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SOUTHEASTERN GEOLOGY

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Vol. 9, No. 2

1968

MINERAL FACIES IN THE TERTIARY OF THE CONTINENTAL SHELF AND BLAKE PLATEAU

by

Charles E. Weaver
Georgia Institute of Technology

ABSTRACT

X-ray analyses of JOIDES core samples from the Continental Shelf and Blake Plateau show the presence of a variety of authigenic materials. Calcite is the dominant carbonate mineral in the Eocene and Oligocene sediments. In the Miocene sediments dolomite is the dominant carbonate mineral in the west and calcite in the east. Phosphatic sand is abundant in the Miocene shelf facies. K-feldspar is a major component of the western Eocene limestone residues and clinoptilolite of the eastern Eocene and Oligocene. The Lower Miocene contains an abundance of attapulgite and sepiolite, and the Upper Miocene montmorillonite. The pre-Miocene silicate minerals are believed to be largely authigenic and the post-Oligocene ones largely detrital.

INTRODUCTION

X-ray analyses were made of bulk and residue (EDTA adjusted to pH 8) samples (162) from four wells on the Continental Shelf slope, and Blake Plateau. Most of the Tertiary section was sampled in these core holes that were drilled as part of the Joint Oceanographic Institutions' Deep Earth Sampling Program (JOIDES, 1965). Location of the wells and a stratigraphic cross-section is shown in Figure 1.

Lithologic and faunal studies (JOIDES, 1965) indicate the Eocene and Oligocene sediments are largely calcareous. On the shelf these sediments are relatively coarse grained, well sorted and were deposited in relatively shallow water. On the Blake Plateau the pre-Miocene sediments are largely calcareous oozes and were deposited in water approximately as deep as that in which they are now found. As many as five volcanic ash beds were found in the slope and plateau Oligocene sediments. Miocene sediments beneath the shelf are phosphatic sandy silts and silty clays which were deposited in a shelf environment. The Miocene sediments have been eroded from the slope. On the shelf they consist of calcarenitic sand or ooze and were deposited in water approximately the same depth as that in which they presently occur.

This thin Tertiary section contains a wide variety of minerals, many of which are authigenic or diagenetic in origin (Figure 2).

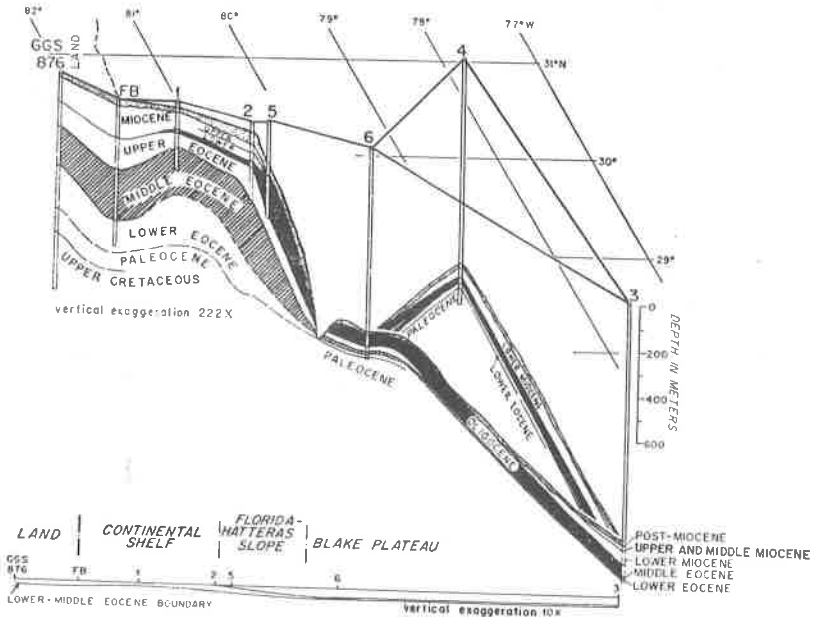

Figure 1. Isometric fence diagram showing the stratigraphy of the Continental Margin of the east coast of Florida. From JOIDES (1965).

Acknowledgement

This study was supported by Grant GP-4967 from the National Science Foundation.

RESULTS

Carbonate rocks dominate the section. Calcite is the dominant carbonate mineral in the Eocene and Oligocene sediments. Dolomite, when present, is minor except in one sample. Dolomite is the dominant carbonate mineral in the shoreward, shallower water Miocene and systematically decreases seaward with calcite becoming dominant. Quartz sand and clay, as a major lithology, occurs only in the Miocene of the two westernmost wells. Phosphate is restricted to this detrital facies.

Most of the dolomite is the Mg-rich variety with the Ca/Mg ratio ranging from 1.25 to 1.75 (211 reflection 2.90 Å to 2.93 Å).

X-ray analyses (oriented slides) of the fine fraction of the sands and muds and the residues of the carbonate rocks indicate that montmorillonite is present in all samples and quartz in all samples except the volcanic ash beds.

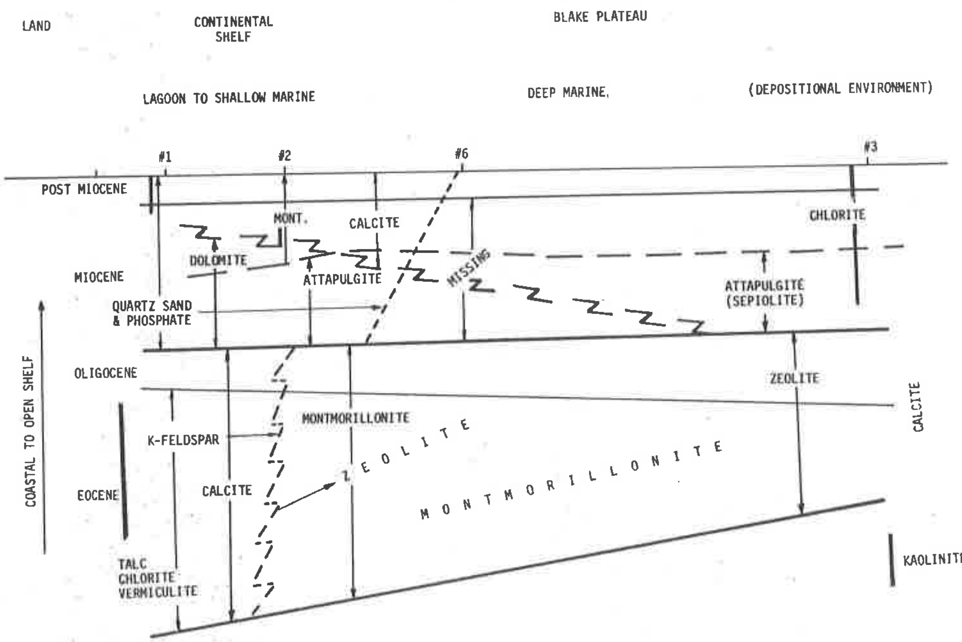

Figure 2. Idealized cross-section showing the general mineral distribution in four wells located on the Continental Shelf, and Blake Plateau of the east coast of Florida.

Illite is present in nearly all samples but is least common in the Miocene sediments of the westernmost well. It is most abundant in the post-Miocene and Upper and Middle Miocene of Well No. 3 on the Blake Plateau. Biotite is present in most ash beds and a few other pre-Miocene samples.

Kaolinite, probably detrital, is present in minor amounts in the Upper and Middle Eocene of Well No. 1 and in the uppermost Miocene and post-Miocene. It is most abundant in the Miocene of Well No. 3. In this latter well it is also present in the Lower Miocene. In the Miocene the kaolinite distribution is similar to the calcite (increasing in abundance from west to east).

Talc and mixed-layer chlorite-vermiculite (15 Å glycolated; 12 Å heated) are present in Middle Eocene samples of Well No. 1 (coastal environment) and in the lower samples dominate the clay suite. We have found that talc is a common component of Recent carbonate muds in the Bahamas, where it presumably formed authigenically. The Eocene talc and presumably the chlorite-vermiculite are also probably authigenic.

K-feldspar is a major component of the residue of the Eocene limestones of Well No. 1 (coastal to shallow shelf environment). Electron micrographs indicate the K-feldspar is fine grained (0.5-10 μ) and subhedral suggesting that it is authigenic. K-Ar values are being obtained. Minor amounts of Na and K-feldspar, presumably detrital, are present in the overlying Miocene sediments throughout the shelf and plateau area. Feldspar is scarce in the other sediment. Seaward from Well No. 1 the Oligocene and Eocene sediments, deposited in a deeper water environment, contain clinoptilolite rather than K-feldspar (minor amounts of plagioclase feldspar may be present). Trace amounts of clinoptilolite occur in the Lower Miocene of Well No. 3. Some heulandite may be present but heat treatments (Mumpton, 1960) suggest most of the zeolite is clinoptilolite. A clinoptilolite-rich residue was found to contain 1.5% K. Opal-cristobalite (4.09 Å) and volcanic glass are common in the zeolite bearing interval suggesting that the interstitial solutions were probably saturated with respect to amorphous silica. The amount of insoluble residue in the zeolitic facies is considerably larger than that in the K-feldspar facies. This is in part a dilution effect as the more seaward section is the thinner. Both quartz and kaolinite, presumably detrital, are relatively more abundant in the sediments containing K-feldspar. This suggest that much of the noncarbonate material in the deeper water zeolitic facies may have been derived from volcanic material.

Clinoptilolite is a high silica zeolite and presumably formed in a solution which had a higher silica activity and a lower K^+/H^+ ratio than that in which the K-feldspar formed (Garrels and Christ, 1965). Hay (1966) states that clinoptilolite, montmorillonite, and opal are the common alteration products of rhyolite glass in marine deposits; whereas, K-feldspar (and other zeolites) are the dominant alteration products in saline alkaline lakes. Water similar to this latter type could have been present in the pores of the shallow coastal sediments.

The Lower Miocene sediments are characterized by the presence, in abundance, of the Mg-rich chain structure clays attapulgite and sepiolite. These clays constitute from approximately 50 to 90 percent of the clay suite in the Lower Miocene samples. Minor amounts are present in the Middle Miocene and little, if any, in the Upper Miocene. The mineral and chemical change between the Oligocene and Miocene is sizable and abrupt. On the basis of the mineralogy the chemical change represents a decrease in K and Si (and probably Al) and an increase in Mg.

In part this difference could be due to a decrease in the relative amount of volcanic ash supplied to the shelf and plateau. Another factor is the increase in the relative amount of detrital material supplied to this area during the Miocene and Post-Miocene. The attapulgite and sepiolite could be detrital. Our studies of the Miocene in Georgia and Florida strongly suggest that attapulgite and sepiolite are formed in restricted lagoon and tidal flat environments and montmorillonite in a normal marine environment. Attapulgite and sepiolite are most abundant in the Lower Miocene. Due to the nature of the environments in which they formed much of this clay has been reworked and transported into a marine environment. In the Lower Miocene of the shelf and plateau deposits these clay minerals occur in sands, silts, muds, and limestones, indicating that at least some of them are more likely to be detrital than authigenic.

Montmorillonite is the dominant clay in the post-Lower Miocene sediments. Some of this clay is a mixed-layer illite-montmorillonite containing less than 50 per cent illite layers. Chlorite, though minor, is most abundant in the post-Lower Miocene sediments of Well No. 3 on the Blake Plateau. As the samples containing chlorite have the highest kaolinite and illite content the chlorite is probably detrital, though it may have been upgraded in the marine environment. Most of the major rivers draining the Appalachians carry a clay suite containing these three clay minerals (some contain minor amounts of montmorillonite). The chlorite is commonly partially weathered to vermiculite. The lateral distribution of clays in the post-Lower Miocene sediments is broadly similar to that suggested by Biscaye's (1965) limited data on the bottom clays in this area, i.e., montmorillonite increases shoreward and kaolinite, chlorite and illite seaward. This suggests that, in this area, the source of clay and the current pattern has not changed materially since the Middle Miocene.

The shallowest sample from the Blake Plateau (8 feet, Well No. 3) contains a montmorillonite which only partially expands (12 Å to 15 Å) when treated with ethylene glycol but does not appear to be a mixed-layer clay. This sample was boiled in NH_4F for five minutes to remove interlayer material. This increased the amount of expansion but complete expansion was not obtained. The sample was too small to work with further. Chemical analyses of the material taken into solution showed 2.2% Fe, 0.06% Mg, and 0.7% Al was removed. This high iron interlayer material is similar to that found by Rex (1967) for a sample from the Pacific Ocean. Due to the prolonged exposure to sea water it seems likely this interlayer material may have been acquired at the site of deposition. Interlayer material of a different composition, 1.5% Fe, 1.7% Mg, and 3.0% Al, was found for two incompletely expanded montmorillonite samples from the Eocene of Well No. 6.

Lateral non-carbonate mineral changes within the Miocene are believed to largely reflect a detrital distribution pattern. Later variations in the Oligocene and Eocene non-carbonate minerals are due to the formation of authigenic minerals that reflect environmental differences.

Vertically there are three significant mineral changes which suggest changes in the determining background more drastic than the lateral changes. During the Eocene and Oligocene little detritus other than volcanic ash was supplied to the area and most of the silicate minerals formed from the volcanic material. During the Miocene, in this area and regionally, carbonate deposition decreased in importance and detrital silicates increased. Carbonate sediments are most common in the Lower Miocene. Dolomite is the major carbonate mineral; whereas, calcite is the dominant mineral in the pre-Miocene sediments. The presence of abundant dolomite, attapulgite, sepiolite and phosphate in the Lower Miocene suggest that regionally shallow water, restricted circulation environments were widespread in the near-shore area. From the Middle Miocene on this type of environment decreased in importance and an environmental complex evolved which was similar to that now present in the area. Under these latter conditions few authigenic minerals were formed and the detrital suite predominated.

REGIONAL MINERAL FACIES

Reynolds (1966) found that the Paleocene and Lower Eocene clays from the Alabama Coastal Plain contained major amounts of montmorillonite, opal-cristobalite, clinoptilolite and heulandite. The source material was volcanic ash. In South Carolina the Eocene and Oligocene clays contain largely montmorillonite with varying amounts of opal (Heron, et al., 1965). Few analyses have been made of the Eocene and Oligocene carbonate rocks of Florida and Georgia. A few scattered samples analysed by the author contained predominantly montmorillonite and varying amounts of opal-cristobalite.

Mineralogically the Miocene of Florida, Georgia and South Carolina are similar to that in the offshore wells. Montmorillonite is the most common clay but attapulgite and sepiolite are abundant. Opal-cristobalite, which is not present in the offshore material, is abundant locally. Zeolites are rare but minor amounts have been found by Heron and Johnson (1966). In the Lower Miocene of North Carolina and Maryland, in addition to montmorillonite, cristobalite (diatomite) and clinoptilolite are present (Gibson, 1967). Phosphate is abundant both in the Miocene Coastal Plain sediments and the Continental Shelf sediments.

The mineral suites of the Continental Shelf and Plateau are similar to those in the surrounding sediments in the S. E. United States; however, the data are too limited to allow a detailed determination of the three dimensional distribution and interrelation of the various mineral facies.

The data indicate that there probably was an abundance of volcanic material supplied to the area during the Eocene, Oligocene and early and Middle Miocene time. Climatic conditions could have accounted for some of the differences in mineral suites, particularly in the Miocene. Gibson (1967) found that in the early Miocene cold water fauna were dominant at least as far south as approximately the middle of North Carolina. To the south in Georgia and Florida subtropical to tropical fauna prevailed. The latter environmental conditions might be expected to favor the development of hypersaline conditions and the formation of magnesium silicates and dolomite.

