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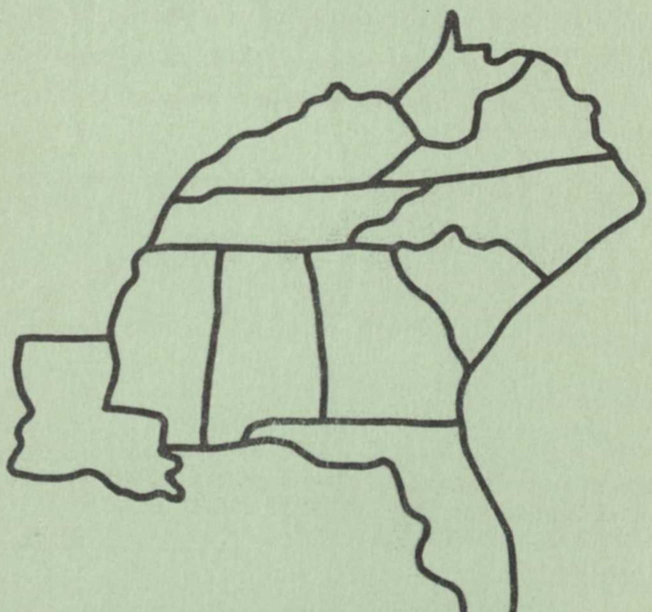

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SOUTHEASTERN GEOLOGY

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ORGANIC TRANSLOCATION OF METALS

By

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ABSTRACT

Organic translocation of metals is an important geologic process. Soil scientists have obtained considerable data on this subject in their studies of podzolization. Experiments have shown that plant materials contain substances capable of translocating metals. Organic translocation and subsequent precipitation may be a catalytic type of reaction. This hypothesis may explain certain aspects of metal distribution. Podzolization is a function of parent material, climate, topography, vegetation and time. It probably reaches its maximum in the humid tropics. Podzolization theory may aid exploration for mineral deposits and help to explain the genesis of some ores.

INTRODUCTION

Organic translocation of metals may be important to geologists in two ways. First, the process may affect the reliability of geochemical prospecting by soil sampling as follows: A. surface anomalies may be masked by the metals being translocated below the sampling zone; B. varying degrees of translocation may create confusing patterns even if sampling is done at pedogenetically similar horizons, e.g. B_2 horizons instead of simply at arbitrary depths; C. erosion may expose zones of concentration in either contemporary or fossil soils, which may be erroneously interpreted as significant anomalies. Second, some ore deposits may be formed or enriched by organic translocation. This has been suggested in specific cases by Lovering (1934), Freise (1931), Watson (1905) and others. Krauskopf (1955, p. 447-448) has made the general statement, "The lack of information about organic processes of concentration is particularly unfortunate, because it is precisely these processes that apparently are responsible for the greatest enrichment of rare metals in sedimentary rocks." Many soil scientists and geologists, e.g. Robinson (1951), Joffe (1949) and Park (1959) have suggested that laterite represents an illuvial concentration by organic processes.

PODZOLIZATION AND PODZOLS

Organic translocation of metals has not been extensively investigated by geologists, except for a few empirical experiments to be referred to later. Soil scientists have given a great deal of attention to this matter, because the soil-forming process called podzolization has generally been considered to consist largely of simultaneous movement of organic matter and sesquioxides. Podzol is an old Russian peasant word meaning "like ashes". Podzol originally meant a soil with a strongly bleached surface. Russian soil scientists apparently still use podzol and podzolization in this sense. However, in the United States and elsewhere podzol has come to mean a specific kind of bleached soil in which organic matter and sesquioxides are segregated in lower horizons of the profile. Some controversy exists as to the proper definition of podzolization. Many soil scientists would like to abolish the term since it has also been applied to clay translocation, sesquioxide translocation alone, organic matter translocation alone and simply the process(es) leading to the formation of one or more profile characteristics considered to be typical of podzols. Nevertheless, the traditional international concept of podzolization has been that of organic translocation of metals especially iron and aluminum. Joffe (1949) has probably given the best summary of the history of the term and the ideas as to the nature of the process, while the recent review of Stobbe and Wright (1959) is the best modern treatment of the subject.

Most introductory texts describe podzolization as being a phenomenon of cool climates which reaches its fullest expression in the Podzol great soil group. A Podzol is defined by United States soil scientists and many Europeans as a soil with a layer of raw humus on the surface, a bleached layer underlying it which is high in silica and low in sesquioxides relative to the parent material, followed by a dark brown or black layer rich in organic matter, which in turn is underlain by a reddish or yellowish horizon rich in sesquioxides relative to the parent material. In other words, there has been an apparent translocation of organic matter and sesquioxides from the surface horizons, followed by precipitation of these constituents in separate zones of the subsoil. Later in this paper several references will be made to analyses of podzols, to conditions prevailing in podzols, etc. For the most part these comments are based on studies of podzols as described above since these are the soils that seem to epitomize the process. Such soils are usually only a few feet deep. However, sesquioxide translocation has occurred to much greater depths in some areas and this too has been termed podzolization although organic matter has not yet been demonstrated to be involved. For example, most of the soils of the North Carolina Piedmont are currently called Red-Yellow Podzolic soils. Similarly, many people have referred to laterite-containing soils as "podzolized". Apparently organic matter has not accumulated at depth in either case but the evident downward movement of sesquioxides combined with bleached quartzose surface horizons has been considered evidence of podzolization. Carter and Pendleton (1956) have discussed this view at length and have concluded that sesquioxide translocation and accumulation at depth is the principal soil-forming process in all humid regions. These authors do not discuss the role of organic matter presumably because of lack of data. However, the author has recently found that organic matter coatings are common on cleavage planes, joints, vein quartz, etc. in the saprolite underlying soils in the North Carolina Piedmont. These coatings of organic matter, which have been observed to extend as deep as forty feet with no signs of diminishing, seem to confirm the idea that podzolization can extend to considerable depths.

To summarize, there is considerable evidence and opinion that podzolization is a widespread phenomenon.

The rest of this paper will be devoted to a discussion of the mechanisms involved in podzolization and the factors determining its rate.

MOBILIZATION OF METALS

In order to study the role of organic compounds in the movement of metals in soils, a number of workers have attempted to duplicate podzolization in the laboratory. Harrar (1929), Gallagher (1942), Fetzer(1946) and others utilized simple organic acids and a variety of techniques in an attempt to duplicate podzolization. The reasoning behind these experiments was that various organic acids are known to occur in the soil and/or in plants and that these already identified compounds either are the most likely agents or are similar to other organic compounds which are responsible for metal translocation. These assumptions are now thought to be debatable or at least oversimplified. Gallagher found that oxalic acid passed through a column of soil effectively bleached the surface material, deposited some sesquioxides farther down the column and removed others completely. Harrar worked only with iron compounds and only tested solubilities in various acids, but his data are useful in showing how solubility varies. Fetzer likewise tested only solubilities in isolated systems. He worked with manganese, copper, iron and gold and tested a wide variety of organic acids including a filtered peat extract which was singularly ineffective. This latter point has been confirmed by Bloomfield (1955). The work by these and other workers has demonstrated that the dissociation constant of the acid is not significantly related to its dissolving power. Other investigators have attempted to approximate natural conditions more closely by utilizing plant extracts prepared by soaking leaves, etc. in water and then passing the filtered extracts through columns containing either soil or artificially prepared mixtures of quartz and freshly precipitated metal oxides. Bloomfield (1955), Schnitzer and DeLong (1954), Lossant (1954) and Thorp et al (1957) have shown conclusively that plant extracts are effective in mobilizing iron and aluminum. Lovering (1934) found that pine needle extracts could mobilize lead. Schnitzer and DeLong observed that extracts from fresh young plant material are more effective than extracts from old dry plant material with actual "canopy drip" having the greatest efficiency per unit of organic solute, although the total organic solute content of the drip was relatively very low. Bloomfield's data showed greater effectiveness of young fresh material as did that of Miller and Ohlrogge (1958). This may indicate that rainwater leachates from trees are a significant factor in podzolization. The organic solute content of such leachates may be quite high (Kramer, 1957). In fact, Tamm (1951) found over 100 mg. /liter in rainwater collected under Scotch pine.

A somewhat different approach was taken by Joffe (1932-40) who constructed a type of lysimeter by which he was able to collect the soil solution from different horizons of a natural soil as the liquid percolated through. Analyses of these solutions tended to show good correlations between organic matter and sesquioxide content. Perhaps the most ambitious yet controversial experiment was that performed by Freise (1931) who diverted a Brazilian "black water" stream over a sluice containing gold-impregnated gravel and found that the gold was mobilized and then reprecipitated. In conclusion, it seems permissible to state that a wide range of experiments have demonstrated that there are naturally-occurring organic compounds which are capable of chemically mobilizing metals in the soil.

