12 | -4165 | 3,29 |
| Wayne | 35°17.2' | 78°03.2' | 1952-53 | 255 | 168 | - 87 | 3,29 |
| | | | | | | | |
| OFFSHORE: | 33°24.0' | 77°15.0' | 1965 | 5479 | 0 | - 5479 | 8 |
| | 33°29.8' | 77°08.5' | 1965 | 6004 | 0 | - 6004 | 8 |
| | 34°02.6' | 76°28.0' | 1965 | 8333 | 0 | - 8333 | 8 |
| | 34°18.3' | 76°12.0' | 1965 | 10367 | 0 | -10367 | 8 |
| | 34°12.5' | 76°34.0' | 1965 | 8923 | 0 | - 8923 | 8 |
| | 34°20.0' | 76°57.0' | 1965 | 4823 | 0 | - 4823 | 8 |
| | 34°23.9' | 77°03.5' | 1965 | 3510 | 0 | - 3510 | 8 |
| | 34°11. ' | 76°59.5' | 1954 | 3806 | 0 | - 3806 | 13 |
| | 33°14. ' | 78°12. ' | 1954 | 2822 | 0 | - 2822 | 13 |
| | 33°52. ' | 76°58. ' | 1954 | 4823 | 0 | - 4823 | 13 |
| | 35°47. ' | 75°12. ' | 1954 | 10630 | 0 | -10630 | 13 |
| | 34°37.2' | 75°46.4' | 1974 | 16930 | 0 | -15,930 | 12 |
| | 34°54.1' | 75°40.6' | 1974 | 14075 | 0 | -14075 | 12 |
| | 35°09.6' | 75°35.5' | 1974 | 11350 | 0 | -11350 | 12 |
| | 35°55.6' | 75°25.4' | 1977 | 7715 | 0 | - 7715 | 15 |
| | 35°53.4' | 75°19.3' | 1977 | 9100 | 0 | - 9100 | 15 |
| | 35°51.2' | 75°13.2' | 1977 | 9755 | 0 | - 9755 | 15 |
| | 35°49.0' | 75°07.0' | 1977 | 10785 | 0 | -10785 | 15 |
| | 35°46.8' | 75°00.9' | 1977 | 14595 | 0 | -14595 | 15 |

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# PETROGRAPHY OF THE GRANITIC BASEMENT BENEATH

## THE COASTAL PLAIN, GATES COUNTY, NORTH CAROLINA

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## ABSTRACT

A 1-inch diameter hole located in the center of a large gravity anomaly in Gates County, North Carolina, was drilled through the Coastal Plain sediments to basement. Crystalline basement was encountered at 323 m, and 87.5 m of continuous core was recovered. The basement rock, herein named the Dort Granite, is an amphibole-biotite granite which has been cut by two episodes of brittle fracture.

## INTRODUCTION

Approximately thirty syn-and post-metamorphic plutons (Fullagar and Butler, 1979) crop out of the southeastern U.S. Piedmont in a belt trending northeast from Georgia to Virginia. Most of the granitoid plutons in the exposed Piedmont produce closed, nearly circular gravity lows (Popenoe and Bell, 1974; Glover, 1963; Cogbill, 1977). Gravity surveys over the Coastal Plain in eastern North Carolina and Virginia have outlined similar gravity anomalies (Dept. of Defense, 1976), suggesting that additional granitoids underlie the Coastal Plain sediments. One of the most prominent gravity "lows" (-20 mgal) is located astride the North Carolina-Virginia border near the community of Dort, in Gates County, North Carolina (Fig. 1). As part of a study of granites in the southeastern Piedmont, a 1-inch diameter hole was drilled to basement near the center of the anomaly near Dort. Basement was encountered at 323.0 m; 87.5 m of continuous core was recovered from the top of the crystalline basement rocks, to a depth of 410.5 m.

## LITHOLOGY

The rock recovered from the basement is a gray, coarse-grained amphibole-biotite granite, herein named the Dort Granite. Minerals visible in hand specimen include subhedral, pale pink K-feldspar, 0.5-2.0 cm long; subhedral to anhedral plagioclase up to 1.5 c.m. long; quartz grains up to 1.0 cm long; and biotite flakes, 0.1-0.5 cm across. Color index (C.I.) ranges from 8 to 15. Most plagioclase grains are saussuritized and tinged pale green. In a few segments of the core, the alignment of biotite and K-feldspar defines a moderately to steeply dipping foliation which varies from weak to strong.

Locally the granite is cut by small (1-5 cm) pegmatite and aplite dikes composed of quartz, plagioclase, and alkali feldspar. Near the bottom of the core, several mafic clots up to 20 cm across are included in the granite. The rock recovered from the core shows varying intensities of alteration and brittle fracture (Fig. 2).