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A NEW CHRONOLOGY FOR BRAIDED STREAM SURFACE FORMATION IN THE LOWER MISSISSIPPI VALLEY

by

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ABSTRACT

According to the existing Late Quaternary chronology for the Lower Mississippi Valley (Fisk, 1944), the widespread braided-stream surfaces in the valley mark the end of a period of alluviation that immediately preceded the development of the modern meander belts, i.e., the surfaces were formed during the waning stages of the Late Wisconsin glaciation. Recent investigations have uncovered stratigraphic evidence to indicate that some of the surfaces were affected by a period of major entrenchment in the alluvial valley during a period of waxing glaciation following their formation. This observation, plus the presence of radiocarbon dates indicating a 29,000 -to 31,000-year-old age for one of the surfaces in the valley, have necessitated seeking a new chronology for valley events.

The chronology that is proposed attempts to show a correlation between valley events and the concepts of Late Quaternary sea level variations as recently set forth by Shepard (1963) and Curray (1965). According to the chronology, certain braided-stream surfaces were formed 25,000 to 30,000 years ago during or shortly preceding a high sea level stand corresponding with the Farmdalian Substage while others postdate the subsequent and latest period of low sea level stand that occurred 18,000 to 20,000 years ago. The older braided-stream surfaces are probably a time equivalent of the Deweyville Terrace that is widespread along several Coastal Plain streams.

BACKGROUND

The Quaternary deposits of the Lower Mississippi Valley have an estimated volume of approximately 1,000 cubic miles (Fisk, 1944) and extend over an area of about 37,000 square miles between Cairo, Illinois, and near Baton Rouge, Louisiana (Figure 1). On the basis of lithology, the elongated mass of alluvium is commonly divided into a coarse-grained substratum composed mainly of sands and gravels and a fine-grained topstratum consisting principally of clays, silts, and fine sands (Kolb and Shockley, 1959). The substratum, by far the larger of the two units, varies from about 25 to 120 feet in thickness.

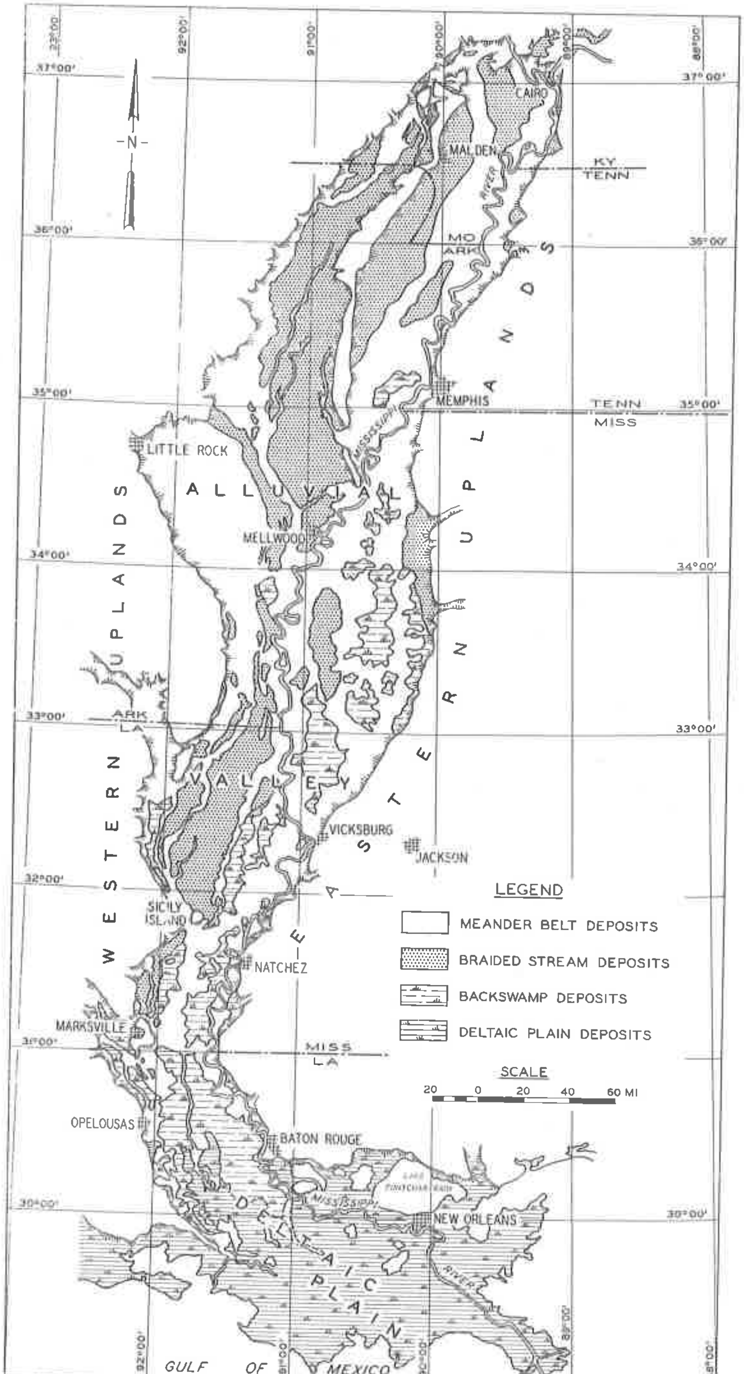

Figure 1. Classification of Quaternary topstratum deposits in the Lower Mississippi Valley.

According to Fisk (1944), the substratum was deposited during the period of major eustatic sea level rise resulting from the waning of the Late Wisconsin glaciation. Deposition of the sands and gravels was by shallow, anastomosing, braided streams overloaded with glacial detritus. This deposition was confined to the basal part of the entrenched valley that had been formed during the preceding period of sea level fall corresponding with the waxing Late Wisconsin glaciation.

As indicated in Figure 1, the topstratum includes sediments deposited by both braided and meandering streams. The braided-stream topstratum deposits, interpreted by Fisk (1944) as representing the last materials to be laid down before the disappearance of continental glaciation, are merely the somewhat finer-grained, uppermost portions of the substratum. The finer grain sizes reflect a decreasing source of coarse glacial debris as well as a shallowing of stream gradients. Following the deposition of the braided-stream topstratum deposits, the Mississippi and Ohio Rivers, no longer choked with glacial outwash, began to meander thoughout the length of the valley and eventually developed extensive meander belts. Meandering of these streams, plus their major tributaries, has resulted in the removal and reworking of large areas of braided-stream deposits; however, thousands of square miles of the deposits remain as slightly dissected alluvial plains or "braided-stream surfaces."

Thus, according to Fisk, both the braided-stream deposits and the meandering stream deposits postdate the maximum extent of the Late Wisconsin glaciation which was also the time of maximum sea level lowering. Fisk, like Russell (1940), chose this time of maximum lowering of sea level as the dividing point between the Pleistocene and the Recent.

THE PROBLEM

During the course of preparing detailed engineering-geologic quadrangle maps in the southern part of the Mississippi alluvial valley (Saucier, 1967), the writer became aware of certain physiographic and stratigraphic conditions that appeared to conflict with Fisk's interpretation of the age of the braided-stream surfaces. The particular surfaces involved are Macon Ridge, which was formed by an early braided Arkansas River as it entered the Mississippi Valley, and an unnamed area of braided-stream surface lying to the southwest of Sicily Island, which was thought to be formed by a braided course of the Mississippi River about the same time (Figure 1).

Along the southwest side of Macon Ridge are several small ephemeral streams that serve to transmit runoff from the ridge to the slightly lower Ouachita River valley along the west side of the ridge. These streams, one of the largest of which is named Turkey Creek (Figure 2), undoubtedly are located in some of the old narrow and

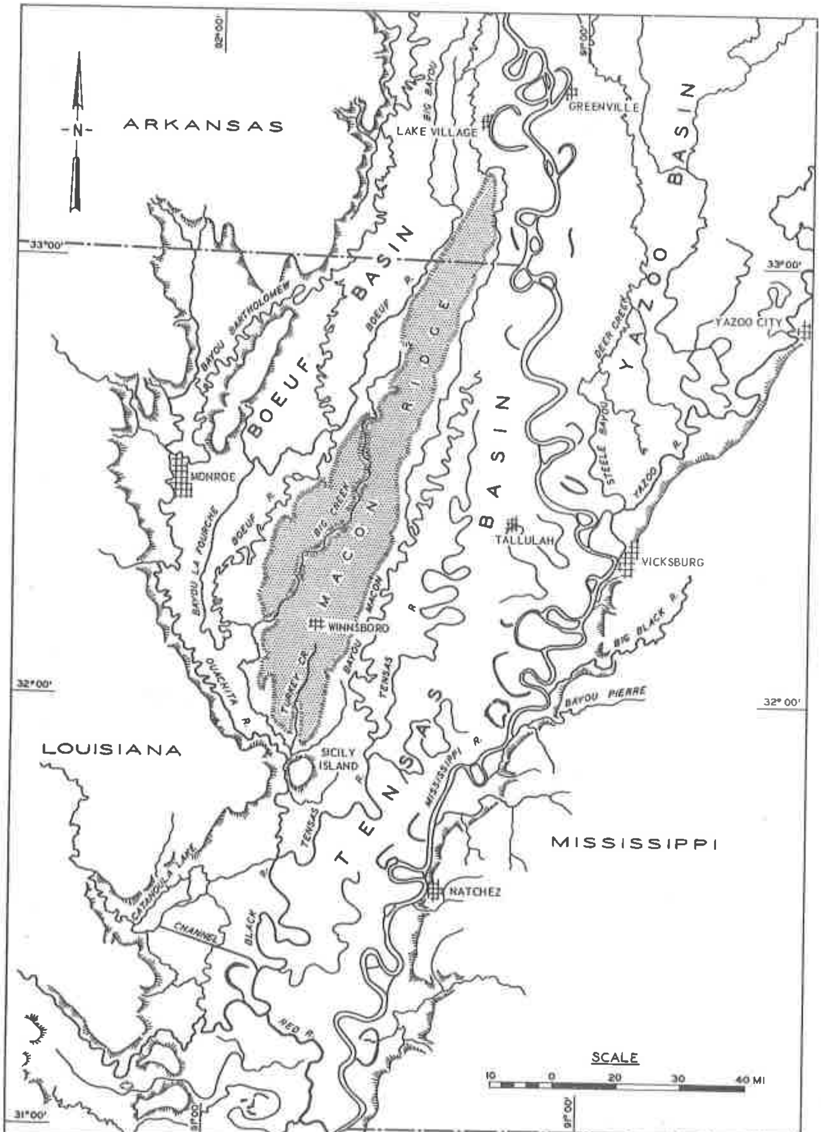

Figure 2. Geographic setting, Macon Ridge and vicinity.

shallow braided channels that are still discernible on the surface. Turkey Creek and the other streams are unusual in that they exhibit wide, flat, floodplains that strongly suggest the presence of appreciable alluvial fill.

It is possible that a certain amount of alluvium could have been deposited as a result of "alluvial drowning" since the Ouachita River valley experienced the development of several meander belts of the

Arkansas River after the braided surface was abandoned. The development of any of the meander belts, which are now marked by such streams as Boeuf River and Bayou Bartholomew (Figure 2), could have resulted in an influx of fine-grained sediments during floods into Turkey Creek and the other streams. However, borings across the lower end of the Turkey Creek floodplain indicate the alluvial fill to be at least 30 feet thick and possibly as much as 75 feet thick. It seems improbable that this atypical thickness of alluvium could have accumulated unless Turkey Creek had formed an entrenched valley in Macon Ridge. Such an entrenchment could only have occurred as a result of the stream adjusting its gradient to a lower-than-present floodplain level (i. e., an entrenchment) in the Ouachita valley or an uplift of Macon Ridge. There is no indication that the ridge has been affected structurally and heretofore there was no reason to suspect that the Ouachita River floodplain was significantly lower than present during the Recent.

According to existing concepts, the Ouachita valley area was last entrenched during the Late Wisconsin glaciation. If it had been this entrenchment to which Turkey Creek adjusted its gradient, this would mean that Macon Ridge was pre-Late Wisconsin or Pleistocene in age. This age assignment for Macon Ridge is untenable since the ridge does not correlate topographically or morphologically with the youngest Pleistocene terrace deposits flanking the alluvial valley (i. e., the Prairie Terrace), which Fisk assumed was formed during the Bradyan Interglacial Stage..

The problem of the age of the braided stream surfaces in the alluvial valley became more acute as a result of subsurface data acquired along the route of a channel being constructed by the U. S. Army Corps of Engineers southeast from Catahoula Lake (Figure 2). Borings along the channel indicate an extensive area of backswamp deposits having an average thickness of about 75 feet directly abutting or lying stratigraphically adjacent to an area of braided-stream deposits. As indicated in section A-A', Figure 3, the braided-stream deposits are truncated abruptly along the contact with the backswamp deposits; interfingering is totally absent.

Backswamp deposits consist of sediments laid down in shallow ponded areas (either swamps or shallow lakes) during periods of overbank flooding. These homogeneous, fine-grained sediments apparently began accumulating to appreciable thicknesses over large areas only after braided-stream conditions terminated in the alluvial valley and all streams were restricted to narrow meander belts (Fisk, 1947). The thickness of the deposits is an indication of the amount of aggradation of the floodplain that has taken place largely as a result of shallowing stream gradients during the late stages of sea level rise.