There are many who still maintain that other agents are responsible for podzolization including sulfuric acid, ammonium salts and purely physical translocation in downward-moving water possibly sorbed to clay or organic matter but not in chemical solution. Coleman* has suggested that limited movement may take place simply by metal ions in solution alone since a certain degree of solubility always exists. According to this theory precipitation would occur when the solubility product was exceeded, i. e. in lower horizons. It is doubtful whether such a process could operate rapidly enough to explain observed rates of podzol formation. A great many soil scientists have followed, more or less, the ideas of Mattson who spoke in terms of humus-protected soils. Bloomfield's (1956) work on clay dispersion has indicated that such colloidal transport may be of some importance in clay accumulation, but few modern workers believe that metals move in this fashion.

PRECIPITATION OF METALS

The problem of podzolization is two-fold - first is mobilization and second is precipitation. So far we have been concerned with the first aspect.

One of the reasons that some people have been reluctant to believe in mobilization by solubility is that subsequent precipitation is so difficult to explain. Of course, metals may be completely removed in the ground water, but the classical concept of podzolization includes at least partial precipitation within the weathering profile.

Let us discuss the alternatives to solution. One line of evidence supporting the physical translocation hypothesis is that podzols are most frequently developed in coarse materials where physical movement is easiest. There is a tendency for the horizons of precipitation to be somewhat finer in texture. Micropedological studies by Stobbe and Wright (1959) have shown that organic matter can be carried downward physically by water "in distinct waves". The principal difficulty with the physical translocation theory is that many of the true podzols, perhaps a majority, fail to show a decrease in permeability or other physical barrier to produce a sieving action. Somewhat different problems are encountered by the proponents of the isoelectric precipitation theory who postulate various types of soils which are precipitated or flocculated by pH and redox change Such changes frequently cannot be demonstrated to exist. Martin and Reeves (1957-1958) have suggested that the sesquioxides in the lower horizons flocculate downward-moving colloidal organic matter. This is theoretically reasonable, but it does not explain the mobilization and precipitation of the metals. The advocates of true organic solutions cannot demonstrate Eh-pH changes or salt contents sufficient to cause solubilization and then precipitation. Another possibility which has been often suggested is decomposition by microorganisms. There are two major difficulties with this biological precipitation hypothesis. One is that there is relatively little biological activity in many podzols. The other is that a principal characteristic of classical podzols is the presence of organic matter in a lower horizon and its persistence is often ascribed to the absence of biological activity.

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* Personal communication from N. T. Coleman, N. C. State Soils Dept.

Catalytic Decomposition

It seems to the author that the above discussion indicates that another explanation is required for the precipitation of both organic matter and metals in the lower horizons. This explanation may be the rather vague one suggested by Swindale and Jackson (1956) that organic complexing agents can "lose their effectiveness with time." There are several indications that this is more or less what happens. For one thing, many of the experiments with laboratory-produced podzols have been so designed that time seems the only possible variable to explain the ultimate precipitation. Similarly, Freise's sluice experiment appears to be a case either of mere physical movement or of "temporary solution" which Fetzer (1946) found so difficult to accept. The trouble with the physical or mechanical explanation is that most of the experimenters have been careful to include blanks or controls using only plain water and in these cases little or no translocation has been observed. Auto-decompositon is not without foundation in organic chemistry and many "catalytic" reactions are of this type. Martell and Calvin (1952) cite several instances where organic complexes form and then decompose to give new products. The author has found that filtered pine needle extract passed through aluminum-saturated clay will develop a black precipitate after a few days. If it is assumed that something like this occurs, it is easier to explain the marked differences between the organic matter of the surface and lower horizons of podzols (Martin and Reeves, 1957-1958).

Unmixing of Metals

The catalytic theory of podzolization suggested above provides the basis for a new attack on the problem of differential translocation and segregation of metals. First, metals differ considerably in their initial susceptibility to complexing, depending upon their chemical characteristics, their mode of occurrence, the numbers and species of other metals present and the nature of the complexing agent. Second, the resulting complexes vary widely in their stability with respect to the external environment. Third, there are great differences in the catalytic activity of metals. All of these points seem to be interrelated. For example, Basolo and Pearson (1958) noted that in the catalytic decarboxylation of oxalosuccinic acid the following sequence was observed in order of decreasing efficiency: Al^{3+} - Fe^{3+} - Cu^{2+} - Fe^{2+} - Zn^{2+} - Mg^{2+} - Mn^{2+} - Ca^{2+}. Although series relationships such as the one just given vary somewhat, depending on the organic compound involved, the overall order for stability, catalytic activity and other properties is usually about the same. The extensive literature on this subject has recently been reviewed by Basolo and Pearson (1958), Williams (1959) and Chaberek and Martell (1959). Basolo and Pearson have generalized the following series. (Note that these are for ions of equal valence. There is some overlapping and variation when ions of different valences are present). Monovalent: Ag - Tl - Li - Na - K - Rb - Cs; divalent: Pt - Pd - Hg - UO_2 - Be - Cu - Ni - Co - Pb - Zn - Cd - Fe - Mn - Ca - Sr - Ba; trivalent: Fe - Ga - Al - Sc - In - Y - Pr - Ce - La. If the catalytic theory outlined above is correct, it would seem that metals translocated by podzolization should tend to be deposited in a similar order. For example, Fe^{+3} and Al should tend to be deposited together near the surface, and zinc and lead should tend to occur close together deeper in the profile. Further study is needed to see whether such relationships are generally found in podzolized soils. This introduction may indicate the desirability of further study of podzolization processes.

FACTORS AFFECTING PODZOLIZATION

It now remains to review briefly the factors affecting the degree to which podzolization takes place. These are virtually equivalent to the five soil-forming factors that form the basis of the science of pedology. Each will be considered separately.

Parent Material

Under this heading is included the chemical and physical composition of the rocks from which the soil is formed with porous acid sediments being the most easily podzolized. Generally, decreasing permeability means decreased leaching and high base content will mean an overload of the podzolization system. (This is a gross over-simplification as is shown by such exceptions as the Gray Wooded soils which combine a podzol profile and high base status. See Vegetation). More specifically, the state of metals in the surface soil prior to translocation presumably has some relation to their susceptibility to podzolization. Boyle (1959) has discussed this question of mode of occurrence at some length in connection with the problems of lead isotope distribution. The following remarks are partially based on his article. There are about seven "states" in which metals may occur in the soil: (1) free native metal; (2) free compounds such as oxides and sulfides; (3) components of the lattice of primary minerals especially the rock-forming silicates – feldspars, amphiboles, pyroxenes, micas, etc; (4) lattice components of secondary minerals, principally clays; (5) exchangeable ions especially on clays and immobile organic matter; (6) interlayer positions in clay minerals such as the copper vermiculite described by Bassett (1958); (7) in other phase boundary situations as postulated by DeVore (1955). Little is known as to the influence of these various states on the degree of podzolization. It might be thought to be a simple matter of free metals and compounds being most readily available, primary lattice components least available and exchangeable ions somewhere in between. Most of the experiments on organic leaching have utilized freshly precipitated oxides but this may be unrealistic. Metals in primary but unstable minerals might be more available than well-aged free oxides. Exchangeable copper, already mobilized sufficiently to get onto an exchange position, may be more available than relatively inert native copper. The author's experiments on controlled clay decomposition by hydrogen saturation indicate that most of the exchangeable aluminum ions so common in Piedmont soils are derived from the breakdown of the clay mineral lattice. Another complication is that some ions are bound more tightly to the exchange positions, which themselves may vary in strength, than are others, and this relative strength of bonding varies with the concentration of the different species of ions as well as with the suite of species involved. The preceding is hardly more than an introduction to the problem of availability, but it indicates the inadvisability of generalizing as to the mobility of metals even without the complications which organic matter introduces.

Climate

The effect of rainfall is primarily to increase simple leaching, but this indirectly favors podzolization by removing soluble weathering products which otherwise would by mass action tend to overload the system. If podzolizing agents are derived from leaves by leaching during rainfall, then increased precipitation will directly influence podzolization. The effect of temperature on organic complexing is not clear, but an increase in temperature might tend to increase the rate of weathering thus overloading the system and slowing down podzolization. This would be true in the early stages of soil development while easily weatherable minerals still remain. It may explain why podzols have been considered to be more characteristic of boreal climates. Another common belief is that higher temperatures prevent podzolization on the surface and in the solum. Recent studies of warm region soils cast grave doubts on these ideas since it has been shown that true podzols do exist in the tropics and that many tropical soils have a high content of organic matter. This belief stems from the idea that podzolizing agents are derived from the peat-like material which accumulates on the surface of podzols in northern regions, but as pointed out above this has been fairly well disproved. High rainfall and high temperatures promote vegetative growth thus providing more complexing agents.

Topography

The principal influence of topography on podzolization is probably in its control on the amount of water passing through the profile. This does not mean that podzolization will necessarily be greatest in depressions since two opposing effects must be taken into account. One is that a depression may receive the weathering products from the surrounding areas thus overloading the system. The other is that the breakdown of primary minerals may be more rapid in continually moist areas, which again tends to overload the system, particularly since excessive clay formation may inhibit the removal of weathering products by decreasing permeability. Therefore, in one area podzolization may be more intense in swampy areas while in others it may proceed faster on ridges. Topography can exercise an indirect influence by altering both the microclimate and the vegetation pattern. There is also the knotty question of landscape development, peneplanation versus pedimentation. United States soil scientists consider pedimentation to be the more tenable theory for landscape development no matter what the climate Pedimentation stresses backwearing while peneplanation emphasizes downwearing. Other factors being equal, pedimentation would result in surfaces of varying age, with podzolization being greatest on the oldest surface. Peneplanation would imply equal podzolization throughout. Pedimentation also complicates a landscape by covering portions of it with pedisediments. This creates polygenetic profiles which makes interpretations difficult. Backwearing creates complications by exhuming various horizons of soils formed in previous weathering cycles. All of this means that rigorous landscape analysis, similar to that done by Ruhe and Scholtes (1956), is necessary for proper interpretation of soils.