## PETROGRAPHY

In thin section, K-feldspar appears as microperthitic microcline clouded red-brown. According to microprobe analyses, bulk compositions average $An_0Ab_8Or_{92}$. Plagioclase is unzoned and has an average composition of $An_{20}Ab_{79}Or_1$; it shows both
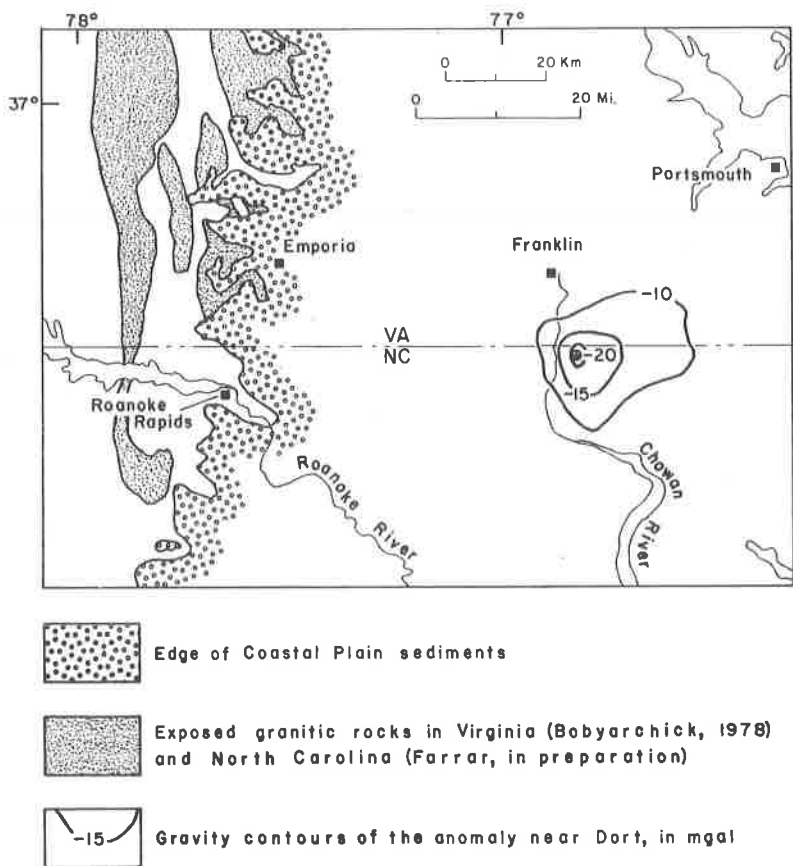
Figure 1. Location map for Drill Hole DO-1 showing gravity anomaly (Dept. of Defense, 1976) and nearest outcrop of the Petersburg Granite (Farrar, in preparation).

Carlsbad and albite twinning. The plagioclase is generally saussuritized to epidote $\pm$ chlorite $\pm$ carbonate $\pm$ white mica. In most grains, the epidote is strongly concentrated near the center of the feldspar, suggesting that the original plagioclase was normally zoned. Quartz grains have undulose extinction; myrmekite occurs locally.

Biotite is pleochroic tan to dark brown or dark olive green. Compositions (Table I) plot near the center of biotite compositions determined for postmetamorphic plutons in the exposed Piedmont (Fig. 3a; Speer et al., 1980). Chlorite has partially replaced biotite in even relatively unaltered rocks, and epidote occurs along the cleavage planes of scattered biotite grains. Anhedral amphibole comprises about 1% of the fresh samples (e.g. DO-1114); it does not occur in many parts of the core because of the extensive alteration. The amphibole in pleochroic: X = tan, Y = yellow-green, Z = blue-green, with 2V approximately 65°. Following the nomenclature of Leake (1978), it is a potassian ferroan pargasitic hornblende (Table I). The analyses plot within the cluster of analyses of amphiboles from postmetamorphic granites in the southeastern U.S. (Fig. 3b) (Speer, et al., 1980).

Primary accessory minerals include titanite (Fig. 4a), apatite, opaques, zircon, and allanite. Some titanite grains enclose a corroded opaque grain, suggesting that a portion of the titanite formed by a reaction that consumed oxides. In all but the freshest samples, titanite is partially altered to carbonate + rutile + quartz. Allanite, which is commonly altered, occurs as zoned, prismatic crystals up to 0.3 cm long.

Secondary minerals comprise chlorite, epidote, and calcite. Epidote, the most abundant, is optically negative with 2V = 80-85°, and r > v; it is pleochroic colorless to yellow-green. The chlorite (Table I) can be classified as a pycnochlorite (Hey, 1954).

# TABLE 1. Microprobe Analyses

|  | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|
| $SiO_2$ | 41.9 | 40.7 | 29.0 | 28.7 | 36.7 | 37.2 | 37.4 | 35.9 | 37.7 | 37.2 |
| $TiO_2$ | 0.5 | 0.5 | 0.0 | 0.0 | 1.7 | 1.6 | 1.7 | 1.6 | 1.8 | 1.8 |
| $Al_2O_3$ | 11.1 | 11.5 | 18.1 | 18.7 | 14.9 | 15.7 | 15.6 | 15.5 | 15.1 | 15.2 |
| $FeO*$ | 22.1 | 22.5 | 21.4 | 21.7 | 22.2 | 21.5 | 21.8 | 20.7 | 22.3 | 21.8 |
| MgO | 7.3 | 7.3 | 18.0 | 18.2 | 10.5 | 11.0 | 10.8 | 10.7 | 10.1 | 9.9 |
| MnO | 0.4 | 0.5 | 0.8 | 0.7 | 0.3 | 0.3 | 0.3 | 0.4 | 0.3 | 0.3 |
| CaO | 11.1 | 11.1 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| $Na_2O$ | 1.7 | 1.9 | 0.0 | 0.0 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 |
| $K_2O$ | 1.6 | 1.7 | 0.1 | 0.0 | 9.8 | 9.9 | 9.8 | 9.5 | 9.7 | 9.8 |
| $H_2O**$ | 1.9 | 1.9 | 11.6 | 11.7 | 3.9 | 4.0 | 4.0 | 3.9 | 4.0 | 3.9 |
| Sum | 99.6 | 99.6 | 99.0 | 99.7 | 100.1 | 101.3 | 101.5 | 98.3 | 101.0 | 100.0 |
| Si | 6.49 | 6.35 | 3.00 | 2.94 | 5.64 | 5.62 | 5.64 | 5.58 | 5.71 | 5.70 |
| $Al_t$ | 1.51 | 1.65 | 1.00 | 1.06 | 2.36 | 2.38 | 2.36 | 2.42 | 2.29 | 2.30 |
|  | 8.00 | 8.00 | 4.00 | 4.00 | 8.00 | 8.00 | 8.00 | 8.00 | 8.00 | 8.00 |
| $Al_o$ | 0.52 | 0.47 | 1.20 | 1.20 | 0.34 | 0.41 | 0.41 | 0.42 | 0.41 | 0.44 |
| Ti | 0.06 | 0.06 | 0.00 | 0.00 | 0.20 | 0.18 | 0.19 | 0.19 | 0.21 | 0.21 |
| Fe | 2.86 | 2.94 | 1.85 | 1.86 | 2.85 | 2.71 | 2.75 | 2.70 | 2.83 | 2.80 |
| Mg | 1.68 | 1.70 | 2.77 | 2.79 | 2.41 | 2.48 | 2.43 | 2.49 | 2.29 | 2.27 |
| Mn | 0.06 | 0.06 | 0.07 | 0.06 | 0.04 | 0.04 | 0.04 | 0.05 | 0.04 | 0.04 |
|  | 5.18 | 5.23 | 5.89 | 5.91 | 5.84 | 5.82 | 5.82 | 5.85 | 5.78 | 5.76 |
| Ca | 1.84 | 1.86 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Na | 0.52 | 0.56 | 0.00 | 0.00 | 0.02 | 0.04 | 0.03 | 0.03 | 0.02 | 0.04 |
| K | 0.31 | 0.33 | 0.01 | 0.00 | 1.91 | 1.91 | 1.89 | 1.87 | 1.89 | 1.92 |
|  | 2.67 | 2.75 | 0.01 | 0.00 | 1.93 | 1.95 | 1.92 | 1.90 | 1.91 | 1.96 |
| O | 24.00 | 24.00 | 18.00 | 18.00 | 24.00 | 24.00 | 24.00 | 24.00 | 24.00 | 24.00 |

