AQUIFER STORAGE AND RECOVERY
MYRTLE BEACH, SOUTH CAROLINA

PHASE I: FEASIBILITY STUDY
A HYDROGEOLOGIC INVESTIGATION

By

**Joffre E. Castro, Brenda L. Hockensmith,
and Robert E. Curley**

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ABSTRACT

The Aquifer Storage Recovery (ASR) concept and its applicability in unconsolidated sediments of the Coastal Plain in South Carolina is being investigated at Myrtle Beach, in Horry County. Two aquifer storage recovery strategies might be feasible. In both strategies, potable water would be injected into the deep, confined Cretaceous aquifers during water-surplus periods, mostly winter months, and would be retrieved in the peak water-demand periods during the following summer. The result would be increased water capacity of the system without necessitating expansion of the surface-water treatment plant.

In Phase I, the subject of this report, substantial hydrogeologic data were collected and analyzed during the coring and construction of a 1,427-foot test hole. Fourteen selected core samples were intensively studied to determine their properties and evaluate their potential as injection zones.

Two of the five unconsolidated formations at the site appear to be suitable for injection: (1) the Cape Fear Formation, and (2) the Black Creek Formation.

The Cape Fear Formation has five sand units that were identified as possible injection zones. Porosity ranged from 10 to 18 percent, clay content from 26 to 34 percent, and the cation-exchange capacity from 5 to 10 milliequivalents per 100 grams. The average hydraulic conductivity was estimated at 70 gpd/ft^2 (gallons per day per foot squared).

The Black Creek Formation has three units identified as potential injection zones. Generally the units were better defined and more homogeneous than those of other formations underlying the study area. The clay content ranged from a trace to 18 percent and was reported to be glauconite. The cation-exchange capacity values were between .4 and 19 milliequivlanents per 100 grams. These aquifers have effective porosities as great as 24 percent, but because of poor sorting the hydraulic conductivity is only about twice that of the Cape Fear.

The hydrologic and geologic data not only suggest that injection and recovery of treated water is feasible at the site, but also that the aquifers of the Black Creek Formation are the most suitable. Geochemical data, collected from the column testing of the core samples identified aerobic oxidation as a probable reaction that may influence the chemical composition of the recovered water. No evidence was found to support initial concerns regarding clay dispersion or clay swelling, which could make aquifer storage and recovery not feasible.

INTRODUCTION

The city of Myrtle Beach in Horry County, S.C., is located on the Atlantic Coast, in the extreme upper eastern part of the State (Fig. 1). This area is part of the Lower Coastal Plain physiographic province of South Carolina. It has a mild, subtropical climate with an average annual temperature of 63° F and an average annual precipitation of 50 inches (SCWRC, 1983). This area, with its mild climate and nearby beaches, has an economy based primarily on tourism. The Horry County area has used ground water from the Black Creek Formation since the early 1900s. Since 1988, the area has relied on surface water. Before changing to surface water, the area was using over 7.2 billon gallons per year of ground water.

The large influx of tourists during the summer months increases the water demand by as much as 70 percent. Consequently, the large demands caused potentiometric levels in the region to decline nearly 10 ft (feet) per year. At that rate, the aquifers of the Black Creek Formation, which are the primary source of ground water supplies, would have started being dewatered as early as 1990. Additionally, ground-water withdrawals in Horry County have reversed the natural seaward hydraulic gradient and increased the potential for saltwater intrusion.

The continued development of the region, combined with the effects of the large ground-water withdrawals, prompted consideration of public-supply management alternatives. The most obvious alternative was a shift to surface sources for public supply. This was done, and in June 1988 a surface water treatment plant, located on the Atlantic Intracoastal Waterway (AICW), began operation to serve the city of Myrtle Beach. The nominal capacity of the treatment plant, as normally estimated, is a function of the maximum daily demand computed from a 25- or 30-year projection based on population growth. The city of Myrtle Beach, in 1992, had a maximum daily demand almost 1½ times the average summer demand and nearly twice the winter demand. The required capacity of the treatment plant, consequently, is exceedingly large compared to actual demands, even when the full capacity of the plant is implemented in a series of expansion steps. Moreover, days with a demand as large as the maximum daily are few in a year, probably less than six.

Operation of the plant under these conditions is more difficult and expensive, especially, during the first half-life of the plant. It is more difficult because the plant has to operate at flow rates below the optimum capacity, and plant operators have to cope with seasonal changes in quality of raw water. It is more expensive because plant production is based on a varying demand and not on an optimum flow.

A potential solution, for systems with exceedingly large peak daily demands occurring a few times a year, is an ASR system of wells. The wells can provide for peak daily demands, reducing the required size of the treatment facility and therefore, decreasing the capital-cost investment. For existing treatment plants, ASR wells can provide extra capacity during short, but high demand periods and, hence, defer expansion of the system until full capacity of the plant is utilized the year around. Additionally, ASR wells can be used to reduce production costs by (1) stabilizing plant production to an optimum flow rate and (2) producing more of the less-expensive-to-treat winter water, which could be stored for later use, and less of the more-expensive-to-treat summer water.

Since switching to surface water for public supply in mid-1988, the City has seen a positive environmental impact in the slow but continuous recovery of the hydrostatic pressure in the Black Creek Formation. The characteristic cone of depression centered at Myrtle Beach appears to have moved south toward the Myrtle Beach Air Force Base site, near Surfside Beach. Although the recovery has been substantial, water levels are not yet at desirable elevations nor are they near predevelopment levels.

It has been concluded that two aquifer storage recovery strategies might be feasible at this locality. The first strategy would involve injecting treated surplus drinking water from the AICW plant into the Black Creek aquifers. This would also enhance water-level recovery and reduce the potential for saltwater intrusion. The second strategy would entail storing the surplus freshwater in the non-potable aquifers of the Middendorf and Cape Fear Formations. With both strategies, the water would be injected in the winter months and recovered in the peak water demand period during the following summer months. This would increase the water capacity of the system without necessitating expansion of the surface water treatment plant.

Purpose and Scope of the Investigation

This investigation has been divided into two phases (1) the collection of hydrogeologic data and construction of a prototype ASR well, which is the subject of this report, and (2) the injection and recovery cycles. The purpose of the first phase of the investigation was to determine the hydrologic feasibility of an ASR project in unconsolidated Coastal Plain sediments. The project focuses on the Cretaceous formations to a depth of 1,404 ft bls (below land surface). A test hole to bedrock was

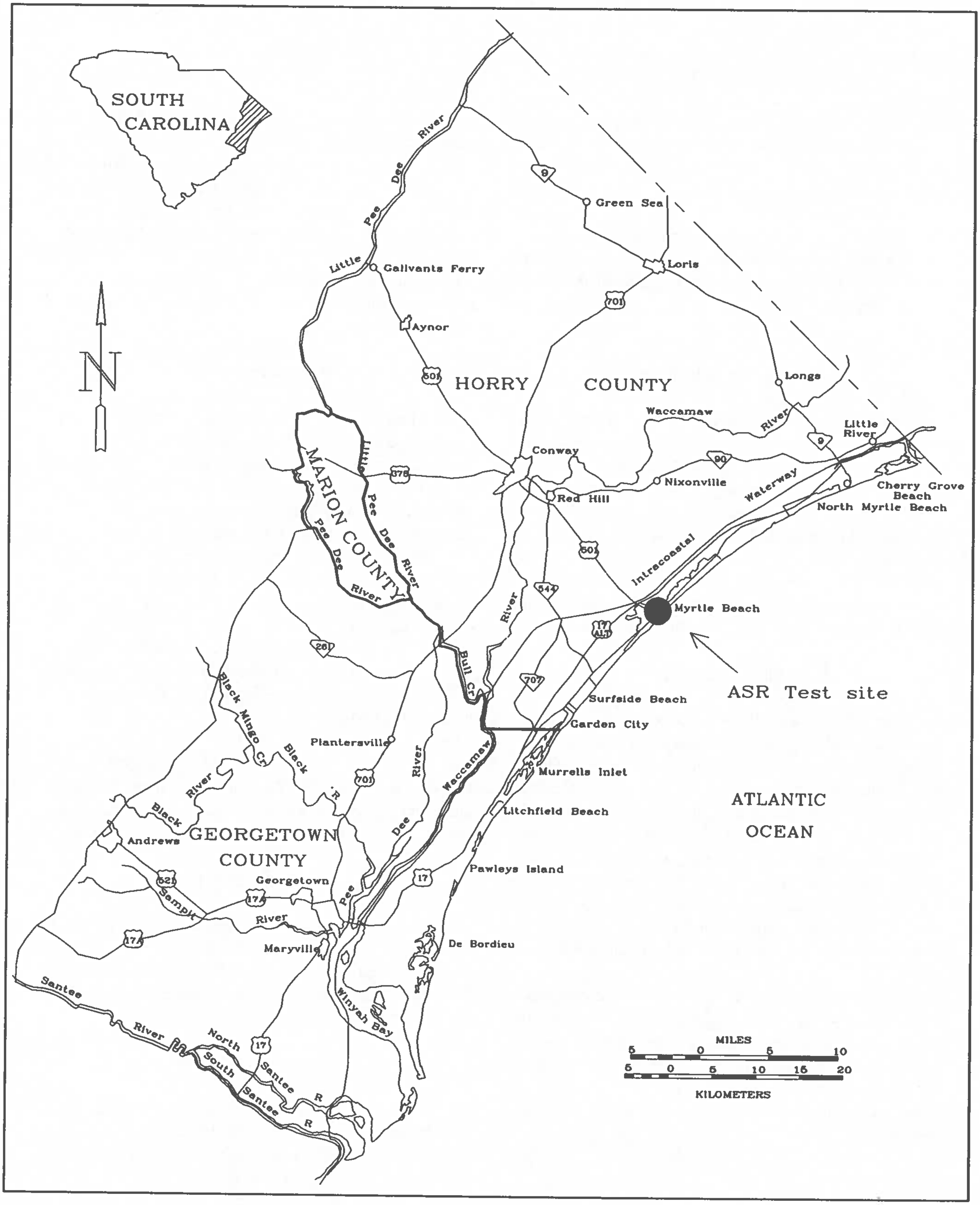

Figure 1. Location of the Aquifer Storage and Recovery (ASR) test site.

drilled through the Black Creek, Middendorf, and Cape Fear Formations. From this test hole, sub-surface hydrogeologic information was gathered, including geologic samples (drill cuttings and core samples), water samples, and hydraulic-head measurements. Additionally, pumping and geochemical column tests were made so that additional hydrologic properties of the aquifers, such as permeability, could be determined. Laboratory tests measured mineralogic and hydrologic properties of selected core samples.

Analyses and interpretation of these data, supplemented with existing information, were completed in order to characterize the hydrostratigraphy of the study area and evaluate permeable units for potential use as injection zones.

Previous Investigations

The regional hydrogeology of Horry and Georgetown Counties has been described in reports by Pelletier (1985), Zack (1977), and Spigner and others (1977). A preliminary investigation of the hydrogeology of the ASR testing site, utilizing data from wells within a 2-mile radius of the test hole, was prepared by Castro and Hockensmith (1987). Castro (1987) authored a preliminary report identifying aquifer pretreatment methods necessary to reduce undesirable effects of mixing treated surface water with native formation water.

Acknowledgments

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HYDROGEOLOGY OF THE ASR TEST SITE

Overview

Lithologic and hydrologic information for the ASR test well (5S-f1) at Myrtle Beach was obtained from drill cuttings and core samples. Drill cuttings were collected every 5 ft of depth, or at lithology changes, to a depth of 375 ft bls. Continuous core was extracted from 376 to 1,427 ft bls. All samples were described on the site and later analyzed in detail at the laboratory. Additionally, geophysical logs of the test well were made and used in establishing the stratigraphy of the region, preparing a lithologic column, and in computing formation factors and porosities.

Regional Geology

Sediments overlying the crystalline bedrock in Horry County are classified into five principal geologic units. They include the Cretaceous-age Cape Fear, Middendorf, Black Creek, and Peedee Formations and the shallow deposits of Tertiary and Quarternary ages. A brief description of these formations appears in Table 1.

Two geologic sections were prepared for this area. The northwest-southeast section (A-A', Plate 1) begins at the Brittons Neck well (10Q-p2) in Marion County, extends eastward to Conway, and then southeastward through the ASR test site. A second geologic section (B-B', Plate 1) begins at Estherville (10X-v1) and continues northeastward through the ASR test site to Calabash, N.C. (2Q-j2). Lithologic information from the Clubhouse Crossroads well (23CC-il), located west of Charleston, S.C., was used in making stratigraphic correlations for section B-B'. In general, major lithologic units were traceable for the entire length of each section.

Site Hydrogeology

For the purpose of description, the formations at the test site have been divided into units. Plate 2 contains lithologic and geophysical illustrations from the test site. A description of drill cuttings from the test well is presented in Plate 1.

Crystalline Bedrock

Bedrock at the ASR site is a quartz-biotite schist that is encountered at 1,423 ft bls. Its eroded surface dips to the south-southeast. Coring activities penetrated 4 ft into the schist, to a depth of 1,427 ft bls.

TABLE 1. LITHOLOGY OF QUATERNARY, TERTIARY, CRETACEOUS, AND PRE-CRETACEOUS FORMATIONS IN THE ASR STUDY REGION

SYSTEM	SERIES	GEOLOGIC FORMATION	FORMATION DESCRIPTIONS
QUATERNARY	PLEISTOCENE	SHALLOW DEPOSITS	Blue, gray, yellow, and brown sandy marl; gray to buff fine-grained quartz sand.
TERTIARY	EOCENE AND PALEOCENE	UNDIFFERENTIATED TERTIARY DEPOSITS AND BLACK MINGO FORMATION	Greenish-gray glauconitic sand with thick beds of coquina (loose, fossiliferous) limestone.
CRETACEOUS	UPPER CRETACEOUS	PEEDEE FORMATION	Gray, calcareous, fossiliferous clay; gray, glauconitic, calcareous, fine- to medium-grained, muddy sand; and coquina.
		BLACK CREEK FORMATION	Well-sorted, calcareous, fine- to medium-grained quartz sand; calcareous silty clay; and glauconitic, calcareous, muddy, fine- to medium-grained quartz sand.
		MIDDENDORF FORMATION	Multicolored clay and olive-gray, clayey, coarse, feldspathic sand.
		CAPE FEAR FORMATION	Fining-upward sequences of multicolored, silty, clayey, coarse feldspathic sand to multicolored clay.
PRE-CRETACEOUS		SAPROLITE	Yellowish-brown to yellowish-orange, sandy silt.
		CRYSTALLINE BEDROCK	Quartz-biotite schist.

No specific water information for the crystalline bedrock at this site was available, but the water is believed to be brackish and small in quantity.

Overlying the crystalline bedrock is a layer of saprolite that extends from 1,397 to 1,423 ft bls. It is a yellowish-brown to yellowish-orange, sandy silt containing 7 to 10 percent mica, mostly as biotite. Although no water samples were obtained, the water is also suspected to be brackish because the overlying formation water of the Cape Fear and Middendorf Formations is brackish.

Cape Fear Formation

The Cape Fear Formation overlies the saprolite. It consists of fining-upward sequences, grading from silty or clayey coarse sand to clay, which dip and thicken to the southeast. The clay is multicolored (olive-gray, red, brown, and yellow), usually mottled, and may be micaceous. The sand is yellow, reddish-brown, or reddish-gray, coarse- to fine-grained, subangular, and generally poorly sorted. Feldspars are mostly orthoclase and are present in trace to minor amounts; muscovite is minor to abundant; and heavy minerals range from trace to minor amounts. Iron staining is common.

The Cape Fear Formation is not presently a source of drinking water or industrial supply. This is due primarily to the high salinity, of the water and the deep drilling that is required to tap the aquifers. A chemical analysis of water taken from the 1312-1332 ft bls temporary screened interval (Cape Fear Formation) is included in Appendix 2.

At the test site, the Cape Fear Formation consists of unconsolidated clay, silty clay, sandy silt, and coarse- to fine-grained sand. It extends from 1,077 to 1,397 ft bls, with a total thickness of 320 ft. Sediments of this formation have been divided into units as follows:

Unit	Interval (ft bls)	Thickness (ft)
1	1,377 - 1,397	20
2	1,263 - 1,377	114
3	1,165 - 1,263	98
4	1,077 - 1,165	88

Within the Cape Fear sandy sediments (Units 2 and 4), the average grain size ranged from coarse to fine, with pebble-size or larger grains frequently present. In most of these samples, the silt and clay were between 5 and 15 percent in volume. The coarser zones tended to be more poorly sorted and contained the greatest percentage of feldspar. Muscovite and chlorite were present in trace to minor amounts, heavy minerals were detected in trace amounts, and iron staining was prevalent in some sections. Several fining-upward sequences were observed in both sandy zones.

Unit 1. Unit 1 lies at the base of the formation and is a friable, micaceous, sandy silt. It is variegated greenish-gray, reddish-brown, and yellowish-orange.

Unit 2. Consisting of interbedded sand and clay layers, Unit 2 ranges in thickness from 8 to 24 ft. The clay is olive-green or yellowish-brown, generally hard, silty, micaceous, and noncalcareous. The sand zones, olive-gray to yellowish-brown, are silty, coarse- to very fine-grained, subangular, and poorly to very poorly sorted. The sand is micaceous and noncalcareous, and it also contains significant amounts of feldspar (mostly potassium).

Unit 3. Thick, mottled clay dominates most of this unit. It is mostly dark reddish-brown and greenish-gray, micaceous, and very indurated. Between 1,211 and 1,224 ft bls, there is an intervening sand that is reddish-brown and olive-gray, fine to medium grained, and very micaceous.

Unit 4. This is the uppermost portion of the Cape Fear Formation at the test site. It is composed of thick sand beds with some greenish-gray and reddish-brown, slightly micaceous interbedded clay between 2 and 7 ft in thickness. The sand is mottled grayish-pink, yellowish-brown, and reddish-brown, coarse to fine grained, and moderately to poorly sorted. This sand was found to be micaceous and noncalcareous, with abundant feldspar.

Middendorf Formation

The Middendorf Formation lies on top of the Cape Fear Formation and consists of multicolored (red, yellow, olive-gray, orange, and brown) noncalcareous clay and gray or olive-gray clayey sand. The clay in this formation is generally hard and mottled, with a waxy appearance. It also contains minor to abundant amounts of muscovite. The sand units are clayey or silty and poorly sorted, ranging from very fine pebbles to fine sand. Feldspar, muscovite, and heavy minerals are present in trace to minor amounts. Clay and fine sand laminations and interbeds are common in the Middendorf Formation, as are fining-upward sequences. These sequences are between 3 and 15 ft in thickness and consist of coarse sand grading to clay (Gohn, 1983; Prowell, and others, 1985). A more recent stratigraphic study of the Middendorf Formation in the ASR study area may be referred to for additional descriptive information (Gohn, and others, 1992).

The aquifers of the Middendorf Formation contain brackish water in most of the region, although freshwater possibly occurs in the extreme western portion of Horry County. Poor water quality and excessive drilling depths have prevented Middendorf aquifers from being utilized for public or industrial water supplies in this area.

At the ASR site, the Middendorf lies between 961 and 1,077 ft bls and is composed of at least four fining-upward sequences. These sequences are made up of poorly sorted, coarse- to medium-grained sand, clayey sand, silty clay, and clay. The associated clay is mottled reddish-brown, yellowish-orange, and olive-green; it is noncalcareous and micaceous. The sand units contain minor amounts of feldspar and trace amounts of heavy minerals. Sequences range in thickness from 10 to 25 ft and are more clearly defined in the upper half of the formation. This formation has been separated into three units:

Unit	Interval (ft bls)	Thickness (ft)
1	1,046 - 1,077	31
2	977 - 1,046	69
3	961 - 977	16

Unit 1. This unit is a mottled, reddish-brown and greenish-gray clay. It is hard and fractured and contains minor amounts of very coarse sand with some very fine pebbles. The clay is micaceous and contains some iron stained grains and oxides.

Unit 2. Four clay layers, ranging from 7 to 20 ft in thickness, make up Unit 2. The clay resembles that of Unit 1, although very fine pebbles are less common. Separating the clay layers is a medium- to fine-grained, poorly sorted, clayey sand or sand that is micaceous with minor amounts of feldspar and traces of heavy minerals.

Unit 3. This unit makes up the top of the Middendorf Formation. It is an olive-gray, micritic, clayey sand, medium- to coarse-grained and very poorly sorted. Feldspar, pyrite, heavy minerals, and iron-stained grains are common in minor amounts.

Black Creek Formation

The Black Creek Formation, which overlies the Middendorf Formation, is made up of dark-gray to light-gray, fine-grained, micaceous, phosphatic, and glauconitic sand and clay. This composition suggests that these sediments were deposited in a marine-marginal marine environment (Colquhoun, and others 1983; Speiran and Aucott, 1991; and Gohn, and others, 1992). The units usually contain interbeds and laminations of fine sand and clay. Lignite is common throughout the formation, occurring as thin interbeds or disseminated in the sediments. Shell fragments have been noted in trace amounts throughout the formation; however, they are most abundant in the shallower units. Thin layers of calcareous cemented sandstone are numerous, particularly in the upper third of the formation.

Aquifers of the Black Creek Formation were, until 1988, the primary source of freshwater supplies in Horry County. The water is of a sodium bicarbonate type, soft, alkaline, and low in iron; however, it commonly has objectionable concentrations of fluoride, sodium, and total dissolved solids.