Vegetation

This factor can be important both in terms of quantity and quality of podzolizing agents. In general, the greater the rate of plant growth, the greater the supply of complexing materials. Quality differences may either increase or decrease this effect. Plants which consume and recycle large amounts of nutrients will tend to delay podzolization. "Acid-loving" plants will have less of this type of effect. The extreme podzolizing efficiency of certain plants, such as some conifers, may be explained simply in terms of the low nutrient content of their litter. Many feel that these plants make a positive contribution to podzolization by producing more abundant or more powerful complexing agents. The experiments previously cited indicate that this may be true to some degree, but this aspect has probably been overemphasized. Another possibility is that different plants produce complexing agents of varying selectivity. The Gray Wooded soils could be formed under plants whose complexing agents show a strong preference for iron over calcium. There is the complication introduced by edaphic control on vegetation and perhaps on climate that makes it difficult to unravel cause and effect relationships. As a soil becomes degraded by continued leaching and podzolization, the plant population may shift in composition. An extreme example is the case of the "trace element deserts" of Australia (Anderson and Underwood, 1959). It is possible that soil degradation and vegetation shifts may result in climatic changes since many parts of the world are dependent on convectional rainfall derived from local transpiration.

Time

Appreciable podzolization can take place in a few hundred years on acid sandy materials in temperate climates (Bloomfield, 1955), and wooden pilings have been "bauxitized" in a few decades in the Guianas*. Beyond isolated examples such as these, little can be said. Theoretically, the only limits to the depth of podzolization are a stagnant water table or impermeable rock. A thorough analysis of the various soil-forming factors should permit at least a qualitative prediction for a given situation.

* Personal communication from T. J. O'Neill, Kaiser Aluminum & Chemical Corp.

CONCLUSIONS

It might be said that so far as geochemical prospecting by soil sampling is concerned, the implications of podzolization theory are largely negative. To the degree that podzolization has taken place, soil sampling will be unreliable as a guide to underlaying primary ore bodies. Since podzolization varies with topography and vegetation even if climate and time are constants, it is not sufficient to confine sampling to B_2 horizons. Neither is deep sampling the answer, even if it were feasible, because the depth to which podzolization effects may be encountered are not yet known. On old landscapes in humid regions the effects may go very deep. It will probably be found that soil sampling will have its principal usefulness on young landscapes and in arid regions. The modest success achieved in areas like the North Carolina Piedmont does not necessarily contradict this statement. Some of the Piedmont landscape appears to be relatively young and some of the soils have been scarcely affected by podzolization. Any such highly dissected landscape offers good prospects for soil sampling because recently exposed ore deposits will still be evident in the soils as well as in plant and stream analyses. The possibility of false anomalies also exists because of exposure of podzolic accumulations. The soils on an old featureless undissected plain, highly podzolized, will contain few indications of underlying ore bodies. Podzolization theory is rather negative in that it tends to contradict many aspects of current thought regarding the effects of surface environments on supergene enrichment, laterization and placer deposition. Podzolization theory has several positive implications which the author plans to develop in subsequent papers. These are as follows: (1) An understanding of podzolization theory might permit a geologist trained in soil science to recognize the degree of podzolization of the soils from a given landscape and make it possible to judge the reliability of geochemical prospecting. (2) An analysis of present and past soil-forming factors could be useful in exploration for secondary ore deposits resulting from podzolization. (3) The possible catalytic nature of podzolization may plav a part in the formation of oil and other bituminous materials.*

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CLAY MINERAL RELATIONS IN TWO TRIBUTARY BASINS WITHIN THE YORK RIVER TRIBUTARY BASIN

By

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ABSTRACT

Clay mineralogy of source materials and stream sediments of a Piedmont and a Coastal Plain tributary basin are compared. They are similar. Kaolinite, vermiculite, illite, montmorillonite and mixed-layer clay minerals are found in the source area and stream sediments of both basins. An atypical vermiculite, common to source and sediment materials, is recognized. Expandable illite is restricted to Piedmont soils. Provenance largely determines the qualitative clay mineralogy of stream sediments in a small drainage basin. Clay mineralogy of the sediments is not, however, a perfect reflection of provenance, the near absence of mixed-layer clay minerals in stream sediments being a major difference. Average intensities of basal reflections of stream clays are less than that of the materials serving as the source material.

INTRODUCTION

During a study of the sediments of the York River tributary basin, Virginia, (Figure 1), several small tributaries of the system were selected for detailed investigations. The purpose of this was to obtain a more precise evaluation of the effects of provenance on stream sediments mineralogy by determining as clearly as possible the relationships between the clay mineralogy of the soils and bedrock serving as the source material for the stream sediments and the stream sediments themselves. Specifically, it was desirous to compare the sediments in streams dominated by two completely different source areas whose drainage basins were small enough to eliminate or minimize the effects of tributary dilution and make a detailed sampling program practical.

Primary basis for selection was the geological setting of the basin. Two Piedmont tributaries and three Coastal Plain tributaries were selected for study. This paper reports the results obtained from two of these studies which illustrate the relationships found. The Ni River, a Piedmont tributary, is dependent for its sediment load on weathering products from igneous and metamorphic rocks and is compared with Garnetts Creek, a Coastal Plain tributary, where all stream materials must be second cycle sediments.

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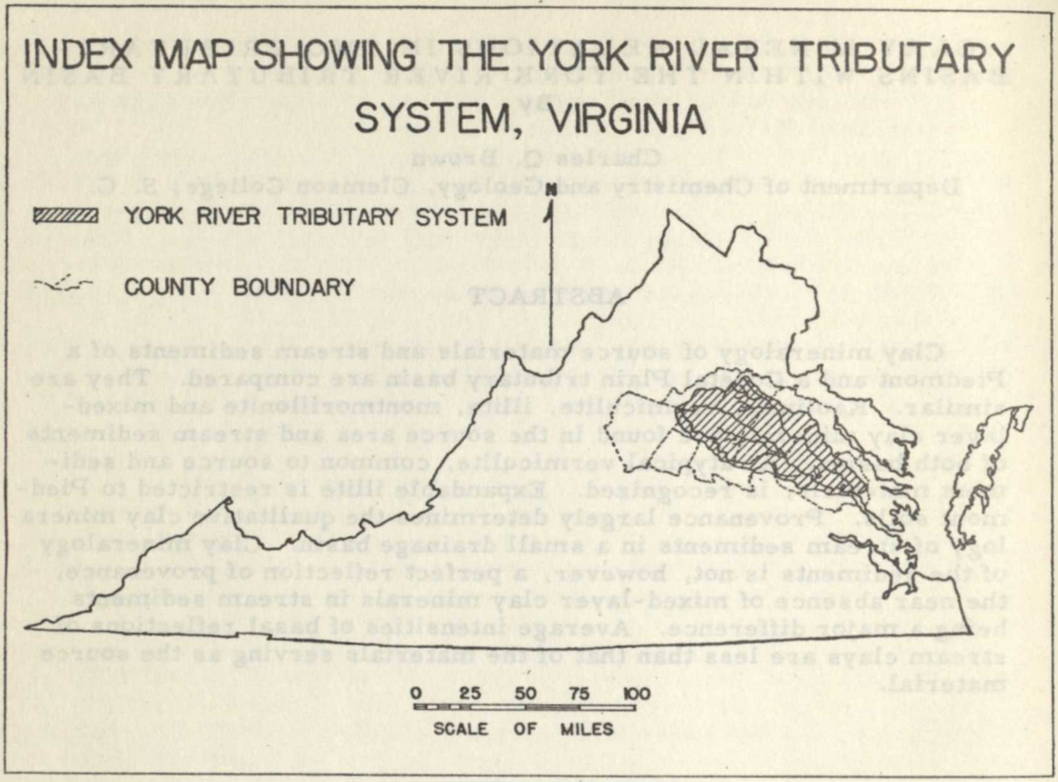

Figure 1

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general direction of B. W. Nelson.

FIELD METHODS

Stream sediments and weathering products (source materials) of the basin were sampled. Bottom sediments of the tributaries were obtained either by an Ekman dredge or by manually scooping along the stream bottom. These sample sites are indicated by a code consisting of letters prefixed to numbers. At nearly every source material sampling site, two samples were taken. One sample was taken to represent the surface materials, and a second sample was a composite subsurface sample including B and C horizons, and clayey parent rock material. Source samples were taken from highway cuts, forests and recently plowed fields by means of a hand auger or a hand spade.

Surface samples are indicated by a number (e. g. 20). If a subsurface zone is sampled also a "b" is suffixed to the surface sample number. (e. g. 20b).