1,2 Amphibole, DO1-1114
3,4 Chlorite DO1-1114
5-10 Biotite, DO1-1114
* All Fe as FeO
** $H_2O$ calculated

# TABLE II. Modes of samples from DO-1

|  | DO1-1075 | DO1-1079 | DO1-1114 |
|---|---|---|---|
| Quartz | 28.8 | 27.9 | 33.1 |
| K-feldspar | 22.5 | 17.2 | 18.4 |
| Plagioclase | 39.0 | 39.9 | 33.6 |
| Biotite + chlorite | 8.9 | 12.6 | 13.2 |
| Amphibole | - | - | 0.3 |
| Epidote | 0.4 | 0.2 | tr |
| Titanite | 0.4 | 2.2 | 1.1 |
| Opaques | tr | tr | 0.2 |
| Accessories | tr | tr | 0.1 |
| no. points | 1450 | 1450 | 1450 |

The texture of the granite is allotriomorphic inequigranular. Few grains are euhedral or subhedral; most have embayed and irregular edges, and some are bordered by fine-grained mosaics of quartz and feldspar (Fig. 4b).

Modal analyses of representative samples are shown in Table II; in Streckeisen's (1976) classification, the rocks plot along the monzogranite-granodiorite boundary.

The mineralogy of the mafic clots is the same as that of the granite, with greater amounts of dark minerals, and C.I. about 40. Biotite is present in higher proportions than amphibole. Most mafic clots are finer grained than the granite, with the grain size of the major minerals ranging from 0.1 to 1.0 cm.

## FRACTURE FILLINGS

The granite in the core is cut by numerous veins of at least two generations. First generation veins are steeply dipping and filled (0.1-1.0 cm wide) with calcite +
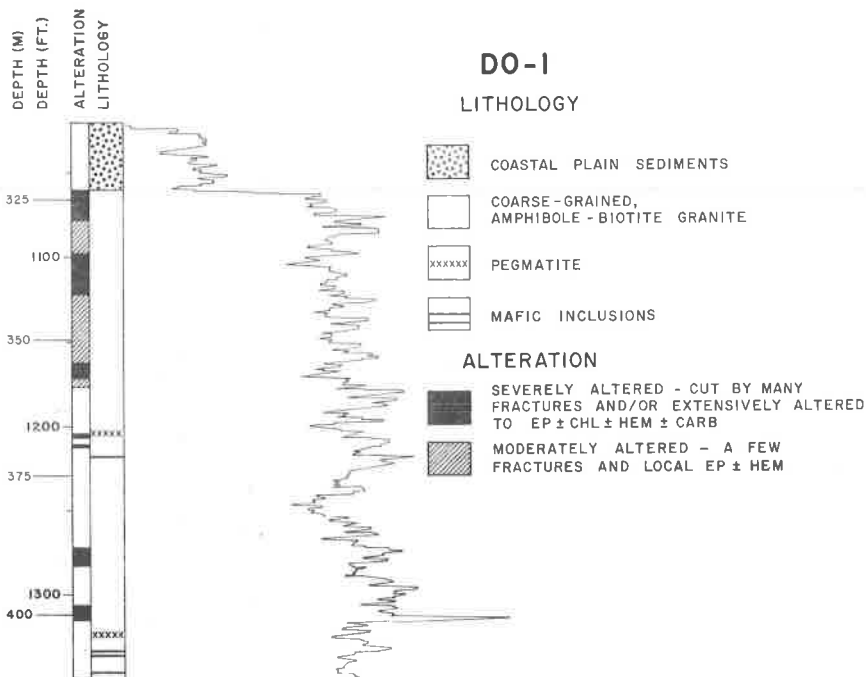
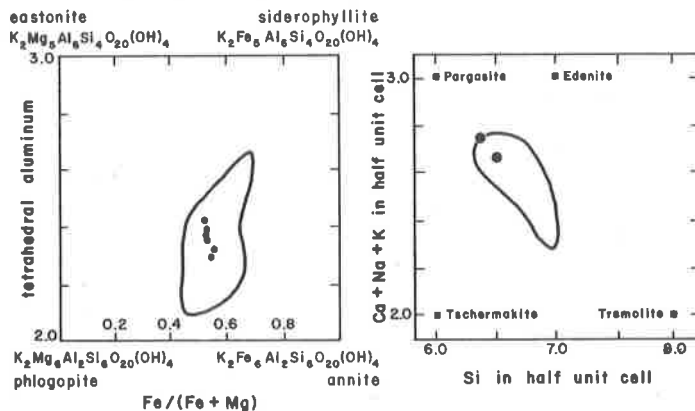Figure 2.  Lithologic and gamma logs of DO-1.