The Black Creek Formation lies between 288 and 961 ft bls at the test site. The sediments consist mostly of relatively clean, olive-gray, fine- to very fine-grained, micaceous and glauconitic sand. The sand is interlayered with thin laminations of dark olive-gray clay, with some thick layers present.

Glauconite is abundant (up to 30 percent) in all of the sand units, with the greatest abundance occurring between 534 and 631 ft bls. Phosphate, in the form of shark teeth and large pebble-size grains, is common. Lignite is found in traces or in distinct laminations. Pyrite was detected, mostly as casts and cement, in amounts up to 2 percent. Above 438 ft bls, thin streaks of very hard, medium- to fine-grained, calcareous sandstone commonly occur.

The clay units at the test site are olive-gray to grayish-black, calcareous, moderately micaceous, and contain as much as 3 percent of glauconite.

The hydrostratigraphy of the Black Creek Formation at the test site has been divided into twelve units:

Unit	Interval (ft bls)	Thickness (ft)
1	893 - 961	68
2	848 - 893	45
3	833 - 848	15
4	810 - 833	23
5	783 - 810	27
6	716 - 783	67
7	631 - 716	85
8	489 - 631	142
9	438 - 489	51
10	348 - 438	90
11	324 - 348	24
12	288 - 324	36

Unit 1. At the base of this formation is a thick, olive-gray, micritic clay. This clay is hard and fissile and contains glauconite from trace amounts to 7 percent near the top. Phosphate, pyrite, and shell fragments are common and vary from trace to minor amounts.

Unit 2. This unit is a carbonate zone consisting of a hard, greenish-gray, shelly micrite that contains as much 50 percent shell fragments.

Unit 3. Unit 3 is a hard, olive-gray clay with shell fragments from a trace to 7 percent. Lignite is common.

Unit 4. Overlying Unit 3 is a light olive-gray, very fine-grained sand containing moderate amounts of mica, glauconite, and lignite. It is interbedded with thin clay laminations.

Unit 5. A micaceous, olive-black clay makes up this unit. The clay contains minor amounts of glauconite and lignite. Occurring with the clay are thin laminations of very fine sand.

Unit 6. This unit is a light olive-gray, fine- to medium-grained, micaceous sand interbedded with thin laminations of clay and lignite. A few 2- to 7- ft thick clay layers are included in this unit. Glauconite makes up as much as 20 percent, but it generally decreases with depth.

Unit 7. Overlying Unit 6 is a thick, olive-black clay that is fissile and micaceous, with thin laminations of very fine-grained sand, glauconitic sand, and sandy clay.

Unit 8. This zone is a sand sequence similar to Unit 6, but thicker and containing more glauconite, along with traces of phosphate and pyrite.

Unit 9. Unit 9 contains soft, olive-black, micritic clay with a glauconite content of 1 to 7 percent and pyrite from trace amounts to 2 percent.

Unit 10. The fine-grained, olive-gray sand defining Unit 10 contains up to 10 percent glauconite and has fewer clay laminations than underlying units. At least three hard, thin streaks of sandstone occur in this zone. This sand unit, referred to locally as the "principal sand," is the most heavily tapped aquifer in the region.

Unit 11. This unit consists of clay similar to that described in Unit 9.

Unit 12. The sand making up this unit is similar to the sand of Unit 10.

Pee Dee Formation

The uppermost Cretaceous unit in Horry County is the Peedee Formation. It consists of thin, interbedded, fine-grained sand and clay with intermittent loose-shell and coarse-sand lenses. This suggests a nearshore depositional environment (Swift and Heron, 1969; Colquhoun and others, 1983).

The Peedee Formation crops out in an area encompassing northwestern Horry and Georgetown Counties. It extends westward into Marion and central Florence Counties. A smaller and narrower outcrop area exists just to the east. Both are important recharge areas for this formation.

In general, the aquifers of the Peedee Formation are under confined conditions, but they are not used for municipal water supplies because of unsatisfactory water quality and low well yields. Water from these aquifers is highly variable in quality, ranging from poor to excellent. Throughout most of Horry and Georgetown Counties, the Peedee water contains low concentrations of fluoride and generally low concentrations of chloride. The water is high in calcium and magnesium and relatively high in iron and hydrogen sulfide. Many of these water quality problems are localized with no apparent pattern to their occurrence; therefore, utilization of this aquifer has been confined to a few small areas.

The Peedee Formation lies between 80 and 288 ft bls at the test site. It is made up of light-gray to olive-gray sand, clayey micrite, and micritic sand. The upper portion of the Peedee Formation, from 80 to 173 ft bls, is micritic and contains thin streaks of hard, fine-grained sandstone. Underlying this micritic zone is a 22-ft thick, fine-grained, micritic sand. The basal unit of the formation is an olive-gray to black clay. Glauconite is the predominant accessory mineral, increasing with depth to between 5 and 7 percent. Pyrite is prevalent, and both shell fragments (including gastropods and cephalopods) and phosphates are present in trace amounts. Traces of lignite were noted above 115 ft bls.

Shallow Deposits

The shallow deposits in the region are of Tertiary and Quaternary ages. They consist of undifferentiated beds of fine, clayey sand; fine, calcareous sand; and coquina (loose and fossiliferous) limestone.

Most individual beds are not extensive, making the shallow aquifers of limited significance. Both water-table and confined conditions occur in these sediments. Recharge to the aquifers is mostly dependent upon local precipitation.

Water quality in the shallow deposits is highly variable and greatly influenced by the mineralogy of the aquifer sediments. Generally, the water is soft and very low in fluoride, chloride, and sodium; therefore, these aquifers are utilized only for domestic wells and small-scale irrigation.

LABORATORY ANALYSES

Hydrologic data were obtained by making a petrographic analysis of 39 thin sections prepared from selected cuttings and core samples. In addition, 14 10-inch core samples were examined by x-ray diffraction

(XRD) and scanning electron microscope (SEM). These samples were tested for vertical and horizontal permeability, porosity, and cation-exchange capacity (CEC). The core samples were also used in energy-dispersive chemical analysis (EDX), as well as for grain-size determination.

Thin-Section Study

Thin-section analyses were done on samples from every formation, including the shallow deposits. Detailed analyses are shown in Table 2.

Crystalline Bedrock. Analysis of a thin section from the 1,427-ft bls sample indicates that the ratio of quartz to biotite is 4 to 1, with no other mineralogical constituents detected. The foliation of the minerals is shown in Figure 2, where the quartz exhibits the undulatory extinction typical for metamorphic rocks. Further analysis revealed no intergranular porosity; however, weathered fractures, some several inches wide and filled with saprolite, are visible in the core samples.

A thin section sample from 1,404 ft bls indicates that the saprolite contains 50 percent silt and clay, 40 percent quartz, and 10 percent mica. Some foliation, a remnant of the original rock, is present. The mica (biotite) is intensely weathered. Effective porosity of this sample is estimated at 10 percent.

Cape Fear Formation. Twelve samples from the Cape Fear Formation were analyzed in thin section. In general, the sand units contain large amounts of feldspar, mostly potassium feldspar (K-feldspar), which run from 18 to 39 percent. Plagioclase is between 0 and 8 percent and K-feldspar is between 16 and 31 percent. A photomicrograph of the 1,086-ft bls sample (Fig. 3) from Unit 4 shows grain coatings and feldspars contained in these sediments. Mica, mainly as muscovite, is noted in amounts up to 5 percent. Clay is generally present as grain coatings, as seen in the photomicrograph from the 1,356-ft bls sample of Unit 2 (Fig. 4). No glauconite or carbonate is recorded in any sample. Effective-porosity values, determined from thin-section analysis, range from 10 to 20 percent for the sand of the Cape Fear Formation. The greatest porosities are observed at 1,086 and 1,297 ft bls (Units 4 and 2, respectively).

Middendorf Formation. Analyses of four samples from this formation were made. Only one sample, 970-ft bls (Unit 3), is classified as sand. It is composed of 10 percent argillaceous matrix, 16 percent feldspar (equal Na- and K-feldspar), and 10 percent lithic fragments. It has an effective porosity of 17 percent. The remaining three samples range from 57 to 93 percent argillaceous matrix, with 0 to 8 percent composed of feldspar, often noted as highly weathered. Clay is commonly present as grain coatings.

The photomicrograph of the sample from 1,012 ft bls (Fig. 5) illustrates the poor sorting of quartz and feldspar grains, as well as the angularity of the Middendorf sediments.

Black Creek Formation. Thirteen thin sections from the Black Creek Formation were described. Eight have been classified as either sand or clayey sand. Glauconite is present in amounts up to 18 percent, muscovite to 2 percent, and carbonate grains to 6 percent. A photomicrograph from 624 ft bls (Fig. 6) serves to illustrate the presence of glauconite in some of these sediments, commonly occurring in pellitic form. Thin-section analysis of samples from this formation indicate that the effective porosity is between 14 and 25 percent.

Sand taken from this formation generally appears clean, with little clay (5 percent or less) noted in six of these samples.

Peedee Formation. Three thin sections, made from drill-cuttings samples (124, 175, and 265 ft bls from the Peedee Formation), were analyzed. Samples 124 and 175 ft bls are clayey sand with argillaceous matrix percentages of 44 and 32 and carbonate cement percentages from 5 to 12, respectively.

K-feldspar was detected at 2 percent at 175 ft bls; it was not seen at other depths. At 124 ft bls, glauconite is 3 percent, while at 265 ft bls it was determined to be 8 percent. All samples reveal carbonate grains (mostly as shell fragments of gastropods and cephalopods) from 1 to 5 percent. Porosities were not determined because thin sections were made from drill cuttings.

Shallow Deposits. One thin-section analysis was made for these deposits. The 59-ft bls sample shows that it is made up of 48 percent quartz, 34 percent carbonate cement, and 15 percent argillaceous matrix, with minor shell fragments, glauconite, and plagioclase. No other laboratory analyses were made on these shallow deposits.

X-Ray Diffraction

X-ray diffraction analysis was done on samples from the Cape Fear, Middendorf, and Black Creek Formations. The data are shown in Table 3 and may be compared with data taken from the thin-section analysis (Table 2).

Cape Fear Formation. Analysis determined the samples to be feldspathic sand, with K-feldspar being

TABLE 2. MINERAL AND POROSITY PERCENTAGES DETERMINED BY THIN-SECTION ANALYSIS OF SAMPLES TAKEN AT THE ASR TEST SITE

DEPTH (ft bls)	FORMATION	UNIT	MATRIX (Argillaceous)	FRAMEWORK GRAINS							CEMENT	POROSITY
				Quartz	Plagioclase	K-feldspar	Glauconite	Mica	Carbonates	Other		
24	SHALLOW	-	5	20	0	0	0	0	75	0	--	--
59	SHALLOW	-	15	48	1	0	0	0	2	0	34	--
124	PEEDEE	-	44	45	0	0	3	1	2	0	5	--
175	PEEDEE	-	32	53	0	2	0	0	1	0	12	--
265	PEEDEE	-	61	26	0	0	8	0	5	0	0	--
305	BLACK CREEK	12	54	42	0	0	0	0	4	0	0	--
315	BLACK CREEK	12	23	53	0	0	0	0	6	0	18	--
355	BLACK CREEK	10	76	22	0	0	2	0	0	0	0	--
404	BLACK CREEK	10	5	86	1	0	8	0	0	0	0	24
465	BLACK CREEK	9	98	2	0	0	0	0	0	0	0	--
501	BLACK CREEK	8	93	7	0	0	0	0	0	0	0	--
550	BLACK CREEK	8	4	77	1	0	15	3	0	0	0	24
589	BLACK CREEK	8	0	81	0	0	17	0	1	1	0	23
622	BLACK CREEK	8	0	81	0	0	18	0	0	1	0	24
624	BLACK CREEK	8	0	77	0	0	17	2	0	0	4	24
662	BLACK CREEK	7	99	1	0	0	0	0	0	0	0	--
723	BLACK CREEK	6	0	91	1	0	0	0	1	7	0	25
752	BLACK CREEK	6	49	46	0	3	0	2	0	0	0	14
857	BLACK CREEK	2	99	1	0	0	0	0	0	0	0	--
907	BLACK CREEK	1	70	29	0	1	0	0	0	0	0	--
937	BLACK CREEK	1	90	9	0	0	1	0	0	0	0	--
970	MIDDENDORF	3	10	64	8	8	0	0	0	10	0	17
1012	MIDDENDORF	2	57	34	5	3	0	0	0	1	0	9
1026	MIDDENDORF	2	93	7	0	0	0	0	0	0	0	--

TABLE 2. MINERAL AND POROSITY PERCENTAGES DETERMINED BY THIN-SECTION ANALYSIS OF SAMPLES TAKEN AT THE ASR TEST SITE (CONTINUED)

DEPTH (ft bls)	FORMATION	UNIT	MATRIX (Argillaceous)	FRAMEWORK GRAINS							CEMENT	POROSITY
				Quartz	Plagioclase	K-feldspar	Glauconite	Mica	Carbonates	Other		
1062	MIDDENDORF	1	60	35	0	5	0	0	0	0	0	–
1086	CAPE FEAR	4	33	44	1	18	0	2	0	2	0	20
1120	CAPE FEAR	4	23	52	4	16	0	0	0	5	0	17
1142	CAPE FEAR	4	80	19	0	1	0	0	0	0	0	–
1187	CAPE FEAR	3	97	3	0	0	0	0	0	0	0	–
1222	CAPE FEAR	3	23	35	8	31	0	1	0	2	0	16
1244	CAPE FEAR	3	93	5	0	2	0	0	0	0	0	–
1264	CAPE FEAR	2	70	15	0	13	0	2	0	0	0	–
1297	CAPE FEAR	2	27	46	3	22	0	0	0	2	0	20
1312	CAPE FEAR	2	93	5	0	2	0	0	0	0	0	–
1337	CAPE FEAR	2	60	30	0	5	0	5	0	0	0	–
1356	CAPE FEAR	2	37	42	0	19	0	1	0	1	0	10
1371	CAPE FEAR	2	97	3	0	0	0	0	0	0	0	–
1404	SAPROLITE	-	50	40	0	0	0	10	1	0	0	10
1427	BEDROCK	-	0	80	0	0	0	20	0	0	0	0

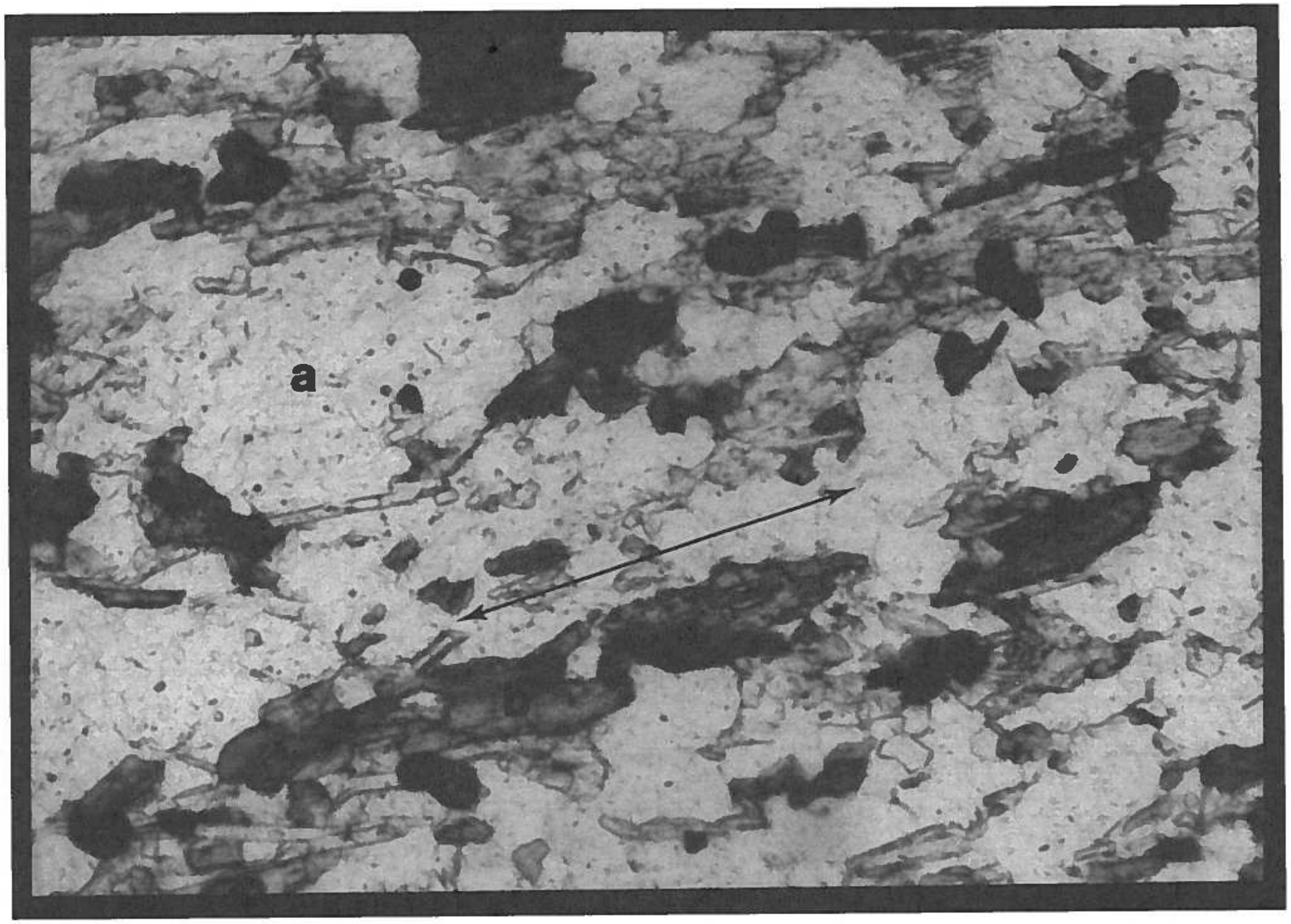

Figure 2. **Photomicrograph from petrographic slide of 1,427-ft bls sample, showing quartz (a), biotite (b), and orientation of foliation (arrow).**

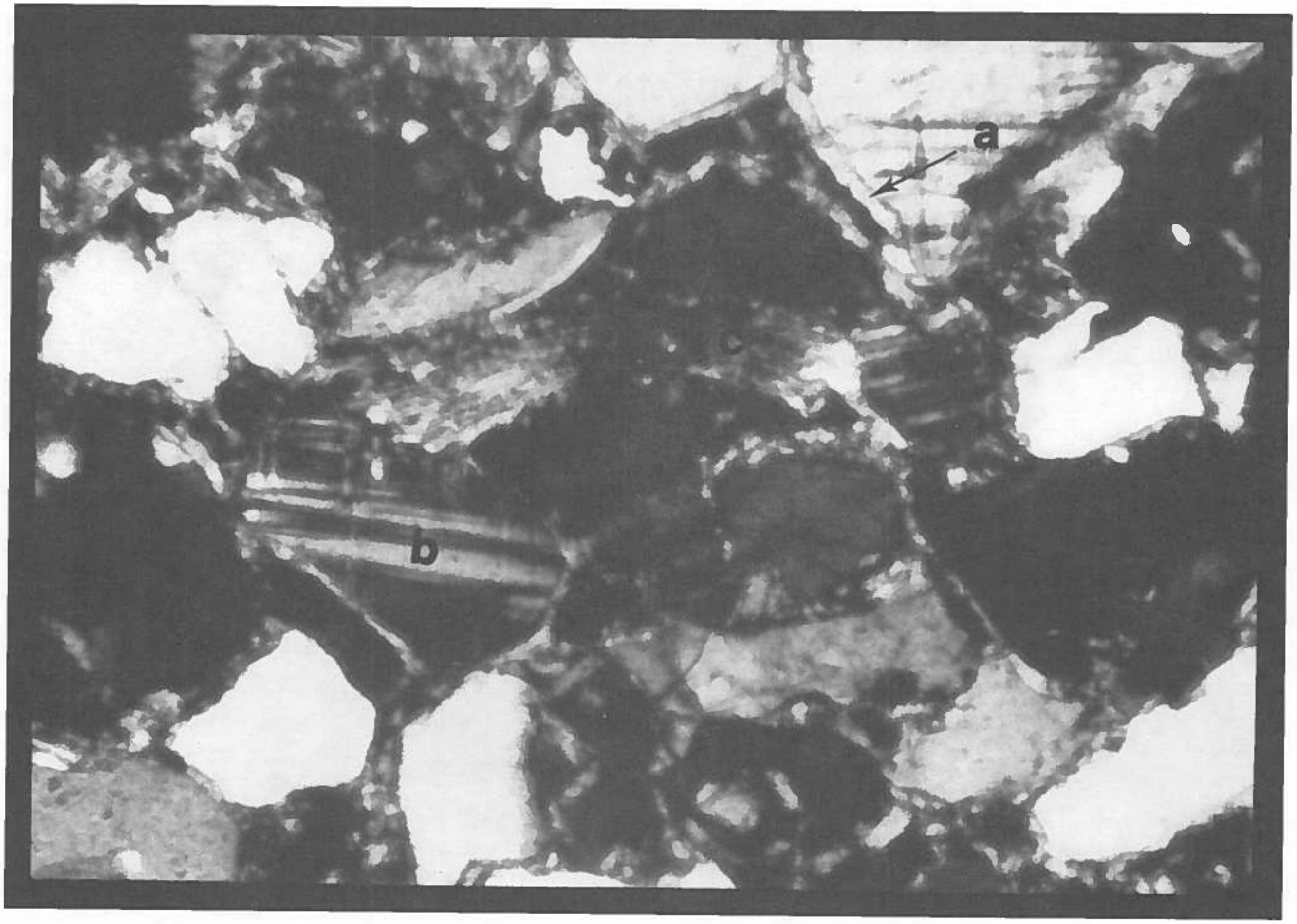

Figure 3. Photomicrograph from petrographic slide of 1,086-ft bls sample, showing clay grain coatings (a), k-feldspar (b), and muscovite (c).