LABORATORY PROCEDURE

X-ray analyses of all samples were made using powder diffraction techniques. Each sample was x-rayed untreated as an oriented aggregate. Further x-ray analyses which were necessary to distinguish the clay mineral phases present were then made. Other treatments consisted of ethylene glycol saturation and heat treatments at various temperatures.

All samples were given the same laboratory treatment. The samples were prepared for x-ray analysis as follows:

(1) A slurry of the sample was made in about 1000 ml. distilled water to which 5-10 drops of concentrated ammonium hydroxide was added as a dispersing agent. Dispersal of the suspension was accomplished by gentle mechanical stirring for 10 minutes.

(2) A suspension of less than two micron size fraction was allowed to dry on glass microscope slides to form an oriented aggregate specimen for analysis.

(3) X-ray analyses of the samples were made using a General Electric XRD-5 recording x-ray diffractometer. Samples were analyzed with copper X-alpha radiation after the following treatment:

(a) air dried

(b) glycolated

The prepared slides were heated in an ethylene glycol atmosphere at 75°C for one hour, after which they were allowed to cool and remain in the atmosphere overnight, following the procedures of Brunton (1955).

(c) heated

The samples were placed in a furnace which had been brought up to a temperature of 200°C, 300°C, 400°C, and 500°C, and allowed to remain at this temperature for one hour.

Not all samples were given the complete sequence of heat treatments. A sufficient number were observed, however, to enable the characteristics of the minerals to be determined.

Results were then interpreted in terms of clay minerals present.

CLAY MINERALOGY OF THE BASIN

Kaolinite is characterized by x-ray diffraction peaks at 7.14 A° (001) and 3.56 A° (002) from untreated oriented aggregate specimens. The kaolinite structure does not expand on glycolation but is unstable at 500°C.

Definite peaks or intensity maxima on plateaus in the 10 A° region are interpreted as illite. Normally the 10 A° peak does not shift on glycolation or heat treatment.

Though it is not typical of the basin, an illite characterized by a peak or hump in the 10.0 A° region which shift to a larger Angstrom spacing when glycolated is present at site 256 and 255b. The intensity of the peak is typically about 150 counts, though no two are exactly alike in the degree of expansion. When heated at 500°C for one hour. expandable illite is not distinguishable from ordinary illite. All hydrated layers collapse to 10 A° under these conditions.

Response of vermiculite to thermal treatment is varied. However, the general response is a shift of the first-order basal spacing, normally at 14.5 A°, to a lower spacing. Heating samples at 200°C, 300°C, 400°C, and 500°C, shows that vermiculite either (1) fully collapses (about 10 A°) at 300°C, (typical vermiculite) or (2) collapses fully only when heated at temperatures exceeding 600°C, (atypical vermiculite). The collapse of atypical vermiculite is gradual between 200-600°C, though there are variations in detail.

The atypical vermiculite is the same as or similar to the mineral identified as dioctahedral vermiculite by Rich and Obenshain (1955, p. 336). It is probably the same mineral identified as a chlorite-like mineral by Brown and Ingram in the lower Neuse River, (1954, p. 198).

Montmorillonite is characterized by a 14 A° basal reflection which shifts to about 17 A° or higher when glycolated. On heating at 200-300°C, the 14 A° spacing shifts to about 10.0 A°. Some of the montmorillonite bearing samples show a slight asymmetry on the high angle slope which probably indicates differential hydration in the natural state.

Mixed-layer clay minerals involve interstratification of 10 A° and 14 A° minerals only. The samples may have a small or large proportion of interstratified layers. They are characterized by asymmetrical slopes and ill-defined peaks or broad humps in the 10 A° to 14 A° region. The layers of these mixtures are distributed randomly in the crystallites.

THE NI RIVER - A PIEDMONT TRIBUTARY

The Ni River (Figure 2) is a moderate sized tributary which heads about four miles southwest of Chancellorsville, Va. It flows generally southeastward for about 19 miles before joining the Po River. It lies almost entirely within the Piedmont and illustrates the source-sediment relations for that province.

Figure 2 shows the sample sites and their relationships to the geology of the basin. (Stose, 1928). It should be noted that the basin is dominated by the Peters Creek Quartzite, granite, the Baltimore (?) gneiss, and the Wissahickon Schist, though there is some quartz diorite and ultrabasic material in the basin. The Ni River crosses two miles of Coastal Plain Aquia greensand before it joins the Po River, and the Calvert formation flanks the stream on the north and south up to about Mn 1.

Clay Mineral Relations

A summary of the clay mineralogy of the samples is given in Tables 1 and 2. For convenience, the sediment and source mineralogy are shown in the same table. The sediment samples are arranged from top to bottom in the table in an upstream to downstream sequence. Source samples are arranged above sediment samples corresponding to their field occurrence as shown in Figures 2 and 3. For example, in Figure 2, sample 259 is a source sample which is downstream from Mn4 but serves as a source for site Mn3. These sites are arranged correspondingly in Table 1. As indicated on the keys for Tables 1 and 2, asterisks represent the intensity of X-ray peaks in counts. Source samples are plotted above a continuous dashed line. River sediment samples are plotted above a solid line. It is an easy matter to quickly compare mineralogy of source materials and corresponding sediments from head to mouth in the basin.

(a) Source materials - In the source area, kaolinite is the mineral with the highest frequency of occurrence, and gives the most intense first order basal reflections. It occurs in all source samples and has an average peak intensity of 300 counts. Vermiculite is found in 73% of the samples and its first order basal reflections average 160 counts. Illite occurs in 46% of the

Figure 2. Sample localities and general geology of the Ni River basin. (From Stose, 1928).

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samples with an average intensity of 90 counts. Montmorillonite, occurring in 12% of the samples, is the least frequent and gives the weakest first order basal reflections, averaging 50 counts.

Mixed-layer clay minerals are quite common with a 62% frequency and an average intensity of 70 counts.

(b) Stream sediments - In the stream sediments, kaolinite, illite, and vermiculite are always present. Montmorillonite is found in 50% of the sediment samples and mixed-layer clay minerals occur in only 17% of the samples. Kaolinite and vermiculite give the highest average intensities. Both average 150 counts. Illite is next highest with 115 counts, followed by mixed-layer clay minerals which average 50 counts. Montmorillonite averages only 25 counts.

TABLE 1

Intensities of first-order basal spacings of source and sediment samples of the Ni River basin.

Sample Sites		Kaolinite	Illite	Vermiculite	Montmorillonite	Mixed-Layer
Source	Sediment					
265		****************	**********	****		
266		******************		**********		****
266b		************		**********		****
264		********************		******		****
264b		****************		********		******
267		******		****		
267b		**************		****		**
	Mn5	************	********	**********		****
261		****************	******	**	**	
262		******************		****		**
260		********	**	**		**
260b		************		**		****
	Mn4	**********	****	********		
	Mn4b	< **********************	******	**********		
		********				
263		******		****		
263b		********************		****		**
259		< **********************		******		**
		**********				
256		**********	**** e	**		
256b		****************	****	****	**	
	Mn3	************	****	****	**	
257		****		******		**
257b		< **********************		******		****
		**************				
258		**	**** e			
258b		**				
255		**				**
255b		**********	** e			
254		**	**			
254b		********				**
	Mn2	********	****	**	**	
252		******	**			**
253		****	**			**
253b		**	**	**	**	
	Mn1	******	**	**	**	

e = expanding Illite

Table 1

Summary

Comparing source clays with sediment clays, one at once notes the discrepancy between the frequency distributions. Montomorillonite occurs with 12% frequency in the source area and 50% frequency in the sediments. Although kaolinite is the only mineral in all source samples, kaolinite, illite, and vermiculite occur in all sediment samples. Expanding illite occurs in the source materials, but is not found in the sediments.

Mixed-layer clay minerals are much more prevalent in source materials (62% frequency) than in sediments (17% frequency).

Intensities from basal reflections of sediment clays are much less than source materials. Average intensities for sediments is up to 100% less than for source materials.