Figure 3.  (a) Plot of analyses of biotite from the Dort Granite; and (b) amphibole analyses.  In each diagram, the lines enclose compositions of the respective phases in post-metamorphic granites in the exposed southeastern Piedmont (Speer, et. al., 1980).

epidote $\pm$ chlorite.  In one sample (DO-1122), a few chlorite crystals contain grains of blue fluorite.

In the vicinity of the first generation veins, the granite is green and friable for a distance of 10 to 20 cm from the fracture.  Where the core is cut by numerous veins, the green color may continue over a distance of more than a meter.  Thin sections show that the pervasive green color is caused by the presence of abundant epidote and chlorite, which entirely replace biotite and amphibole.  Titanite grains, with euhedral outlines still distinct, are completely altered to turbid mats containing clots of opaque minerals.  Saussuritization is extensively developed in plagioclase, and calcite is the most abundant saussuritization product.

Second generation veins cuts and clearly postdate those of the first.  They are horizontal, and filled with calcite alone (0.1-0.2 cm).  No alteration is apparent in the adjacent granite.
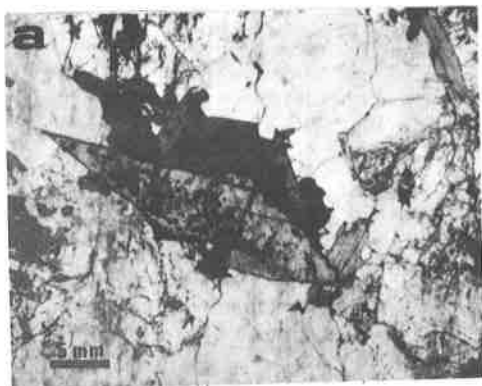
42

Figure 4. (a) Photomicrograph of euhedral titanite grain in sample taken from 339.5 m. The titanite is bordered by biotite, magnetite, K-feldspar, and quartz. (b) Photomicrograph (X-Nicols) of large microcline grain bordered by recrystallized mosaic of quartz + K-feldspar.

## DEFORMATION

Several petrographic features of the Dort granite suggest that it was mildly deformed during or after intrusion. Quartz grains have undulose extinction and show development of subgrain boundaries. Large quartz and feldspar grains are bordered by a crystal hash of fine-grained quartz and feldspar. These fine-grained mosaics appear to have recrystallized during or after deformation, while the granite was still fairly hot, because the fine-grained crystals commonly have sutured grain boundaries, and meet at angles of $120^\circ$.

The granite was subsequently subjected to two periods of brittle deformation. During the first episode, steep fractures formed, and hydrothermal fluids rich in $CO_2$ + $H_2$ + $F_2$ circulated through the fractures. The fluids produced a mineral assemblage of calcite $\pm$ epidote $\pm$ chlorite $\pm$ fluorite in the fractures, and epidote + chlorite + calcite in the granite. During the second episode the granite was fractured along nearly horizontal planes. $CO_2$-rich fluids filled the fractures with calcite, but had little effect on the granite mineralogy.

## COMPARISON TO THE PETERSBURG GRANITE

In mineralogy, mode, and grain size, the Dort Granite closely resembles the Petersburg Granite, which crops out as close as 65 km to the northwest (Farrar, in preparation) (Fig.1). In both granites, biotite is the dominant mafic mineral; amphibole occurs in minor amounts in both the Dort Granite and some phases of the Petersburg Granite. The Petersburg Granite also shows primary textures, similar to those of the Dort Granite, that are indicative of slight recrystallization following mild deformation (Bobyarchick, 1978).

## CONCLUSIONS

The basement rock encountered in a drill hole in Gates County, North Carolina, is a coarse-grained granite which resembles petrographically the syntectonic (Bobyarchick, 1978) Petersburg Granite. The similarity of the two granites suggests that some lithologies in the exposed Piedmont also occur to the east under Coastal Plain sediments. In addition, the recovery of granite from a drill hole centered on a pronounced gravity low suggests that gravity data can be used as an indication of the nature of the basement rocks beneath Coastal Plain sediments.

## ACKNOWLEDGEMENTS

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# CHLORAPATITE FROM NORTHERN VIRGINIA:

# THE FIRST OCCURRENCE IN THE UNITED STATES

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## ABSTRACT

Chlorapatite occurs in the Fairfax trap quarry at Centreville, Fairfax County, and in the Bull Run trap quarry, Loudon County. Both quarries are in Triassic diabase. The euhedral to subhedral stubby prismatic crystals vary from 1 mm to 40 mm long, and are cloudy white to light greenish-gray. The crystal morphology and optical data are given. Chemical analyses, especially for specimens from the Fairfax quarry, indicate a fluorian-hydroxylian chlorapatite. X-ray diffraction powder data are presented and discussed, and it is shown the mineral can be separated from the related species on the basis of these data. Single crystal X-ray studies indicate hexagonal symmetry in contrast to the monoclinic symmetry of some natural and synthetic chlorapatite.