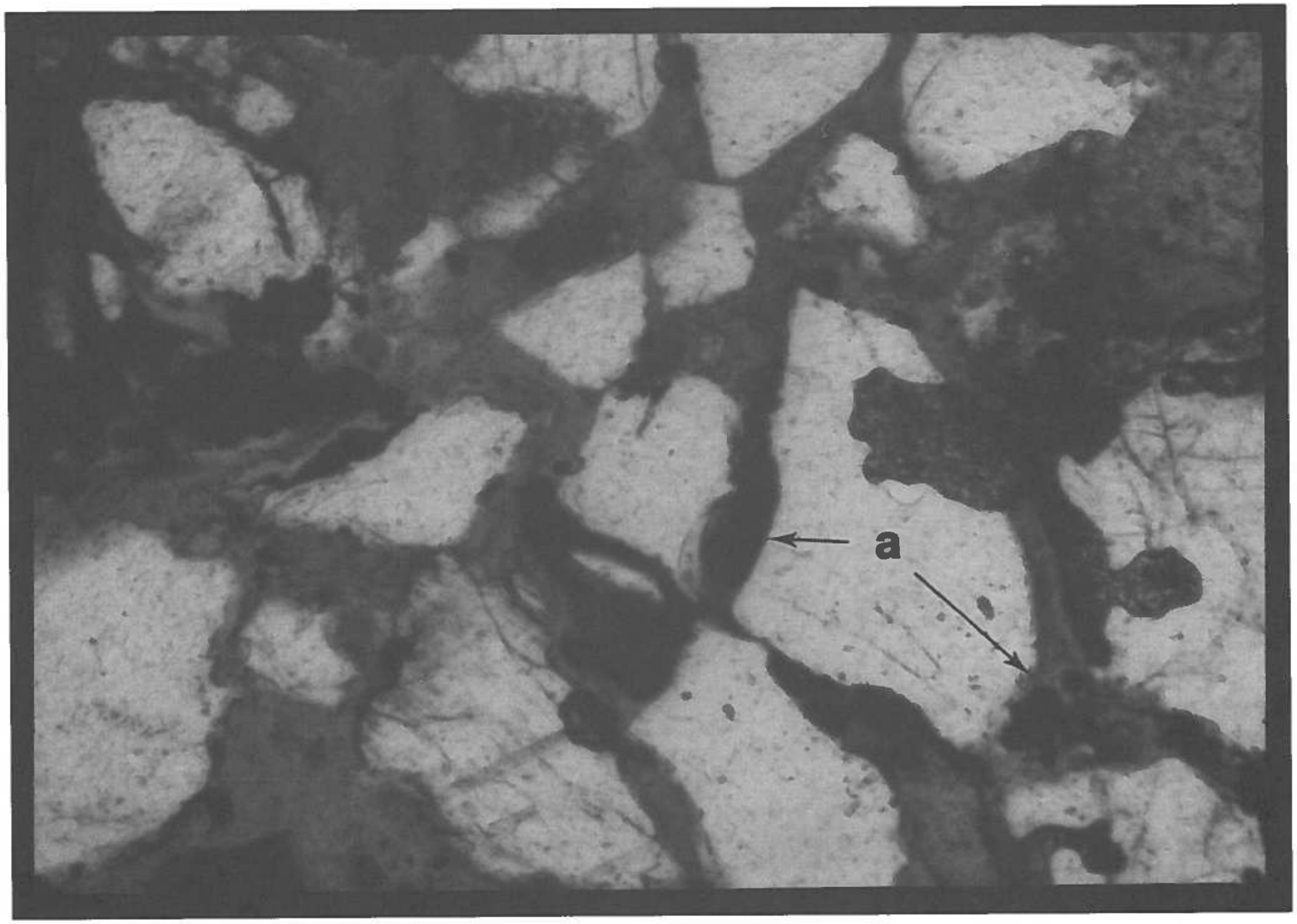

Figure 4. Photomicrograph from petrographic slide of 1,356-ft bls sample, showing clay grain coatings (a).

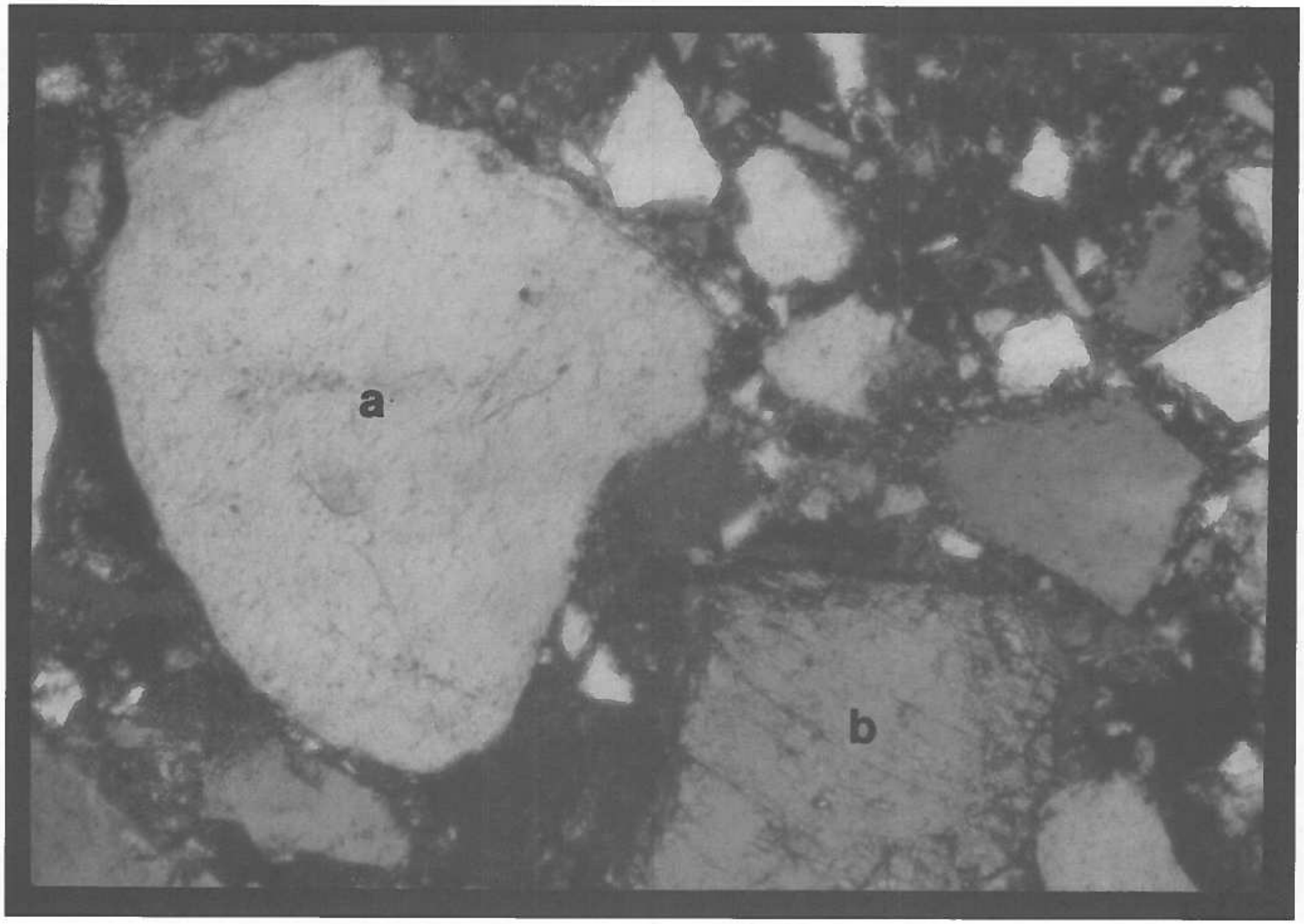

Figure 5. Photomicrograph from petrographic slide of 1,012-ft bls sample, showing quartz (a) and feldspar (b) displaying high angularity.

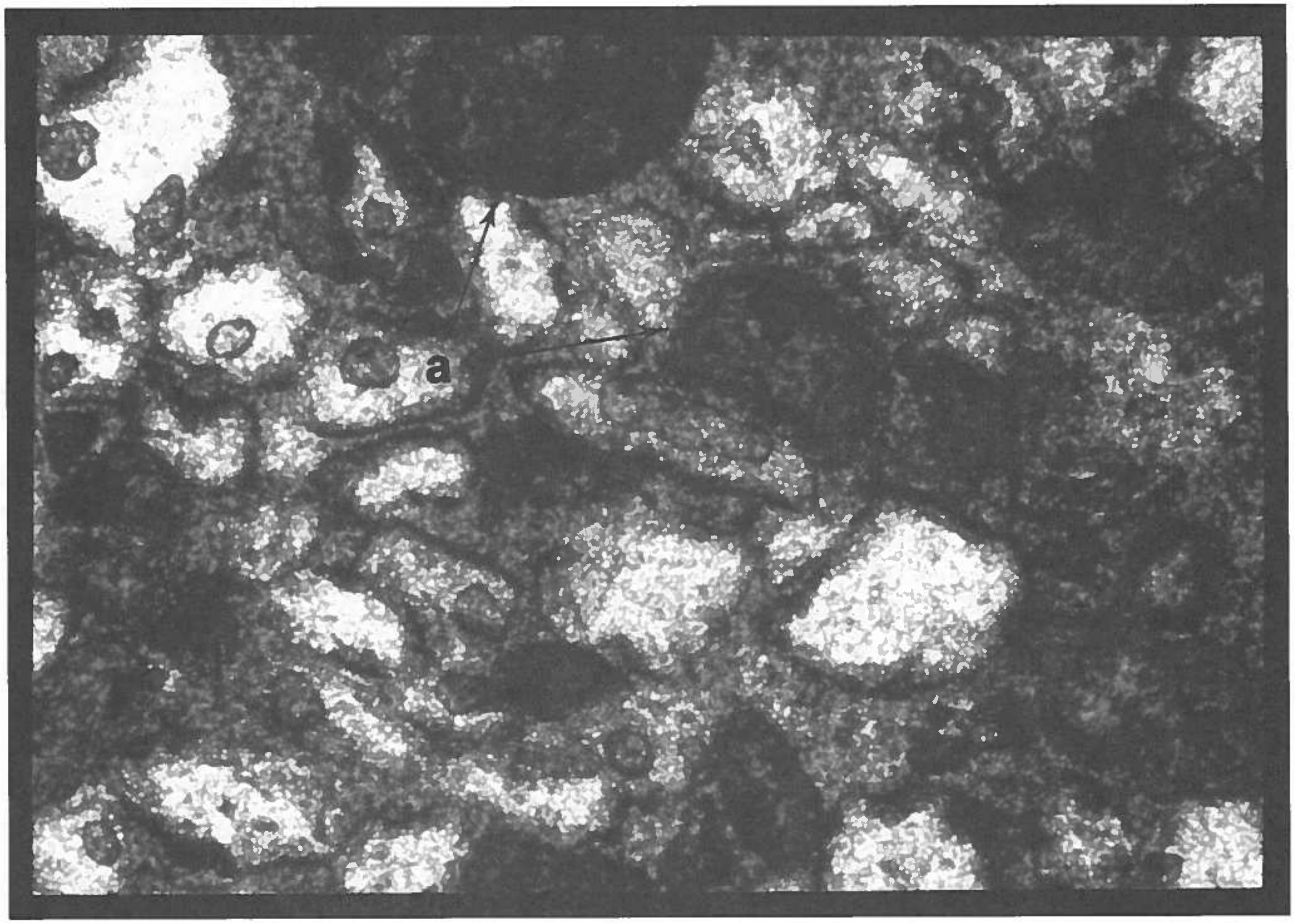

Figure 6. Photomicrograph from petrographic slide of 624-ft bls sample, showing glauconite (a).

TABLE 3. X-RAY DIFFRACTION MINERAL PERCENTAGES FOR THE CAPE FEAR, MIDDENDORF, AND BLACK CREEK FORMATIONS AT THE ASR TEST SITE

FORMATION	UNIT	DEPTH		FELDSPARS		TOTAL	CLAY CONSTITUENTS				TOTAL	ACCESSORY MINERALS				
		(ft bls)	Quartz	Plagioclase	K-feldspar	Feldspars	Kaolinite	Chlorite	Illite/Mica	Smectite	Clay	Calcite	Dolomite	Gypsum	Siderite	Pyrite
BLACK CREEK	10	404	86	3	4	7	0	<1	3	1	4	1	0	<1	0	2
	8	550	85	1	2	3	0	<1	5	6	11	<1	<1	0	0	1
	8	589	77	1	2	3	0	<1	11	7	18	<1	<1	0	0	2
	8	624	82	0	3	3	0	<1	7	8	15	<1	0	0	0	0
	6	723	94	0	4	4	0	0	<1	<1	0	<1	0	0	<1	1
	6	752	59	1	4	5	4	0	5	23	32	1	0	0	0	3
MIDDENDORF	2	1012	76	7	9	16	3	0	2	3	8	<1	<1	0	0	0
CAPE FEAR	4	1086	82	2	9	11	4	0	1	2	7	0	<1	0	0	0
	4	1088	70–80	*	*	10	5–10	*	*	5–10	10–20	*	*	*	*	*
	4	1120	85	1	7	8	2	0	<1	4	6	<1	1	0	<1	0
	3	1222	77	5	11	16	3	0	2	2	7	0	0	0	0	0
	2	1280	70–80	*	*	10	5–10	*	5	5	15–20	*	*	*	*	*
	2	1297	76	4	14	18	1	0	2	1	4	<1	1	0	0	1
	2	1356	84	2	6	8	4	0	1	2	7	1	<1	0	0	0

Values are percent volume of sample

*No data available

the dominant fraction.

Carbonate, as both calcite and dolomite, is present in four of the samples in very minor amounts. Clay percentages range from 4 to 20 percent at 1,297 and 1,280 ft bls, respectively. Results from a single laboratory analysis demonstrate that the clay content does not differ significantly among units.

Middendorf Formation. Only a single sample, 1,012 ft bls, was available for analysis. Sand is the dominant constituent at 76 percent; feldspar, with nearly equal amounts of K-feldspar and plagioclase, is at 16 percent; and clay composes 8 percent of the sample.

Black Creek Formation. Percentages obtained from x-ray diffraction show quartz to be the dominant mineral (59 - 94 percent). The 752-ft bls sample has the lowest amount of quartz and contains the most clay. Feldspar occurs mainly as K-feldspar, with lesser amounts of plagioclase. Pyrite is present in five of the six samples analyzed. Calcite has been detected in all samples at trace to minor amounts. Chlorite, illite, and smectite range from trace amounts to 23 percent, with chlorite being the least abundant and smectite being the most abundant.

Scanning Electron Microscope

Cape Fear Formation. The SEM analysis indicates that samples are poorly sorted, with minor amounts of clay adhering to the grains. Most of the sand ranges from coarse to fine grained (Fig. 7, photomicrograph of 1,222-ft bls sample). From laboratory analysis, authogenic (formed in place) kaolinite makes up most of the clay. Another interpretation, offered by Michael Waddell of the Earth Sciences and Resources Institute (oral communication), suggests that this kaolinite is detrital. Additionally, the feldspar grains within the samples show dissolution. SEM analysis on the 1,086-ft bls sample, Unit 4, (Fig. 8) shows a medium- to very fine-grained sand with good visible porosity. Smectite platelets coat the grain surfaces.

Middendorf Formation. Analysis of the Middendorf Formation reveals that sediment is a coarse- to medium-grained sand with allogenic (transported) clay. Iron oxide coats some grains. Figure 9, taken of the 1,012-ft bls sample, illustrates a coarse- to medium-grained sand. There is also evidence of feldspar dissolution.

Black Creek Formation. Among samples taken from the Black Creek Formation, SEM results show that most of the sand samples are well-sorted, fine-grained quartz sand with excellent visible intergranular porosity, as observed in Figure 10, 624 ft bls. Authogenic smectite on feldspar grains can also be noted in this figure. Figure 11 (404 ft bls) exposes two distinct grain sizes, very fine and medium. This sample also shows a good example of feldspar dissolution. Figure 12 (723 ft bls) shows a grain-size range from coarse to very fine and feldspar dissolution.

Illite and smectite are the clay types noted in these samples. Streaks of clay and abundant organics are noted at 752 ft bls in Unit 6. Within the fine-grained, well-sorted sand from 550 ft bls (Fig. 13), it is interesting to note the euhedral pyrite.

Determination of Porosity and Permeability

These results were determined from actual core-sample analysis. The porosity values differ from those determined by thin-section analysis in that the core-sample analysis determines total porosity and the thin-section analysis calculates effective porosity. Within the Cape Fear Formation, these values are as much as 8 percent greater. These higher values may be due to analysis limitations. Specifically, the drying technique in the laboratory is critical when clay is present in samples, and the adsorption of gas on the sample surface tends to give erroneously high porosity values. Permeability values were also determined by core-sample analysis. Although the values are given as air permeabilities and not water permeabilities, they serve to illustrate the differences between the formations and units. It is important to note that air permeability must not be directly converted to hydraulic conductivity without bench calibrations. Water permeability in millidarcies (md), however, is converted to hydraulic conductivity at 24°C in gallons per day per square foot by multiplying by 1.82×10^{-4} (Freeze and Cherry, 1979). Core samples selected for laboratory analysis were often biased toward clean sand units, which is the reason some of the vertical permeability values are equal to or greater than the horizontal permeability values. Table 4 includes porosity and permeability data from core analysis of the Cape Fear, Middendorf, and Black Creek Formations.

Cape Fear Formation. Porosities in the Cape Fear Formation are between 29 and 40 percent. Both vertically and horizontally, permeabilities are quite variable. Generally, horizontal permeabilities are greater than vertical permeabilities, with the highest being 9,690 md (1,120 ft bls, Unit 4). The lowest vertical and horizontal permeabilities are observed in the 1,086-ft bls sample from Unit 4. They are 1,070 and 1,725 md, respectively. Laboratory reports state that some samples were very friable and fell apart. Two samples, 1,222 and 1,297 ft bls, could not be analyzed because of this problem.

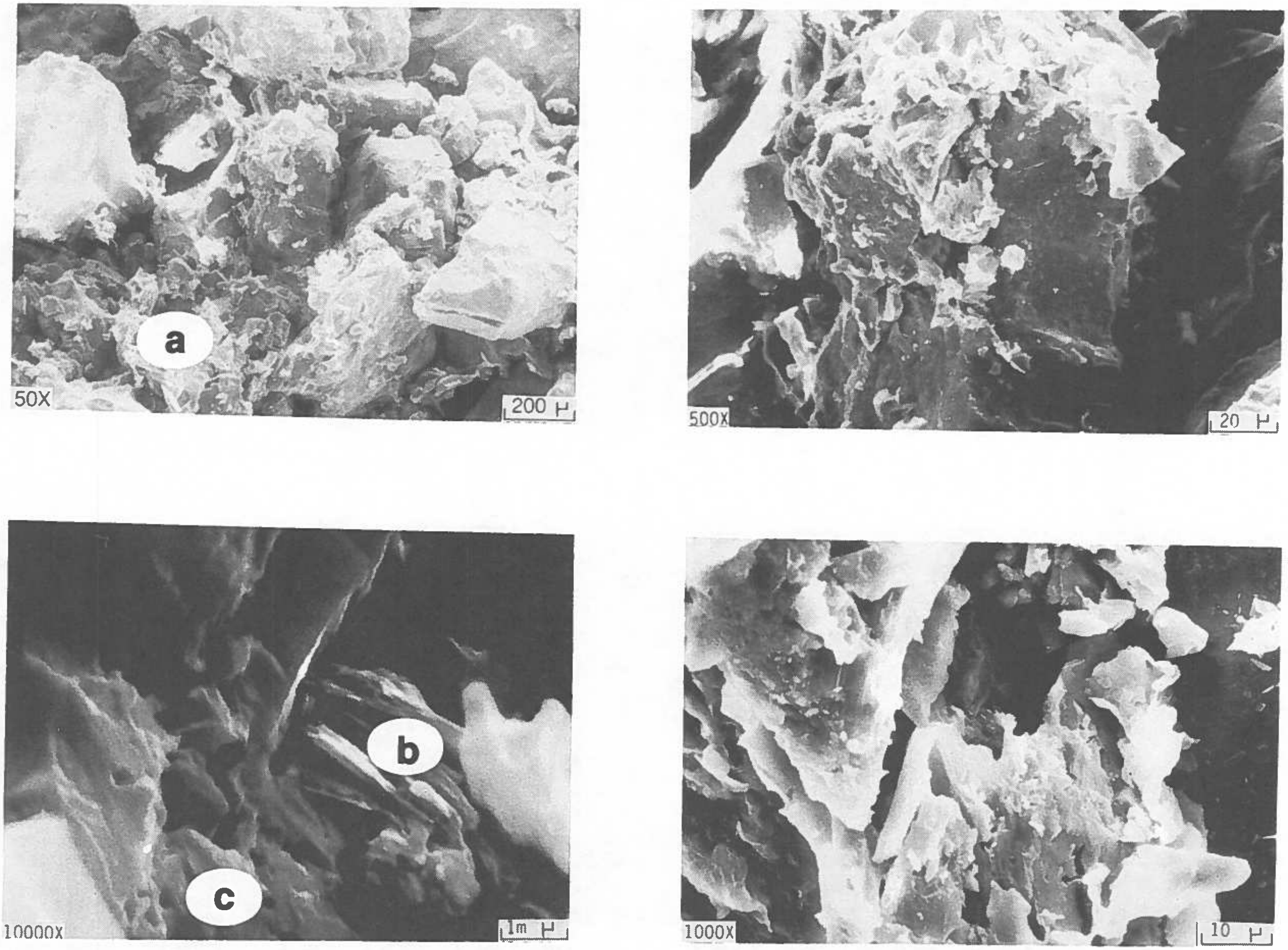

Figure 7. Photomicrograph from SEM analysis of 1,222-ft bls sample, showing coarse- to fine-grained sand (a), authogenic kaolinite (b), and feldspar dissolution (c) (clockwise from upper left).