As previously mentioned, the sequence of events in the depositional history of the alluvial valley postulated by Fisk (1944) includes a change from braided to meandering conditions late in the Quaternary

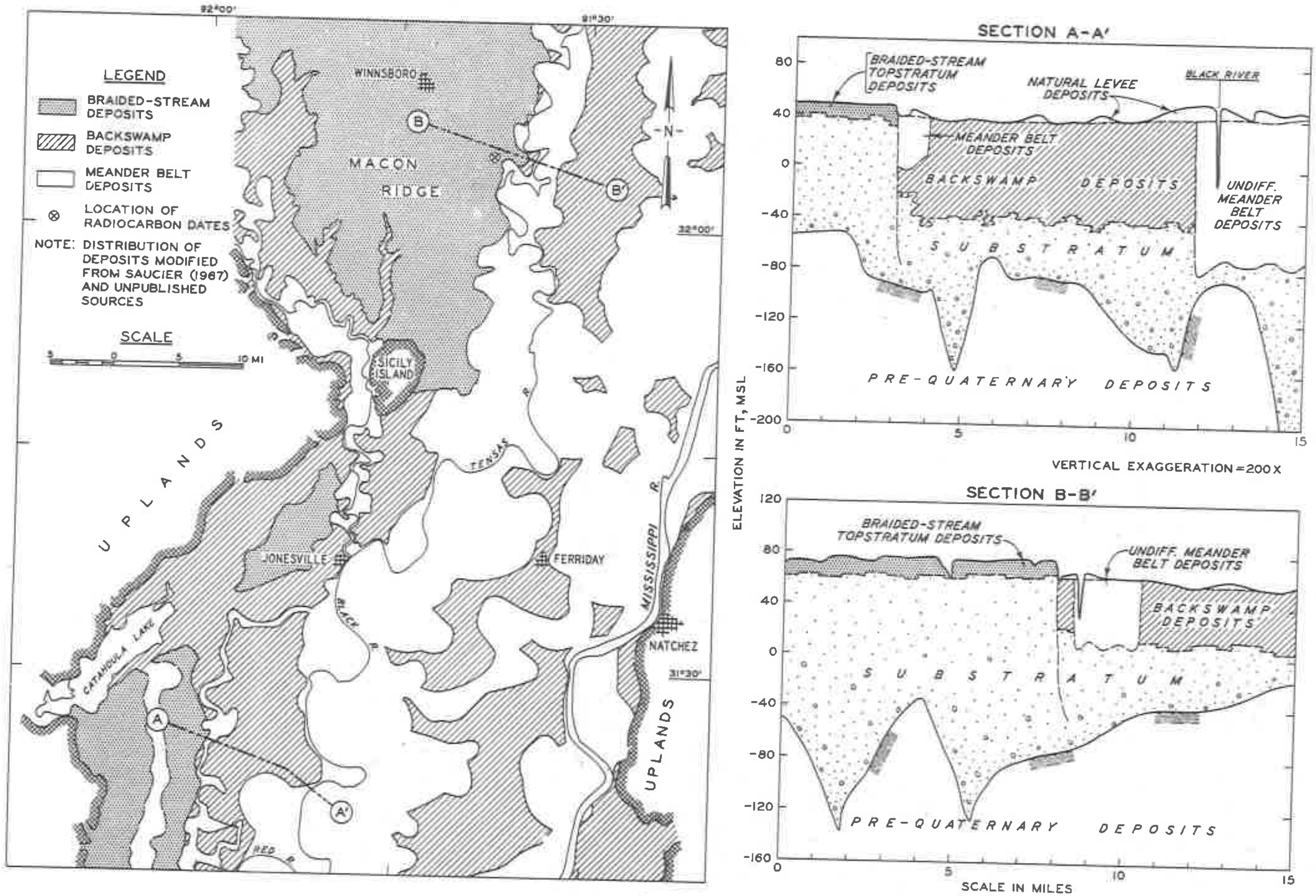

Figure 3. Distribution and stratigraphic relations of deposits in the Macon Ridge area.

history of the valley. This occurred at a time when continental glaciation had almost completely ended in North America and sea level had risen to within a few feet of its present level. By this time, most of the aggradation of the valley had already occurred and subsequent minor changes were limited to those caused by shifts in meander belts and subsidence of parts of the valley as a result of faulting. Thus, assuming a relatively stable floodplain level after the braided-stream surfaces were formed, the destruction of large braided-stream surface areas could have occurred only by the lateral migration of meandering streams. If this was the case, meander belt deposits such as those deposited in point bar, abandoned channel, and abandoned course environments everywhere should lie directly adjacent to the truncated margins of the braided-stream areas; materials such as backswamp deposits that indicate continuous vertical aggradation should not be present at these locations.

In the writer's opinion, the stratigraphic relationships existing southeast of Catahoula Lake can only be interpreted as indicating that, following formation of the braided-stream surfaces, the alluvial valley in this area experienced a period of entrenchment during which the floodplain was lowered on the order of 75 feet and possibly more. The vertical accretion that subsequently occurred was caused by sedimentation derived from meandering courses of the Mississippi River and its tributaries. The possibility that the conditions existing southeast of Catahoula Lake represent a local anomalous condition caused by some unusual occurrence such as faulting is highly improbable and is essentially precluded by the presence of several similar areas along the eastern and western sides of Macon Ridge (Figure 3). Backswamp deposits having thicknesses of at least 50 feet lie directly adjacent to the braided-stream deposits of Macon Ridge at three locations along the eastern side of the ridge near the latitude of Winnsboro, Louisiana (Section B-B, Figure 3).

The first indication of a finite age assignment for the braided-stream deposits comprising Macon Ridge came to light with the location of an unpublished radiocarbon date[1/] on freshwater shells from a locality in Franklin Parish, Louisiana, about 8 miles southeast of Winnsboro, Louisiana (SE1/4 SW1/4 NW1/4, Sec 26, T13N R8E). The shells, situated in what was most likely a shallow freshwater lake or pond now located at a depth of about 12 feet below ground surface, were assayed by Humble Oil and Refining Company in 1957 (Laboratory Sample No. G-110) and yielded a date of 31,200±2,400 years before present. In correspondence accompanying the dating, Fisk stated that he assumed this date to be anomalous and indicated that it probably was associated with older underlying Pleistocene deposits (Bradyan age)

1/ Contained in correspondence on file at the U. S. Army Engineer Waterways Experiment Station, Vicksburg, Mississippi.

such as those that occur at isolated points about 10 miles north of the dated locality. He speculated that the shells may have been contaminated with younger carbonates during postdepositional weathering.

In late 1966, the writer visited the locality and collected a second sample of freshwater shells from the same stratigraphic location. The lake or pond deposit containing the shells is about 5 feet thick and consists of mottled gray and red silty clay. This material is overlain by about 7 feet of tan silt and is underlain by gray-brown sandy clay. The shells were assayed by Geochron Laboratories, Inc. (Laboratory Sample No. GXO844) and yielded a date of $29,100 \pm 1,200$ years before present. The considerable agreement between the two dates enhances the probability that they are valid dating of the deposit; there was no indication at the locality that the shells were associated with older Pleistocene deposits rather than the braided-stream deposits.

The silt deposits lying above the dated horizon have been classified as noncalcareous loess (Peoria loess) by several writers (Wascher and others, 1948) and are generally regarded as such by most contemporary pedologists. If these thin but widespread deposits are true eolian loess, the inference can be made that they are equivalent to the Vicksburg loess (Peoria equivalent) as defined by Krinitzsky and Turnbull (1967) and which has been radiocarbon dated at between 18,000 and 25,000 years before present. Thus, this is a possible further indication of the age of the Macon Ridge braided-stream deposits.

A NEW CHRONOLOGY

It has only been during the last 5 years that a new concept of Late Quaternary events and chronology has emerged that could possibly make tenable a 30,000-year-before-present age for Macon Ridge. The new chronological concept, advanced by Shepard (1963) and Curray (1965), suggests that sea level did not simply fall to a low stand that lasted until 20,000 to 30,000 years ago as a result of Late Wisconsin glaciation and thence rise to its present level about 3,000 to 5,000 years ago as a result of the waning of the glaciation (Figure 4a). Rather, evidence is now available to indicate that (a) sea level fell to a low stand with waxing glaciation more than 40,000 years ago, (b) sea level rose to a high stand about 25,000 to 35,000 years ago that approximates present sea level (referred to by Curray as the Mid-Wisconsin Transgression), (c) sea level fell to a second low stand about 18,000 to 20,000 years ago (the Late Wisconsin Regression), and finally (d) sea level rose to its present level which was attained about 3,000 to 5,000 years ago (the Holocene Transgression) (Figure 4b). The Mid-Wisconsin Transgression is tentatively correlated by Shepard (1963) with the Farmdalian Substage and the Late Wisconsin Regression with a period of waxing glaciation, probably the Woodfordian Substage.

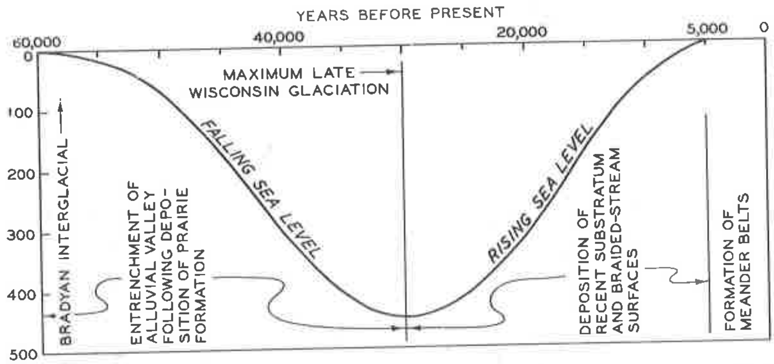

Figure 4a. Late Quaternary chronology and events according to Fisk and McFarlan (1955).

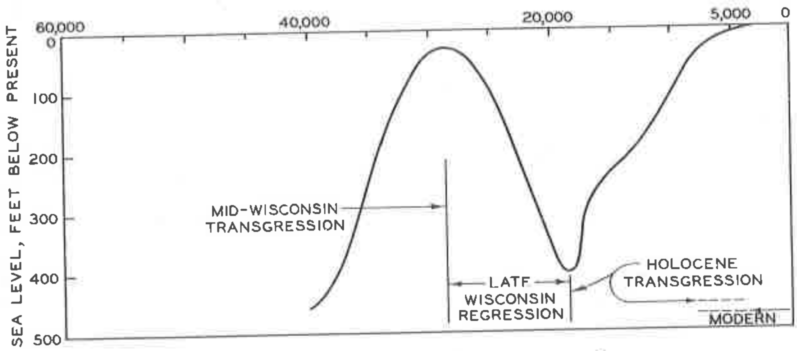

Figure 4b. Late Quaternary chronology and events according to Curray (1965).

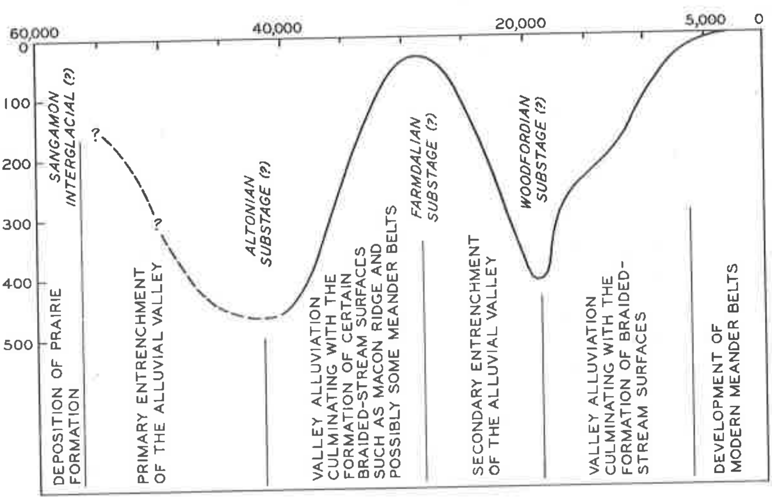

Figure 4c. Postulated Late Quaternary chronology and events as related to the formation of braided-stream surfaces.

The concept of a high sea level stand about 25,000 to 35,000 years ago followed by a period of major sea level fall appears to accord well with the new data regarding braided-stream surfaces in the alluvial valley and as a consequence, the following new hypothesis of valley events and chronology is advanced (Figure 4c).

The Prairie Terrace of the Lower Mississippi Valley traditionally has been assigned to the Bradyan Interglacial Stage; however, if it represents fluvial deposition during an interglacial stage and if it is older than 35,000 to 40,000 years as radiocarbon dates indicate (McFarlan, 1961), it appears more plausible to correlate it with the Sangamon Interglacial Stage. Following its deposition, which probably occurred 60,000 to 75,000 years ago, the alluvial valley was deeply entrenched. The entrenchment was partly a result of streams adjusting their gradients to a falling sea level during the waxing Early Wisconsin glaciation but mostly a result of changes in river regimes brought about by major climatic changes. The maximum valley entrenchment may have occurred as recently as 40,000 to 45,000 years ago during the Altonian Substage (Figure 4c).

With the waning of the Early Wisconsin glaciation, braided streams began filling the entrenched valley with large volumes of sediments, mostly sands and gravels. This stage of valley alluviation lasted until about 25,000 to 30,000 years ago (the Farmdalian Substage) and was climaxed with the deposition of Macon Ridge and certain other braided-stream surfaces in the alluvial valley. There is not sufficient information at this time to indicate whether or not the period of high sea level stand and glacial retreat lasted long enough for the ancestral Mississippi River and its tributaries to change from a braided to a meandering state over large areas of the valley and create widespread meander belts. There are several occurrences of meander scars in the alluvial valley heavily veneered with younger backswamp deposits that suggest formation during this stage; however, none have been dated or investigated in detail.

A second entrenchment of the alluvial valley began with the onset of the Late Wisconsin glaciation and reached its greatest extent about 18,000 to 20,000 years ago during the Woodfordian Substage (Figure 4c). The greatest effect of the entrenchment must have been the removal of large quantities of sands and gravels deposited by braided streams during the preceding period of waning glaciation; it is doubtful that the entrenchment attained a magnitude sufficient to cause any significant scouring of the pre-Quaternary "bedrock" such as occurred during the Altonian Substage except possibly at the extreme southern end of the valley. In addition, large areas of braided-stream surface such as Macon Ridge apparently were little affected by the entrenchment and probably experienced only minor surface erosion and the local incision of streams such as Turkey Creek. Although much of the scouring during the entrenchment must have resulted from downcutting of streams adjusting to a falling sea level and changing sediment loads, a certain amount of scouring by the lateral planation of meandering streams probably occurred during both this and the preceding period of entrenchment (Durham, 1965).

Waning of the Late Wisconsin glaciation resulted in a second wave of alluviation by braided streams between 18,000-20,000 years ago and 4,000-5,000 years ago. It is probable that the braided condition of the ancestral Mississippi River gave way to a meandering condition as early as 12,000 to 14,000 years ago in the southern end of the valley,2/ whereas a braided condition may have lasted until as late as 4,000 years ago in parts of the northern end of the valley. This suggests that most of braided-stream surfaces in the northern part of the valley probably date from this period of alluviation rather than from the preceding one about 25,000 to 30,000 years ago.

Since the development of meander belts in all parts of the alluvial valley, the extent of braided-stream surfaces has been gradually reduced as a result of the lateral migration of the meandering streams. Moreover, considerable volumes of substratum sand and gravel have been reworked to depths of 100 to 150 feet and occasionally to as much as 200 feet within the meander belts. Because of the nature of the deposits, it is not possible to differentiate the braided substratum from the reworked substratum. Similarly, it is not possible to differentiate the older (pre-Famdalian) substratum sand and gravel deposits from the younger (post-Woodfordian) substratum deposits. Consequently, it is only within the uppermost topstratum deposits of the alluvial valley that the Quaternary deposits can be identified as to age; the meander belt and backswamp areas being of Recent age and the braided-stream surfaces being of both Recent and Pleistocene age (following Russell's definition of Recent).

According to Bernard and LeBlanc (1965), the braided-stream surfaces in the Lower Mississippi Valley correlate with the Deweyville Terrace. This low terrace, present on certain of the Mississippi River tributaries and at least eight Gulf and Atlantic Coastal Plain rivers (Gagliano and Thom, 1967), is characterized by meander scars several times larger than those on the present streams, thus suggesting formation during a period of appreciably greater-than-present discharge. Radiocarbon dates on organic materials from the terrace range from 17,000 to over 30,000 years before present (Bernard and LeBlanc, 1965). These writers believed the terrace was formed during the period of the last sea level rise partly because no coastwise plain equivalent had been found. Gagliano and Thom (1967), however, cite evidence to indicate that the Deweyville Terrace must predate the last glacial advance and consequently tentatively assign it to the Farmdalian Substage. This age assignment is further substantiated by the recent location of what is believed to be a buried coastwise plain equivalent of the Deweyville Terrace in various parts of south Louisiana (unpublished data assembled by this writer). The plain definitely appears to have been entrenched and exposed to subaerial weathering during a post-depositional low sea level stand (the Woodfordian Substage). Thus, the Deweyville Terrace is considered as a time-equivalent of the older braided-stream surfaces in the alluvial valley.