## INTRODUCTION

Although chlorapatite, $Ca_5(PO_4)_3Cl$, is listed in nearly every mineralogy textbook as a well-known apatite species, it is not generally realized that the mineral is very rare. It has been reported from Norway (Hendricks and others, 1932; Morton and Catanzaro, 1964), Japan (Seto, 1932; Harada, 1938), Canada (Hounslow and Chao, 1970), India (Babu, 1972), and in some stony meteorites (Shannon and Larsen, 1925). Studies of an apatite-rich vein in a specimen of diabase from the well-known Fairfax trap quarry at Centreville, Fairfax County, Virginia, have recently shown the mineral to be chlorapatite. After this discovery small euhedral chlorapatite crystals from the Bull Run trap quarry in Loudon County, Virginia, were also identified.

Both quarries are in Triassic diabase outcrops which are only two of many similar localities in northern Virginia. Because these Triassic rocks are tectonically and genetically related to many similar occurrences scattered across New Jersey, Pennsylvania, Maryland, Virginia, and North Carolina, further study may show chlorapatite is widespread in this geologic environment. However, it should be noted here that tiny apatite crystals recovered from a pink feldspar-rich vein in diabase from a similar exposure near Goose Creek, Virginia, yielded X-ray data typical of fluorapatite. Also recent surveys of New Jersey trap quarries (Peters, Peters, and Weber, 1978; and Sassen, 1978) have not recorded the presence of apatite. Mason (1960) did note apatite from the Palisades sill, a New Jersey diabase intrusive, but did not indicate the species.

The general mineralogy of the Fairfax quarry was described by Medici (1972) while that of the Bull Run quarry was described by Freeland (1979).

## DESCRIPTION OF THE CHLORAPATITE

Specimens from the Fairfax quarry have a vitreous to greasy luster and consist of translucent light greenish-gray chlorapatite in the crystal cores with opaque white

alteration zones of fluorapatite along the crystal margins and internal fractures. The largest crystal observed measures 4 cm by 1.5 cm, although crystals measuring from 3 mm to 10 mm are more common. The crystals vary from euhedral to subhedral. Goniometric and X-ray studies of one relatively small crystal showed a combination of second order prisms, a ($11\bar{2}0$), and smaller first order prisms, m ($10\bar{1}0$). Although on this imperfect crystal other faces were absent (some broken off), cleavage planes parallel to c (0001) and m ($10\bar{1}0$) were detected. The indices of refraction are e = 1.650 (third decimal estimated) and o = 1.653. The specific gravity of the chlorapatite from Fairfax is 3.17.

These chlorapatite crystals occur in a vein in diabase where they compete for space with crystals of a black to greenish-black pyroxene, which according to X-ray studies is close to the diopside end of the diopside-hedenbergite series. These subhedral crystals average 1 cm across. Minor amounts of bornite are also in the vein. Small radiating needles of green amphibole are associated with the margins of some of the chlorapatite crystals. The original vein was at least 1 cm wide, but the specimen available for study was broken so only the contact with one wall was observable. Between the chlorapatite-pyroxene vein and the dark gray medium-grained diabase matrix rock is a lighter gray transition zone (1 cm wide) rich in white plagioclase. Although the species was not indicated, apatite crystals have been reported previously at this deposit (Dietrich, 1970; Medici, 1972).

The chlorapatite from Bull Run occurs as vitreous, stubby, euhedral crystals which vary from cloudy white to clear grayish. All the crystals studied are less than 1 mm across, usually between 0.50 and 0.75 mm. Goniometric measurements were made of several specimens. The largest forms are c (0001) and m ($10\bar{1}0$) followed by x ($10\bar{1}1$) and a ($11\bar{2}0$). The angle, measured from the perpendiculars to c (0001) and x ($10\bar{1}1$), varies from 39°23' (3 sharp faces) on one crystal to 39°35' (1 sharp face) on a second specimen, indicating c/a ratios of 0.711 and 0.716 respectively. These data correlate well with the c/a ratio expected for chlorapatite (0.7041) which is smaller than those for fluorapatite (0.7346) and hydroxyl-apatite (0.7305), calculated from the data of Young and Elliott (1966). Measurements of the indices of refraction yielded the following in which the third decimal is estimated: e = 1.643, o = 1.647. The specific gravity was not determined for the Bull Run chlorapatite because the few available crystals are laced with inclusions and attached minerals, and are very small.

The chlorapatite crystals from the Bull Run quarry occur either singly or are intergrown with each other. They are intermixed with loosely aggregated, matted asbestiform white amphibole, dark green to black amphibole needles, fine-grained platy to spherulitic green chlorite, euhedral white plagioclase plates, wedge-shaped amber-colored titanite, and clear datolite crystals. Many of the apatite crystals have grown around and incorporated dark amphibole needles. The minerals in this association have recently been described by Freeland (1979).

## X-RAY DIFFRACTION DATA

The X-ray diffraction powder data given in Table 1 represent the averaged values from five diffractometer traces of translucent unaltered chlorapatite from Fairfax. The reflection angles were obtained with a goniometer scanning of one quarter degree 2θ per minute (nickel-filtered copper radiation). Accuracy was checked using a silicon standard and fluorapatite from Durango, Mexico with known parameters (Young and others, 1969). The precision reported as the standard deviation was 0.05° 2θ (or 0.004 A in the region of the strongest reflections). In order to index the powder data, all possible reflections allowed by the P6₃/m space group were calculated through 1.20 A. The unit cell a = 9.53, c = 6.86, determined from our powder data, was used in the calculations. No appreciable differences were observed for the Bull Run specimens.