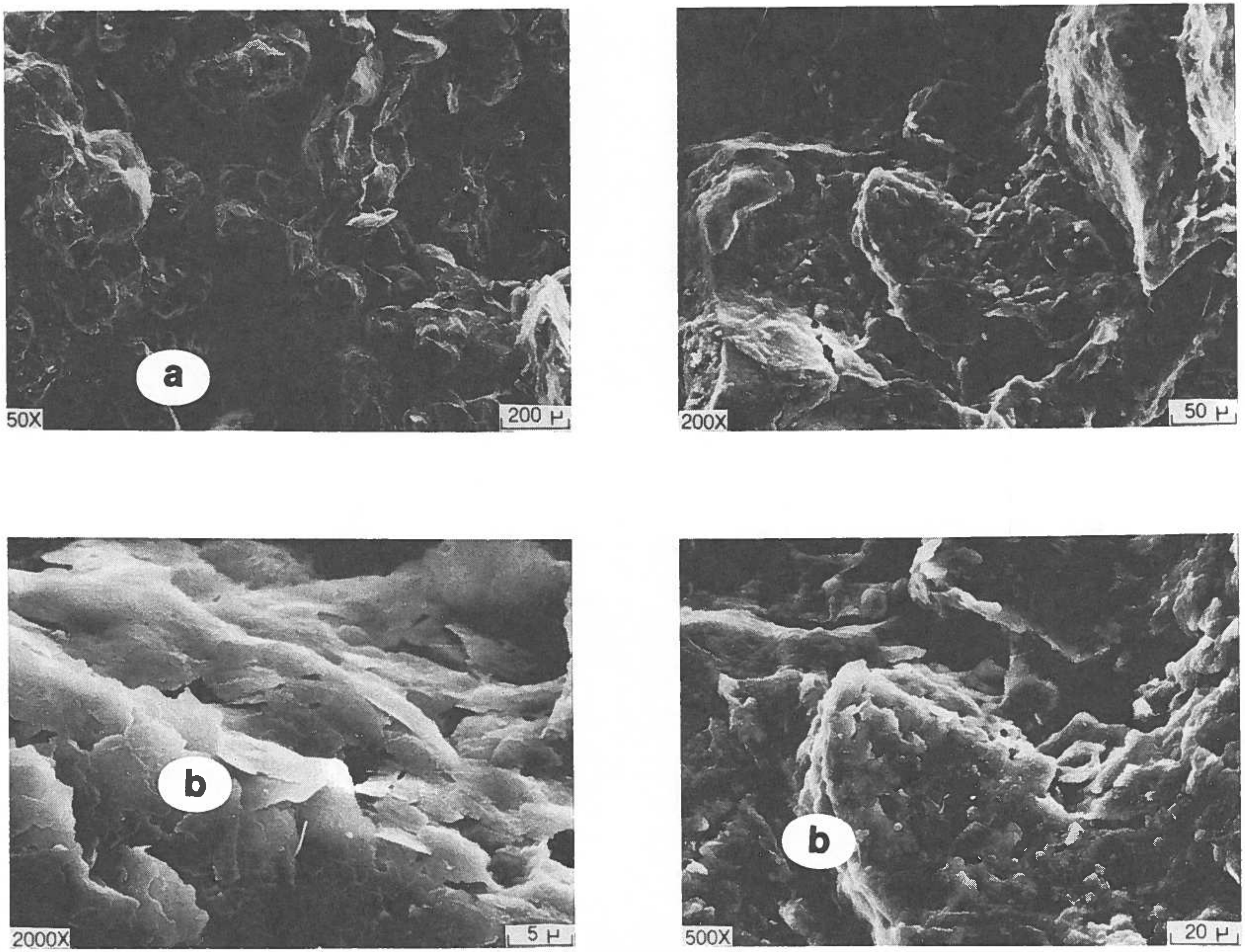

Figure 8. **Photomicrograph from SEM analysis of 1,086-ft bls sample, showing medium- to very fine-grained sand (a) and smectite on grain surfaces (b) (clockwise from upper left).v**

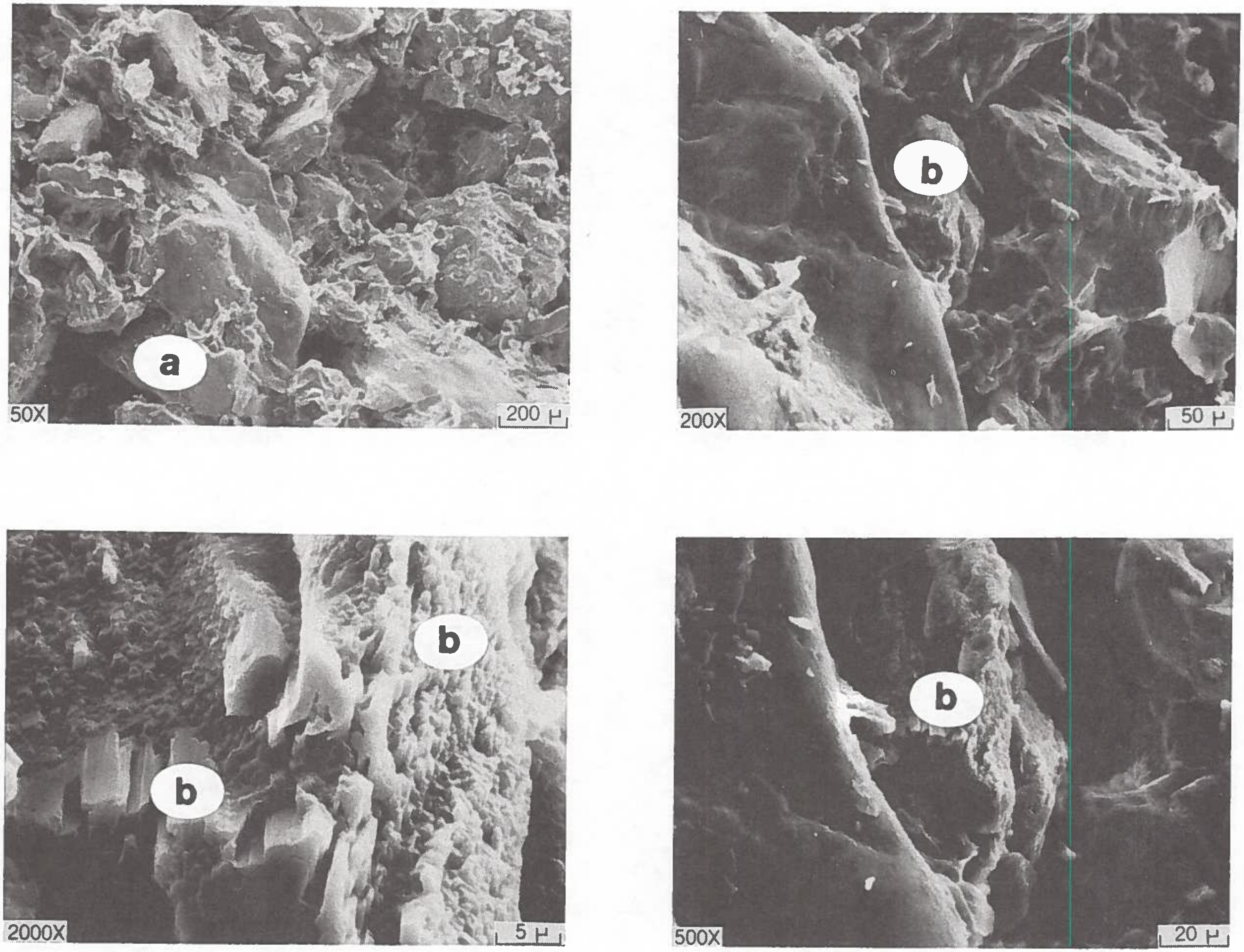

Figure 9. **Photomicrograph from SEM analysis of 1,012-ft bls sample, showing coarse- to medium-grained sand (a) and feldspar dissolution (b) (clockwise from upper left).**

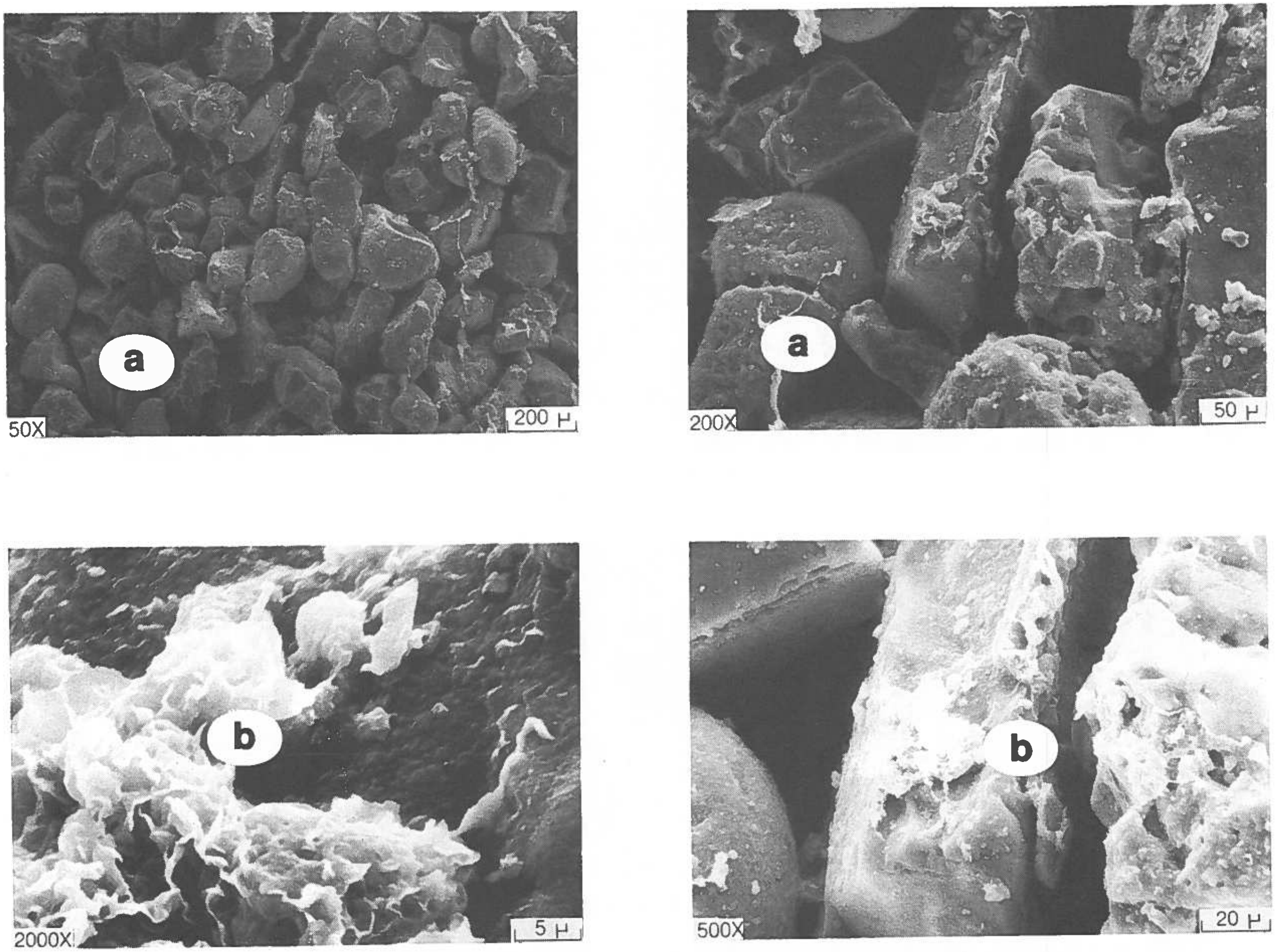

Figure 10. Photomicrograph from SEM analysis of 624-ft bls sample, showing well-sorted, fine-grained sand (a) and authogenic smectite on feldspar (b) (clockwise from upper left).

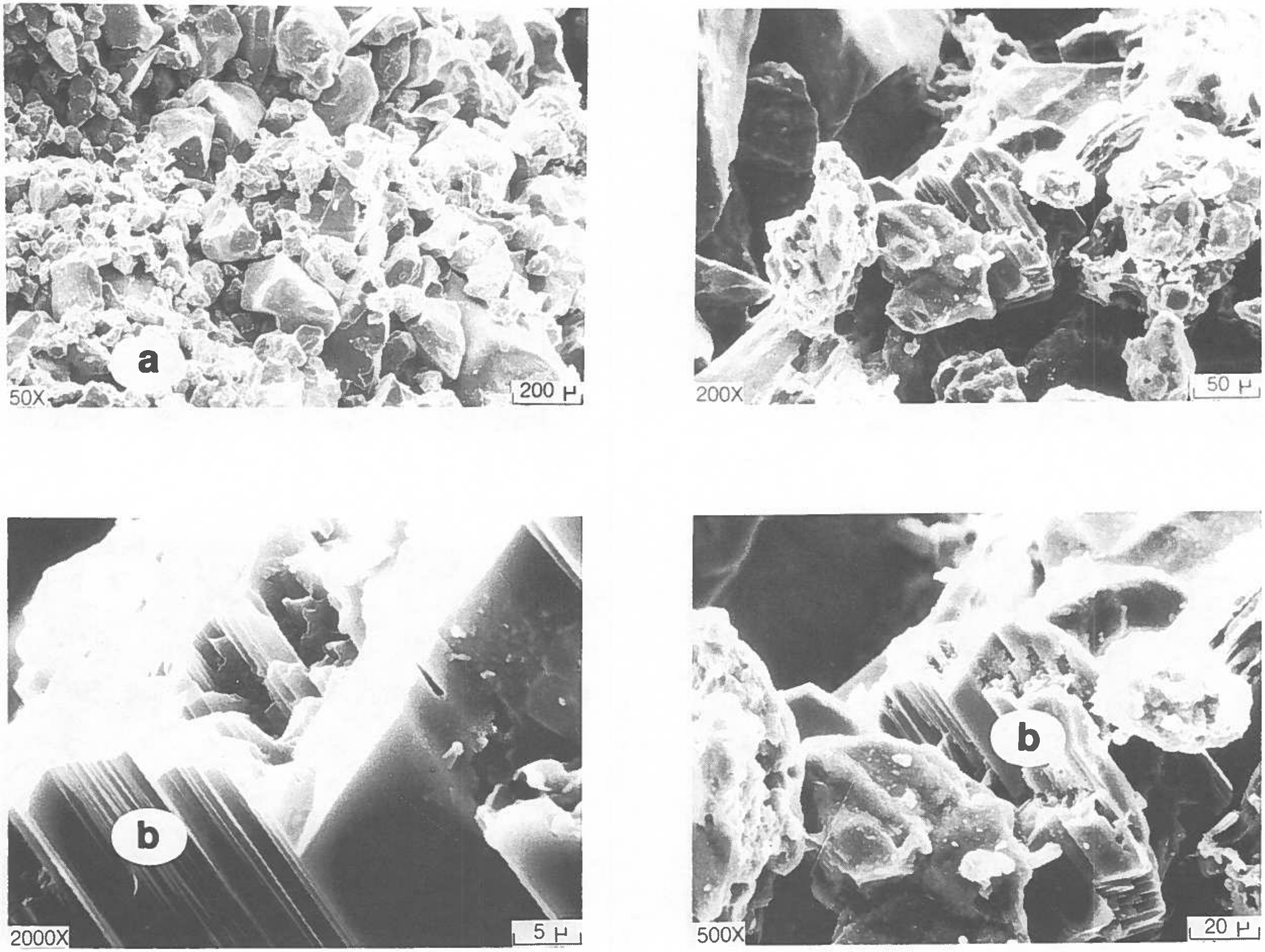

Figure 11. Photomicrograph from SEM analysis of 404-ft bls sample, showing very fine and medium grain sizes (a) and feldspar dissolution (b) (clockwise from upper left).

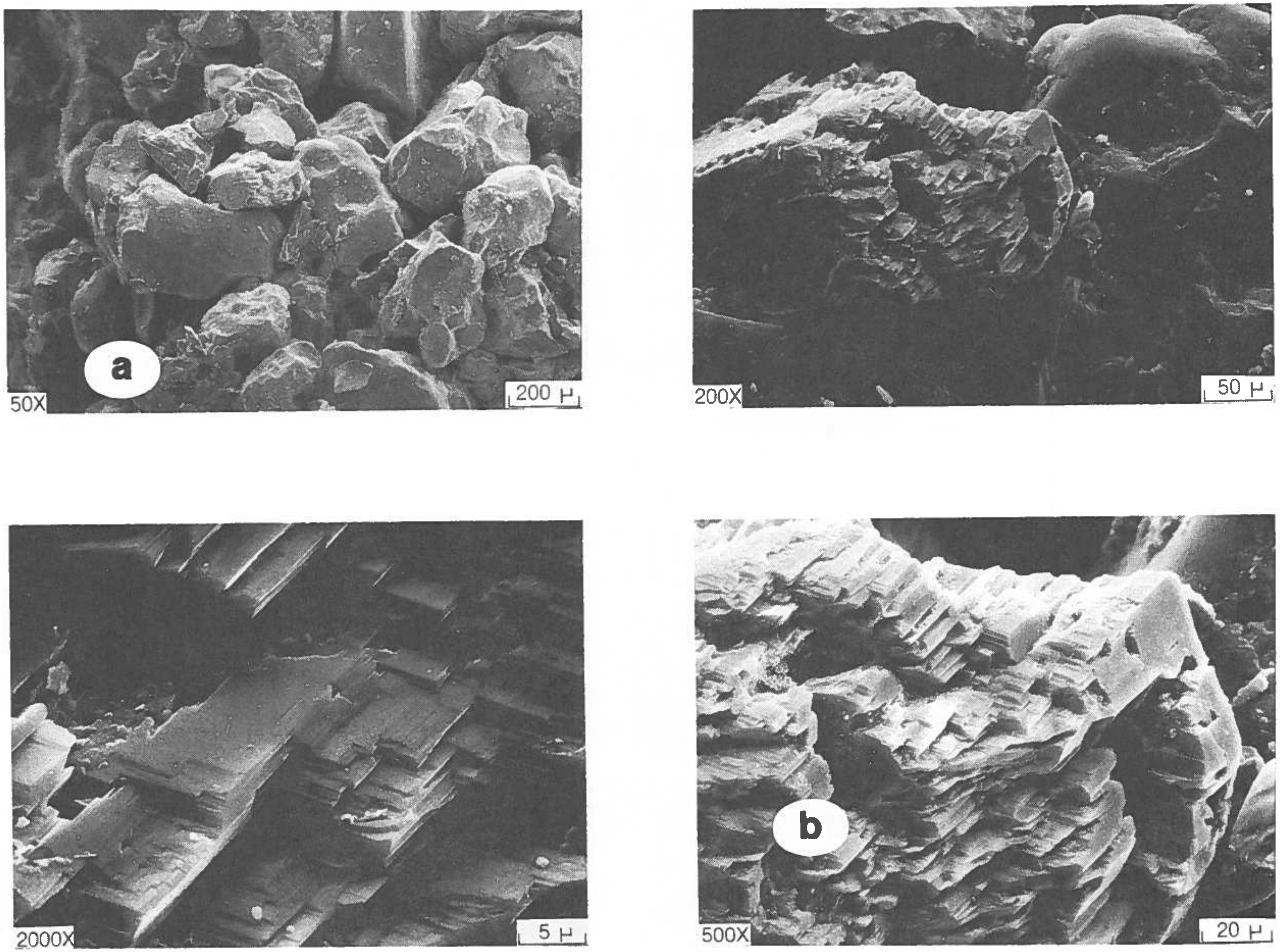

Figure 12. Photomicrograph from SEM analysis of 723-ft bls sample, showing coarse and very fine grain sizes (a) and feldspar dissolution (b) (clockwise from upper left).