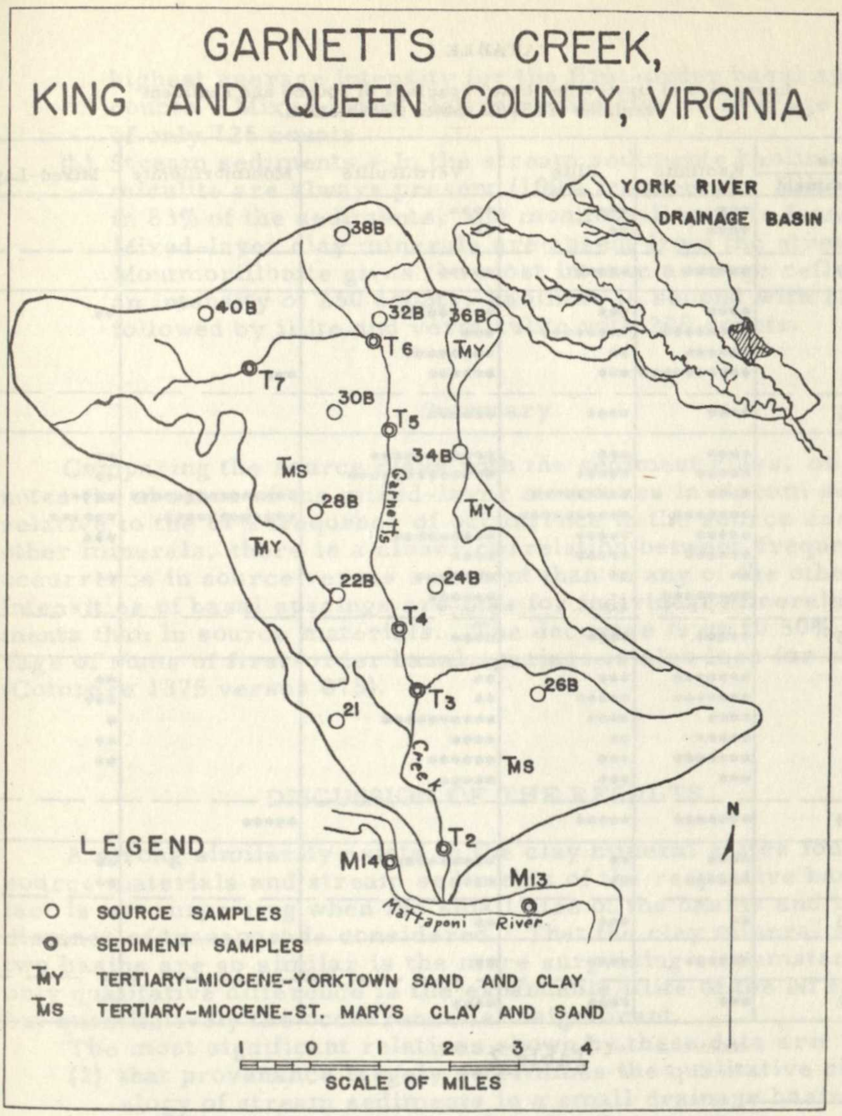

Figure 3. Sample localities and general geology of the Garnetts Creek basin. (From Stose, 1928).

GARNETTS CREEK - A COASTAL PLAIN TRIBUTARY

Garnetts Creek (Figure 3) is a small tributary which heads just northeast of St. Stephens Church, Va. It flows generally eastward for about 3. 5 miles before making a rather sharp turn to flow generally south for nine miles before joining the Mattaponi River. It is a stream characterized by rather clear waters. It lies entirely within the Coastal Plain and falls about 100 feet from head to mouth. Garnetts Creek illustrates source-sediment relations for the Coastal Plain province.

Clay Mineral Relations

The sample sites and their relationship to the geology of the basin are shown in Figure 3 (Stose, 1928). Surficial geology is dominated by

TABLE 2

Intensities of first-order basal spacings of source and sediment samples of the Garnetts Creek basin.

Sample Sites		Kaolinite	Illite	Vermiculite	Montmorillonite	Mixed-Layer
Source	Sediment					
40		***	***	****		
40b		****	**	**		
	T-7	******	*****	*****		
38		****	***	*********		**
38b		********	********	***		
32		******	**	********		
32b		**********	***	******	***	
	T-6	****	****	******		
36		****	***	***********		**
36b		*****	*****	*************		**
42		****	*********		***************	*****
42b		*******	**********		************	******
30		*****	*****	*********		***
30b		******	*****	****		
34		**	**	*******		**
34b		********		******		
	T-5	*****	****	****		
28		*******	***	**		**
28b		*******	*****	**		***
22		****	****	**********		*
22b		*****	**	****		**
24		*******	***	******		**
24b		***	***	*****		
	T-4	*******	*****		*****	
26		****	**	*********		**
26b		******	**	****		**
	T-3	**	***	**		
21		******	****	**		
	T-2	***	****	****		

* = 50 counts

Table 2

Pleistocene terrace deposits which almost everywhere cover the two older formations of the basin, the St. Marys and Yorktown of Miocene age. The surface consists largely of fine to coarse sands with varying proportions of clay which are gray, buff, yellow and red. Most of the area is cultivated or is in forest. There are few cuts exposing sections to view. As a result, most of the samples are soils from plowed fields, forests, and fallow fields. At 38b and 40b cuts expose sands, sandy clays, and sands and gravels of the Pleistocene terrace. Samples 42 and 42b are probably from the St. Marys formation underlying the upland sands. The samples are from a one foot greenish-gray clay layer at a depth of 15 feet.

(a) Source materials - In the source area kaolinite is the most widespread mineral, occurring in all the samples (Table 2). Illite has a slightly higher frequency occurrence (96%) than vermiculite (91%). Both are only slightly less widespread than kaolinite. Montmorillonite is the least frequent mineral (13%). Mixed-layer clay minerals are common in the source area, being found in 61% of the samples.

Montmorillonite, though it ranks last in frequency, has the highest average intensity for the first-order basal spacing, 500 counts. Mixed-layer clay minerals give an average intensity of only 125 counts.

(b) Stream sediments - In the stream sediments kaolinite and vermiculite are always present (100% frequency). Illite is present in 83% of the sediments, and montmorillonite is found in 17%. Mixed-layer clay minerals are absent from the stream sediments. Montmorillonite gives the most intense average reflections with an intensity of 250 counts, kaolinite is second with 225 counts, followed by illite and vermiculite with 200 counts.

Summary

Comparing the source clays with the sediment clays, one at once notes the absence of the mixed-layer structures in stream sediments, relative to the 61% frequency of occurrence in the source area. For other minerals, there is a closer correlation between frequency of occurrence in source versus sediment than in any of the other basins. Intensities of basal spacings are less for individual minerals in sediments than in source materials. The decrease is up to 50%. The average of sums of first-order basal spacings is also less for sediments. (Compare 1375 versus 875).

DISCUSSION OF THE RESULTS

A strong similarity exists in the clay mineral suites found in the source materials and stream sediments of the respective basins. This fact is not surprising when the small size of the basins and the maximum distance of transport is considered. That the clay mineral suites of the two basins are so similar is the more surprising circumstance. The only qualitative difference is the expandable illite of the Ni River Basin, but quantitatively the occurrence is insignificant.

The most significant relations shown by these data are:

(1) that provenance largely determines the qualitative clay mineralogy of stream sediments in a small drainage basin,

(2) that the clay mineralogy of the sediments of even a small tributary is not, however, a perfect reflection of provenance, either qualitatively or quantitatively,

(3) that the average intensity of basal reflections of stream clays is less than that of the materials serving as the source material,

(4) that mixed-layer minerals are much less common in the sediments than in the source area.

That provenance is a fundamental qualitative control of the clay mineral composition of the sediments is born out by the fact that all minerals found in the source area are also found in the sediments. The only exception to this is the occurrence of expandable illite. This apparent discrepancy is easily explained by considering the very small percentage of expandable illite in any sample, as well as the small areal distribution of those soils containing that mineral. That expandable illite is lost through dilution in the stream sediments is favored over an alteration to a normal illite.

That the sediments are not a true reflection of the source area is indicated by consideration of the frequency of occurrence of the minerals in sediment samples and the source area. Appearance of a mineral in a large number of sediment samples does not prove wide distribution in the source area, as the montmorillonite occurrence in the Ni Basin indicates. Neither is an evaluation of provenance on safe grounds from a consideration of the relative intensity of basal reflections in the sediments. Though montmorillonite has only 17% frequency in the Garnetts Creek source area it has a higher average intensity than kaolinite, which, by volume, is far more prevalent than montmorillonite. Relative intensity of the minerals one to another seems to carry over from the source area to streams except for montmorillonite and mixed-layer structures.

Near absence of mixed-layer structures in the stream sediments of both basins is perplexing for such small drainage nets. Most authorities do not believe a fresh wat er stream capable of significant alteration of clay mineral structures. Certainly for such small streams alteration would not be expected. The data reported here do not permit a conclusive statement in explanation of this relationship. Chemical data on the waters could prove beneficial in the solution of this problem, but it is felt that physical phenomena are perhaps the operating mechanisms.

Two processes could explain the situation in these basins. Differential transportation and deposition is one alternative and indeed may be operative with certain minerals such as montmorillonite. However, on the basis of unpublished data (Brown, 1958) collected during a study of the entire York River tributary basin, it is felt that the apparent "unmixing" of mixed-layer structures may be a real physical unmixing.

An explanation of the reduced intensities given by sediment clays relative to source samples is not readily explained. Possible explanations may be an increase in percentages of amorphous materials or finer sized sediment particles, the latter being compatible with the physical unmixing hypothesis.

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STRUCTURAL CONTROL OF THE NORTH CAROLINA COASTAL PLAIN

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ABSTRACT

The North Carolina Coastal Plain is not a simple homoclinal structure. The Great Carolina Ridge is an area of uplift and the Hatteras Axis is one subsidence; both are transverse to the Appalachian trend. Midway between those two features is the Cape Lookout-Neuse Fault Zone, also transverse to the Appalachians. Several data in the literature suggest a fourth structural feature, a to date unnamed fault zone with a trend parallel to the Appalachians. As a possible fifth feature, a "zone of subterranean disturbances", suggested by Shaler, 1871, but not proved to date, is mentioned. In conclusion it is suggested that the capes along the present shoreline have been controlled by these structural features.