Examination of diffraction data indicated there is significant zoning in the chlorapatite from Fairfax. Since the a dimension is the most sensitive to variations in chlorine, fluorine, and hydroxyl content (Table 2), diffractometer traces from the powder of a compositionally-zoned crystal should manifest a-dependent peaks which are broader relative to the c-dependent peaks. The Fairfax chlorapatite reflections dependent upon the a parameter (i. e. h00 and hk0) show significant broadening and in

Table 1. X-Ray Data for Chlorapatite from Fairfax quarry (nickel filtered copper radiation).

| hkl | d calculated (Å) | d observed (Å) | I |
|-----|------------------|----------------|---|
| 100 | 8.25 | 8.26 | 11 |
| 101 | 5.28 | 5.29 | 8 |
| 110 | 4.765 | 4.774 | 2 |
| 200 | 4.127 | 4.129 | 6 |
| 111 | 3.914 | 3.912 | 8 |
| 201 | 3.536 | 3.542 | 5 |
| 002 | 3.430 | 3.434 | 69 |
| 102 | 3.167 | 3.169 | 15 |
| 210 | 3.119 | 3.122 | 11 |
| 121 | 2.840 | 2.840 | 95 |
| 112 | 2.784 | 2.779 | 100 |
| 300 | 2.751 | 2.750 | 63 |
| 202 | 2.638 | 2.633 | 50 |
| 301 | 2.553 | 2.556 | 3 |
| 310 | 2.289 | 2.292 | 26 |
| 311 | 2.171 | 2.169 | 14 |
| 302 | 2.146 | 2.148 | 6 |
| 400 | 2.063 | 2.066 | 8 |
| 203 | 2.000 | 2.000 | 5 |
| 222 | 1.957 | 1.957 | 51 |
| 312 | 1.904 | 1.905 | 15 |
| 320 | 1.893 | 1.895 | 12 |
| 213 | 1.844 | 1.842 | 59 |
| 321 | 1.825 | 1.824 | 14 |
| 410 | 1.801 | 1.800 | 9 |
| 402 | 1.768 | 1.766 | 17 |
| 303 | 1.759 | 1.758 | 6 |
| 004 | 1.715 | 1.717 | 8 |
| 104 | 1.679 | 1.677 | 1 |
| 322 | 1.658 | 1.656 | 5 |
| 313 | 1.618 | 1.616 | 18 |
| 420 | 1.560 | 1.557 | 1 |
| 403, 421 | 1.532, 1.521 | 1.529 | 7 |
| 214 | 1.503 | 1.500 | 11 |
| 502 | 1.487 | 1.487 | 6 |
| 323, 304 | 1.458, 1.455 | 1.455 | 14 |
| 511 | 1.449 | 1.451 | 35 |
| 332 | 1.441 | 1.443 | 9 |
| 215 | 1.256 | 1.255 | 8 |
| 414, 611 | 1.242, 1.238 | 1.240 | 9 |

the case of (300), there are actually several closely spaced reflections. Reflections dependent upon the c parameter are generally narrow. The smallest shifts in the a parameter occur within the translucent and apparently unaltered cores of the apatite crystals. There exists a larger deviation between the unit cells of the translucent portion and the opaque portion.

In order to verify these conclusions about the translucent and opaque portions, numerous X-ray diffraction powder films were prepared using cameras of 11.46 cm diameter (nickel-filtered copper radiation). Only a small quantity of mineral is required in this technique, and this can be selected from specific zones within the crystals. Films obtained from the opaque altered areas are visually different from those obtained from the translucent chlorapatite, and the interplanar spacings of the opaque zone are much closer to fluor-hydroxyl-apatite than chlorapatite.

Because Canadian chlorapatite (Hounslow and Chao, 1970) and synthetic chlorapatite (Prener, 1967) have been found to be monoclinic with space group $P2_1/a$, a single crystal X-ray study was made of the Virginian specimens to check their

Table 2.  Comparative Physical Data for Apatite.

| | a(A) | c(A) | c/a | e | o | Specific Gravity |
|---|---|---|---|---|---|---|
| Synthetic Chlorapatite | 9.634[1] | 6.783[1] | 0.7041 | 1.6675[2] | 1.6684[2] | 3.172[4] |
| Synthetic Hydroxyl-apatite | 9.442[1] | 6.883[1] | 0.7305 | 1.664[3] | 1.651[3] | 3.152[4] |
| Synthetic Fluorapatite | 9.364[1] | 6.879[1] | 0.7346 | 1.630[2] | 1.6325[2] | 3.212[4] |
| Unaltered Chlorapatite from Fairfax quarry | 9.53 | 6.86 | 0.7198 | 1.650 | 1.653 | 3.17 |
| Chlorapatite from Bull Run quarry | --- | --- | 0.7135 | 1.643 | 1.647 | --- |

[1] Young and Elliot (1966)
[2] Palache and others (1951)
[3] Mitchell and others (1943), optical data for nearly pure natural hydroxyl-apatite
[4] Calculated

Table 3.  Chemical Data for Fairfax Apatite - Major Elements.

| | Chlorapatite, Unaltered Crystal Core | Fluorapatite, Altered Crystal Rim | Theoretical $Ca_5(PO_4)_3(Cl,F,OH)$[2] |
|---|---|---|---|
| CaO | 54.87% | 52.83% | 55.38% |
| $P_2O_5$ | 40.62 | 39.95 | 42.06 |
| $Cl_2$ | 3.22 | 2.02 | 2.33 |
| $F_2$ | 0.84 | 1.95 | 1.25 |
| $H_2O$[1] | 0.50 | 0.25 | 0.56 |
| Total | 100.05 | 97.00 | 101.58 |
| O = Cl,F | 1.08 | 1.28 | 1.58 |
| Corrected Total | 98.97 | 95.72 | 100.00 |

[1] $H_2O$ determined by difference as OH necessary to fill monovalent site.
[2] Cl:F:OH = 1:1:1, Palache and others (1951)

symmetry. Rotation and Weissenberg (showing a* and c*) photographs were made of several crystals representing both localities.  Superlattice reflections, like those reported for the Canadian chlorapatite, were not observed so it is concluded the Virginian material is hexagonal.