2/ An estimate based on unpublished radiocarbon dates on meander belt deposits near the southern end of the valley.

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OBSERVATIONS ON THE DISTRIBUTION OF SANDS WITHIN THE POTOMAC FORMATION OF NORTHERN DELAWARE

by

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ABSTRACT

The Potomac Formation is a continental unit of Cretaceous age that is widespread in the northern Atlantic Coastal Plain. In northern Delaware sands within the Potomac are important aquifers and their correlation has received much attention but has proven to be very difficult. An experimental approach is presented here in which well logs of the Potomac are correlated using basement as a datum plane and the proportion of wells containing sand (as opposed to clay) at intervals above basement is calculated. This is thought to provide an indication of the variations in sand and clay content of the sediment supplied to the basin during Potomac time. The resulting graph of the proportion of wells containing sand plotted against distance above basement appears to be compatible with what is known of the geology and hyrology of the Potomac Formation in Delaware.

INTRODUCTION

A recent hydrologic investigation in northern Delaware that centered on the Potomac Formation has provided impetus to reconsider methods of determining the distribution of sand bodies within a dominantly clayey continental sedimentary deposit. The intensive, short-term hydrologic investigation was conducted under the auspices of the Water Resources Center of the University of Delaware and its results are presented by Sundstrom, et al. (1967).

The writer has benefited from intensive discussion of the internal stratigraphy of the Potomac Formation with the members of the panel of consultants who carried out the hydrologic investigation: Frank C. Foley, William F. Guyton, Raymond W. Sundstrom, and William C. Walton; and also from debate with his colleagues at the Delaware Geological Survey and the Department of Geology of the University of Delaware. Mention of these persons should not be construed to mean that they are necessarily in agreement with the author.

GENERAL GEOLOGY

The area of investigation encompasses the Coastal Plain portion of New Castle County, Delaware (Figure 1). This is part of the inner Atlantic Coastal Plain from the Fall Zone to a line roughly parallel to the Fall Zone and about 25 miles to the south-southeast. The wedge of Coastal Plain deposits increases in thickness in this area from a feather edge at the Fall Zone to a maximum of approximately 2,300 feet in the southeast. The basal Coastal Plain unit is the Potomac Formation, which comprises most of the bulk of the entire sedimentary mass. Above the Potomac, in a truncated off-lapping sequence, lie transitional and marine Upper Cretaceous and marine Tertiary units. The basic geology of the area has been discussed by several authors and is briefly summarized by Jordan (1962) and Spoljaric and Jordan (1966). Almost the entire surface of the Coastal Plain in this area is covered by a veneer of fluvial sands of Pleistocene age, the Columbia Formation (Jordan, 1964). Relief is low and most geologic study is necessarily based on information derived from wells.

A study of the sedimentary petrology of the Cretaceous formations of northern Delaware by Groot (1955) provides the basic description of the Potomac Formation. Several formations are recognized within the non-marine Cretaceous deposits of Maryland and New Jersey (the Potomac Group); however, differentiation in Delaware is not adequate and the Potomac is considered to be a single formation (additional discussion of stratigraphic problems may be found in Groot and Penny, 1960 and Jordan, 1962). Groot (1955) demonstrated that the Potomac is a genetically related sequence derived from the Appalachian Highlands and deposited under continental conditions by a distributary stream system in a manner that may be likened to a system of coalescing alluvial fans.

Brenner's (1963) palynological study and analysis of previous plant-fossil studies placed the age of the basal non-marine beds in Maryland as probably upper Neocomian. The upper beds of the Potomac were determined to be of probable Cenomanian age by Groot and Penny (1960). Additional discussion of the age of these deposits may be found in Berry (1911, 1916), Dorf (1952), and Groot, Penny, and Groot (1961). From such investigations it may be seen that intraformational time correlation within the Potomac is a difficult task beyond the scope of an "applied" project.

Lithologically, the Potomac consists primarily of interbedded sands and clays. The sands are quartzose, and tend to be fine and moderately well-sorted. Clays are often variegated, silty, and tough. Clayey sands and sandy clays are also present.

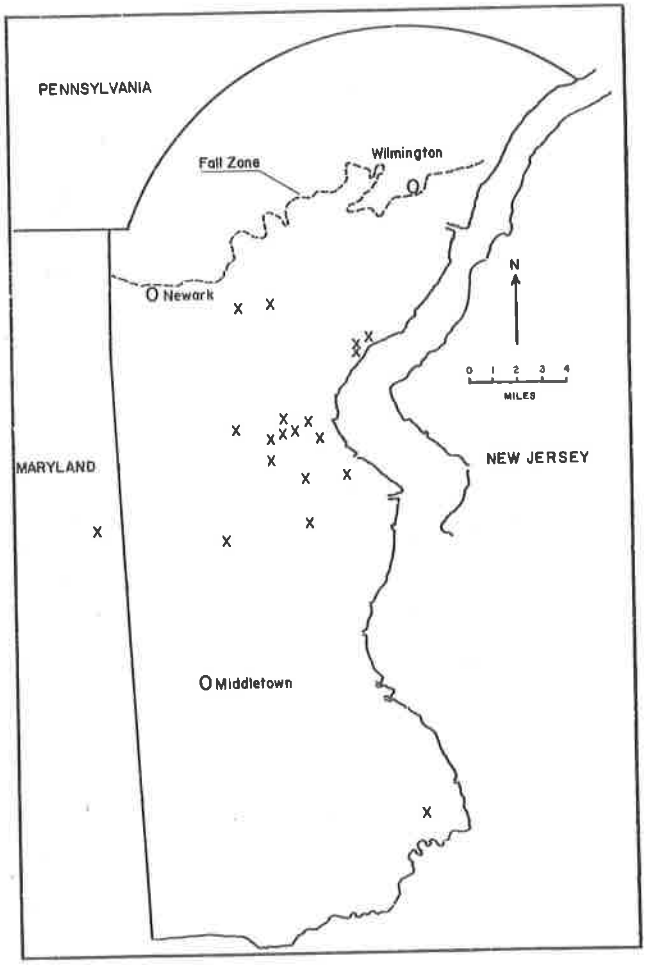

Figure 1. New Castle County, Delaware, showing locations of wells (x).

PRACTICAL PROBLEMS

The applied hydrologic study required some knowledge of the position, size, shape, and, especially, the degree of interconnection of sand bodies. Results were required in a short time (six weeks) on the basis of existing data only. A new and detailed program of stratigraphic investigation was indicated, but was impossible under the circumstances. As have other geologists in the past, the staff of the Delaware Geological Survey attempted a variety of standard forms of written and geophysical well log interpretation and correlation. It was concluded that individual sand or clay beds could not be traced with certainty for distances of even one-half mile. Zonation, or grouping of beds according to dominant aggregate characteristics, was found to require considerable generalization in order to extend zones over distances of one mile or more. Correlation for distances of five miles or more is required in parts of New Castle County because of the spacing of significant wells. The most satisfactory treatment of a unit with the horizontal and vertical variability of the Potomac appears to lie in lithofacies mapping. Sufficient well control for the application of these techniques is available only in the east-central portion of the study area. Spoljaric (1967) presents a detailed lithofacies study of this specific area which successfully defines and explains the distribution of sand, but not necessarily sand beds.

METHODS OF STUDY

The Potomac lies on the eroded surface of the ancient crystalline basement complex. The eroded basement surface, essentially the Fall Zone Peneplain, was generated in Jurassic and earliest Cretaceous time. The change in this area from a site of erosion to one of deposition signifies a major change in the relationship of the Appalachian Mountain System to the Atlantic Coast Geosyncline (or its prototype). Sedimentation requires a source area, which is provided by uplift, and a basin of deposition, which is provided by relative subsidence. The epeirogenic uplift of the Appalachian System and the concomitant downwarping of the Coastal Plain region generated the Potomac Formation in this sense.

The source area of the Potomac Formation, due to climate, topography, and rock type, supplied predominantly fine-grained detritus. The available sand was winnowed from silt and clay and deposited mainly in stream channels, resulting in elongate, thin fluvial sand deposits. The confined sand bodies are considered to be subsidiary elements within a fine-grained matrix.

If all conditions affecting the input of sediment into the depositional basin and subsequent modification within the basin remained constant throughout the period of deposition, sand bodies should be distributed in a grossly homogeneous manner in three dimensions within the Potomac Formation. The lack of success of several diligent attempts at internal lithologic correlation in the Delaware area suggests a randomness in the distribution of lithologies and indicates the sparseness of diagnostic features for the separation and correlation of individual sands and clays.

Hydrologic data have complemented geologic study in the generalized delineation of two ground-water reservoirs which tend to be sandy and constitute the best aquifers within the Potomac. The hydrologic evidence is summarized in the following manner by Sundstrom, et al. (1967, p. 46):

The pumping tests show that the lower and upper sand zones have very low coefficients of storage, indicating that they are confined. The water-level measurements made in the wells during pumping tests do not show that the upper zone is markedly affected by pumping from the lower zone and vice versa. This indicates that at least locally, and perhaps for a considerable distance, the two sand zones are separated effectively by clay.

The hydrologic evidence strongly suggests changing geologic conditions during the deposition of the Potomac Formation and requires rather discrete and separate bodies of sand and clay. It is disturbing that this is not inherent in the purely geologic data, although fluctuations might well be expected during such a long period of time. Sediment input appears to have been continuous, indicating the presence of streams at all times, which might mean continuously, three-dimensionally, connected sandy channels. The clays and sands are interbedded and individual beds of either cannot be certainly identified as belonging to one or the other of the reservoirs or to the confining layers. The problem is one of the degree of interconnection existing physically, genetically, and hydraulically between sands.

In some intervals, based on the hydrologic evidence, sand channels must diminish in number and/or size so as to provide only very devious or "leaky" interconnections. Changes of a general nature, such as in climate or tectonic relationships, would affect the texture of the Potomac sediments by causing a corresponding shift in the ratio of sand to silt and clay brought into the basin. Although the distribution of stream channels, and therefore sands, might still be essentially random (at least from the perspective of 100 million years), the amount of sand relative to silt and clay could be expected to vary through stratigraphic zones representing the times of change of regional factors. Such changes seem to provide a more satisfactory explanation of the hydrologic observations than do local changes in the depositional milieu.

The problem of internal stratigraphic control remains, but is circumvented in the following procedure by referring all wells to basement datum. Basement provides a uniform and unmistakable starting point for measurements. The Potomac-basement contact is considered to have a relatively narrow time value, at least a more significant time value than any known plane within the Potomac or the angular unconformities that truncate its upper surface. Based on the principle of original horizontality and the tectonically negative aspect of the Coastal Plain which has induced syn-and post-depositional seaward tilting, it is assumed that the gross stratification of the Potomac is essentially parallel to the surface of the basement complex. The basement, which, in fact, has a relief on the order of 50 feet in the study area, is treated as if it were planar. The downdip increase in thickness of 1,600 feet in 25 miles is assumed to be accomplished by the addition of younger beds rather than the thickening of older strata. If rates of deposition were essentially uniform laterally, then time lines should be approximately parallel to basement throughout the thickness of the Potomac. Spoljaric (1967) uses somewhat similar reasoning in his lithofacies analysis, although he does not concur in the value of the basement reference plane.

The framework thus conceived is arbitrary, but seems to approximate natural conditions. The assumptions made are thought not to introduce errors of greater magnitude than those present in other imponderables, for example, compaction, that are encountered in any such study method. Also, the area of study is very small in comparison with the areal extent of the Potomac Formation and this minimizes stratigraphic errors. By using basement as a datum plane and summing the proportions of sand and clay found in wells at intervals above and parallel to basement a statistical summary approximating the distribution of sand and clay may be made.

RESULTS

A sample consisting of 19 wells distributed over the Coastal Plain of New Castle County was treated experimentally. Well locations are shown in Figure 1. A wide distribution was sought; although a confined area might well yield more precise results, it would not be as severe a test. The only stipulations made in the selection of wells were that (1) they penetrate to basement, and (2) that electric logs were available. A clay (shale) base line was established for each electric log and the log interpreted on this basis simply as representing sand or clay at intervals of 10 feet starting at the basement and continuing upward through the Potomac section. The proportion of wells showing sand at each 10 foot increment was tabulated in terms of the percentage of the total number of wells in the sample at that distance above basement. For example, 100 feet above basement, 14 of 19 wells, or 74 percent, contain sand. The higher the percentage of wells containing sand at any given interval, the higher was the ratio of sand to clay in the detritus supplied to the area in that vague, but probably small, time interval represented by that particular slice of the Potomac. Percentages of sand at each 10 foot interval are plotted against distance above basement in Figure 2.

Because wells located farther from the Fall Zone penetrate greater thicknesses of the Potomac Formation than those in the northeastern portion of the area, and because measurements are made from the bottom up, the number of wells in the sample decreases upward in the section. This, in turn, decreases the statistical accuracy of the method for the upper part of the section shown (particularly 500 to 600

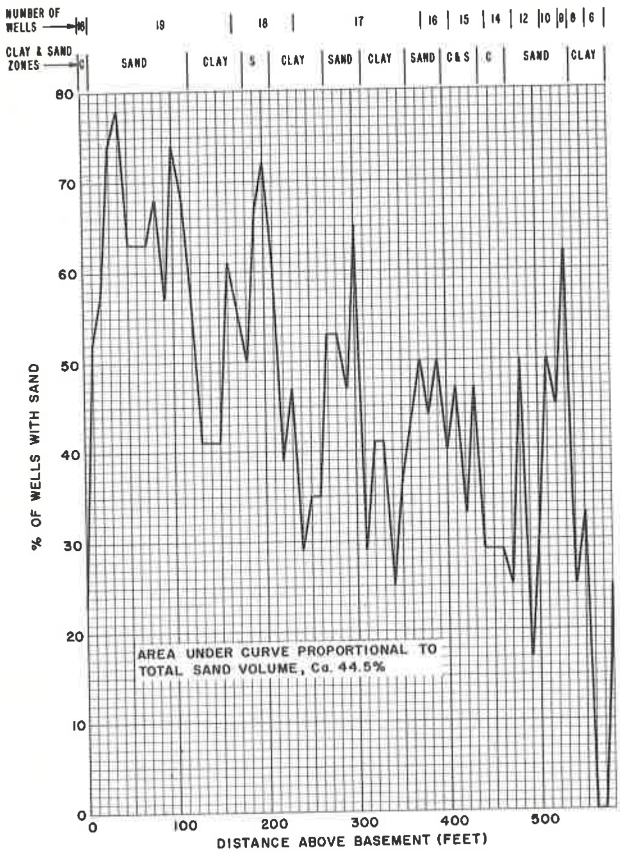

Figure 2. Distribution of sands within the Potomac Formation.

feet above the basement). The numbers of wells used in each calculation and the relatively sandy and clayey zones are given on Figure 2.

The designation of sandy and clayey zones does not mean that sheets of sand and clay are present, rather, as the percentage of sand does not reach either 100 or 0 where sufficient well control is present, it indicates the interbedded nature of each slice and suggested which element, sand or clay, is dominant.