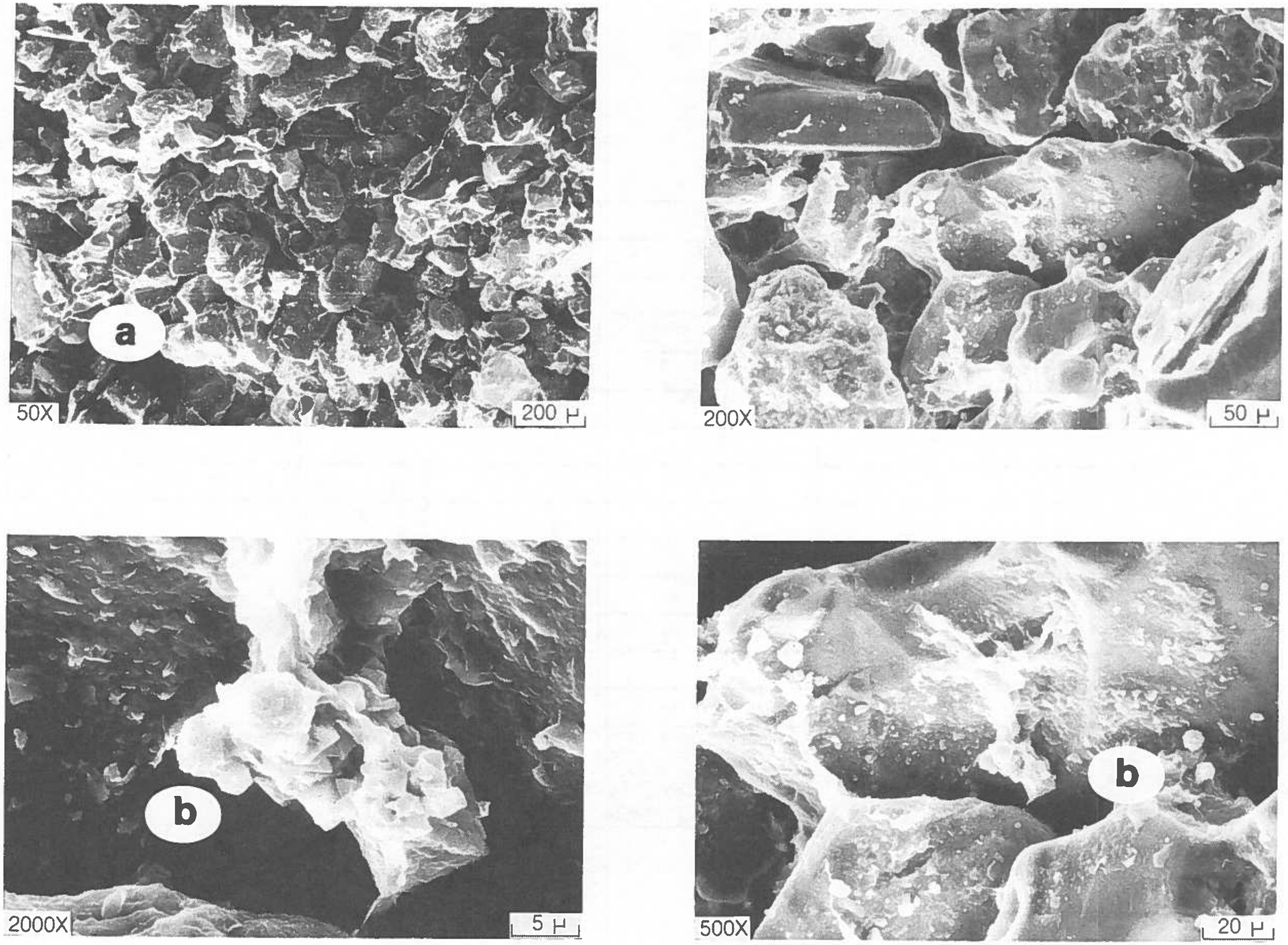

Figure 13. Photomicrograph from SEM analysis of 550-ft bls sample, showing fine-grained, well-sorted sand (a) and euhedral pyrite (b) (clockwise from upper left).

TABLE 4. POROSITY AND AIR PERMEABILITY VALUES FROM CORE SAMPLES TAKEN FROM THE ASR TEST WELL

FORMATION	UNIT	DEPTH (ft, bls)	PERMEABILITY (millidarcies)		POROSITY (%)
			HORIZONTAL	VERTICAL	
BLACK CREEK	10	404	8400	7700	37
	8	550	5525	4070	36
	8	589	6170	5475	41
	8	624	7360	6415	40
	6	723	8980	*	36
	6	752	*	*	46
MIDDENDORF	2	1012	3430	3490	35
CAPE FEAR	4	1086	1725	1070	35
	4	1088	9437	2494	29
	4	1120	9690	8075	37
	3	1222	*	*	34
	2	1280	7530	4400	40
	2	1297	9320	*	35
	2	1356	4635	6200	32

*Sample unsuitable for testing

Middendorf Formation. The 35-percent porosity value is within the range of those recorded for the Cape Fear Formation, but the horizontal and vertical permeabilities are much lower (3,430 and 3,490 md).

Black Creek Formation. Porosities for this formation are shown to be between 36 and 46 percent. Horizontal permeabilties are from 5,525 to 8,980 md and vertical permeabilities are between 4,070 and 7,700 md. Compared to the other formations, the Black Creek has more consistent horizontal permeabilities.

Specific Gravity

Table 5 displays the specific-gravity values for the three formations that were analyzed. The values for the Cape Fear Formation are between 2.16 and 2.57. The low value, 2.16, is due to a high organic content. The sample from the Middendorf Formation has a specific gravity of 2.52; while values from the Black Creek Formation range from 2.35 to 2.62.

Grain Density

Grain-density values for the Cape Fear, Middendorf, and Black Creek Formations are listed in Table 5. Values for all the sampled formations are nearly the same, ranging from 2.62 to 2.70 g/cc (grams per cubic centimeter).

Cation-Exchange Capacity

Cation-exchange capacity was determined for samples taken from the Cape Fear, Middendorf, and Black Creek Formations. This analysis determines the ability of the aquifer matrix to adsorb ions from a solution by way of an exchange process. In general, high exchange rates, above 10 milliequivalents per 100 grams (meq/100 g) of sample, are not desirable. High cation-exchange rates increase the likelihood that the sediments will affect water quality. Most of the samples from the test site exhibit low CEC values, which makes them preferable for the injection of surface water. Table 5 shows CEC values for samples taken from these three formations.

Energy-Dispersive Chemical Analysis

EDX plots were constructed to show the analysis results for samples taken from the ASR test site (CH2M Hill, 1990). EDX analysis of the Cape Fear Formation samples indicate that they are quartz sand, as reflected by high silica content, and contain K-feldspar in varying quantities. This can be denoted by the responses for aluminum, silica, and potassium. Pyrite, indicated by iron and sulfur, has been detected for the 1,297-ft bls sample. Organic material, indicated by titanium, sulfur, and vanadium, is present in samples 1,221, 1,297, and possibly 1,356 ft bls.

The EDX analysis for the 1,012-ft bls sample from the Middendorf Formation shows that it is a quartz sand containing K-feldspar. It should be noted that iron, possibly as pyrite, has been detected in greater amounts than in any of the Cape Fear Formation samples.

The sand of the Black Creek Formation is shown, from EDX analysis, to be a fairly clean quartz. Pyrite has been detected in small amounts, along with glauconite. Sulfur has been noted in all samples, except 723 ft bls, and indicates that small amounts of pyrite occur in these sediments. Carbonate exists in minor amounts as indicated by the small peaks for calcium. The clay interbeds in sample 752 ft bls have contributed to the higher aluminum value compared to the remaining samples. The potassium is associated with mica, illite, and K-feldspar in the samples.

Grain-Size Analysis

Grain-size analysis was made on samples taken from the Cape Fear, Middendorf, and Black Creek Formations. Cumulative-curve graphs from sieve analysis and an explanation for deriving the sorting coefficients (listed in appendix table) are contained in Appendix 3.

Cape Fear Formation. Sieve analyses were made for 22 samples to determine their grain-size distributions. The sand of this formation ranges widely, from well sorted to poorly sorted.

Nine samples from Unit 2 were analyzed. The average of the sorting coefficients indicates that sorting is moderate, at 1.45. The median grain size average is 0.0179 inch. There seems to be a tendency for sorting to become poorer with depth. Correlation of median grain size with the degree of sorting is not distinguishable.

Only two samples from Unit 3 were analyzed. The sieve results show that sand in this unit is moderately sorted and has a median grain size of medium and an average sorting coefficient of 1.74.

Eleven samples were obtained from Unit 4. Sorting coefficients range from 1.25 to 2.00, averaging 1.54. They generally increase with depth, although they may vary within specific beds. Median grain size is coarse.

From sieve analysis, the samples from the Cape Fear Formation appear mostly moderately sorted. Other laboratory methods reveal that this may not be true. Thin-section analysis, geophysical logs, and lithologic analyses show much greater silt and clay percentages. SEM

TABLE 5. SPECIFIC GRAVITY, GRAIN DENSITY, AND CATION-EXCHANGE CAPACITY OF THE CAPE FEAR, MIDDENDORF, AND BLACK CREEK FORMATIONS

FORMATION	UNIT	DEPTH (ft bls)	SPECIFIC GRAVITY	GRAIN DENSITY (g/cc)	CEC (meq/100 g of sample)
BLACK CREEK	10	404	2.35	2.63	4
	8	550	2.45	2.62	4.6
	8	589	2.6	2.61	3.8
	8	624	2.51	2.63	3.4
	6	723	2.62	2.64	0.4
	6	752	2.41	2.64	19.2
MIDDENDORF	2	992	*	*	*
	2	1012	2.52	2.66	10.9
	2	1017	*	*	*
CAPE FEAR	4	1086	2.48	2.65	7.1
	4	1088	*	2.62	7.1
	4	1120	2.57	2.65	5.8
	3	1222	2.31	2.64	4.6
	2	1280	*	2.63	10
	2	1297	2.16	2.66	6
	2	1356	2.43	2.7	10

*No data available

(scanning electron microscope) pictures reveal sand grains coated with clay, making sand-fraction overestimates and clay underestimates likely. Therefore, sorting coefficients are probably artificially low and the actual sorting is poorer.

Middendorf Formation. Grain-size analyses were made for three samples from the Middendorf Formation. Sorting coefficients are similar and average 1.64. Median grain size is medium.

Black Creek Formation. Values for the six samples analyzed did not vary much throughout the formation. Units 6 and 8 have respective sorting coefficients of 1.41 and 1.35 and a medium to fine median grain size. The sole sample analyzed from Unit 10 has a sorting coefficient of 1.84 and the median grain diameter of a medium sand.

As a whole, these sand zones have better sorting and are more fine-grained than those of the Cape Fear and Middendorf Formations.

HYDRAULIC ANALYSIS FROM GEOPHYSICAL LOGS

The use of geophysical logs (Plate 2) in the water well industry has commonly been in a qualitative manner to identify water-bearing units. This report, however, used the geophysical logs as the source of qualitative and quantitative information. The logs, because they provide valuable information on the properties of the formations, were used to estimate total and effective porosity and to obtain information about the water quality. Specifically, the spontaneous-potential log was used to compute the formation water resistivity, which was used to calculate the formation factor and then the total porosity. Additionally, the neutron and density logs were conjunctively used to estimate effective porosity and the volume fractions of sand and clay present in the formation (Appendix 4).

It is of interest to note that the image of the electric logs shown in Plate 2 is in reverse order of that normally found in water wells. The guarded focused log, which has the largest radius of investigation, shows less resistance than does the short-normal, which has the shortest radius of investigation. The reason for this is that the drilling-mud water came from the surface-water treatment plant which has significantly less dissolved solids than the native ground water. The surface water, therefore, has larger resistivity values.

The Southeastern Regional Office of the U.S. Geological Survey provided the geophysical unit used to log the borehole. A total of 12 logs were obtained:

- Caliper
- Single-Point Resistance
- Long-Normal Resistivity
- Short-Normal Resistivity
- Focused Guarded
- Spontaneous-Potential
- Natural-Gamma
- Neutron
- Density
- Acoustic
- Temperature
- Televiewer

Cape Fear Formation

Geophysical log analysis was done on Units 2 and 4 in this formation. Each of these units is divided into subunits. Subunit 2A is between 1,340 and 1,360 ft bls; Subunit 2B lies within the 1,317- to 1,329-ft bls range; and Subunit 2C is between 1,263 and 1,287 ft bls. Crossplots of neutron porosity versus density were constructed for these subunits and are located in Appendix 4. Subunit 2A displays a large proportion of clay and silt within the sand and has an average effective porosity of 12 percent. A more compact distribution of the sand points, possibly associated with the homogeneity of the sand bed, is observed in Subunit 2B, where the effective porosity is 14 percent. Subunit 2C shows a large variation in density value ranges for both sand and clay, ranging from 10 to 25 percent. The average effective porosity is 14 percent.

Unit 4 is divided into two subunits: Subunit 4A (1,147 to 1,165 ft bls) and Subunit 4B (1,077 to 1,140 ft bls). Appendix 4 contains neutron porosity versus density crossplots for this unit. Subunit 4A reveals a large proportion of clay in the sand bed. Effective porosity averages 11 percent for this subunit. Subunit 4B has the largest screened interval, 63 ft. It exhibits a wide range of densities, which varies the porosity from 5 to 30 percent.

Middendorf Formation

Only one unit was screened in this formation. That was Unit 2, between 1,012 and 1,020 ft bls. Appendix 4 displays the neutron porosity versus density crossplot for this interval. Clay content is low, at 8 percent, and the porosity averages 23 percent.

Black Creek Formation

The logs obtained from this and higher formations are shown to be greatly distorted. It is suspected that interference with the drilling fluid, owing to the large borehole diameter (12 1/4 inch), blocked most of the response from the formation. A crossplot of neutron porosity versus density for sediments between 324 and 489 ft bls is in Appendix 4. No trend is shown, as neither type of lithology appears as a separate cluster.

Since there was an absence of geophysical data, porosity values from thin-section analysis (Table 6) were used to calculate hydraulic conductivity.

AQUIFER HYDRAULICS

Summary of Hydraulic Data

Hydrologic data were extrapolated from the various analyses and compiled to show the hydraulic properties of the Black Creek, Middendorf, and Cape Fear Formations. The results from these analyses are shown in Table 7. Hydraulic conductivities and transmissivities for each formation were determined by averaging the two effective porosities given for each unit (Table 6) and using the results in the Kozeny-Carmen (Bear, 1972) hydraulic conductivity formula (Appendix 4). As previously stated, the effective porosity values were used instead of total porosity values for computing the hydraulic properties, as they tend to give a better indication of the sediments' true hydraulic nature.

Aquifer Pumping Test

On November 28, 1989, a 4-hour constant-head pumping test and 1 1/2 hour recovery test of the ASR test well were made on the Cape Fear and Middendorf Formations. Prior to the test, the static water level was 87.81 ft below a datum 2 feet above land surface. Initial flow during the pumping test was measured at 93 gpm. After 4 hours, the flow had decreased to 54 gpm. The transmissivity was calculated to be 770 gpd/ft (gallons per day per foot) during the test and 730 gpd/ft during the recovery phase. An average transmissivity value of 750 gpd/ft was determined to be reasonable for this well. A single-well estimate of storativity was calculated to be 4.5×10^{-3}. At completion of the pumping test, specific capacity was 0.64 gpm/ft.

With 90 feet of screen in the test well, hydraulic conductivity was equated to be approximately 8 gpd/ft^2, or 35 md at formation temperature, for the screened intervals. Values determined from horizontally cut plugs from the cores of the upper three screened intervals ranged from 1,725 to 9,690 md. Using an independent analytical approach based on thin-section and geophysical-log analysis, higher values (equivalent to 1,425 to 5,025 md) were calculated for the screened intervals in the Cape Fear Formation.

Column Tests

Column tests were made by CH2M Hill, of Gainesville, Fla., (CH2M Hill, May 1990) on selected cores in an effort to verify conclusions based upon geochemical simulation analysis prior to a planned test injection. It was anticipated that clay swelling, clay dispersion, and geochemical problems may occur at this site and that the simulation would aid in identifying potential solutions. Since the ASR technology is relatively new to the water supply industry, so too are potential solutions to ASR geochemical issues. Therefore, column testing was conducted as a precautionary step before risking potential adverse geochemical reactions in an existing well.

During the testing, the column, which contained a foot-long core sample, was flushed with several pore volumes of treated surface water. Reduction of head, as water flowed through the sample, was regularly measured. The changes, moreover, were related to hydraulic conductivity. At the end of each test, the core sample was split open and chemical changes were described.

Analysis of the Black Creek Formation core samples was constrained by several factors. The low permeability of the clayey sand caused flow rates through these samples to be low. This provided time for bacterial activity to develop, thereby adversely affecting both permeability and water quality. Another limiting factor in this analysis was the extent of clay laminations in these cores, which caused a substantial decrease in flow rate. Finally, leaks in the membrane wrap around the cores caused testing problems for three of the samples. These limitations were addressed by utilizing shorter, unfrozen cores in later tests; splicing the cores in order to remove significant clay lenses; rechlorinating and filtering recharge and formation water prior to testing; minor modifications to the testing apparatus; and the addition of two more core tests.

Further analysis revealed that pH reduction of the recharge water, which would occur as a result of chemical stripping of the oxygen, may tend to increase formation permeability. While this was tested in only one Myrtle Beach core sample, comparable results have occurred during column tests for another ASR site in Coastal Plain clayey sand.

Four cores from the Middendorf and Cape Fear Formations were tested in order to obtain permeability data and information on silt migration within the samples. The silt-migration test was originally designed to determine the threshold injection pressure at which silt begins to mobilize within the core. To simulate well conditions, a 20-slot brass screen was used at the sample ends.

Column tests yielded permeability values well below those calculated from the pumping test. The latter indicated a permeability of approximately 35 md, whereas the range of values from the column tests was between 1 and 28 md.

Silt could not be mobilized following the procedures utilized in these tests. This was in contrast to the con-

TABLE 6. PERCENT POROSITY VALUES AT THE ASR TEST SITE
(AS DETERMINED FROM THIN-SECTION, CORE-SAMPLE, AND GEOPHYSICAL-LOG ANALYSES)

FORMATION	UNIT	INTERVAL (ft bls)	#THIN-SECTION	##CORE SAMPLE	##GUARDED FOCUSED RESISTIVITY LOG	#NEUTRON DENSITY LOG
BLACK CREEK	10	348–438	24	37	*	*
	8	489–631	24	39	*	*
	6	716–783	20	41	*	*
MIDDENDORF	2	961–977	17	*	*	*
	2	1012–1020	9	35	51.8**	23
CAPE FEAR	4B	1077–1140	19	36	32.5	7**
	4A	1147–1165	*	*	31.9	10.7
	3	1211–1224	16	*	33.5	*
	2C	1263–1287	*	40	34.9	14.3
	2B	1317–1329	*	*	35.3	13.7
	2A	1340–1360	10	32	30.1	12
SAPROLITE	N/A	1397–1423	10	*	*	*
CRYSTALLINE BEDROCK	N/A	1423–?	0	*	*	*

*No data available

**unrealistic values

#Determines effective porosity

##Determines total porosity

TABLE 7. HYDRAULIC CONDUCTIVITY AND TRANSMISSIVITY VALUES FOR SELECTED INTERVALS AT THE ASR TEST SITE

FORMATION	UNIT	SAMPLE INTERVAL (ft bls)	SAND THICKNESS (ft)	MEDIAN GRAIN SIZE (in)	POROSITY VALUE (%)	HYDRAULIC CONDUCTIVITY (gpd/ft^2)	AVERAGE HYDRAULIC CONDUCTIVITY (gpd/ft^2)	AVERAGE TRANSMISSIVITY (gpd/ft)
BLACK CREEK	10	348–438	90	0.011	24	190	155	40,000
	8	489–631	113	0.008	24	100		
	6	716–783	53	0.016	20	210		
MIDDENDORF	2	961–977	16	0.013	17	80	127	3,000
	2	1012–1020	8	0.024	16	220		
CAPE FEAR	4B	1077–1140	52	0.018	19	220	135	19,000
	4A	1147–1165	18	0.023	11	60		
	3	1211–1224	13	0.022	16	190		
	2C	1263–1287	24	0.012	14	40		
	2B	1317–1329	12	0.026	14	200		
	2A	1340–1360	20	0.016	11	30		
SAPROLITE	-	1397–1423		*	*	*	*	*
CRYSTALLINE BEDROCK	-	1423–?		*	*	*	*	*

*No data available

tinuous silt flow experienced during extended well development. The only movement of fines noted seemed to occur in conjunction with pressurizing the cores before each test, while the frozen cores were thawing. This material, however, was believed to be drilling mud, not silt. The data finally suggest that the bottom screened interval provides most of the flow to the well , that aquifers overlying the Middendorf and Cape Fear Formations are less saline, and that water produced from these formations may have a high iron content.

WELL DESIGN AND CONSTRUCTION

The ASR test well was drilled to a depth of 1,427 ft bls and completed to a depth of 1,330 ft bls with 90 ft of screen. Figure 14 is a detailed well-construction diagram of the completed well, and Table 8 shows the screened intervals of the well. The following outline details the chronology of the construction:

- A 12 1/4-inch diameter borehole was drilled to a depth of 80.6 ft bls and subsequently reamed to a diameter of 21 inches. A pit casing with a 21-inch inside diameter (ID) was installed to 80 ft bls and pressure grouted with neat cement.
- The 12 1/4-inch borehole was continued to a depth of 376 ft bls, and coring operations were begun. The coring procedure created a 5 1/4-inch borehole down to a depth of 762.8 ft bls. The borehole was later reamed to 12 1/4 inches.
- From 762.8 to 907.8 ft bls, a 6 1/4-inch borehole was maintained for continued coring. After this interval was cored, the entire borehole, from below the pit casing (80 ft bls), was reamed to a diameter of 14 inches. 8-inch ID casing was then installed from 2 ft above land surface to 907.8 ft bls and the entire borehole was then pressure grouted with neat cement.
- A 5 1/4- to 6 1/4-inch borehole was drilled between 907.8 and 1,427.2 ft bls. This diameter was dependent on the type of coring bit that was used. The 1,330- to 1,427.2-ft bls interval was back-grouted with neat cement. The interval between 907.8 and 1,330 ft bls was then reamed to a 7 7/8-inch diameter and 6-inch ID screens and casing were installed (Table 8).
- The annulus between the borehole and the 6-inch screen and casing was allowed to cave in and create a natural filter pack. A rubber flange (K-packer) was fitted at 880 ft bls in order to form a water-tight seal between the 8-inch and 6-inch casing.