The basement rock beneath the sedimentary cover has the character of peneplained block mountain rather than that of a folded mountain chain.

INTRODUCTION

This paper attempts to collect and evaluate opinions about the structural conditions of the Atlantic Coastal Plain, especially in North Carolina. Consideration of this problem developed during studies in the University of Virginia, Charlottesville, Va., 1954-55, in connection with preparation of annotated bibliographies for the Hydrographic Office, U. S. Navy, on harbor approaches along the Atlantic Coast. My curiosity was wakened by the peculiar surface features of the subsea prolongation of Cape Hatteras, Cape Lookout, and Cape Fear, by coastal arcs connecting them, by the fairly equal distances between them, and by what relationship they have to structural features of the Coastal Plain. During my following three years with the North Carolina State College, Raleigh, N. C., I became more familiar with the geology of the Coastal Plain of North Carolina.

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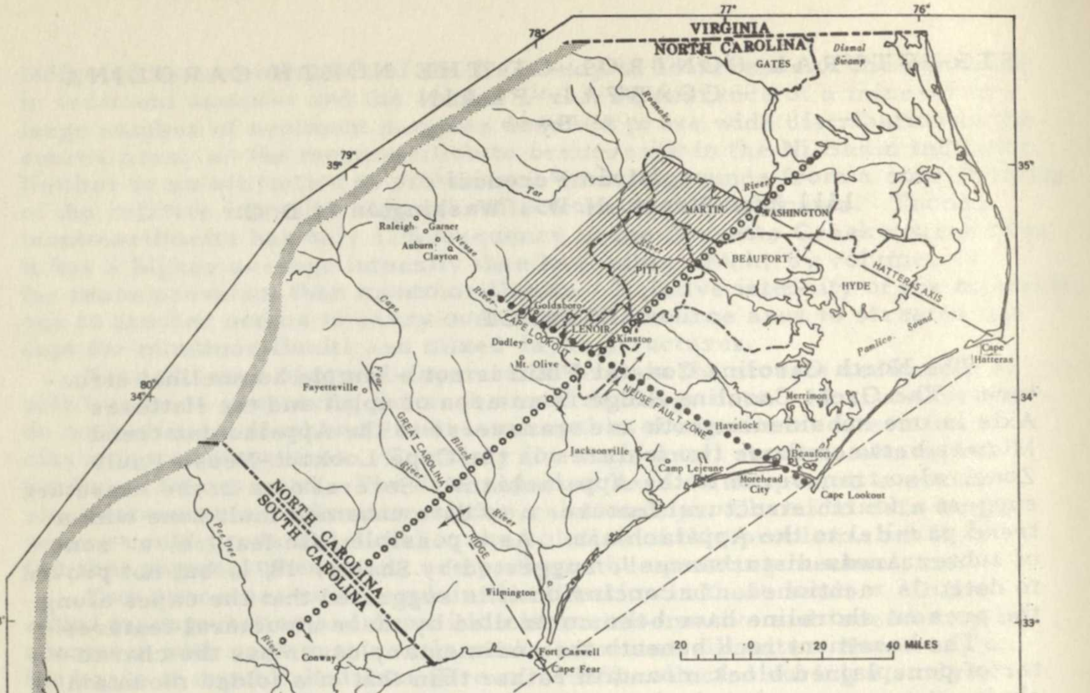

Figure 1

THE GREAT CAROLINA RIDGE (CAPE FEAR ARCH)

Dall in 1892 described a structural feature under the name "Great Carolina Ridge" as "an elevated ridge of perhaps very ancient origin, whose extension may be seen in the contours of the sea bottom far off the coast" (p. 182).

In 1926 Stephenson dealt with it again as "a broad upwarp, having its axis near the boundary between North Carolina and South Carolina", and so indicated it on an accompanying sketch map (p. 468, and pl. 1), although well records described by him in 1912 (p. 163-167, and p. 169-171) suggested an axis farther northeast.

In 1927 Mansfield showed the existence of this elevated ridge by comparing surfaces of the basement rocks as determined in the Havelock, N. C., Wilmington, N. C., Fort Caswell, N. C., and Summerville, S. C., wells. He concluded that this "seems to verify the opinion of Stephenson that the course of the Cape Fear River across the Coastal Plain approximately marks the axis of the broad structural uplift, dating from the interval marked by unconformity between the Cretaceous and Tertiary sediments, and the uplifted position has been maintained without marked subsidence until the present" (p. 11). This location of the axis of the Great Carolina Ridge was accepted by Stephenson in a sketch map in his 1928 paper in which he described it as a "broad upwarp in the Cape Fear region in Eocene time" which "raised Upper Cretaceous beds to the surface near the coast" (p. 892 and p. 889, fig. 1).

MacCarthy and his coauthors in a short abstract in 1933 described evidence that this area, especially referring to the southwest flank of the Great Carolina Ridge, reflects differences in the dip of the basement rock surface, a relatively steeper dip toward the coast line than inland. They interpreted this as two erosional surfaces with their intersection about 17 miles west of Conway, S. C. (p. 21).

Prouty used the name "Cape Fear Arch" instead of the former name Great Carolina Ridge, marking it as "an anticlinal fold (arch) through Wilmington running parallel with the Cape Fear River basin toward the north-west." He indicated it also on his sketch map adapted from Stephenson, as well as on his diagram (Prouty, 1936, p. 485, p. 486, fig. 1, and p. 487, fig. 2).

In 1936 Cooke dealt with the area between the Santee River in South Carolina and the Cape Fear River in North Carolina where "the present land for a considerable distance inland from the present coast both north and south of that area was submerged. This old land area, the Great Carolina Ridge of Dall, may have projected for many miles into the Atlantic as a peninsula, separating an enlarged Chesapeake embayment from an enlarged Gulf of Mexico, Florida being at the time submerged" (p. 99). Jackson (Eocene) time began "with a crustal movement that raised the region between the Cape Fear River in North Carolina and the Santee River in South Carolina, thus producing the Great Carolina Ridge and depressed the regions on both sides of it" (p. 156). Describing the structural conditions of the South Carolina Coastal Plain, he stated that "only deposits of the Upper Cretaceous and Eocene formations are in South Carolina conspicuously deformed on the west limb of the Great Carolina Ridge, whose crest or axis lies not far from the North Carolina-South Carolina state line and nearly parallel to it and whose northeast limb is in North Carolina" (Cooke, 1938, p. 158). "Upon the beveled surface lie thin patches of nearly horizontal marine Miocene formations (remnants separated by erosion)" (p. 159).

As a result of further magnetometer investigations, MacCarthy mentioned that "evidence supporting Stevenson's suggestion of a north-west-southeast uplift near Wilmington has been obtained" whereas roughly parallel to the coast a "magnetically disturbed zone . . . consisting of a series of subparallel highs and lows, has been found", which has been traced from Myrtle Beach, S. C., to the vicinity of Wilmington, N. C., "with further evidence suggesting that it may continue through Burgaw toward extreme northeastern North Carolina", representing "a folded and perhaps fractured zone" (MacCarthy, 1936, p. 405). In 1937 MacCarthy and Straley gave a more detailed picture of these magnetic disturbances referring to the "Wilmington anticline". They stated that "magnetic evidence for or against the existence of this uplift might be expected but because of the nature of the country, observations have not been made" (p. 363). A short abstract by MacCarthy and Straley in 1938 gave as "results to date: (1) a magnetically disturbed area in the neighborhood of the Wilmington, N. C., arch, . . . (3) a series of low magnetic highs extending in an interrupted irregular line from the latitude of that of Beaufort" (p. 1953). Johnson's remarks on magnetic disturbances in northeastern North Carolina are published only in a short abstract (p. 1951).

Richards in 1945 dealing with well records of North Carolina Coastal Plain wrote about a "conspicuous high . . . noted in the vicinity of Cape Fear, North Carolina", which "has been recognized for a long time and is known as the Great Carolina Ridge", indicated on three cross sections (p. 953 and p. 941-943, figs. 20-21). In 1947 Richards wrote: "In any case the basement and all formations rise sharply near Cape Fear. This is one of the most conspicuous structural features of the East Coast and is called the Great Carolina Ridge or the Cape Fear Arch. At Wilmington, the basement rises to a depth of only 1, 109 feet and then dips again toward South Carolina" (p. 47). The Ridge is shown on a generalized cross section from Fort Monroe, Va. , to Hilliard, Fla. , (p. 46). A third paper in 1948 again reflects the elevated position of the Great Carolina Ridge in a cross section from Fort Monroe, Va. , to Paris Island, S. C. ,' (Richards, 1948, p. 55, fig. 2).

Straley and Richards in 1950 gave the same cross section, and with reference to the Ridge stated that the "basement rises at Wilmington to within 425 meters" (correctly 338 meters = 1, 109 feet) "of the surface, and extends north-westward toward the Piedmont at an equal or greater elevation" (p. 88, fig. 2).

Berry in 1951 described the "Carolina Ridge", as "one of the most prominent features of the basement" oriented "roughly parallel with the valley of Cape Fear River"(1951, p. 414). He also noted seaward change on the basement slope (1948, p. 87, fig. 1, and 1951, p. 412-413, fig. 116).