## CHEMICAL DATA

The major elements in the apatite from Fairfax were determined by wet chemical analyses, however, the chlorapatite from Bull Run was not analyzed due to the small quantities of impure material available.  Mineral grains to be analyzed were sorted under the microscope to minimize impurities.  The specimens were powdered and oven dried (105° C) to remove adsorbed water.  Each sample (100-200 mg) was weighed and dissolved in 10% nitric acid. Dissolution was carried out in plastic beakers and samples were stored in plastic bottles to avoid loss of fluorine by reaction with silica glass. Dilution of samples to constant volume was performed rapidly to avoid loss of HF volatiles.  Calcium was determined by standard atomic absorption spectrophotometric techniques including use of lanthanum as a complexation and ionization buffer and a deuterium arc to compensate for scattering.  Phosphate analyses were performed according to the Standard E.P.A. technique (Environmental Protection Agency, 1974), i.e., the single-reagent molybdenum blue method.  Chloride and fluoride were analyzed with specific ion electrodes by the calibrated electrode technique of Duff and Stuart

(1971) and Evans and others (1970) and by the standard additions method of Burton (1971). A 1.5 M sodium citrate solution mixed 1:1 with unknowns and standards was used both to normalize ionic strengths and to prevent interferences due to complexation. Edmund (1969) demonstrated the superiority of sodium citrate over the conventional ionic strength-complexation buffers. When using specific ion probes, better accuracy is attained if the standards have the same concentrations of dissolution acid, calcium, and phosphate as the unknowns even if a very strong ionic strength buffer is used. Reagent-grade, halogen-free $CaHPO_4$ dissolved in 10% nitric acid was used to provide the proper matrix for the standards. The sodium citrate also buffered the pH into the proper range (5-7) for fluoride analysis. As done by Walters and Luth (1969), water was determined by difference as $OH^-$ necessary to fill the monovalent structural site because of the difficulty and unreliability of most methods available for water determination. Apatite must be heated above $1400^\circ$ C to remove all structural water and it is not known how much halogen and $CO_2$ are lost simultaneously. The precision of the data for major elements in Table 3 is better than 2.5% as relative standard deviation. The chemical data in Table 3 are of the same chlorapatite for which X-ray data are reported in Table 1. Accuracy for the major elements was checked by analyzing fluorapatite from Mexico (Young and others, 1969) along with our samples. The chemical formulas of the apatite from Fairfax in Table 4 were calculated assuming exactly three phosphate anions and no significant contribution from the minor elements. Minor and trace elements, determined by semiquantitative spectrographic analysis, are reported in Table 5.

## DISCUSSION

The chemical data clearly indicate that chlorine is the dominant anion in the monovalent structural site for the greenish translucent portion of the mineral. Thus the mineral from Fairfax is considered to be chlorapatite even though only 48% of the possible sites are filled by chlorine. Analyses of other chlorapatite crystals from Fairfax indicate chlorine fills between 50% and 62% of the chlorine sites. The chlorine content apparently varies with the proximity of the analyzed grains to the chlorine-rich cores of the zoned crystals. Therefore whether the criterion for chlorapatite is Cl >(OH + F) or Cl> OH and Cl> F, the cores of the Fairfax crystals can be accepted as fluorian-hydroxylian chlorapatite.

The white portions of the chlorapatite have the composition of chlorian fluorapatite. These same white zones occur along internal fractures in the crystals. This relationship indicates a paragenetic sequence for the minerals in the vein. After the intrusion of the diabase, the chlorapatite-diopside vein was deposited along a joint. Subsequently the host rock was deformed sufficiently to fracture the chlorapatite crystals and then apparently a fluorine-bearing solution partially replaced the chlorine and hydroxyl in the apatite yielding a zoned crystal. The chlorine and hydroxyl depletion relative to the core demonstrates the preference of the monovalent site for fluorine.

Apparently zoning from chlorapatite to fluorapatite is a unique feature of the Fairfax quarry. Two of the other four terrestrial occurrences for chlorapatite, Japan and Norway, have crystals of chlorapatite which are altered externally to hydroxylapatite (Harada, 1938; Morton and Catanzaro, 1964).

The calcium and phosphate analyses indicate there is very little deviation from stoichiometry in the apatite from Fairfax. The slight excess of calcium relative to phosphate may indicate very minor substitution of silicate, vanadate, or carbonate for phosphate. Indeed the spectrographic analysis (Table 5) verified the presence of some vanadate and silicate. The spectrographic analysis also reveals the presence of minor amounts of many elements which are known to substitute for calcium the apatite structure, i.e., Mn, Na, Sr, Y, Yb, La, Nd, and Ce. However, the possibility that some of the minor and trace elements may be from inclusions, perhaps diopside or actinolite, cannot be completely discounted. Considering the minor elements, it is understood why the major element analyses total a little less than 100% (Table 3).

The X-ray data show that the chlorapatite from Fairfax has a unit cell ($\underline{a}$ = 9.53, $\underline{c}$ = 6.86) intermediate between chlorapatite and fluor-hydroxyl-apatite (Table 2). The

Table 4.  Chemical Formulas of Fairfax Apatities[1].

| | Chlorapatite, Unaltered Crystal Core | Fluorapatite, Altered Crystal Rim | Theoretical $Ca_5(PO_4)_3(Cl,F,OH)$ |
|---|---|---|---|
| $Ca^{2+}$ | 5.13 | 5.02 | 5.00 |
| $PO_4^{3-}$ | 3.00 | 3.00 | 3.00 |
| $Cl^{1-}$ | 0.48 | 0.30 | 0.33 |
| $F^{1-}$ | 0.23 | 0.55 | 0.33 |
| $OH^{1-}$ | 0.29 | 0.15 | 0.33 |

[1] Based on $PO_4 = 3.0$

Table 5.  Semiquantitative Chemical Data for Fairfax Apatite – Minor Elements.