The type of filter pack and the screen slot size both contributed to extended well development time and have been viewed as shortcomings to the construction of the well. The use of an artificial filter pack instead of the opted natural one, would certainly shorten the development time.

The water-based mud system used in the drilling of the test well and the coring operation is detailed in Appendix 5.

SUMMARY AND CONCLUSIONS

An investigation of the Aquifer Storage Recovery (ASR) concept and its applicability in unconsolidated sediments of the Coastal Plain in South Carolina has proceeded in two phases (1) collection of hydrogeologic data and construction of a prototype ASR well, the subject of this report, and (2) study of injection and recovery cycles.

In order to collect the necessary data, a borehole was drilled to a depth of 1,427 ft bls, of which 1,051 ft was continuously cored. Total recovery was rated at 91 percent. The excellent recovery was the result of various techniques used to increase the amount of core samples taken from unconsolidated sediments. These techniques included the use of a plastic liner being implemented into the CP wireline system to facilitate recovery and handling of core samples, as well as the close monitoring of mud properties.

The substantial hydrogeologic data collected and analyzed during the coring and construction of this test hole was invaluable in defining the regional and site hydrogeology. Fourteen core samples were chosen and intensely analyzed to determine their suitability as injection zones. Zones with the greatest porosity and permeability and the least silt and clay, particularly smectite, are the most preferred. The results of the different analytical methods were obtained by comparing the individual samples within subunits and the average values for each unit. In characterizing the units, special consideration was given to the fact that some of these methods are not directly analogous.

The crystalline bedrock at the well site was described as a quartz-biotite schist. No intergranular porosity was detected, although weathered fractures filled with saprolite were visible. No specific water-quality information was obtained; however, it is probably brackish.

The Cape Fear Formation consists of two thick sand zones containing several interbedded clay layers that delineated fining-upward sequences. Within these zones, five distinct sand beds have been identified as possible injection areas. These five possible injection zones have a porosity range from 10 to 20 percent, with clay content being between 26 and 34 percent. The aggregate transmissivity is estimated at 19,000 gpd/ft. The water in the formation is classified as brackish, with chloride at 1,400 mg/L and sodium at 1,273 mg/L. Subunits 2B (1,317-1,329 ft bls) and 2C (1,263-1,287 ft bls) appear to be the most suitable injection zones.

The Middendorf Formation is composed of at least

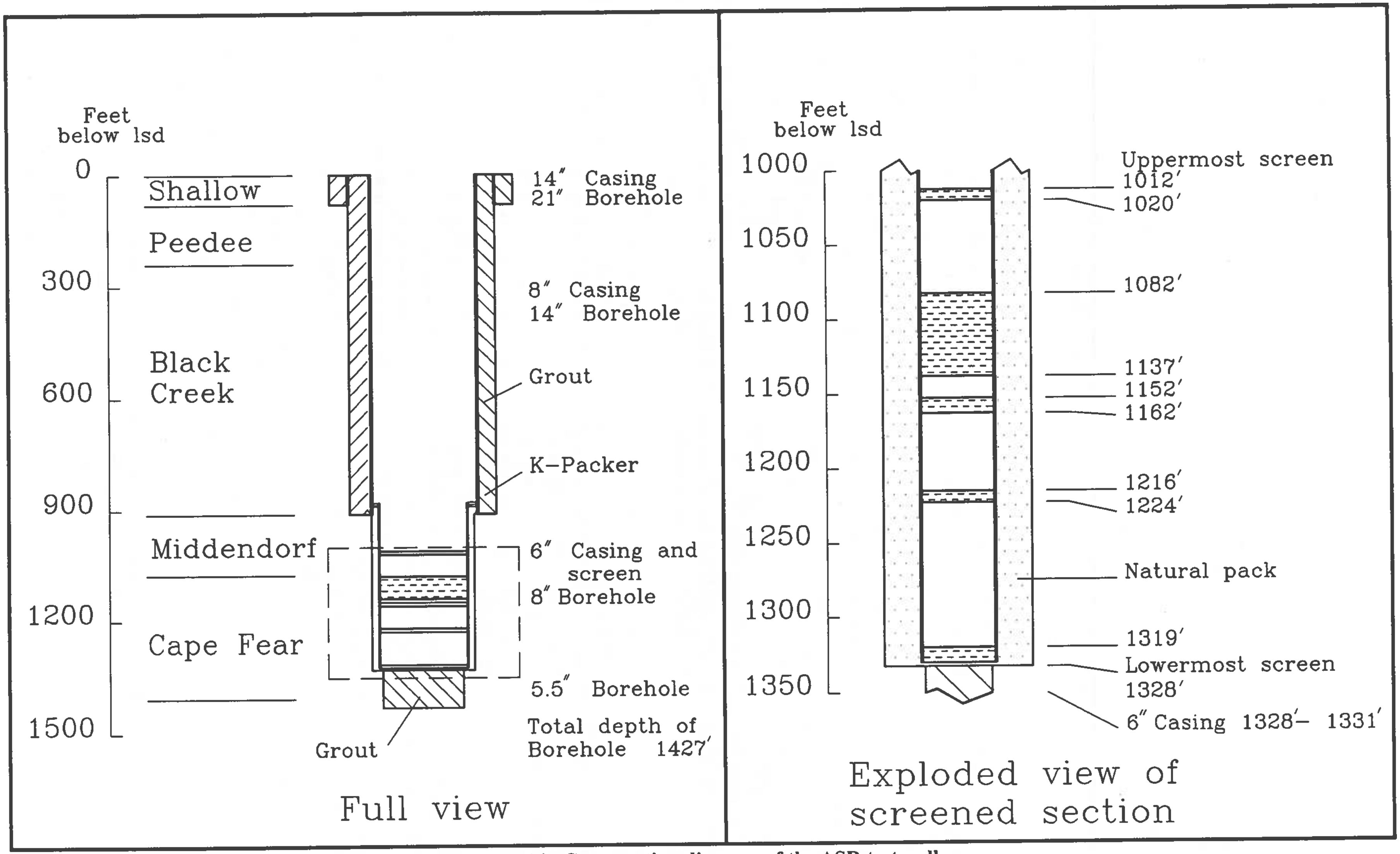

Figure 14. Construction diagram of the ASR test well.

TABLE 8. SCREENED INTERVALS OF THE ASR TEST WELL

SCREENED INTERVAL (ft bls)	FORMATION	UNIT	SCREEN SLOT SLOT SIZE		SCREEN LENGTH (ft)	TOTAL SCREEN LENGTH (ft)
			Recommended	Implemented		
1012-1020	MIDDENDORF	2	No. 15	No. 15	8	90
1082-1137	CAPE FEAR	4	No. 20--30	No. 15	55	
1152-1162	CAPE FEAR	4	No. 30	No. 15	10	
1216-1224	CAPE FEAR	3	No. 20	No. 15	8	
1319-1328	CAPE FEAR	2	No. 40	No. 15	9	

*Screen slot size number is the width of the slot in 1/100" (No. 15=0.015") four poorly sorted, fining-upward sequences. The sand is clayey and silty. Feldspar, muscovite, and heavy minerals are present in trace to minor amounts. Effective porosity ranges from 9 to 23 percent, with a clay content of 8 percent, commonly as grain coatings. The transmissivity was estimated at 3,000 gpd/ft. The aquifer contains brackish water in most of the region. The cation-exchange capacity, at 10.9 meq/100 g, is the greatest of all analyzed sand samples. Water from samples in this formation is also brackish, although sodium chloride concentrations are less than those in the Cape Fear Formation. No zones appear to be suitable for injection.

The Black Creek Formation is made up of fine-grained, micaceous, phosphatic, and glauconitic sand and clay containing interbeds and laminations of fine sand and clay. Lignite is common, shell fragments are in trace amounts, and thin layers of calcareous cemented sandstone are numerous, particularly in the upper third of the formation. The clay (chlorite, illite, and smectite, reported as glauconite) ranges from trace amounts to 18 percent. Samples have excellent intergrain porosities that range from 14 to 25 percent, with an average of 23 percent. The transmissivity was estimated at 40,000 gpd/ft (this value is probably somewhat higher, as a sand interval was excluded from analysis). The cation exchange capacity ranged from 19.2 to 0.4 milliequivalents per 100 grams of sediment, although most values were less than 5. The water is of a sodium bicarbonate type, soft, alkaline, and low in iron. It has objectionable concentrations of fluoride, sodium, and total dissolved solids. The zones within the upper half of the formation (288-631 ft) are the most suitable units for injection.

The Peedee Formation consists of sand, clayey micrite, and micritic sand. Glauconite increases with depth, pyrite is prevalent, and shell fragments and phosphates are common. The aquifers of the Peedee are localized, with medium to low transmissivities; thus units within this formation were not considered as possible injection zones.

The shallow deposits consist of undifferentiated thin beds of fine clayey sand, fine calcareous sand, and limestone. The hydrogeologic characteristics of these aquifers are limited and were not considered adequate for an ASR project.

Analysis of the hydrogeological and geochemical data suggests that the injection of treated surface water into the aquifers of the Black Creek Formation is feasible. No significant changes of porosity or transmissivity are anticipated as the result of long-term injection cycles, nor is substantial deterioration of the water quality expected. Therefore, it is recommended that the Aquifer Storage and Recovery Steering Committee proceed with the implementation of a prototype site in the Black Creek Formation and to conduct a series of short-term and long-term injection tests. Special attention, however, must be given to the chemistry of the aquifer and to the quality of the injected, recovered, and native ground water.

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APPENDIX 1

DESCRIPTION OF DRILL CUTTINGS AND CORE SAMPLES FROM ASR TEST WELL 5S-f1

Depth (ft bls)	Shallow deposits and Tertiary formations
0-4	Clay fill; pale brown (5YR5/2)
4-9	Clay, possibly fill; pale brown (5YR5/2)
9-19	Sand; olive-gray (5Y4/1)
19-29	Shell hash; very pale orange (10YR8/2) and olive-black (5Y2/1), coarse to fine cobble-sized grains; mostly pelecypods, accessory bryozoa, gastropods.
29-44	Sand; olive gray (5Y4/1), fine-grained, with coarse sand and very fine pebbles; poorly sorted; subrounded; numerous shell fragments, accessory phosphate, trace glauconite.
44-80	Sand; olive-gray (5Y4/1) to light olive-gray (5Y6/1); coarse to fine-grained, poorly sorted; subangular; friable; micritic, accessory pyrite, glauconite, phosphate, trace heavy minerals.
	Peedee Formation
80-119	Micrite; light gray (N7), clayey; sandy, fine grained; minor glauconite; trace heavy minerals, shell fragments, wood, pyrite; few streaks of calcareous sandstone.
119-173	Micrite; light olive-gray (5Y6/1); clayey, some sand; minor glauconite, mica; trace phosphate, pyrite, heavy minerals; numerous streaks of hard calcareous, fine-grained sandstone and siltstone.
173-195	Sand; light olive-gray (5Y6/1), micritic; fine grained with some very fine pebbles; poorly sorted; subangular to subrounded; accessory glauconite, pyrite (commonly biomoldic); trace phosphate, rose quartz.
195-230	Clay; olive-black (5Y2/1), some micrite; accessory glauconite, pyrite (some as large pebble-size clasts); trace shell fragments; few streaks of hard, micritic sandstone.
230-252	Clay; olive-gray (5Y4/1); micritic, some sand; abundant glauconite; accessory pyrite; trace shell fragments.
252-288	Clay; olive-gray (5Y4/1); some micrite, some sand; abundant glauconite, accessory pyrite; trace shell fragments; some micritic sand clasts near base.
	Black Creek Formation
288-324	Sand; olive-gray (5Y4/1) to olive-black (5Y2/1); becoming clayey near top; fine-grained, with some coarse grains; poorly sorted, subrounded to subangular; abundant glauconite, pyrite, accessory shell fragments; streak of calcareous sandstone at 310.
324-348	Clay; olive-gray (5Y4/1) to olive-black (5Y2/1); some fine-grained sand; minor glauconite, pyrite, trace shell fragments; very lightly calcareous; streak of calcareous sandstone at 327.
348-438	Sand; light olive-gray (5Y6/1) to dark greenish-gray (5GY4/1); fine grained moderately to well sorted; sub-rounded; abundant glauconite, decreasing with depth; minor pyrite, commonly biomoldic; and lignite increasing to abundant with depth; few clay clasts;few streaks of calcareous sandstone at 374, 410, and 420.
438-489	Clay; olive-black (5Y2/1) to brownish-black(5YR2/1); hard to soft, accessory glauconite overall, abundant at 470-472; minor pyrite, mica and local shell fragments; calcareous.
489-508	Sand; olive-gray (5Y4/1) to olive-black (5Y2/1); medium to fine-grained; well sorted; subrounded; abundant glauconite, accessory pyrite, phosphate; streak of hard micritic sandstone with rare phosphatized sharks tooth (1.5 cm) and coarse pebble of phosphate at 506; slightly calcareous; interbedded with clay laminations.
508-512	Clay; olive-black (5Y2/1); slightly calcareous.

512-522	Sand; olive-gray (5Y4/1) to olive-black (5Y2/1); medium to fine-grained, well sorted, subrounded; abundant glauconite, accessory pyrite, phosphate, slightly calcareous; interbedded with clay laminations.
522-534	Clay; olive-black (5Y2/1); slightly calcareous; interbedded with micaceous, very fine-grained sand with abundant glauconite; trace slickensides at 528.
534-573	Sand; dark greenish-gray (5GY4/1); fine to very fine grained; well sorted; subangular to subrounded; glauconitic; micaceous, trace lignite, pyrite, slightly calcareous, interbedded with clay laminations.
573-584	Clay; olive-black (5Y2/1); accessory glauconite, glauconite at 577; trace pyrite, phosphate, muscovite; shell fragments; slightly calcareous interbedded with fine-grained sand laminations.
584-631	Sand; olive black (5Y2/1) to greenish black (5GY2/1); some clay; fine grained; moderately sorted; subangular to subrounded; glauconitic, increasing with depth, abundant lignite, muscovite; trace pyrite, phosphate; slightly calcareous; interbedded with numerous clay and lignite laminations.
631-716	Clay; olive-black (5Y2/1); fissile, hard to soft; abundant to accessory glauconite decreasing with depth, trace pyrite; micaceous, slightly calcareous; interbedded with micaceous, very fine-grained sand and silt laminations.
716-733	Sand; olive-gray (5Y4/1); medium to fine-grained; moderately sorted; subrounded; micaceous; minor glauconite but glauconitic at 729; pyrite; trace Inignite becoming abundant at base; interbedded with clay laminations.
733-740	Clay; olive-black (5Y2/1); hard, fissile; trace muscovite, lignite, pyrite; interbedded with lignite and few sandy clay laminations.
740-766	Sand; olive-gray (5Y4/1); medium to very fine-grained; moderately sorted; sub-angular to subrounded; micaceous; abundant lignite; minor glauconite, pyrite, trace phosphate, slightly calcareous locally; interbedded with lignite and clay laminations.
766-769	Clay; same as 733-740.
769-771	Sand; same as 740-766.
771-773	Clay; same as 733-740.
773-783	Sand; olive-gray (5Y4/1); fine-grained with some very coarse grains; poorly sorted; subangular; slightly micaceous; abundant lignite; minor glauconite, pyrite; interbedded with clay laminations.
783-793	Clay; olive-black (5Y2/1); hard to soft, fissile; abundant lignite, minor muscovite, slightly calcareous; interbedded with laminations of fine sand.
793-795	Sandstone.
795-810	Clay; brownish-black (5YR2/1) and olive-black (5Y2/1); hard, fissile; interbedded with lamination of fine sand.
810-833	Sand; olive-gray (5Y4/1); clayey; medium to very fine, becoming coarse with depth; well to locally poor sorting; abundant pyritized lignite fragments, coarse pebble size and smaller, minor glauconite, shell fragments, interbedded with clay laminations.
833-848	Clay; olive-gray (5Y4/1); hard, fissile; slightly calcareous but locally very calcareous; numerous shell fragments increasing with depth; minor lignite; trace pyrite, mica; few thin interbedded shell layers; rare clam shell (3 cm) at 838.
848-860	Limestone; light olive-gray (5Y6/1) and olive-gray (5Y4/1) very hard; wackestone grading downward to packstone; shell fragments near 15 percent at top increasing to 90 percent at base; and oriented along bedding plane; minor glauconite; pyrite, trace muscovite, phosphate.
860-893	Micrite; dark greenish- (5GY4/1) and olive-black (5Y2/1); hard to soft; friable; numerous shell fragments near 50 percent decreasing to minor with depth; very fine sand becomes abundant near base; minor glauconite, pyrite, muscovite; trace phosphate; three thin streaks of limestone at 878, 888 and 892.
893-961	Clay; olive-gray (5Y4/1) to olive-black (5Y2/1); micritic hard; fissile and increasing with depth; accessory glauconite and shell fragments decreasing with depth; minor muscovite, pyrite; interbedded with very fine sand laminations decreasing with depth.

Middendorf Formation

961-977	Sand; olive-gray (5Y4/1); micritic, decreasing with depth; (clayey) medium-grained, with some medium pebbles; very poorly sorted; subangular; minorpyrite, glauconite, heavy minerals; trace feldspar, iron staining.
977-990	Clay; olive-gray (5Y4/1) and dark reddish-brown (10R3/4); mottled; hard, slightly fissile; trace phosphate, muscovite, heavy minerals.
990-996	Sand; light greenish (5G8/1), dark yellow-orange (10YR6/6), and medium reddish-brown (10R4/6); mottled; clayey; fine-grained with some very fine pebbles; very poorly sorted; subrounded; trace oxides, heavy minerals, quartz with dark inclusions.
996-1,011	Clay; dark reddish-brown (10R3/4) and light olive-gray (5Y6/1); mottled; hard to very soft; waxy; minor iron oxides, trace heavy minerals.
1,011-1,021	Sand; yellowish gray (5Y7/2) and moderate reddish- brown (10R4/6); clayey; medium to fine-grained with some very fine pebbles; very poorly sorted, subangular; micaceous minor plagioclase; trace heavy minerals, quartz with dark mineral inclusions, orthoclase iron staining abundant locally; thin sand streak near center.
1,021-1,033	Clay; dark reddish-brown (10R3/4), very dusky red-purple (5RP2/2), and light olive-gray (5Y6/1); mottled; soft to very hard; brittle; waxy; abundant iron oxides; minor muscovite; appearance near top similar to hematite.
1,033-1,036	Sand; light olive-gray (5Y6/1), silty; hard, fine-grained, moderately sorted, subangular; micaceous; interbedded with thin clay layers.
1,036-1,043	Clay; similar to 1021-1033.
1,043-1,046	Sand; light olive-gray (5Y6/1); clayey; friable; fine-grained with some very fine pebbles, very poorly sorted, subangular; minor iron-stained grains; trace feldspar, quartz with dark mineral inclusions; interbedded with thin clay layers.
1,046-1,077	Clay; dark reddish-brown (10R3/4), light greenish-gray (56Y8/1), and dark yellowish-brown (10YR4/2), mottled, few very fine pebbles; very hard to soft, friable, waxy; slightly micaceous; minor iron staining; trace feldspar, heavy minerals; streak of silty clay at 1,054 and sand at 1,064.

Cape Fear Formation

1,077-1,105	Sand; pinkish-gray (5YR8/1), yellowish-gray (5Y8/1), and dusky-red (5R3/4); mottled; medium-grained, with grains to fine pebbles, some silt; moderately sorted, subangular; loose, micaceous; trace feldspar, heavy minerals, chlorite; abundant iron staining locally; abundant feldspar near base.
1,105-1,107	Clay; light greenish-gray (5GY8/1), and dark reddish-brown (10R3/4); mottled.
1,107-1,126	Sand; pinkish-gray (5YR8/1), light greenish-gray (5GY8/1) and yellowish-gray (5Y8/1); coarse-grained, but grains up to (some silt); medium pebbles, very poorly sorted; subrounded; abundant feldspars, both plagioclase and orthoclase; minor muscovite trace oxides, organics, heavy minerals.
1,126-1,128	Silt; dusky-red (5R3/4), moderate yellowish-brown (10YR5/4) and brownish-gray (5YR4/1); clayey; friable.
1,128-1,140	Sand; grayish-pink (5R8/2), dark yellow-orange (10YR6/6), dark reddish-brown (10R3/4) and yellowish-gray (5Y7/2); mottled; very fine to fine-grained with grains up to very coarse sand and very fine pebbles, very poorly sorted; subangular to subrounded; trace heavy minerals and oxides; accessory feldspars and clayey locally.
1,140-1,147	Clay; greenish-gray (5GY6/1), dark reddish-brown (10R3/4) and pale yellowish-green (10GY7/2); trace feldspar, chlorite, oxides; mica, interbedded with thin, fine-grained sand layers.
1,147-1,165	Sand; yellowish-gray (5Y7/2) and dark yellowish-orange (10YR6/6), mottled locally; grain size ranges from very fine to very coarse with grains up to pebbles size, silty, very poorly sorted; subangular to subrounded; abundant feldspar, mostly as orthoclase; minor muscovite, chlorite; heavy minerals.
1,165-1,211	Clay; dark reddish-brown (10R3/4), light greenish-gray (5GY8/1), dark and yellowish-orange (10YR6/6); mottled; very hard, friable; slightly micaceous, trace oxides and grains ranging from very fine sand to very fine pebbles.