Likewise Eardley described the "Cape Fear Arch" as "the most conspicuous feature of the Coastal Plain" (p. 131), indicating it on the index map (p. 70, fig. 22) as a broad bulge of the Cretaceous formations. However, he remarked that "this structure is not truly an arch" as such a structural feature was defined by him in chapter 2 of his book. He concluded that "the unconformities around the Cape Fear Arch indicate the principal times of uplift and erosion to have been at the close of the Cretaceous and again at the close of the Early Miocene".

LeGrand in 1955 referring to the Carolina Ridge stated that "the assumed single homoclinal structure of the Atlantic Coastal Plain becomes complex" in its vicinity. Besides changes in the extension of various Cretaceous formations covering the area, he mentioned a fault line with northeastward trend between Cape Fear River and Black River a few miles from their confluence, and a broad dome-like area, based on presence of brackish ground-water, west of Wilmington, N. C. Although it had "received scant geological attention in the past, the Great Carolina Ridge contains complex structures" (p. 2036-2037).

After this review of opinions, it may be stated that below the area of the Great Carolina Ridge there is a large block of pre-Cretaceous basement rocks, which moved up or down either as a unit, or as smaller blocks independent of adjoining areas of the Atlantic Coastal Plain. This large block of the basement rock extends on its northeast side to Havelock, N. C. , and on its southwest side to the neighborhood of Summerville, S. C. At both places the surface of the basement rocks was found at relatively great depths, 2, 318 feet at Havelock, and 2, 450 feet at Summerville. The crest line is in the vicinity of Wilmington, N. C. , where this surface is at its least depth, 1, 109 feet, and extends northwestward, approximately parallel to the course of the Cape Fear River, toward

Fayetteville, where the block joins the Piedmont. Within this large block are smaller units separated by faults that run at right angle to the northwest-southeast direction of the Great Carolina Ridge, i. e., parallel to the main trend of Appalachian structure. Structural elements of this type were proved by the magnetic investigations of MacCarthy and his associates, and more recently by the observations of LeGrand concerning brackish water areas in the sedimentary cover of the Great Carolina Ridge (LeGrand, 1955, p. 2036).

The separate movement of blocks in the Great Carolina Ridge is "very ancient", as was thought by its first describer, (Dall, 1892, p. 182), but it was proven by LeGrand that movements occurred also within Cretaceous time. The absence of the Tuscaloosa Formation in four deep wells between Conway, S. C., and Jacksonville, N. C., implies a land barrier within the area of the Great Carolina Ridge during Tuscaloosa time. Likewise the apparent absence of the basal strata of the Black CreekFormation in the Wilmington, N. C., well indicated this barrier was above the sea until the latter part of Black Creek time (LeGrand, 1955, p. 2036).

The area was submerged in late Black Creek and Peedee time, but this submergence was followed by an uplift in Paleocene time, since such sediments have not been reported in the area. Submergence during Eocene time only lowered the northeastern flank of the Great Carolina Ridge below the sea, as indicated by surface patches and well data of Upper Eocene limestone. The patches of Middle Eocene (?) sediments near Fayetteville and Raleigh, N. C., also are confined to this flank of the Ridge. On the southwest flank the Black Mingo Formation and overlying younger members of the Eocene series appear only at much greater distances from the crestline of the Ridge.

The submergence during Eocene time was followed by an uplift of greater extent. Along the length of the Great Carolina Ridge the presence of Oligocene sediments has been suggested only by McLean with a questionable reference by Richards (1948, p. 62), from the shallow well at Camp Lejeune, Onslow Co., N. C. On the southwest flank of the Great Carolina Ridge no sediments have been definitely determined as of Oligocene age. The nearest area in South Carolina where such sediments (Flint River Formation) occur lies far distant from the Great Carolina Ridge, near the Savannah River. Also in case if the Cooper Marl of South Carolina repeatedly "shifted back and forth between the Eocene and the Oligocene" by subsequent authors, should be definitely verified as of Oligocene age, as Cooke and MacNeil wrote, the area covered by it lies on the southwesternmost flank of the Great Carolina Ridge (1952, p. 27).

The total absence of Lower and Middle Miocene sediments in the area of the Great Carolina Ridge, as shown by Brown's recent study of well logs from the Coastal Plain of North Carolina (1958, figs. 7-9), is good proof that the entire length of the Great Carolina Ridge during the Early Miocene and Middle Miocene was still above sea level. A new submergence in the Late Miocene resulted in the southeastern part of the north flank of the Ridge being covered by the transgression of the Yorktown sea, while the northwestern portion of this flank remained uncovered. Only during the youngest phase of Upper Miocene transgression, the time of the deposition of the Duplin Formation, was the whole area perhaps below sea level, except for an area on the south bank of the Neuse River near Mt. Olive, N. C., which remained as a peninsula.

Evidence is lacking concerning movements in post-Miocene time.

Perhaps a southeastern strip along the shore line was covered by Pliocene and Pleistocene seas.

THE HATTERAS AXIS

The first author who suggested that "the projection of Cape Hatteras is due to subterranean disturbances" was Shaler in 1871 (p. 112), when he considered the causes "which have led to the production of Cape Hatteras". Although he did not specify the direction of these disturbances, the fact that he linked them with a ridge between Richmond, Va., and Weldon, N. C., clearly reveals a northeast-southwest direction parallel with the Appalachian trend.

In 1891, McGee twice referred to the "Hatteras Axis" - in neither case specifying any direction - "as an axis of interruption or change in epeirogenetic movement during every geologic period since the Cretaceous" (p. 403), and as "an axis of minimum subsidence and minimum uplift" (p. 503).

In 1894, Hayes and Campbell mentioned the Hatteras Axis, and gave its direction as northwest-southeast, a transverse line to the Appalachian trend. This may be deduced from their statement that if the direction of the Hatteras Axis is continued "across the Ohio River its direction will be found to coincide with that of the main or northwestward branch of the Cincinnati Arch" (p. 81), whereas the "Charleston-Memphis axis", passing Atlanta, Ga., forms "a tangent to the great northwestward bend of the Tennessee River" (p. 82). Since then the Hatteras Axis has always been considered as a structural feature transverse to the Appalachian trend.

In 1899, Glenn discussed the Hatteras axis pointing to its role in sedimentation during the Triassic period and also in the Middle Miocene, and referred to it being not "a narrow belt with a close approach to the idea of a line but rather a broad belt or region" (p. 379).

In 1926, Stephenson, referring to major features in geology of the Atlantic and Gulf Coastal Plain, indicated it on his sketch map as an axis, in which two downwarped basement surfaces, - one dipping to the southwest, the other to the northeast, - cross each other (pl. 1). In the text, however, he only states: "North of Cape Hatteras the downwarping in late Tertiary and in Quaternary times affected the Coastal Plain more completely than it did south of this point" (p. 472). In a second paper he shows another line more northward, crossing the shore line somewhere near the Virginia-North Carolina boundary (Stephenson, 1928, p. 889, fig. 1). In his text he referred to "a downwarp affecting the North Atlantic Coastal Plain from Maryland to northern North Carolina" which "resulted in the transgression of the Upper Miocene sea inland to the inner edge of the Coastal Plain in North Carolina and Virginia" (p. 891).

Prouty, in general adopting the data from Stepehenson's 1928 sketch map, does not refer to the "Hatteras axis", but replaces it with a "synclinal fold (trough)" in the area of Norfolk, Virginia(p. 485-486, fig. 1). Later Gardner mentioned it as a zone of transition, where northern faunal elements of the Upper Miocene Yorktown formation were replaced by southern types (p. 70, p. 131, etc.).

Richards in 1945 published two cross sections showing subsurface conditions; both show a low in the basement surface at the well at Havelock, N. C., (p. 941-942, figs. 20-21). In 1947 he stated that "the basement drops decidedly between Fort Monroe (2, 246 feet) and Hatteras (9, 878 feet). However, the north-south slope is not as great as might be indicated since Hatteras is well out to sea. . . If we were to contrast Fort Monroe (2,246 feet), with Havelock, N. C. (2,318 feet) or Morehead City, N. C. (4,036 feet), the slope should not be as great" (p. 47). His generalized cross section in this case indicated the "Hatteras Low" in the line of the Morehead City well (p. 46). Similarly in a 1948 paper he indicated a low in the basement surface in the line of the Morehead City well (Richards, 1948, p. 55, fig. 2). On the other hand, he stated in the same paper that "a study of samples from the deep well at Cape Hatteras shows a thickening of most formations. Also several formations have been recognized in the well that do not crop out in North Carolina" (p. 73).

A cross section in a 1950 paper by Straley and Richards is similar (p. 88, fig. 2). However, they emphasized the "notable feature . . . the basin between the Dismal Swamp and the Carolina Ridge at Cape Fear" (p. 88).

The last cross section found was published by Spangler in 1950; he again indicated the lowest point on the basement surface as at the Hatteras well (25, p. 120-121, fig. 7).

After this review of opinions, it may be stated that the Hatteras Axis represents a line where all formations are at their greatest depth. The line trends northwestward from the Hatteras well.