The following observations concerning the plotted results of this method for the Potomac Formation in northern Delaware seem pertinent:

1. The most striking characteristic of the curve indicating sand-clay content variations with distance above basement is its over-all slope. The trend from relatively high sand

content near basement toward much less sand higher in the section is so consistent as to suggest some validity of method in spite of the assumptions employed. The slope of the curve records a progression, with fluctuations, from coarser to finer textures during Potomac time. This accords well with previous statements that sands in the Potomac tend to be coarser and more concentrated near its base, and also with the concept of progressive denudation and lowering of the source area (c.f. Groot, 1955).

2. Fluctuations of some 15 to 20 percent toward either side of the mean trend of the curve occur sub-regularly. According to the premises of the method, these indicate coarser and finer average sediment inputs superimposed on the general trend toward finer sediment. Five peaks toward the sand-rich pole and five peaks of relatively high clay content are present. The locations of these peaks on the chart theoretically predict the stratigraphic locations of sandy and clayey zones, and the magnitudes of the peaks should be proportional to the probability of a correct prediction.
3. The degree of hydrologic interconnection of sand bodies should be roughly proportional to the relative amounts of sand and clay indicated by the chart. If correct, this yields a layered situation in what at first appears to be a homogeneous mass and could facilitate hydrologic analysis, particularly by modeling techniques.
4. The area under the curve of Figure 2 should be proportional to the total volume of sand in the Potomac, the remainder being assigned to silt and clay. The sandy bed volume indicated is about 45 percent of the total mass in the study area, which is reasonable when compared with available well logs.
5. The method employed loses the geographic position of sand bodies but emphasizes their quasi-stratigraphic position. Geographic orientation can, in a sense, be regained for purposes of predicting sand in a given well by deriving the basement depth for the well location from a structure contour map. By reading the appropriate part of the curve, the depth at which sandy and clayey zones occur could theoretically be calculated with some measure of probability.

The experimental method outlined is considered preliminary, but is thought to have some potential. It resulted from a pressing practical need and was found to be useful as an additional line of evidence in a major hydrologic investigation. The results are reasonable in comparison with the empirically derived hydrologic results of Sundstrom, et al. (1967). Higher effective coefficients of transmissibility are found in the lower part of the Potomac than in the upper sands by the hydrologists, which agrees with the proportions of sand and clay shown in Figure 2. The definite, but leaky (Sundstrom, et al., 1967), barrier between the two major aquifers in the Potomac has been determined to be the clay-rich zone between about 210 feet and 270 feet above basement (Figure 2) on the basis of well correlation guided by the chart. The chart has served to enable the assignment of wells not otherwise correlatable to the upper or lower ground water reservoirs. The chart has been tested against electrically logged wells that were not in the sample used in its computation and has yielded encouraging results. Finally, the statistical summary is capable of logical geologic interpretation that is consistent with Groot's (1955) analysis of the deposition of the Potomac.

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THE PIEZOMETRIC SURFACE OF THE COASTAL PLAIN AQUIFER IN GEORGIA, ESTIMATES OF ORIGINAL ELEVATION AND LONG-TERM DECLINE

by

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ABSTRACT

The principal source of underground water in the Coastal Plain of Georgia is an artesian aquifer consisting of Eocene to Miocene age limestones capped by impervious Miocene sediments. The aquifer, here referred to as the Coastal Plain aquifer, has been heavily pumped and deep cones of depression in the piezometric surface have developed around centers of population and industrial activity. The history of aquifer pressure decline in the area near the Atlantic Coast is well known, but an evaluation of pressure decline for the aquifer as a whole requires a knowledge of original artesian pressures which has not been available to this time. Reports on artesian wells in Georgia published in 1898, 1908, and 1915 provided data which, after selection for reliability, were used to determine the original piezometric surface of the aquifer in an area extending from a line joining Augusta and Fort Gaines to the Atlantic Coast and Florida border.

Comparison of the map of the original piezometric surface with a map of the piezometric surface in 1942 (Warren, 1944) indicates significant changes in aquifer pressures between 1880 and 1942, notably a 40 foot decline in head in the area north of Tifton, Georgia. Comparison of the original piezometric surface map with recent data indicates that pressure declined approximately 35 feet in the area near the coast and 75 feet in the area north of Tifton between 1880 and 1966. The long-term effect of heavy pumping around major municipal and industrial centers on the Atlantic Coast has been surprisingly far-reaching and suggests that a more extensive network of observation wells in needed to adequately monitor aquifer pressures.

INTRODUCTION

The principal source of industrial and municipal water in the Coastal Plain of Georgia and the Florida Peninsula is an artesian aquifer composed of limestones of middle Eocene to middle Miocene age capped by impervious sediments of late Miocene and younger age. It has been called "the principal artesian aquifer" by Warren (1944), "the principal artesian aquifer of Tertiary age" by Stringfield (1953) and several similar or derivative names. Parker (Parker et al., 1955) named it "the Floridan aquifer". It seems desirable to have some way of distinguishing between the principal artesian aquifer as it exists in the Atlantic Coastal Plain and as it exists in the Florida Peninsula. In this paper the name "Coastal Plain aquifer" refers to that part of the aquifer which lies in Georgia and South Carolina and, more specifically, to that portion of the aquifer in which water flows southeast into the Atlantic Ocean. The name adequately distinguishes the principal artesian aquifer from the deeper-lying Fall Line aquifer, primarily clastics of the Tuscaloosa Formation, and the Sea Island aquifer, which overlies the Coastal Plain aquifer and is the principal source of water in the Brunswick area.

The availability of water from the Coastal Plain aquifer is a critical factor in the economy of the lower Coastal Plain and studies of the geology and hydrology of the aquifer have been a principal activity of the United States Geological Survey and Georgia Department of Mines, Mining and Geology for many years (Water Resources Investigations in Georgia, 1965). In recent years there has been difficulty with severe local decline in artesian pressures in the Savannah, Brunswick and Fernandina Beach, Florida areas (Steward and Counts, 1958) accompanied by actual or threatened sea water invasion of the aquifer (Counts and Donsky, 1959, 1963) and an apparent general decline in artesian pressure. Callahan (1959) pointed out that the drought of 1954 and 1955 had materially affected ground water levels in the state and that the period of accurate observation of ground water levels (from about 1940) was too short to permit a full evaluation of ground water level decline. As a part of a general study of the geology and hydrology of the Coastal Plain aquifer it was proposed to determine the long-term decline, if any, in artesian pressures by reconstructing the original piezometric surface and comparing it to the present or recent piezometric surface, thus obtaining a comparison which would span a period of 50 years or more.

Previous Work

Warren published the first map of the piezometric surface of the Coastal Plain aquifer in 1944. The map is for the year 1942 and covers the area southeast of a line from northern Screven to northern Early Counties. The map, alone or combined with other maps, has been republished several times (Thompson, et al., 1956; Callahan, 1964; Stringfield, 1966). A map showing the original piezometric surface, the surface prior to about 1880, for the coastal area of Georgia and extreme northeast Florida was prepared by Warren and appeared in Stringfield (et al., 1941), Warren (1944), and Cooper and Warren (1945). It has been reprinted by Thompson (et al., 1956), Stewart and

Croft (1960), in part by Counts and Donsky (1963) and McCollum and Counts (1964), and by Stringfield (1966), which attests to the fundamental importance of this type of mapped data.

Maps of the piezometric surface for the coastal area only, the eleven Georgia counties nearest the Atlantic Coast, were prepared by Stewart and Counts (1958) for 1957 and by Callahan (1964) for 1960. The U. S. Geological Survey has monitored about 60 observation wells in the coastal area on a continuing basis in a program initiated in 1938. In the latest report on the observation well program (Hackett, 1965) data on 63 Coastal Plain wells are listed, all but eight of which are in the coastal area. Several piezometric maps of limited areas of the Coastal Plain have been published in connection with ground water studies of local areas.

In summary, the condition and history of the piezometric surface of the Coastal Plain aquifer in the coastal area of Georgia are well known. Maps of the piezometric surface for 1880, 1940, 1957, and 1960 have been published and observation wells are being measured on a continuing basis. The remainder of the Coastal Plain is less well known, Warren's (1944) map of the piezometric surface for the area is the only extensive one which has been published and only a few observation wells in the area are monitored.

Acknowledgements

Gregory Ward, Dan Chapell, and James D. Wilson worked with me in the early phases of information resource investigation and trial preparation of data and their assistance is gratefully acknowledged. H. B. Counts kindly provided data, for 1966 and earlier, on water levels in 32 wells in widely scattered locations in Georgia. H. E. LeGrand and P. E. LaMoreaux read the manuscript and offered many constructive suggestions for its improvement. Their experience and insight, generously shared, was invaluable to the final development of the paper.

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PIEZOMETRIC SURFACE

The piezometric surface is defined as "an imaginary surface that everywhere coincides with the static level of water in the aquifer", or "the surface to which the water from a given aquifer will rise under its full head" (Meinzer, 1923). In theory, the principles governing the head in an artesian aquifer, and thus determining the shape of the piezometric surface, are the simple laws of hydrostatics, in practice the picture is much more complicated

The Coastal Plain aquifer consists of a tabular series of limestone beds which dips to the southeast at approximately 20 feet per mile and thickens in the direction of dip at a rate of approximately 10 feet per mile. Water enters the aquifer in recharge areas where the limestones, or lateraly equivalent sandstones, are exposed or are only thinly covered by less permeable sediments and flows downdip toward the Continental Shelf. Water escapes from the aquifer through surface springs, wells, and submarine springs on the Continental Shelf. Water in the aquifer is therefore in constant motion toward some exit and, because the limestone beds are not uniform in thickness or permeability (McCollum and Counts, 1964 and Wait, 1965), the rate of flow within the aquifer varies both vertically and laterally. The upper reaches of the aquifer are probably never full to capacity and were it not for constant recharge of water to the updip parts head in the aquifer would quickly fall to near sea level. Any factor that influences the rate of recharge or rate of discharge of the aquifer therefore affects the artesian pressure, or piezometric surface.

The piezometric surface varies in elevation with seasonal and long-term variation in rainfall, the primary source of recharge for the aquifer. Annual variation in the piezometric surface due to normal seasonal variation in rainfall averages about 2 feet (Warren, 1944). Long-term variation due to one or more years of severe drought followed by one or more years of normal rainfall may amount to as much as 10 feet (Stewart and Counts, 1958). A map of the piezometric surface of a given aquifer therefore may be expected to change in detail with cyclic changes in climate. Further, as noted by Stringfield (1966), artesian pressure within the aquifer may vary with depth. This makes it difficult to say just what the artesian pressure at a given location is, and casts some doubt on the meaning of the head in wells which are producing from considerable thicknesses of aquifer.

With respect to the Coastal Plain aquifer, which might be called a hydrodynamic aquifer because the contained water is in constant motion toward natural outlets on the continental shelf, the concept of a fixed and precisely determinable piezometric surface has little validity. The piezometric surface of the Coastal Plain aquifer is constantly changing in detail in response to relative rates of discharge and recharge. Major features of the piezometric surface, however, are essentially permanent. Recharge areas, drainage divides, large natural outlets and flow lines change only in response to fundamental changes in the hydraulic regimen of the aquifer, such as major withdrawal of ground water from wells. For this reason the <u>shape</u> of the piezometric surface is much more significant than its elevation. A 50 foot drop in elevation of the piezometric surface may in some circumstances be of very little consequence, but a 2 foot drop in elevation accompanied by a reversal of flow may be important especially if this occurs near a submarine outlet and heralds eventual salinization of the aquifer.

Small variations in the artesian pressure of sensitively instrumented observation wells, on the order of a foot or less of head, result from a surprising group of phenomena including heavy rainfalls, changes in atmospheric pressure, ocean and earth tides, earthquakes, and even passing trains. All of these phenomena appear to produce changes in aquifer pressure by compression of the aquifer and temporary reduction of the aquifer pore volume. They are discussed in detail by Stringfield (1966).

SOURCES OF DATA

The map of the original piezometric surface of the Coastal Plain aquifer is based on data from McCallie (1898, 1908) and Stephenson and Veatch (1915). It is assumed that water utilization rates through the period from the completion of the first flowing artesian well in Georgia in 1881 (McCallie, 1898) to the cut-off date for data in Stephenson and Veatch (probably about 1912) was not sufficient to cause significant local-area drawdown. This assumption is further supported by the fact that only data from newly-completed wells was employed and that much of the data in Stephenson and Veatch was from McCallie's earlier records.

There were, however, several sources of significant error in the data on the original piezometric surface. First, many of the well records presented were obtained from the driller's or property owner's memory. Data of this type should be considered very unreliable. Large errors in reported elevations of wells were discovered and, on investigation, appeared to be common. It may also be assumed that many of the wells drilled in the period from 1881 to 1912 were badly-completed, and leaked water from high-pressure aquifer horizons to low-pressure aquifer horizons because of poor casing cementation or insufficient length of casing. In addition, the effect of climatic variation over the 21-year period was not, and probably could not be evaluated.

SELECTION OF DATA

Minimum information required for each well finally accepted as a datum was a location accurate to five miles, total depth or depth to water production, collar elevation, and static head. Wells were first checked for penetration of the Jackson Group, the middle part of the aquifer. Maps showing the depth to the top of the Jackson Group from land surface, and thickness of the Jackson Group, both prepared from data by Herrick (1961), were used in this step. Wells that were completed in either the Jackson Group horizon, or in limestones superjacent to the Jackson Group horizon were used in the study.

The elevation of every well was checked against the Army Map Service 1:250, 000 topographic map series for the area in order to eliminate any large errors in reported elevations. Apparent errors on the order of 50 feet were common in the reported elevations and in the case of a well at Morgan, Calhoun County, the apparent error was 348 feet. This last probably was a typographical error. If a well could be precisely located and all required information except the collar elevation was given, collar elevation was taken from the topographic map. Approximate areas of the Coastal Plain covered by maps of specific contour intervals are shown in Table 1. Approximately 70 percent of the area is covered by 1:250, 000 maps with contour intervals of 50 feet and supplemental 25 foot contours and elevations corrected or determined from the AMS maps should be within 12 feet of the true value in most cases.

Table 1. Area of the Coastal Plain covered by A. M. S. 1:250, 000 topographic maps of various contour intervals.

Contour Inverval, feet	Area, percent
100	8
100 with supplemental 50	21
50	1
50 with supplemental 25	70

Data on static head were checked for consistency against other wells in the area which penetrated the same horizon. As mentioned before, pressures are not necessarily equal at all depths in the aquifer at a given location and absolute consistency could not be expected, even for wells drilled in the same year, but the consistency check did protect against gross errors in the reported static head.

The procedures outlined above yielded data on 181 wells in 124 localities. The data are well-distributed over the Coastal Plain area and control distribution is considered excellent, with three minor exceptions. It would be desirable to have well data in the southern part of the area between the 80 and 100 foot contours (Figure 1), in the central part of the recharge plateau between the 250 and 300 foot contours, and north of the 300 foot contour in the extreme western part of the map. Contour intervals of 20 feet up to the 100 foot contour and 50 feet above the 100 contour produced a rational map that agrees with better than 90 percent of the data. The data do not appear to be sufficiently accurate to justify a 20 foot contour interval over the whole area.

Figure 1 represents an estimate of the average piezometric surface of the Coastal Plain aquifer as it existed prior to the development of artesian-water resources in Georgia after 1880. It is believed to be a good estimate of the surface, perhaps incorrect in some details, but on the whole a true representation..