| | Chlorapatite Unaltered Crystal Core | | Chlorapatite Unaltered Crystal Core |
|---|---|---|---|
| $SiO_2$ | 0.75% | $TiO_2$ | 0.005 |
| $Fe_2O_3$ | 0.25 | $SrO$ | 0.05 |
| $Al_2O_3$ | 0.30 | $BaO$ | < 0.001 |
| $MgO$ | 0.15 | $Y_2O_3$ | 0.025 |
| $MnO$ | 0.05 | $Yb_2O_3$ | 0.002 |
| $V_2O_5$ | 0.03 | $La_2O_3$ | 0.08 |
| $CuO$ | 0.001 | $Nd_2O_3$ | 0.05 |
| $Na_2O$ | 0.05 | $Ce_2O_3$ | 0.15 |
| | | Total | 1.944 |

intermediate composition inferred from the X-ray data agrees well with the chemical data.  The cell for the chlorapatite from Fairfax is similar to the cell determined by Hendricks and others (1932) for chlorapatite from Norway  (a = 9.52, c = 6.85) with chlorine filling 64% of the monovalent sites.  Harada and others (1971) reported a Japanese chlorian hydroxyl-apatite with 33% of the monovalent sites filled by chlorine. The apatite from Japan has a unit cell (a = 9.49, c = 6.85) which is fairly close.  Other natural chlorapatites have a unit cell much closer to synthetic chlorapatite because of their higher chlorine content.  It should be noted, however, that X-ray data for natural apatite can provide only a semiquantitative indication of the chlorine content, because a large variety of ions can substitute for calcium, phosphate, and/or chlorine.

When X-ray diffraction powder films of the specimens from Fairfax were initially examined it was obvious the mineral was an apatite, but not the common fluorapatite species.  A study of the data using the Hull-Davey (1921) chart showed the mineral to have a c/a ratio of approximately 0.71, significantly smaller than the ratios for fluorapatite (0.7346) and hydroxyl-apatite (0.7305).  The spatial relationships, on the chart and the films, between the following three groups of reflections are especially sensitive to variations in the c/a ratio and were found to be good indicators of the apatite species:  102 and 210; 121, 112 and 300; and 402, 303 and 004. In chlorapatite the 102 and 210 reflections are nearly indistinguishable (almost superimposed) while there is a definite separation of them in fluorapatite and hydroxyl-apatite. Also in chlorapatite 121 is somewhat separated in position from the closely juxtaposed 112 and 300 pair, while in fluorapatite and hydroxyl-apatite 121 and 112 form a close pair somewhat separated from 300.  Finally in chlorapatite the 402-303 doublet and 004 are much more widely spaced than in fluorapatite and hydroxyl-apatite. With pictures from powder diffraction films, Wallaeys and Chaudron (1950) illustrated the gradation in the spatial relationships of reflections for a series of six synthetic members of the chlorapatite-fluorapatite series.  Walters and Luth (1969) also emphasize the usefulness of unit cell dimensions for differentiating the apatite species.

The hexagonal symmetry revealed by the single crystal photographs is expected for chlorapatite with the composition of the specimen from Fairfax.  Prener (1967),

from studies of synthetic chlorapatite crystals, observed that the pure substance is monoclinic at room temperatures and transforms to the hexagonal from between $185^{\circ}$ and $210^{\circ}$ C. When it is cooled, the transition is reversible. However, the higher symmetry hexagonal form is easily stabilized by the substitution of small amounts of hydroxyl (Young and Elliot, 1966) and fluorine anions (Prener, 1967), thus explaining the reason natural chlorapatite is usually hexagonal. In studies of synthetic fluor-chlorapatite Prener (1967) concluded that the hexagonal form becomes stable above a certain atomic ratio of $F/(F+Cl)$ somewhere between 0.16 and 0.36. Hounslow and Chao (1970), supporting Prener's (1967) general conclusions, suggested the lower figure of 0.16 is very close to the transitional composition; and further suggested the transition from hexagonal to monoclinic occurs when 82% to 91% of the monovalent sites are filled with chlorine. The chlorapatite from Fairfax has between 48% and 62% chlorine occupancy in the monovalent site, well into the hexagonal range. The chlorapatite from Bull Run is also hexagonal but its c/a ratio suggests that the substitution for chlorine is less extensive and therefore the substance may approach the maximum chlorine content allowed in hexagonal chlorapatite.

The indices of refraction for chlorapatites from Fairfax and Bull Run are closer to the values reported for hydroxyl-apatite than synthetic chlorapatite (Table 2). However, the Virginian chlorapatite indices are close to those reported by Seto (1932), $\underline{e} = 1.651$ and $\underline{o} = 0.657$, for Japanese chlorapatite with chlorine filling 62% of the monovalent positions. It is not surprising that the Virginian and Japanese chlorapatites should have indices close to hydroxyl-apatite because of their high fluorine content. Hydroxyl-apatite has indices of refraction intermediate between fluorapatite and chlorapatite (Table 2). Consequently fluorian chlorapatite should have indices which fall close to hydroxyl-apatite indices.

The chlorapatites from Fairfax and Japan (Seto, 1932; Harada, 1938) share the distinction of being the most chlorine deficient of the natural chlorapatites, i.e., the chlorapatite from Fairfax has 48% to 62% chlorine occupancy of the chlorine positions and the chlorapatite from Japan has 55% to 62% occupancy. As such, these minerals come closest to fulfilling the prediction of Hendricks and others (1932) that there may exist a natural phase with the composition $Ca_{10}(PO_4)_6FCl$ in which there is a statistical ordering of chlorine and fluorine atoms. This hypothetical mineral would bear the same relationship to chlorapatite and fluorapatite that dolomite bears to calcite and magnesite. However, no evidence for such a phase with lower symmetry has been noted.

## ACKNOWLEDGMENTS

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