The southwest limit of the Hatteras Axis area and the northeast limit of the Great Carolina Ridge block is marked by the Cape Lookout-Neuse Fault Zone (a third transverse structural feature to be discussed later in this article). From this fault zone northeastward well records show the thickening of formations toward the Hatteras Axis. Likewise, on the northeast side of the Hatteras Axis formations thicken southwestward toward the Axis, as already referred by several authors, e. g., by Berry (1951, p. 414).

The Lower Cretaceous series, for example, shows this thickening. Although such sediments were distinguished in the Merrimon and Morehead City, N. C., wells, they are not known in surface outcrops nor in well records in the entire area of the Great Carolina Ridge. Upper Cretaceous formations thicken from both directions toward the Hatteras Axis.

Paleocene sediments are limited mostly to the northeast flank of the Great Carolina Ridge, and are not known to occur south and west of Pitt County, as stated by Brown in his Correlation Chart (1958, table 1). The gradually progressing Late Eocene transgression deposited sediments in the area of the Hatteras Axis; such sediments are missing in surface outcrops, and from the subsurface in an area north of the Neuse River. If the thin unit questionably indicated in Brown's cross section as "unnamed Oligocene" (1950, fig. 4), is proved to be Oligocene, then this unit is likewise restricted to the Hatteras Axis area. It is known only in the records of the Hatteras well and in the Pamlico Sound well, as described by Richards (1948, p. 61), and not in surface outcrops.

While the Great Carolina Ridge remained during the Early and Middle Miocene above sea level, probably continuous sedimentation occurred in the area of the Hatteras Axis. In his Correlation Chart Brown does not show proved sediments of Lower Miocene age, but indicates a thickness of nearly 400 feet in the Hatteras well as "unnamed Lower Miocene (?) unit" (Brown, 1958, table 1 and fig. 4). Brown indicates Middle Miocene sediments also by a question mark, and in his Correlation Chart (table 1) states that these phosphate sand sediments are "not known to occur in outcropping sections", but that their "subsurface distribution" is "localized in Beaufort, Washington, Gates and Hyde Counties", i. e., the area of the Hatteras Axis.

The Late Miocene transgression of the Yorktown sea covered the entire area of the Hatteras Axis and deposits accumulated to considerable thicknesses, such as 325 feet at Edenton, N. C. , and more than 500 feet in the Hatteras well, as shown in Brown's cross section (fig. 4). Moreover, faunal evidences prove, according to Gardner (1944, p. 70, pl. 131, etc.), that the sediments of the Yorktown formation north of the Neuse River were deposited in an embayment that was removed from the influence of warmer oceanic waters. This embayment was protected by the peninsula which remained during the Late Miocene time above sea level in the area of Mount Olive, N. C. , on the south side of the Neuse River valley.

THE CAPE LOOKOUT - NEUSE FAULT ZONE

Besides the two main structural features which have just been discussed, two others are indicated. The Cape Lookout-Neuse Fault Zone - a third northwest-southeast directed feature transverse to the Appalachian trend - is midway between the Great Carolina Ridge and the Hatteras Axis. Its existence is indicated by the difference in the depth of the basement rock surface, 2, 318 feet on the southwest side of the fault zone in the Havelock well and 4, 000 feet on the northeast side in the Merrimon test wells, as well as in the Morehead City well. Nearer the Piedmont, in the area of Goldsboro, N. C. , the presence of such a fault zone is suggested in that the Upper Eocene Castle Hayne Limestone, which on the right bank of the Neuse River overlies the eroded surface of the Black Creek and Tuscaloosa Formations, is missing both in surface outcrops and in well records from the left bank area north of the Neuse River. Moreover, the well data and cross sections of Brown (1958, figs. 2-9) indicate that north of the Neuse River there is an area, bounded approximately on the south by the Neuse and on the east by a line drawn along the eastern boundaries of Martin, Pitt, and Lenoir counties, where the Miocene Yorktown sediments directly overlie the Cretaceous formations, without intervening Middle or Upper Eocene sediments. This elevated block must have been above sea level until the end of Middle Miocene time, but sank with the oncoming transgression of the Late Miocene Yorktown sea independently of the adjoining areasouth of Neuse River, which remained above sea level during Late Miocene Yorktown time.

The "Cape Lookout-Neuse Fault Zone" is suggested also by a line along which older sediments became silicified during emergence of this area between Late Eocene and Late Miocene times. The occurrences of silicified older sediments in the Piedmont area, such Eocene deposits in the railway cut at Garner, N. C. , and at the boundary of Wake and Johnston Counties on old Highway 70 between Clayton and Auburn, N. C. , (Richards, 1951, p. 14), the Eocene outcrop with silicified Bryozoan stocks southwest of Dudley, Wayne Co. ,[1] finally the silicified sandstone southeast of Kinston, N. C. , (Stuckey, 1928, p. 22-23), lie in an approximate northwest-southeast line, coinciding with the Cape Lookout-Neuse Fault Zone. This fault zone limits the block of older sediments on the southwest side, which was not covered by the Eocene Castle Hayne Lime-

[1]Information from Richard D. Pusey, U. S. Geol. Survey, Ground Water Branch, Raleigh, N. C. , and also personal observation.

stone, but became inundated by the Yorktown sea in the Upper Miocene.

STRUCTURAL FEATURES PARALLEL TO APPALACHIANS

In addition to the three structural features discussed in the foregoing paragraphs, two structural features may be mentioned which run parallel to the Appalachian trend. The first of these is the line of "subterranean disturbances", as suggested by Shaler (1872, p. 112). This features, however, so far is only suggested by the parallelism of the present coast line southwest of Cape Hatteras to the main trend of the Appalachians.

The second feature, indicated on the sketch map as "Unnamed Fault Zone" is more evident. Its southwest-northeast trend is indicated at the area about 17 miles west of Conway, S. C., where the seaward slope of the basement surface becomes steeper (MacCarthy, 1936, p. 399, fig. 1), the northwestern limit of the magnetically disturbed zone west of Wilmington, N. C., (MacCarthy, 1936, p. 399, fig. 1), the location of the fault near the confluence of the Cape Fear and the Black River (LeGrand, 1955, p. 2036), and the line along the eastern boundary of Martin, Pitt, and Lenoir counties (mentioned on page 12 as a line where the Upper Miocene Yorktown sediments overlie the Cretaceous formations without intervening Eocene sediments). This data indicate a zone of movements, which in its continuation, is perhaps reflected in the magnetic anomalies observed by Johnson in northeastern North Carolina (1938, p. 1951). This is also the zone where the slope of the basement surface steepens in the North Carolina Coastal Plain area, as illustrated by the cross sections of Berry (1951, p. 413, fig. 116).

MORPHOLOGICAL REFLECTIONS OF STRUCTURE

The morphology of the North Carolina Coastal Plain appears to be connected with the structural features. The drainage areas of the Neuse River and the Cape Fear River within the Coastal Plain have a peculiar asymmetry. The left bank tributaries of the Neuse River and the Cape Fear River are longer, and the slopes on the north banks are steeper, in part, almost escarpment-like. The course of the Roanoke River follows, at least in part, the direction of the Hatteras Axis. The sharp northeast turn of the Neuse River near Kinston, N. C., relates to the unnamed fault zone.

It would seem to be not an accidental coincidence that the peculiar configuration of the capes along the present shore line of both Carolinas has developed relating to these structural features: Cape Hatteras to the Hatteras Axis, Cape Lookout to the Cape Lookout-Neuse Fault Zone, Cape Fear to the Great Carolina Ridge, and perhaps, Cape Romain in South Carolina at the southwest boundary of the Great Carolina Ridge. Such a relation between Cape Canaveral, Fla., and structural lines was recently determined by White (1958, p. 1718-1719). How these structural features, although differing in character, have led to formation of the individual capes needs more detailed studies. The coincidence, in any case, is noteworthy. It should be even more interesting if the northeast-southwest "subterranean disturbances" suggested by Shaler (but not proved to date), as a cause leading to the "projection of Hatteras", could be proven as a further structural feature of the Coastal Plain of the Carolinas. In this case the crossing of the transverse structures with this northeast-southwest structure would provide another basis to the idea that the capes have not been formed accidentally at their locations, but through the influence of structural control.

CONCLUSIONS

The North Carolina Coastal Plain is not a simple homoclinal structure but is more complex. The transverse structural features, the Great Carolina Ridge and the Hatteras Axis, influenced the transgression and regression of the seas in different geological times. The middle feature, the Cape Lookout-Neuse Fault Zone had a similar role, but the movements along this zone affected smaller areas of deposition. Besides the parallelism of the assumed northeast-southwest line of Shaler to the main trend of Appalachian structure, an unnamed zone of structural disturbances is suggested. Movement along these features also influenced the morphology of the North Carolina Coastal Plain, and such an influence may be suggested for the whole extent of the Atlantic Coastal Plain. The basement rock beneath the sedimentary cover has the character of a peneplained block mountain rather than that of a folded mountain chain. Former folds, if they were once present, have been obliterated by fault systems developed since the Appalachian Revolution. Structural conditions of the Atlantic Coastal Plain, and gravity and other anomalies indicated more recently by Skeels (1950, plates I-IV, figs. 1-2), can perhaps be more easily interpreted by referring them to blocks in the basement rock mass differing in position.

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