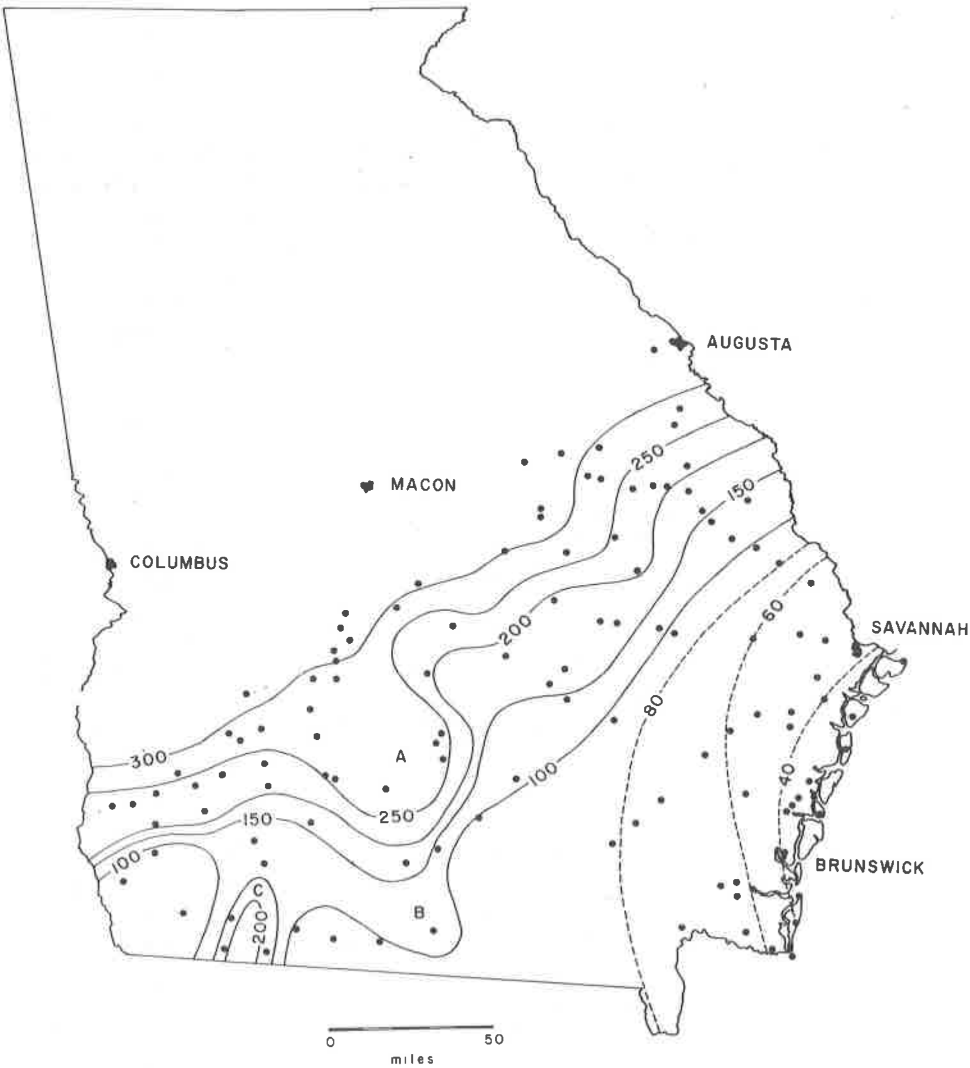

Figure 1. Estimate of the original piezometric surface of the Coastal Plain aquifer in Georgia. Contour interval, 20 feet to 100 feet above sea level (dashed lines) and 50 feet above 100 feet above sea level. Black dots represent data points from sources described in text.

FEATURES OF THE ORIGINAL PIEZOMETRIC SURFACE

The original piezometric surface rose gently from the coast to the 100 foot contour with a gradient of one foot per mile or less. Beyond the 100 foot contour the seaward gradient was 4 feet per mile or more. The location of the 100 foot contour roughly corresponds to the boundary between the Tifton Upland and Coastal Terraces physiographic provinces (Cooke, 1925) and the abrupt change in gradient of the pressure surface may have been related to this change in physiography, although other explanations (below) are possible. Recharge of the aquifer occurred along the inland edge of the map with a broad plateau in the piezometric surface centering on Turner County (A, Figure 1) and extending south as a ridge, an artesian-water-flow divide, to Lowndes County (B, Figure 1). Parts of the aquifer east of the divide drained to the Atlantic Ocean; west of the divide the aquifer drained south to the Gulf of Mexico, and probably should be called the West Florida aquifer. The plateau in the piezometric surface was bounded on the southwest and northeast by the Flint and Ocmulgee Rivers and on the southeast by an escarpment in the piezometric surface with gradients as high as 10 feet per mile. Sever and Callahan are of the opinion that the escarpment is fault controlled, while Warren was, and Stringfield is, of the opinion that it is due to changes in thickness or permeability of the aquifer (see discussion in Stringfield, 1966, and Warren, 1944).

The elongate high area near the southwest corner of Georgia, between Bainbridge and Thomasville (C, Figure 1), does not appear on Sever's (1965) map of the piezometric surface in Seminole, Decatur and Grady Counties and may be spurious, but several lines of evidence suggest that it is a valid feature. The high is defined by three wells in Grady County (Stephenson and Veatch, 1915, p. 269-270) with reported artesian heads of 187, 210, and 270 feet. A fourth well had a reported artesian head of 47 feet and was discarded because it was inconsistent with wells surrounding it and assumed to be improperly completed. In addition, Sever (1965) reports artesian heads of 60 to 90 feet above sea level in the area for 1962 and it would not be reasonable to expect that ground-water pressures at a point less than 30 miles up-gradient from the heavily-pumped Tallahassee area would increase between 1915 and 1962. Sever points out several interesting parallel features that trend northeast in the area east of Bainbridge (C, Figure 1); a ground-water divide in the piezometric surface, the solution escarpment that divides the Dougherty Plain and Tifton Upland, a pronounced structural trough in the Suwannee Limestone (upper part of the aquifer in this area) and the course of the Oclockonee River. A structural trough in the Ocala Limestone coincides with the structure in the Suwannee Limestone and extends much farther to the northeast (Herrick and Vorhis, 1963), suggesting that the structure was active during deposition of the Suwannee Limestone. The coincidence of trend features with the apparent high in the original piezometric surface suggests that the high may have been a real feature. If the piezometric high were related to the features mentioned above, it probably should trend more easterly than as shown, but the distribution of data is such that this interpretation of the contours would be entirely possible. Other possible explanations are that the data for all three wells was grossly misreported, which is doubtful, or that the wells tapped pressure zones which were not representative of the aquifer.

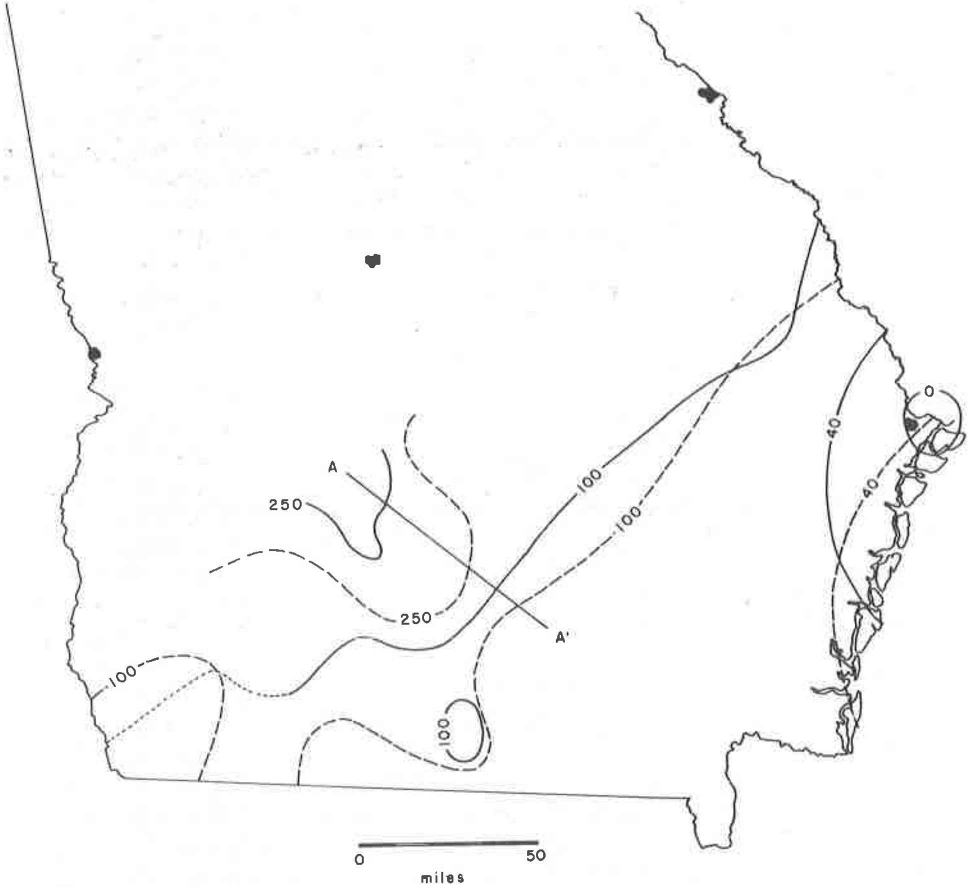

Figure 2. Original and 1942 locations of the 40, 100, and 250 foot contours for the Coastal Plain aquifer of Georgia. Original positions (dashed lines) are from Figure 1, 1942 positions (solid lines) from Warren (1944). Between 1880 and 1942 the 100 foot contour moved toward Savannah, indicating greater recharge in the area northwest of Savannah; but the ground-water divide near Tifton pinched-off, leaving a small, circular recharge area at Valdosta.

CHANGES IN THE PIEZOMETRIC SURFACE

1880-1942

All of the features of the original piezometric surface described above, except for the high area in Grady County, appear on Warren's (1944) map of the piezometric surface for 1942. Differences in the two maps represent changes in artesian pressures and directions of artesian-water flow in the 60 year period from about 1880 to 1942 and are summarized in Figure 2.

In the eastern part of the mapped area changes in configuration of the piezometric surface center around the development of a cone of depression in the heavily-pumped Savannah area. Ground water flow, originally seaward in the Savannah area, reversed on development of the cone of depression. The 40 foot contour retreated about 30 miles up the Savannah River and re-oriented around the cone of depression at Savannah. The 100 foot contour moved toward Savannah in the area between the Ogeechee and Canoochee Rivers, possibly indicating that this area had become more important as a recharge area for the aquifer in response to the lowered pressure at Savannah. In the west-central part of the mapped area, the steep gradient in the piezometric surface at Tifton maintained its position and orientation, which indicates that it has a direct physical cause and is not a balance-of-flow feature, while the 250 foot contour retreated an average of 40 miles to the northwest. At the original gradient across the ground-water plateau of one foot per mile the 40 mile shift in the 250 foot contour would represent a general decline in piezometric head of about 40 feet, which is comparable to the change in hydraulic profile along section A-A' shown in Figure 3. The artesian-water divide extending south from the plateau in the piezometric surface pinched-off between 1880 and 1942, leaving a small, nearly circular area at Valdosta (B, Figure 1) about 100 feet and creating a saddle in the ground-water ridge between A and B of Figure 1.

1942-1960

Data on the piezometric surface for 1960 are limited to the coastal area of Georgia, as previously defined, and are presented by Callahan (1964). Changes in the piezometric surface of the aquifer between 1942 and 1960 were the deepening of the cone of depression at Savannah, development of a cone of depression at Brunswick and extension of the cone of depression at Fernandina, Florida, already present in 1942, into the St. Marys, Georgia area. The 40 foot contour was pulled further inland, especially in the southern portion, in 1960 it curved sharply around the Brunswick cone of depression and closed around the Fernandina cone of depression.

1880-1966

Based on data kindly provided by H. B. Counts of the U. S. Geological Survey, Atlanta (personal communication, 1967) and on the original piezometric surface as presented in Figure 1, the average total decline in artesian pressure for 31 wells, none of which are within cones of depression associated with major withdrawal points on the Georgia coast, from 1880 to 1966 was 34 feet. The average decline does not reflect the distribution of the pressure decline, which was close to the average in the coastal area, on the order of 75 feet in the area of the artesian-pressure escarpment and on the order of 10 feet near the original 300 foot contour.

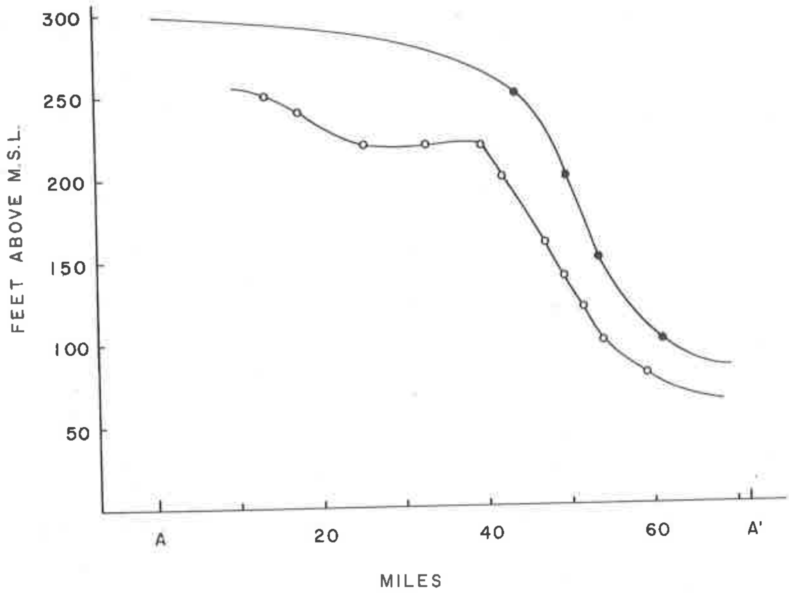

Figure 3. Original and 1942 hydrologic profile along A-A' of Figure 2. The original profile (solid points) is from Figure 1, the 1942 profile (open points) from Warren (1944). The 1942 profile crosses the edge of the 1942 recharge plateau twice and therefore is slightly saddled, it should be interpreted as a smooth curve. The average decline in the hydrologic profile from 1880 to 1942 was approximately 50 feet.

SIGNIFICANCE OF PRESSURE DECLINE

As Callahan (1964) notes, decline in the piezometric surface is not an unmitigated evil. Loss of head in the aquifer tends to increase recharge and reduce the amount of surface water lost to evaporation and transpiration. Decline in artesian pressure also tends to cut off the flow of "wild wells", open flowing wells which Callahan (1960) estimated to amount to 12 percent of the entire production of the aquifer. Moreover, significant salting of the aquifer at Savannah, at recent pumping rates, will not occur for 100 years or more (Counts and Donsky, 1963). Artesian pressure decline does not, therefore, present an immediate and pressing problem.

However, this study of the Coastal Plain aquifer reveals surprisingly far-reaching effects of heavy pumping in the coastal area of Georgia. The effect of heavy industrial and municipal pumping has not been confined to local increases in hydraulic gradient near the pumping center, but apparently has affected pressure levels in the entire

Coastal Plain aquifer, at least as far inland as the gradient escarpment southeast of Turner County, and perhaps as far inland as the 300 foot contour. If this is correct, a much more extensive system of frequently monitored observation wells will be required to predict the effect of future development of artesian-water resources of the Coastal Plain aquifer and to provide the basis for future water management practices. This paper, it is hoped, will provide a point of departure for future studies of the piezometric surface in the upper reaches of the aquifer.