1,211-1,224	Sand; moderate reddish-brown (10R4/6) and light olive-gray (5Y6/1); medium to fine-grained; with grains to very coarse sand; some silt and clay; poorly sorted; subangular; very micaceous; thin clay streak at 1220.
1,224-1,263	Clay; dark reddish-brown (10R3/4), greenish-gray (5GY6/1) and grayish-red (10R4/2); mottled; very hard, minor muscovite and chlorite; trace oxides, locally silty; thin sand streak at 1239.
1,263-1,287	Sand; greenish-gray (56Y4/1) to olive-gray (5Y4/1); medium to fine-grained; becoming finer with depth; silty; micaceous, locally very micaceous and hard.
1,287-1,296	Clay; olive-gray (5Y4/1); hard, fissile; silty; micaceous; trace pyrite.
1,296-1,304	Sand; brownish-black (5Y2/1); medium-grained with particles ranging to fine pebbles, some silt and clay; very poorly sorted; subangular; minor muscovite, trace marcasite, chlorite, feldspar, organics.
1,304-1,317	Clay; moderate brown (5YR4/4) and greenish-gray (5GY6/1); hard; minor muscovite, chlorite.
1,317-1,329	Sand; moderate yellowish-brown (10YR5/4); loose; medium-grained, with grains ranging to very coarse pebbles; some silt and clay; micaceous, minor feldspars, mostly orthoclase, trace oxides, heavy minerals.
1,329-1,340	Silt; olive-gray (5Y4/1), clayey, soft; micaceous.
1,340-1,360	Sand; moderate yellowish-brown (10YR5/4) and moderate reddish-brown (10R4/6), coarse with fine pebbles; clayey and silty; micaceous; minor feldspar; trace pyrite.
1,360-1,377	Clay; olive-black (5Y2/1), dusky-brown (5YR2/2) and pale yellowish-brown (5YR6/2); hard to very hard; locally silty; trace to minor muscovite and chlorite; trace oxides.
1,377-1,397	Silt; light greenish-gray (5GY8/1), pale reddish-brown (10R5/4) moderate yellowish-brown (10YR5/4) and bluish-white (5B9/1); clayey; friable; very micaceous, increasing with depths.

Pre-Cretaceous System

1,397-1,423	Saprolite; dark yellowish-brown (10YR4/2) and pale reddish-brown (10R5/4); very hard very micaceous.
1,423-1,427	Bedrock schist; dark gray (N3); quartz-biotite, very hard.

APPENDIX 2

WATER QUALITY ANALYSIS FOR THE CAPE FEAR FORMATION

(1312-1332 ft bls temporary screened interval)

Constituent	Concentration (mg/L)
pH (units)	8.05
Total alkalinity (as $CaCO_3$)	685
P. alkalinity (as $CaCO_3$)	20
Conductivity (umhos/cm)	5,870
Calcium hardness (as $CaCO_3$)	14
Total hardness (as $CaCO_3$)	58
Non-carbonate hardness (as $CaCO_3$)	0
Carbonate (as $CO_3^{=}$)	58
Total dissolved solids	3,360
Aluminum	3.35
Calcium	7.4
Iron	6.2
Magnesium	5.6
Manganese	0.15
Potassium	8.71
Total silica	10.8
Sodium	1,241
Chloride	1,530
Fluoride	2.54
Sulfate	78
Nitrate + Nitrite (as N)	<0.02
Total organic carbon	<1.0

APPENDIX 3

GRAIN-SIZE ANALYSIS

Sorting coefficients and median grain size values were determined from sieve analyses and grain-size distribution curves generated from these analyses. From the grain-size distribution curves, the sorting coefficients (S_o) were defined by the following equation:

$$S_o = \left(\frac{Q_3}{Q_1}\right)^{1/2} \tag{1}$$

where Q_1 is the first quartile, or the diameter of the sieve opening retaining 75 percent of the sample, and Q_3 is the third quartile, or the diameter of the sieve opening retaining 25 percent of the sample.

The smaller the S_o value is, the better the sorting of the sample. The following table lists the sorting coefficient values that were calculated from sieve analyses:

FORMATION	UNIT	DEPTH (FT BLS)	Q_1	Q_3	S_o
Black Creek	10	404	0.0070	0.0240	1.84
	8	550	.0035	.0073	1.44
	8	589	.0071	.0120	1.30
	8	624	.0075	.0130	1.32
	6	723	.0140	.0280	1.41
	6	752	.0080	.0160	1.41
Middendorf	2	992	.0088	.0170	1.39
	2	1,012	.0110	.0360	1.81
	2	1,017	.0110	.0320	1.71
Cape Fear	4	1,077	.0773	.0130	1.33
	4	1,082	.0130	.0250	1.39
	4	1,086	.0090	.0140	1.25
	4	1,088	.0120	.0290	1.55
	4	1,120	.0190	.0320	1.30
	4	1,122	.0130	.0260	1.41
	4	1,130	.0070	.0270	1.96
	4	1,137	.0090	.0150	1.29
	4	1,144	—	.0120	—
	4	1,157	.0110	.0400	1.91
	4	1,162	.0190	.0760	2.00
	3	1,217	.0072	.0210	1.71
	3	1,222	.0100	.0310	1.76
	2	1,272	.0071	.0120	1.30
	2	1,280	—	—	—
	2	1,284	.0081	.0130	1.27
	2	1,297	.0110	.0210	1.38
	2	1,322	.0150	.0520	1.86
	2	1,327	.0210	.0600	1.69
	2	1,340	—	.0130	—
	2	1,356	.0120	.0280	1.53
	2	1,357	.0110	.0130	1.09

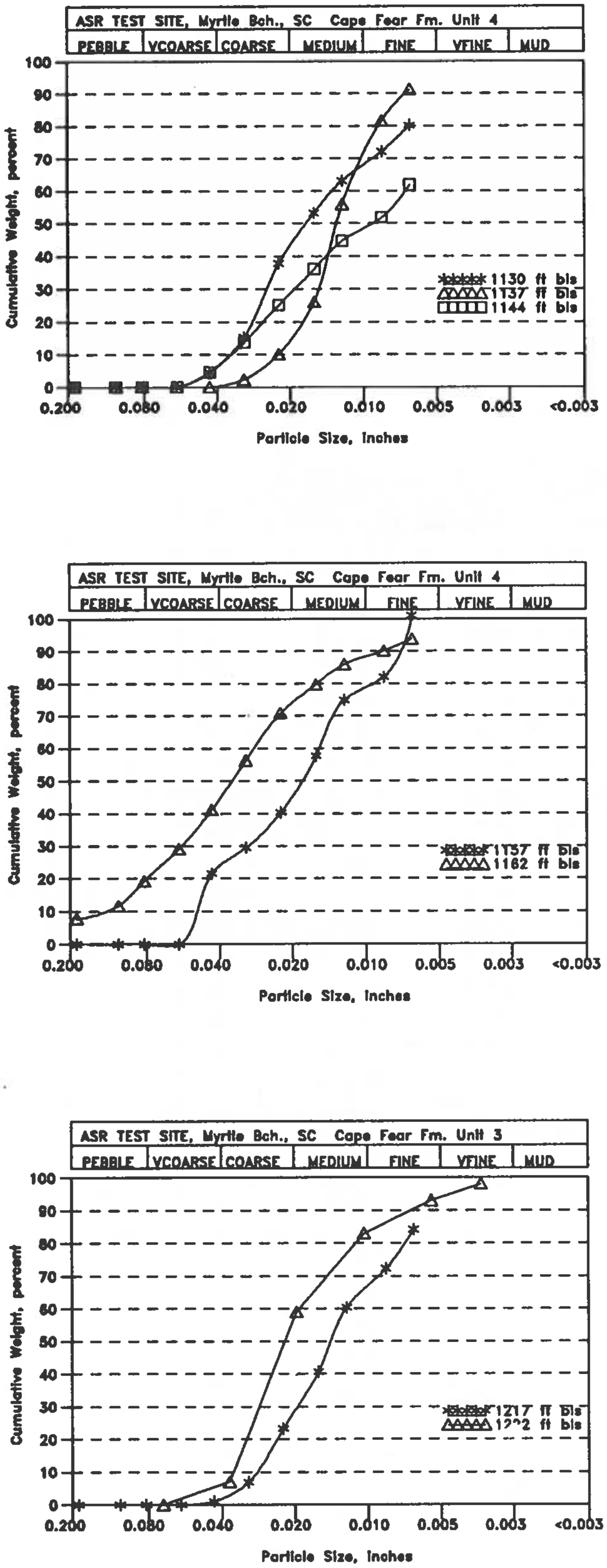


Figure 1(a). Cumulative-curve graphs from grain-size analysis.

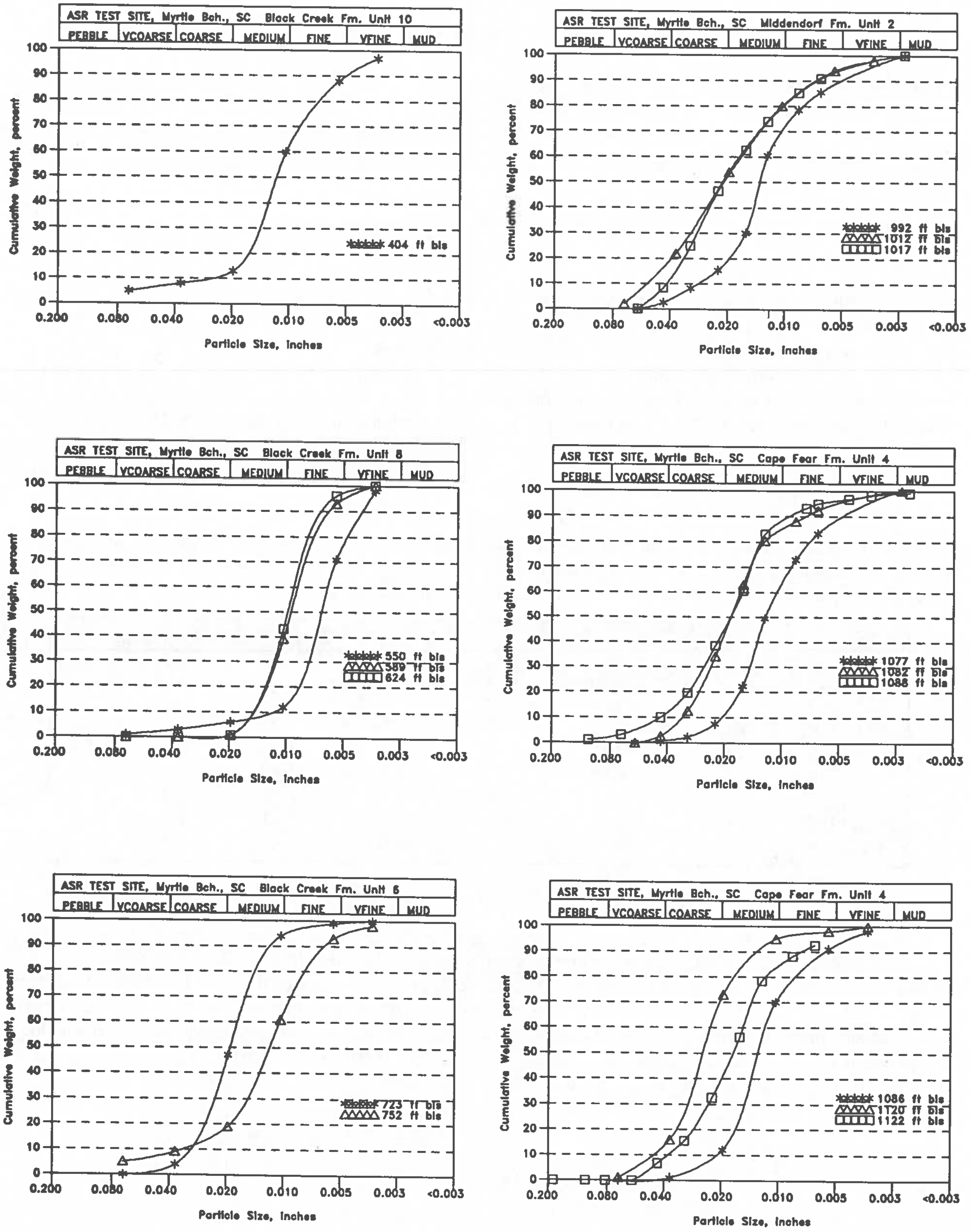


Figure 1(b). Cumulative-curve graphs from grain-size analysis.

APPENDIX 4

GEOPHYSICAL LOGS

Formation Water Resistivity

The formation water resistivity was calculated from the spontaneous-potential log by using the following relations (Schlumberger, 1979):

$$SP=-K\cdot\log\left(\frac{Rm_{fe}}{Rw_e}\right) \quad (2)$$

where

SP is the static spontaneous-potential (millivolts)
K is a coefficient dependent on temperature
Rm_{fe} is the equivalent resistivity of mud filtrate (ohm-m)
Rw_e is the equivalent resistivity of the formation water (ohm-m), and in this study it is assumed to be equal to formation water resistivity, Rw.

The equivalent resistivity of mud filtrate was calculated by this relation (Schlumberger, 1979):

$$Rm_{fe}=0.736\cdot Rm^{1.07} \quad (3)$$

0.736 is a coefficient related to the weight of the mud (10.8 lb/gal); the resistivity of the mud, Rm, was measured on-site at 5.72 ohm-m at 77°F; and Rm_{fe} is 4.76 ohm-m at 77°F. The following table list values of formation water resistivity. Rw_1 and Rw_2 are calculated resistivities and Rw_3 is a measured value.

DEPTH (FT BLS)	SP (mV)	T (°F)	K	RESISTIVITY (ohm-m)			
				Rm	Rw_1	Rw_2	Rw_3
1012-1020	-16.5	78.63	71.46	4.67	2.75	2.8	
1077-1140	-27.0	79.22	71.54	4.64	1.95	2.0	
1147-1165	-27.0	79.66	71.59	4.62	1.94	2.0	1.8
1211-1224	-27.0	79.95	71.63	4.60	1.93	2.0	1.8
1263-1287	-21.0	80.18	71.66	4.59	2.34	2.4	
1317-1329	-28.5	80.51	71.71	4.57	1.83	1.9	1.8
1340-1360	-31.5	80.73	71.74	4.56	1.66	1.7	

Rw_1 Formation-water resistivity at formation temperature
Rw_2 Formation-water resistivity at 77°F
Rw_3 Measured Formation-water resistivity at 77°F

The table shows that the formation water remains constant in the zones from 1,077 to 1,329 ft bls. The first and last zones, however, have the highest and lowest values of Rw, respectively. The first zone has fresher water than the last one. This abrupt change in the formation water resistivity is not only an indication of the difference in water quality but also in the hydraulic discontinuity between the zones. These two zones, as noted in the Hydrogeology Section, belong to different formations. The slightly higher value of Rw in the 1,263-1,287-ft interval is not in sequence with rest of the values; however, no reasonable explanation was found.

Porosity from Formation Factor

Formation factor, F, is defined as the ratio between resistivity (rock and water together) and formation water resistivity. The formation resistivity (Rt) is obtained from the guarded focused log, and the formation-water resistivity (Rw) is computed from the spontaneous-potential log (see above description). For clean sand, the formation factor has empirically been related to porosity. One of the most widely used relations, for unconsolidated sand, is the Humble formula (Dresser Atlas, 1982):

$$F = \frac{0.62}{\theta^{2.15}} \tag{4}$$

The following table contains porosity values computed from electric logs and porosity values measured at the laboratory.

ZONE (FT BLS)	RESISTIVITY (ohm-m)		F	POROSITY (PERCENT)	
	Rt[a]	Rw		LOG	LAB
1012-1020	7.0	2.75	2.55	51.8[b]	
1012					35.1
1077-1147	13.6	1.95	6.97	32.5	
1120					36.8
1147-1165	14.0	1.94	7.22	31.9	
1211-1224	12.6	1.93	6.53	33.5	
1222					34.3
1227					35.2
1263-1287	11.2	1.87[c]	5.96	34.9	
1317-1329	11.2	1.83	5.80	35.3	
1340-1360	13.6	1.66	8.19	30.1	
1356					31.8

[a] Maximum value from guarded focused log
[b] Unrealistic value
[c] Interpolated

Calculated porosity, from the focused guarded log, conforms well with laboratory measurements. It is important to note, however, that laboratory values of porosity are measurements of both isolated and interconnected interstices. This porosity is designated total porosity to differentiate from effective porosity, which is a measurement of the connected interstices only. Calculated porosity—as computed from the spontaneous-potential log—is total porosity and should not be used to estimate effective porosity, except when the sand is clean and with no isolated interstices.

Effective Porosity from Neutron and Density Logs

One of the simplest methods used to estimate effective porosity, if the lithology is known, is the neutron-density crossplot (Schlumberger, 1979). This method provides a graphical solution for computing effective porosity, volume percentage of sand, and volume percentage of clay:

$$P=\theta\cdot P_f+V_1\cdot P_1+V_2\cdot P_2$$

$$\delta=\theta\cdot\delta_f+V_1\cdot\delta_1+V_2\cdot\delta_2 \tag{5}$$

$$1=P+V_1+V_2$$

where

P is the apparent limestone porosity from neutron log
θ is the effective porosity
δ is the bulk density of matrix (g/cc)
1,2 are subscripts referring to quartz and clay fraction, respectively
f is subscript referring to fresh water

The solution to the model is based on the assumption that responses to porosity and lithology changes are linear. In the graphical solution, Figure 1, a cartesian X and Y coordinate system, three reference points are plotted and joined to form a triangle. The X-axis is apparent porosity and the Y-axis is density. The sides of the triangle are then scaled from 0 to 100. The first reference point (1,100) is the "water" point of density 1 gram per cubic centimeter (g/cm^3) and 100 percent porosity. The second reference point is the "sand" point (0, 2.65) of density 2.65 g/cm^3 and zero porosity—a quartz grain with no porosity. The third reference point is the "clay" point. This point is referred to as a typical clay point, and it is obtained at the intersection of two lines drawn from the "sand" and "water" points and enveloping the majority of clay points. A grid is prepared by connecting the divisions on opposite sides of the triangle with straight lines. Lines of the grid parallel to the "sand-clay" baseline represent effective porosity as percent. Lines of the grid parallel to the "sand-water" baseline represent the volume of clay as a percentage and the other grid lines represent the volume of sand as a percentage. Figure 2 shows neutron-density crossplots for various depths.

Hydraulic Conductivity from Porosity

Effective porosity was used in determining hydraulic conductivity within the Cape Fear, Middendorf, and Black Creek Formations. The hydraulic conductivity values were calculated from a commonly used relation known as the Kozeny-Carmen (Bear, 1972) equation:

$$K=662.8\cdot 10^5\cdot d_m^2\cdot\frac{\theta^3}{(1-\theta)^2} \tag{6}$$

where

K is hydraulic conductivity
θ is the effective porosity as a decimal percent
d_m is the representative grain size (d_{50})

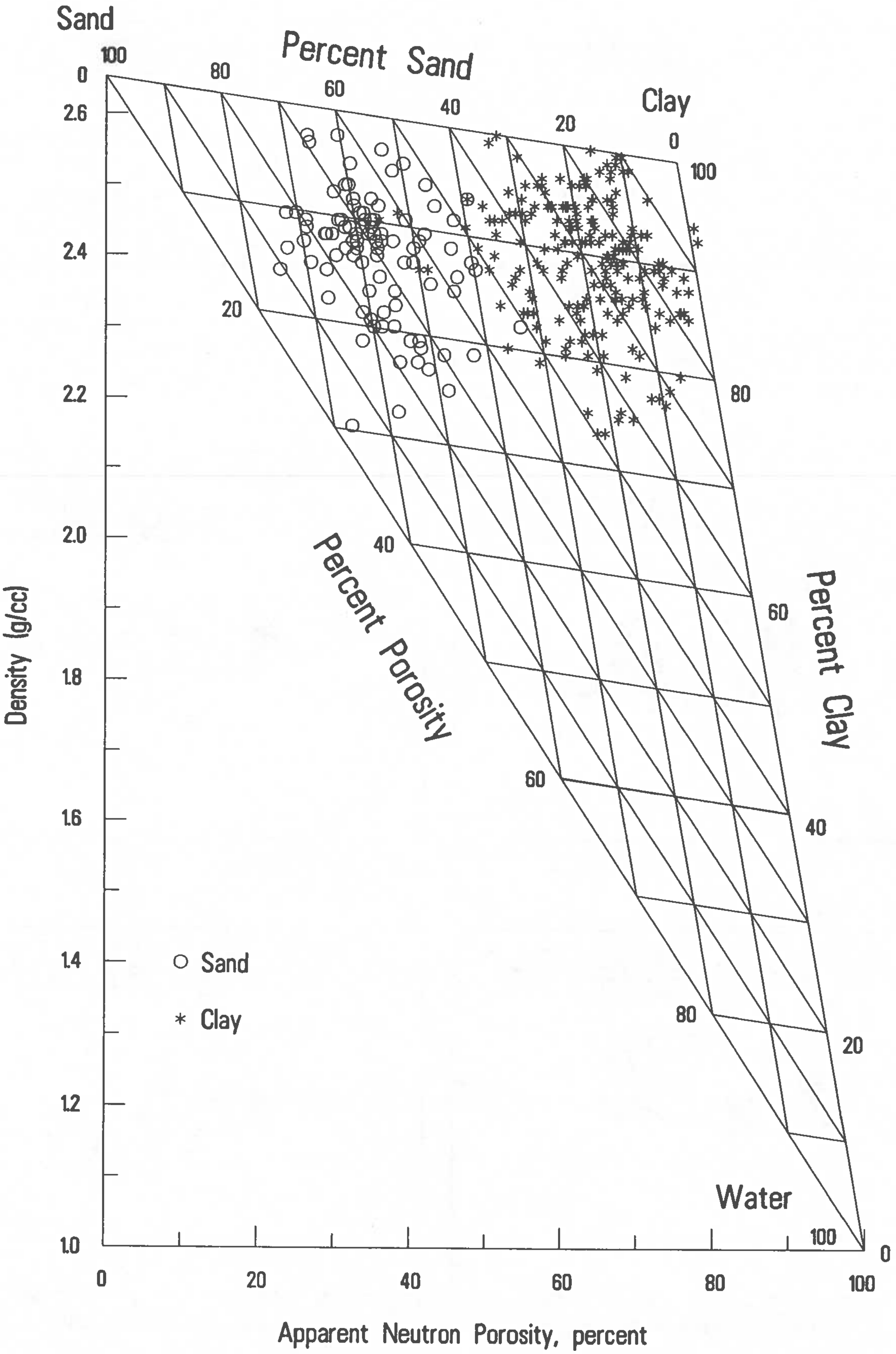


Figure 1. Neutron-density crossplot.