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THE PLEISTOCENE GEOLOGY OF PRINCESS ANNE COUNTY, VIRGINIA

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ABSTRACT

The Nansemond Formation in the subsurface of Princess Anne County, Virginia, was examined using electric logs and drillers' logs and evidence available in borrow pits. It was found that this formation contains numerous complex lithofacies changes due to the development of a prograding off-shore bar, the Princess Anne bar-scarp, as well as the development of secondary bar deposits within the lagoon behind the Princess Anne bar-scarp. Three well defined aquifers which appear to coalesce in the subsurface extension of the prograding off-shore bar transect the remaining lagoonal lithofacies.

A synthesis of available literature and examination of deep well logs suggests the presence of a northwest-southeast trending hinge line marking the western edge of a probable Triassic basin beneath the Coastal Plain of southeastern Virginia and possibly underlying the Chesapeake Bay. Periodic movements within this basin are suggested as the cause for the unusually thick Pleistocene deposits in Princess Anne County.

Ground-water investigations resulting from analysis of well logs in Princess Anne County have resulted in the first piezometric map of the area and a better understanding of the ground-water potential in this area.

INTRODUCTION

Geographic Location

Princess Anne County and the coincident city of Virginia Beach are located in the extreme southeastern portion of Virginia. The maximum elevation, exclusive of sand dunes, is 31 feet. This is also the maximum elevation of the Princess Anne scarp which extends north-south through the county and marks the boundary between Recent and Pleistocene sediments.

Methods and Assumption of Investigation

Subsurface information was obtained from drillers' logs and electric logs of water wells and from examination of available exposures. These data were collated with the purpose of defining the hydrologic systems of Princess Anne County.

During the process of delineating confined aquifers it became apparent that they constituted essentially time equivalent units and possibly could, therefore, serve as useful tools to help clarify the complex facies relationships within the Nansemond Formation. The basic assumption was that these aquifers were formed as the result of climatic accident during a relatively short time span of either a Pleistocene glacial or interglacial stage.

From this assumption it follows that the lowest aquifer contained in a vertical sequence of sediment in which there was no horizontal change in lithology could be considered as the base of the Pleistocene. For practical purposes, therefore, we have defined the base of the Pleistocene as being represented by the lower most aquifer. Since the aquifers in Princess Anne County are discrete, continuous and plottable units, it was possible to measure the thickness of the Pleistocene in this area to be about 200 feet.

To the west of Princess Anne County in the York-James Peninsula and northward, the thickness of the Pleistocene has been previously reported by McLean (1950), Wentworth (1930), and Clark and Miller (1906) as being about 30 to 40 feet. An explanation for the eastward thickening of the Pleistocene was sought in the deep subsurface.

Acknowledgements

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STRUCTURAL SETTING

Subsurface data from both drilled wells and geophysical work (Cederstrom, 1945a, b; Spangler and Peterson, 1950) projected to a line from Sedley, Virginia, through Fort Eustis, Point Comfort, and Cape Henry, Virginia, indicates a marked increase in slope of the basement rock between Fort Eustis and Port Comfort (Figure 1). The basement slopes to the southeast at 32 feet per mile from Sedley to Fort Eustis, Virginia, a distance of 23 miles. At Fort Eustis the basement is intersected at a depth of 1,250 feet while 16 miles to the east at Point Comfort, Virginia, the basement is intersected at 2,235 feet giving a slope of 61 feet per mile. This slope is almost a 100 percent

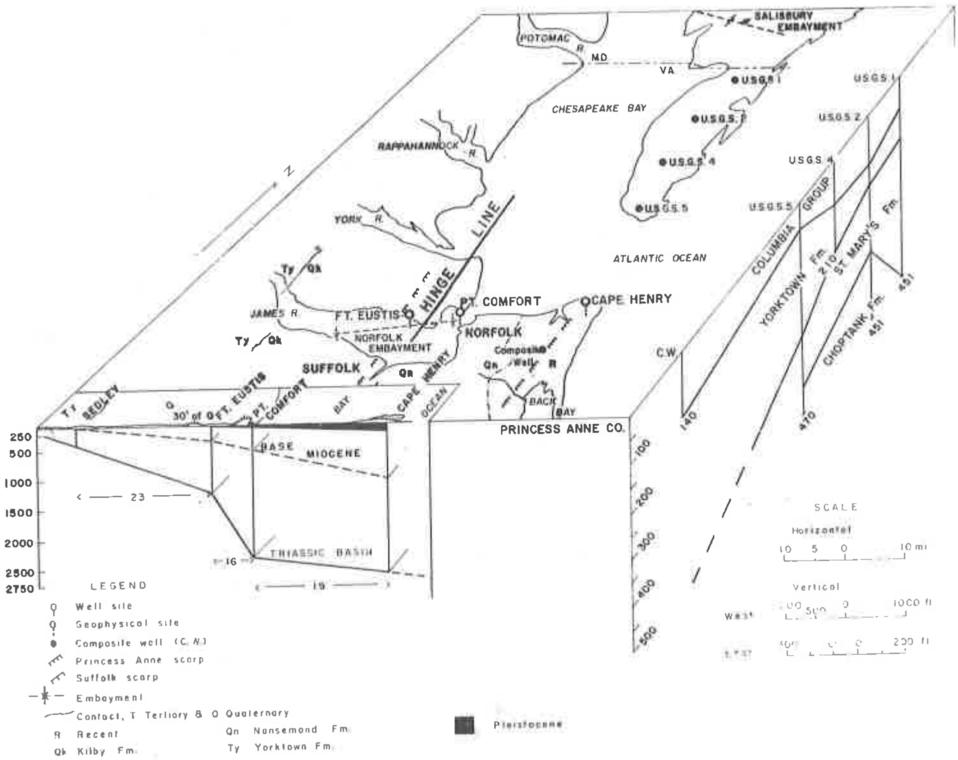

Figure 1. Schematic structural and stratigraphic summary of the southeastern portion of the Virginia Coastal Plain. East-West (front) face of block is a cross sectional view from Sedely, Virginia (off of map) through Princess Anne County, Virginia, showing proposed Triassic Basin. North-South (side) face of block is a cross sectional view from U. S. G. S. well 1 in the Eastern Short area of Virginia to the Composite well in Princess Anne County, Virginia, showing a southward thickening of Miocene and Pleistocene sediments. Vertical scale on left for East-West face of block; vertical scale on right for North-South face of block.

increase over the Sedley - Fort Eustis segment. From Point Comfort 19 miles east to Cape Henry (basement at 2, 700 feet, seismic data) in Princess Anne County the basement slopes at a rate of 24 feet per mile.

Spangler and Pe rson (1950) show a sharp deflection in the basement extending from the North Carolina-Virginia border northwestward, roughly paralleling the James River to the inner edge of the Coastal Plain. A similar deflection at the base of the Miocene is reported by Cederstrom (1945a). Unfortunately, control for construction of this map (Spangler and Peterson, 1950) seems to be lacking from the vicinity of Sedley westward. Consequently, the structure contours seem to have been drawn to conform with contours where more control is available, i.e., Norfolk-Princess Anne Counties. In the Norfolk-Princess Anne area a definite embayment is shown. This embayment is also reflected on subsequent maps drawn on bases of different ages. For example, in Eocene time the embayment took on the outline of a slightly elongated northwest-southeast basin (Spangler and Peterson, 1950).

Structural maps and cross sections of the basement in the vicinity of Quantico, Virginia, presented by Cederstrom (1945b) show a sharp break in the basement approximately 3/4 mile east of Quantico toward the Potomac River. He stated that this declivity "... suggests faulting in the basement rock or a steep pre-Cretaceous erosional scarp " (Cederstrom, 1945b, p. 17). Cederstrom (1945b) further stated that Darton had observed local eastward facing scarps in the bedrock surface a few miles east of Washington, D. C. These three citations indicate a marked break in the basement from Quantico to Princess Anne County, Virginia, trending essentially on a northwest-southeast line. Spangler and Peterson (1950) present an isopach map of the Triassic in the subsurface near Salisbury, Maryland. They place the western edge of the Triassic near the mouth of the Potomac River and its confluence with the Chesapeake Bay. This is in relatively close association with the previously cited declivity at Quantico, Virginia.

Although data allowing for the topographic and structural description of the basement surface are limited (Table 1), it would seem reasonable to suggest the presence of a basement hinge line underlying and roughly parallel to the western edge of the Chesapeake Bay (Figure 1).

It is significant to recall the previously cited Triassic deposits in the subsurface of Maryland and to note the general similarity of the trend relationship of the proposed hinge line with Triassic faulting as exhibited to the west along the Fall Zone in Virginia (Roberts, 1928) and to the south in North Carolina (Spangler and Peterson, 1950). Triassic Basins beneath the Coastal Plain have been cited by Straley and Richards (1948) and Applen (1951). The trends of these basins seem to be similar to the trend of this hinge line. These data suggest a Triassic basin beneath the Chesapeake Bay.

In addition, Cederstrom (1945a) suggests, that, on the basis of a rapid increase in the thickness of the Eocene northward from the James River there exists a westward trending fault along the axis of the James River. This fault approaches the Fall Zone and has a maximum displacement in the Hampton Roads area of 300 to 600 feet. He (Cederstrom, 1945a, p. 71) suggests that the subsidence continued throughout the Eocene and that "In post-Miocene time the area was gently folded as a result of settling movements along a pre-existing fault or series of faults." Cederstrom (1945a, 1945b) presented two structure contour maps on the base of the Miocene underlying Tidewater, Virginia.

Table 1. Summary of Subsurface Data on the Basement Rocks in Tidewater, Virginia

Name of well or geophysical source	Location	Depth in Feet	Basement Lithology	Citation
Socony-Vacuum Bethards No. 1	Eastern Maryland	-5529	Triassic	Spangler, 1950
Ohio Oil Hammond No. 1	East of Salisbury, Maryland	-7150	do	do
Standard Oil of N. J. Md. Esso No. 1	N.E. Coast of Maryland	-7800 est.	do	do
Seismic	Cape Henry, Va.	-2700	-	Ewing, 1937
Ft. Monroe well	Pt. Comfort, Va.	-2240	Triassic xline	Cederstrom, 1945a
Elkins Oil and Gas Co., 1929	40 mi. N. of Norfolk, Va.	-2300	Granite	do
Well - No Name or Number	7 mi. N. W. of Ft. Monroe, Va.	-1172	Drillers log - Hardest kind of stone or granite	do
Moores Bridge Well	Norfolk, Va.	-1762	No basement encountered	do
Well - No Name or Number	Sedley, Va.	-500	Granite ?	do
do	Fort Eustis, Va.	-1300+	do	do
do	Quantico, Va.	-300+	do	do
do	1/3 mi. E. of Quantico, Va.	-360+	do	do
do	1 mi. E. of Quantico, Va.	-525+	No Basement	do
Seismic	East of Quantico, Virginia	-1500	----------	Spangler, 1950
Well - No Name	South of Glenns, Va.	-2305	----------	do
Seismic	Atlantic Ocean	-4000	----------	do

These two maps are at some variance with each other, but in both instances Cederstrom shows in the same general area of Hampton Roads a Miocene flexure dipping to the east with an approximate northwest-southeast strike. This flexure would appear to be essentially at right angles to his postulated James River fault. It appears possible that two sets of faults exist beneath the Coastal Plain of Tidewater, Virginia: (1) an east-west set of normal faults suggested by Cederstrom, and (2) the northwest-southeast hinge line suggested by the authors.

The northwest-southeast trending hinge line appears to have been formed during the Triassic and, considering the Miocene flexure, to have been at least periodically active through that time. Further, considering the unusual thickness of the Pleistocene Nansemond Formation in Princess Anne County (approximately 200 feet) and in the Eastern Shore of Virginia east of the hinge line and Miocene flexure (Figure 1), this fault may have had continuous activity throughout the Pleistocene. Numerous references, for example Doering (1960), can be found which cite evidence for recent vertical movements in the Chesapeake Bay area.

STRATIGRAPHY

Three different concepts on the stratigraphy of southeastern Virginia have been presented over the years (Clark and Miller, 1912; Wentworth, 1930; Moore, 1956; Oaks and Coch, 1963; and Coch, 1965). These concepts presented before the work of Moore (1956) are here of historical interest only. These earlier concepts tied formation names to Pleistocene terraces which were considered principally to be erosional and depositional features formed during various stages of sea level during the Pleistocene. The entire complex of terrace formations were considered by McGee (1886 and 1888) to constitute the Columbia Formation. The Columbia Group (Shattuck, 1906) was defined to contain those units in the Atlantic Coastal Plain of Pleistocene age. The Norfolk Formation was defined by Clark and Miller (1906) as containing Pliocene and Pleistocene equivalents and would be partially contained in and partially underly the Columbia Group. West of the Suffolk scarp, the Sedley and Kilby Formations lie unconformably upon the Yorktown Formation of Miocene age. Therefore, if extant, the Norfolk Formation is present only east of this scarp and beneath the major portion of the Pleistocene sediments, the Nansemond Formation.

The presence of one or more lithic units of Pliocene age in southeastern Virginia is debatable and beyond the scope and data on which this paper was written. Discussion, pro and con, on the Pliocene of Virginia is to be found in papers by Cederstrom (1945a, b), McLean (1950), Spangler and Peterson (1950) and others.

Moore (1956) suggests that only three formations are necessary to interpret the Pleistocene geologic history of the Virginia Coastal

Plain south of the James River. In ascending order, the formations which have an unconformable relationship to the underlying Yorktown Formation are the Sedley Formation (unconformity), the Kilby Formation and the Nansemond Formation. The Sedley and Kilby Formations underlie the Sunderland and Wicomico terraces and are terminated by the Suffolk scarp. The Nansemond Formation underlies the Dismal Swamp terrace and is terminated by the Princess Anne scarp. The Sedley and Kilby Formations are considered by Moore (1956) to be non-marine and the Nansemond Formation to be predominately marine.

It is apparent, as pointed out by Oaks and Coch (1963), that the Suffolk scarp is both a geographic entity and a stratigraphic boundary in southern Virginia. The Nansemond Formation, the youngest formation in the Columbia Group, grades westward into non-marine members (Moore, 1956).

Well data indicates that this formation contains abrupt facies changes within Princess Anne County (Figure 2). Starting in the eastern part of the County, the Princess Anne scarp is a bar deposit which has progressively migrated westward during Nansemond time from some distance off the present-day coast (Wells 20, 19, 16, Figure 2). On the landward or lagoonal side of this bar, the sediments consist of blue gray muds with much shell material and some sand. These deposits grade westward into blue muds with little shell material and represent the deeper, quieter parts of the lagoon. The Princess Anne bar is surficially expressed in the present-day topography as a north-south trending ridge through Princess Anne County. Farther westward, a secondary bar deposit started to develop slightly later and continued to develop concurrently with the Princess Anne bar during Nansemond time and was also prograding westward (Wells 14 and 15, Figure 2). This bar is also expressed in the local topography as a discontinuous north-south trending ridge through Princess Anne County. Behind this secondary bar deposit, another lagoon was present and a facies relationship developed similar to that behind the Princess Anne bar.