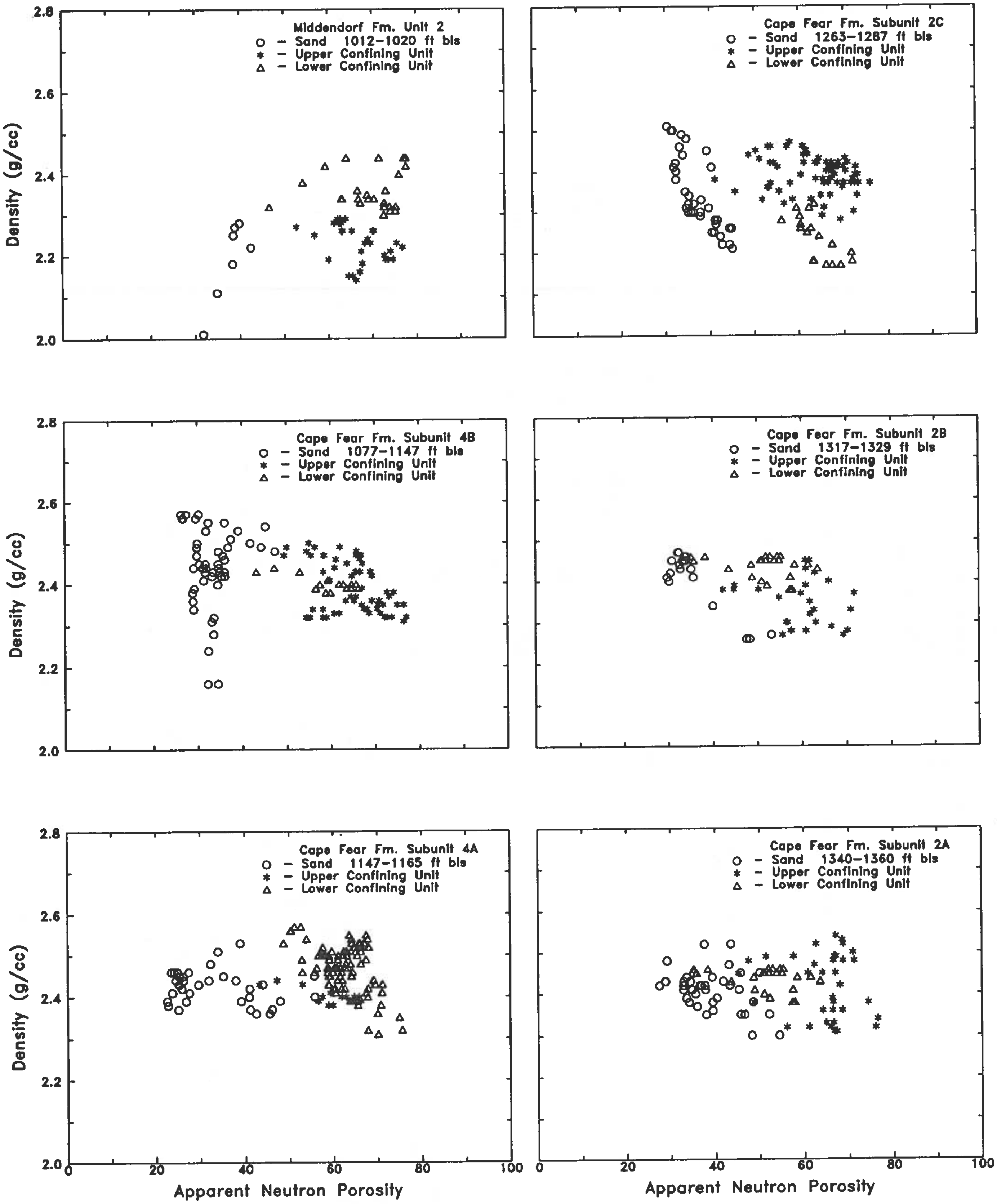


Figure 2. Neutron-density graphs from geophysical-log analysis.

APPENDIX 5

DESCRIPTION OF THE MUD SYSTEM

A water-based mud system, composed of water from the Black Creek aquifers mixed with a beneficiated bentonite product known as Quik-Gel*, was used throughout the drilling and coring operation. All mud was mixed on the site in a 1,200-gallon tank and subsequently pumped into a large (approximately 12-ft deep) U-shaped mudpit.

E-Z Mud*, an anionic polymer, was added to the drilling fluid in certain situations in order to increase mud viscosity without appreciably affecting density. This enhanced recovery during coring operations in the Black Creek Formation.

Because of the flowing artesian conditions encountered while coring the Middendorf and Cape Fear Formations, a barite weighting agent (Baroid*) was mixed into the mud to counter down-hole pressures. Because the anionic polymer and the barite proved incompatible, E-Z Mud was not used in coring operations below the Black Creek Formation.

The composition and physical properties of the drilling fluid used in the coring and drilling operation were of critical importance. They were dictated by a number of factors, including the method of sample acquisition and down-hole pressure. The following outline can be used with this figure to better illustrate the relationship between mud properties, sample type, and down-hole pressure.

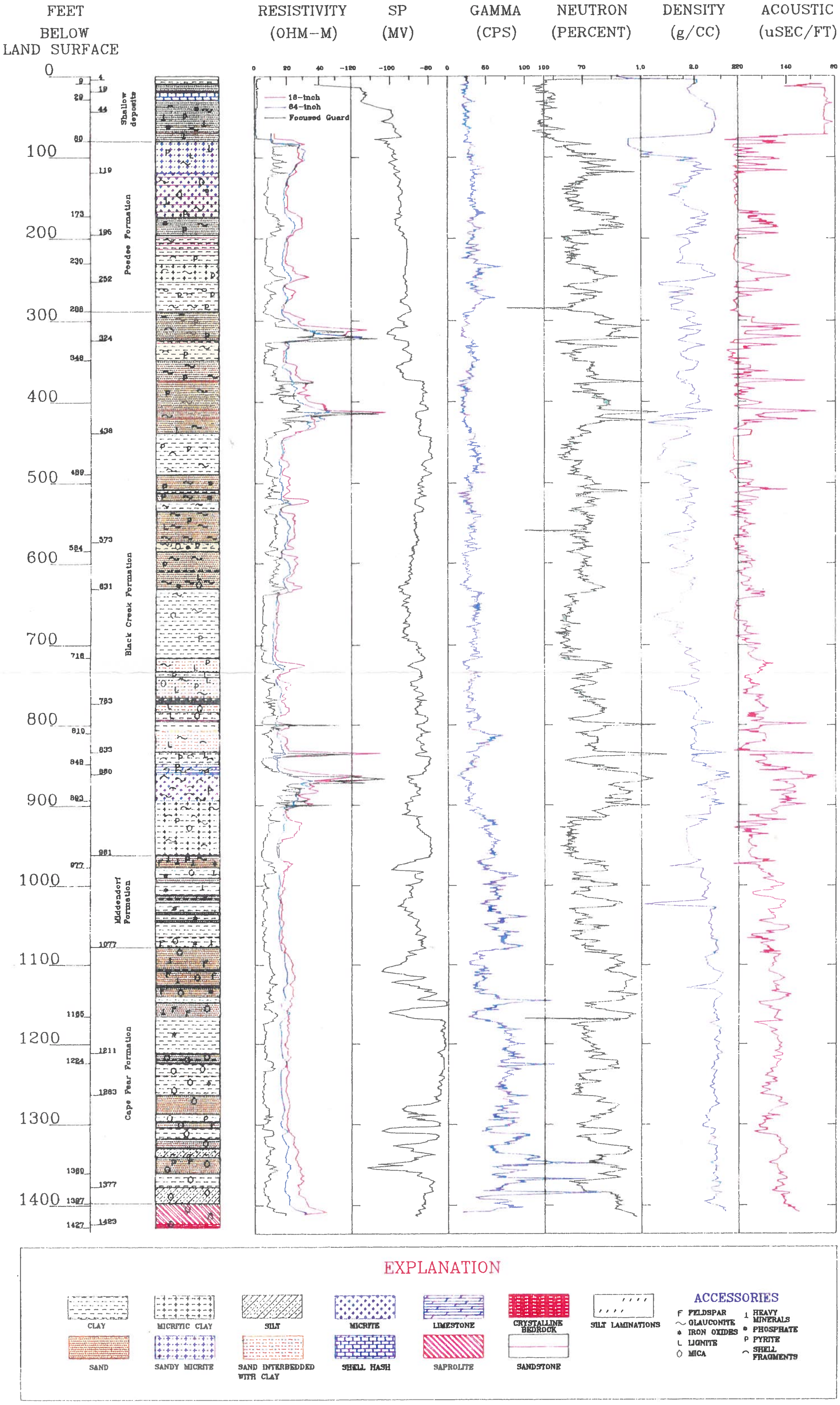
Depth (ft bls)	Description	Additives
0-372	-Drilling operations -Shallow, Peedee, and upper Black Creek Formations -Water table and artesian conditions -Hydraulic head below land surface	Quik-Gel
372-961	-Coring operations -Black Creek Formation -Artesian conditions -Hydraulic head below land surface	Quik-Gel E-Z Mud
961-1427	-Coring operation -Middendorf and Cape Fear Formations and saprolite zone -Flowing artesian conditions -Hydraulic head app. 70 ft above land surface	Quik-Gel Baroid

Control of mud viscosity did not become critical until the coring operation commenced in zone 372-961 ft bls. At this time it was necessary to increase the mud viscosity by adding E-Z Mud, which also served to slightly decrease the mud density. In the lowermost zone (961-1,427 ft bls), where flowing artesian conditions were encountered (a measurement of 30 psi or 69.3 ft of hydraulic head was recorded), it was extremely important to counteract the increased hydraulic head by increasing the mud density with barite. This also resulted in an increase in viscosity. The optimum mud density was achieved when the weight of the mud counterbalanced the hydraulic head.

One of the difficulties associated with mud control is the uncertainty presented by mixing with formation water. An example of this occurred between 600 and 900 ft bls, where the mud viscosity steadily declined. This is thought to be caused by water from the lower Black Creek aquifers mixing with the drilling fluid, thereby decreasing the fluid viscosity.

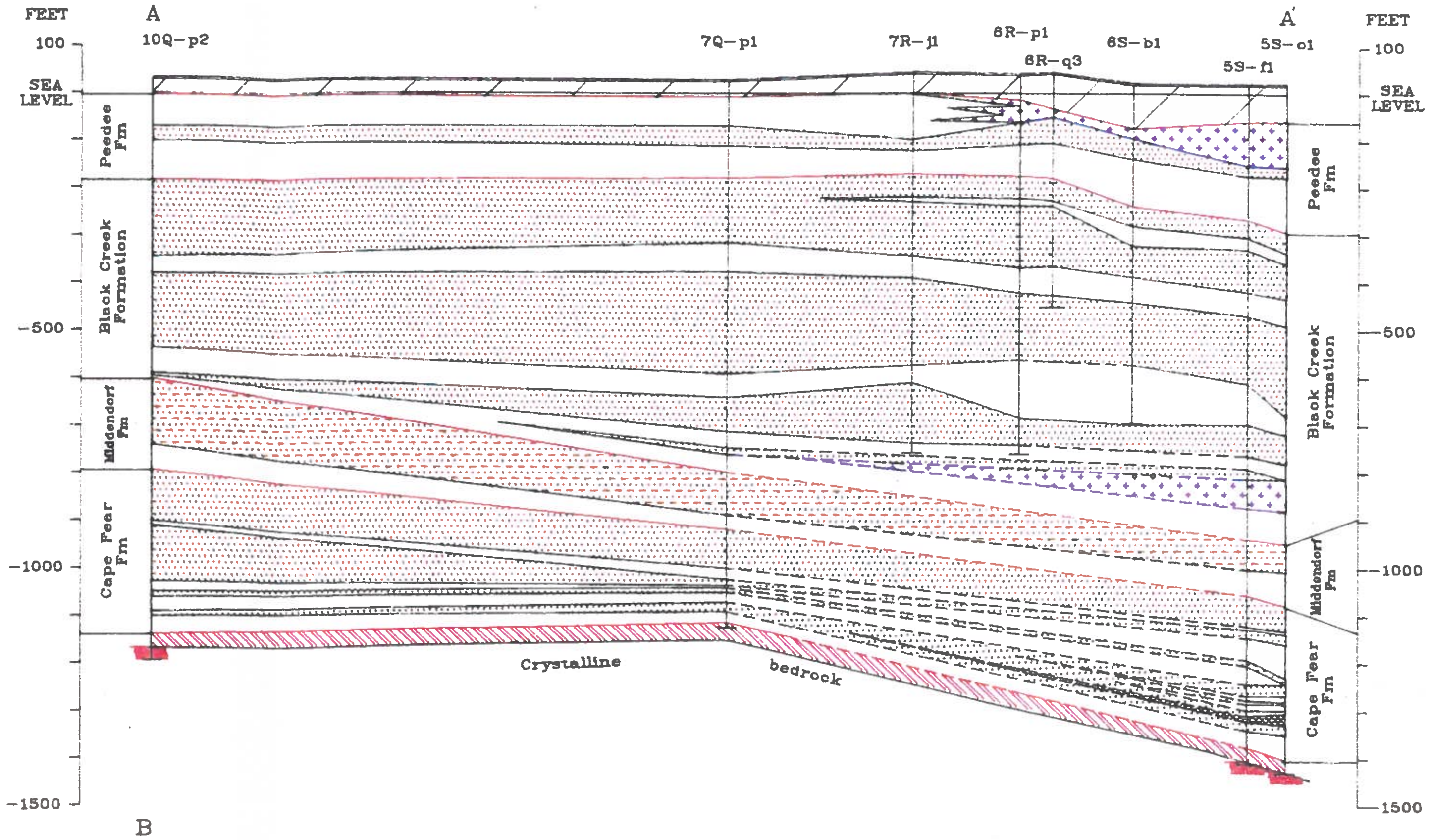
* Quick-Gel, E-Z Mud, and Baroid are all brand names of NL Baroid/NL Industries, Inc.

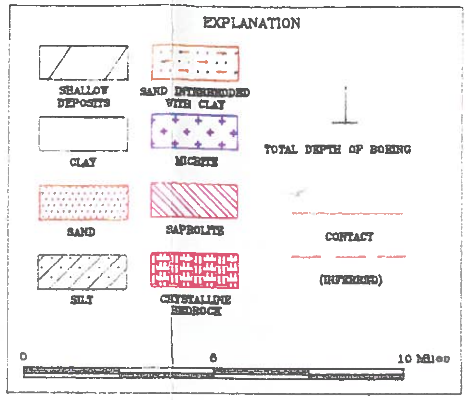
SOUTH CAROLINA DEPARTMENT OF NATURAL RESOURCES
WATER RESOURCES DIVISION REPORT 4, PLATE 1

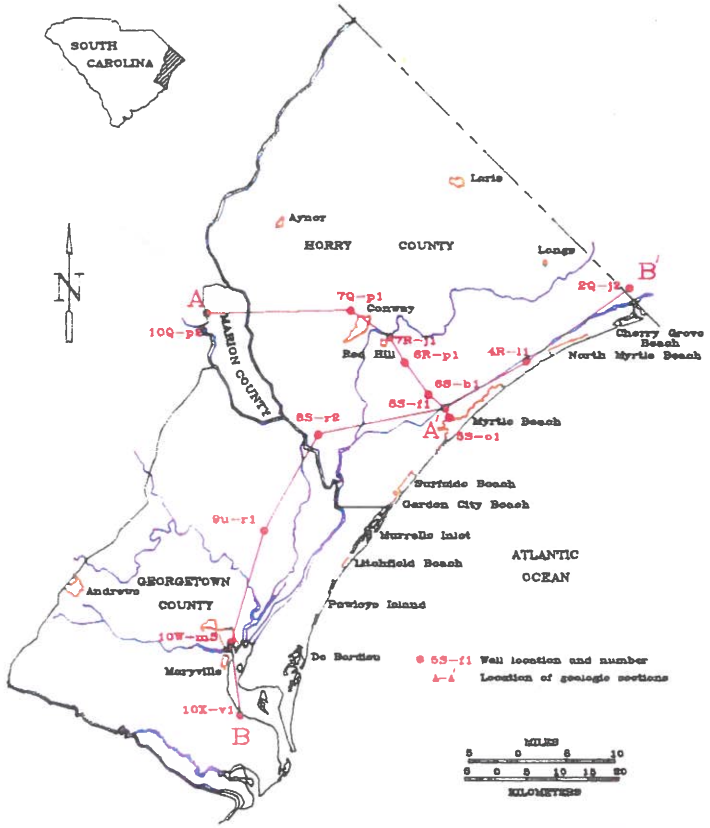


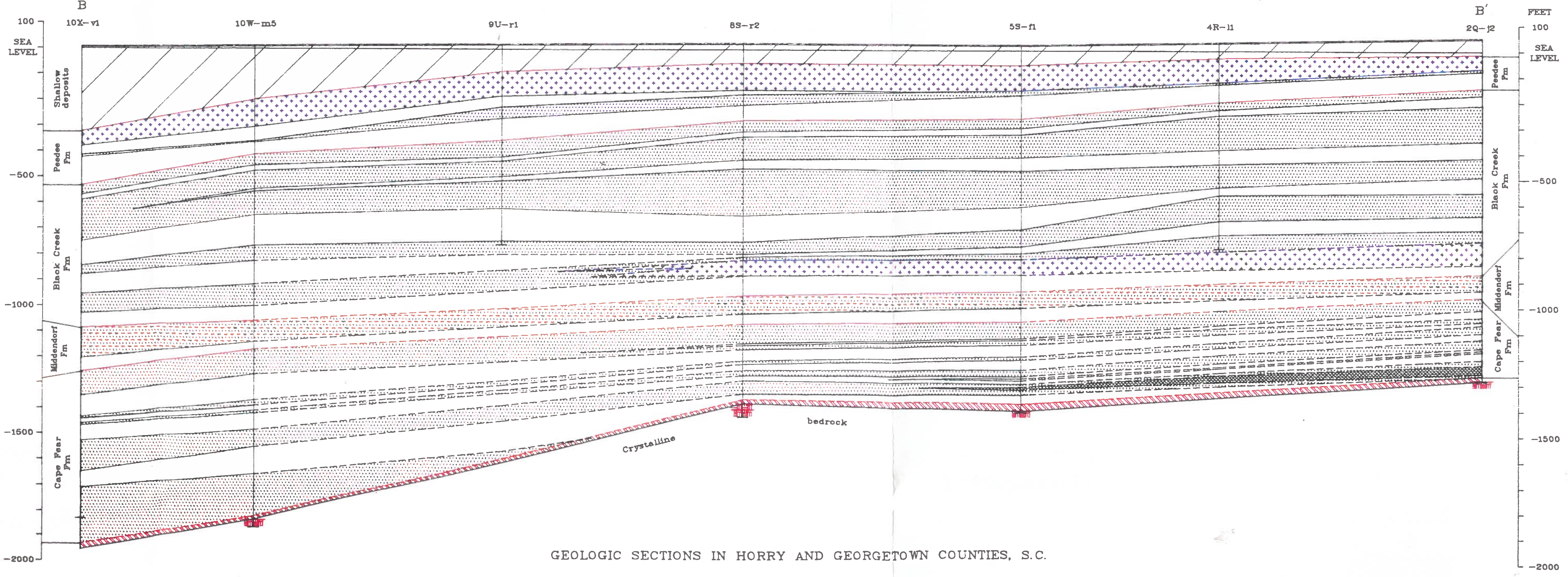
LITHOLOGIC AND GEOLOGIC LOGS FROM THE ASR TEST WELL

SOUTH CAROLINA DEPARTMENT OF NATURAL RESOURCES
WATER RESOURCES DIVISION REPORT 4, PLATE 2









GEOLOGIC SECTIONS IN HORRY AND GEORGETOWN COUNTIES, S.C.