Although facies changes are rapid in this area, three water-bearing coarse sand and gravel units are continuous or nearly continuous throughout the region and transect the remaining lagoonal lithofacies. Eastward, all three aquifers extend under the Princess Anne bar-scarp and coalesce into the older part of the Princess Anne bar deposit (Figure 2). To the west, these beds extend to or nearly to the Norfolk-Princess Anne County line so that progressively older units extend farther west. The result is that only the oldest aquifer extends completely across the area. Stratigraphic relationships as shown in Figure 2 indicate that the secondary bar is younger in origin than the Princess Anne bar-scarp, since its root system is present only in the aquicludes above aquifers 1 and 2 (Figure 2).

The gravels associated with the aquifers suggest deposition under rigorous climatic conditions; deposition could be the result of either ice rafting, as suggested by Wentworth (1930), glacial melt water

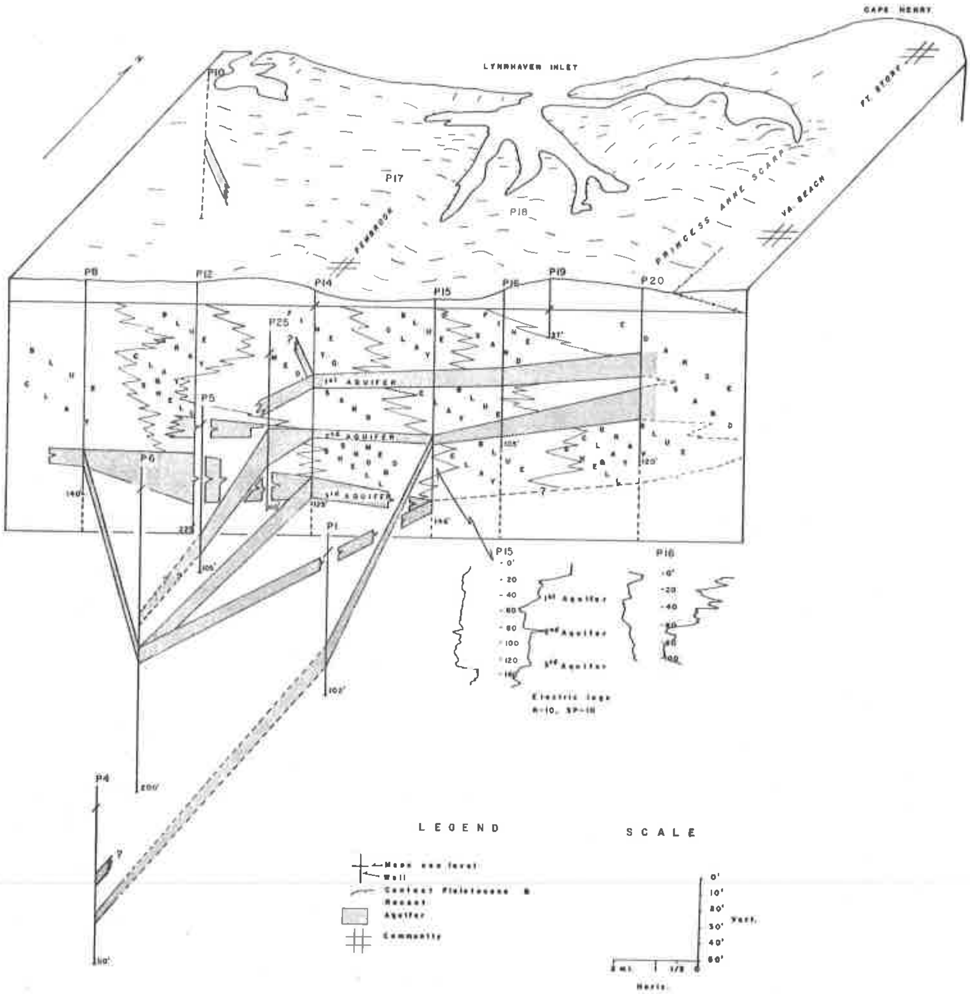

Figure 2. Lithofacies and hydrogeologic interpretation of Princess Anne County, Virginia, showing complex facies change and persistance of aquifers.

which gave streams a competence greatly in excess of the present streams in the region, or more competent streams caused by increased rainfall associated with glaciation. Longshore currents, wave action, and streams are considered by the writers to have been sufficient to distribute these coarse sediments across the area.

Electric and drillers' log data suggest a marked lithologic break at the base of the oldest aquifer which may represent the top of the Yorktown Formation of Miocene age or the Norfolk Formation of Plio-cene-Pleistocene age. Data, however, are not sufficiently precise to draw a firm conclusion on this point.

From evidence presented, it is suggested that the nine new formations proposed by Oaks and Coch (1963) are unnecessary because (1) on the basis of drillers' logs and electric logs throughout Princess Anne County, the proposed formations do not appear to be mappable units in the subsurface, but rather they are parts of a larger facies relationship; (2) these newly proposed formations do not adequately explain existing stratigraphic relationships and only add to the chaos of Pleistocene nomenclature; and (3) it would seem more plausible to consider these units as facies or lithosomes of the upper part of the Nansemond Formation.

GROUND WATER

Surface drainage in Princess Anne County is poorly developed. With the exception of Blackwater River, there are no through-flowing streams. Most of the streams in this County are either sinuous extensions of small inlets representing drowned consequent streams or second generations of consequent streams in the youthful stage of their geomorphic cycle, which have developed during the Recent. Surface runoff is impeded by the low relief of the region. Transpiration and evaporation probably account for the major losses of meteoric water with the remaining portion moving vertically to become part of the unconfined water-table.

WATER-TABLE SYSTEM

The water-table system in Princess Anne County is defined to include all unconfined aquifers that are recharged directly from local precipitation or other surface sources. The water-table system includes the deposits of Pleistocene age west of the Princess Anne scarp and the Recent deposits east of that scarp. West of the scarp the water-table is contained in the Nansemond Formation and to the east in the Recent dune sand. Cederstrom (1945b) has discussed in detail the water-table system in Princess Anne County. This subject, therefore, is not considered in any great detail. His conclusions are probably still valid because no heavy industry or other users of large amounts of unconfined ground water has moved into Princess Anne County. The primary usage of water is domestic, both for household use and for gardening. No figures were available to the writers relative to the gallons per day usage of water in this system. Consequently, no safe yield figures can be determined. However, the population of this County was 19,984 in 1940 and has increased to 163,457 in 1967. Cederstrom (1945b) placed the water level at 5 feet below the surface in this County and suggested that the phreatic water is in equilibrium with the sea water. No comprehensive set of data is available today to suggest that the situation has changed. However, the present water-table level, as adjusted to sea level, in several wells in the Recent dune sands is -30 feet before pumping began. It would appear that salt water incursion is probable in the very near future in those areas underlain by Recent sediment. In parts of the County underlain by Pleistocene sediments the water-table is still apparently at the previously reported 5 foot level.

ARTESIAN SYSTEMS

The known artesian systems of Princess Anne County are contained within the Nansemond Formation. The extent of the artesian system is shown in Figure 2 which was prepared from electric and drillers' log data of wells, the locations and numbers of which are shown on the piezometric map for the County (Figure 3). Aquicludes seem to be everywhere present overlying and underlying the three aquifers. However, the integrity of the aquifers is not everywhere maintained, for facies conditions within the aquicludes bring fine sands and sandy muds in contact with the aquifers (Wells 12, 14, and 15, Figure 2). Therefore, leakage does occur and some surficial water enters the aquifer at places other than the recharge area. Increased urbanization and concomitant usage of phreatic waters may be a significant, but as yet undeterminable, factor affecting the artesian system.

With the exception of a few new shopping centers, heavy usage of waters obtained from the artesian system is confined to institutions (primary and secondary schools). No earlier reference piezometric maps have been made, therefore, the map presented in Figure 3 will serve as a reference datum plane. Static levels, well characteristics and aquifer properties are presented in Table 2.

The position of the zero contour on the piezometric surface is of significance. In the northern portion of the County, including the area from Ocean View to Lynnhaven Inlet (Wells P10, P11, P13, P14, P15, P17 and P27, Figure 3) the zero level extends inland a maximum distance of approximately five miles. The extrapolated position of the piezometric surface directly beneath the strand line of the Chesapeake Bay is 40 feet below mean sea level. It appears that salt water incursion is probable. Similarly, the zero point on the piezometric surface is moving inland as indicated by the static level which is below sea level in the well at the Princess Anne Country Club (Well P20, Figure 3). It would appear probable that in both of these instances the safe yield of the aquifers has been exceeded.

SUMMARY

Correlation within the Nansemond Formation in the subsurface of Princess Anne County has shown that three coarse sand and gravel

Table 2. Summary of Characteristics of Wells Used.

Well No.	Elevation in Feet	Static Level-Feet Below Surface	Q In Gal./Min.	D/W	Specific Yield	Depth To Screen	Log Available Electric	Log Available Drillers	Total Depth
P1	11	6	--	21	--	68	X	X	100
P2	14	6	--	--	--	--	X	-	70
P3	15	8	--	--	--	--	-	X	120
P4	12	8	42	19	2.2	57	-	X	110
P5	12	3.3	--	4	--	84	X	X	105
P6	11	2.5	85	11.5	7.2	110	-	X	200
P7	18	7	75	12	6	74	-	X	95
P8	--	10	120	25	4.8	105	X	X	140
P9	16	5	55	22	2.5	68	-	X	105
P10	1	13	80	22	3.6	50	-	X	100
P11	1	-	18	--	--	68	-	X	126
P12	18	-	--	--	--	--	-	X	225
P13	13	-	--	--	--	--	X	-	206
P14	6	9	50	3.7	12.5	59 88 117	X	X	125
P15	7	12	--	--	--	--	X	X	154
P16	13	8	30	--	--	52	-	X	105
P17	12	9 (Perched)	--	--	--	--	X	-	126
P18	6	4	--	--	--	--	-	X	105
P19	20	12	--	--	--	30	-	X	37
P20	10	10	50	17	3	72	-	X	110
P21	14	9.5	--	--	--	--	-	X	100
P22	19	14	--	--	--	--	-	X	108
P23	20	20.5	50	26.5	1.9	62 90	-	X	126
P24	10	2.5	150	56.5	3	65	-	X	104
P25	15	8	--	12	--	60	-	X	110
P26	--	5	60	14	4.2	55	-	X	84
P27	12	9 (Perched)	15	--	--	--	-	X	33

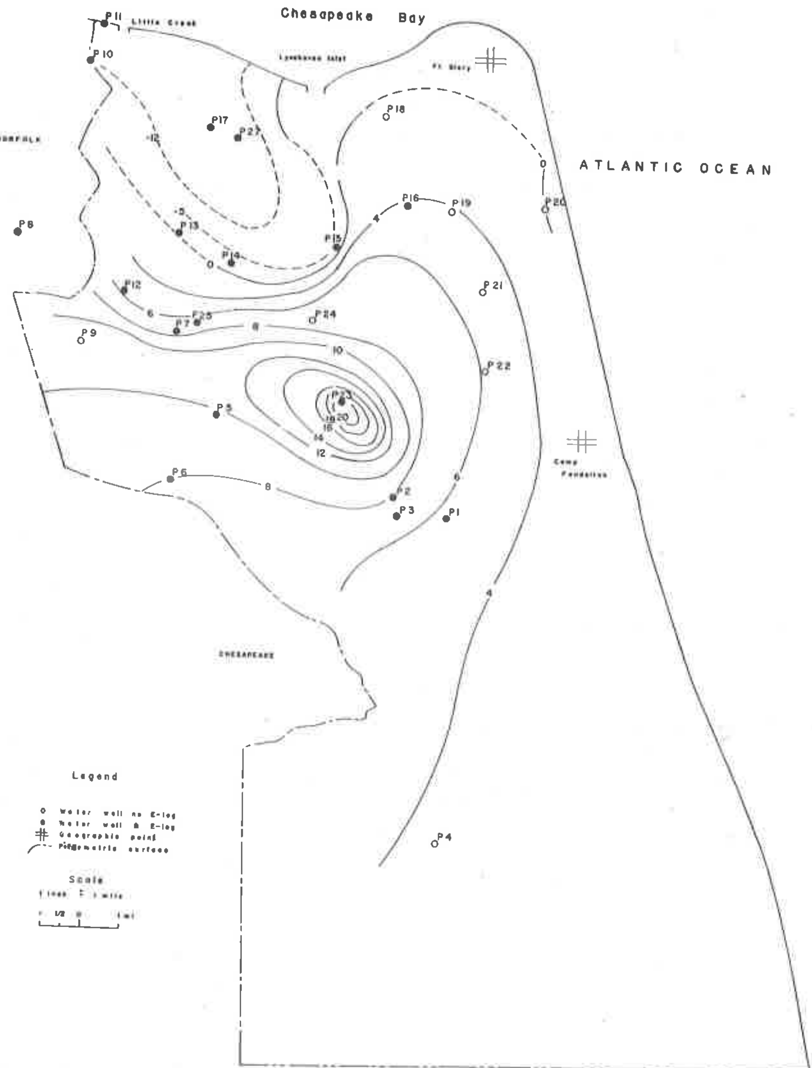

Figure 3. Combined piezometric map of the Pleistocene hydrologic system of Princess Anne County, Virginia.

aquifers cut directly across the observed complex lithofacies relationships within this formation. These aquifers appear to coalesce in the subsurface extension of a once extensive off-shore bar that prograded westward, the surficial remnants of which are now represented by the Princess Anne scarp. These aquifers are also believed to be the result of climatic accident during the Pleistocene Epoch, and as such were deposited either during a glacial or interglacial stage.

Landward of the prograding off-shore bar a lagoon existed in which blue mud with much shell material and some sand was deposited adjacent to the bar. This material grades westward into blue mud deposits with little shell material and probably represents the deeper, quieter parts of the lagoon. Farther to the west a secondary bar deposit started to develop slightly later and continued to develop concurrently with the Princess Anne bar during Nansemond time. It was also prograding westward. A similar facies relationship of bar sands grading into blue muds with much shell material then into blue muds having little shell material also exists landward of the secondary bar.

The base of the Pleistocene in Princess Anne County is approximately 200 feet below sea level where an abrupt change in lithology takes place. This depth also corresponds to the base of the lowermost encountered coarse sand and gravel aquifer. To the west of Princess Anne County in the York-James Peninsula and northward, the thickness of the Pleistocene has been reported to be between 30 and 40 feet. An explanation of this large descrepancy in thickness was sought in the deep subsurface. Interpretation of data presented by Cederstrom (1945a, b), Spangler and Peterson (1950), and Ewing, et. al. (1937) suggests to the authors that a break in the basement from Quantico, Virginia, to Princess Anne County, Virginia, most probably exists. This line is thought to be a hinge line of Triassic age. This fault has a trend similar to other Triassic basins in North and South Carolina. Evidence presented by Cederstrom (1945a) has been interpreted by the authors to indicate periodic activity of this fault through the Miocene. Considering the unusual thickness of the Pleistocene in Princess Anne County, this fault probably was active also throughout the Pleistocene.

A study of the artesian system in this County has shown that the integrity of the aquifers present does not appear to be everywhere maintained, for facies conditions within the aquicludes bring fine sands and sandy muds in contact with the aquifers. Therefore, leakage probably does occur and some surficial waters enter the aquifer at places other than the recharge area.

The first piezometric map of the area has been constructed and will serve as a reference datum plane for future investigations.

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