RECONNAISSANCE HYDROGEOLOGIC INVESTIGATION OF THE DEFENSE WASTE PROCESSING FACILITY AND VICINITY, SAVANNAH RIVER PLANT, SOUTH CAROLINA

By Kevin F. Dennehy, David C. Prowell, and Peter B. McMahon

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MANUEL LUJAN, JR., Secretary

U.S. GEOLOGICAL SURVEY

Dallas L. Peck, Director

For additional information write to:

District Chief
U.S. Geological Survey
Suite 677A
1835 Assembly Street
Columbia, South Carolina 29201

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ABSTRACT

This report presents the data and results of a two-year hydrogeologic investigation of the Defense Waste Processing Facility and vicinity at the Department of Energy's Savannah River Plant in South Carolina. The Defense Waste Processing Facility (S Area) will process high-level radioactive waste into an immobilized state and retain it on-site until a national respository is available for final storage. The report also includes an evaluation of the potential for movement of possible spills of a by-product of the production of defense nuclear materials, a concentrated salt-solution waste. The salt waste is to be solidified and permanently stored near the Defense Waste Processing Facility (Z Area).

A geologic framework was developed for sediments of Tertiary and younger age; including the Ellenton, Congaree, and McBean Formations, the Barnwell Group, the upland unit, and colluvium/alluvium. Results include the identification of a calcareous zone near the base of the McBean Formation in the area east of F area. In addition, the green clay of the McBean Formation seems to be continuous over the study area, whereas the tan clay of the Barnwell Group is absent northeast of the Defense Waste Processing Facility. The green and tan clays range in thickness from 2 to 6 feet and 0 to 10 feet, respectively.

The hydrogeologic framework of the study area consists of 2 to 3 separate water-bearing units. In the northern half of the study area the Barnwell and McBean aquifers are considered to be one aquifer owing to the absence of the tan clay. In contrast, they are separated into two aquifers in the southern half by the tan clay. Underlying these aquifers, and separated from them by the green clay, is the Congaree Aquifer. The hydraulic conductivities of the aquifers range from 10^{-8} to 10^{-4} feet per second. Depth to water varies from 60 feet at the center of the study area to 25 feet in the southwestern part. Directions of ground-water flow in the Barnwell and McBean aquifers are generally to the north, with a component of flow directed downward across the green clay and into the Congaree aquifer. Part of the flow in the Barnwell and McBean aquifers is intercepted by local streams which downcut into these aquifers. On the basis of limited data, the direction of flow in the Congaree aquifer seems to be to the northwest. At least part of the flow in the Congaree aquifer discharges into Upper Three Runs stream northwest of the study area.

Water samples collected from the Barnwell-McBean and Congaree aquifers indicate water in these aquifers can be classified as: 1) acidic

mixed-cation type (upper Barnwell-McBean); 2) alkaline calcium-bicarbonate type (lower Barnwell-McBean and Congaree); and 3) a water intermediate between the previous two types (upper Barnwell-McBean). Chemical changes in water reflect the influence of reactions between sediment and water as water moves from the upper part of the Barnwell-McBean aquifer, to the lower Barnwell-McBean aquifer, and to the Congaree aquifer.

Laboratory column experiments conducted to examine the potential for movement of a simulated salt-solution in sediments from the Barnwell Group indicate chemical reactions between the solution and sediment caused sediment permeabilities to decrease 90 to 95 percent. These results suggest a release of salt solution to sediments of the Barnwell Group would move more slowly than would be expected based on pre-spill measurements of hydraulic conductivity.

INTRODUCTION

The Savannah River Plant (SRP), a Department of Energy (DOE) facility that produces nuclear materials for national defense, is located along the Savannah River approximately 60 mi southwest of Columbia, South Carolina and about 95 mi inland from the Atlantic Ocean. It occupies 300 mi^2 in parts of Aiken, Barnwell, and Allendale Counties in southwestern South Carolina near the Georgia border (fig. 1).

The Defense Waste Processing Facility (DWPF), located near the geographic center of the SRP, plans to process for permanent storage, high-level radioactive waste that has accumulated over 30 years from the production of defense nuclear materials. The DWPF is currently under construction (1987) at what is known as S Area, a tract of approximately 75 acres located adjacent to the H Area separation facility (fig. 2). H Area contains one of the chemical separation facilities that processes reactor-irradiated material. Waste generated by the separation facilities currently is being stored on-site as a concentrated liquid in large carbon-steel tanks. The waste stored in the tanks will be separated into two forms: a high-level radioactive sludge and a concentrated salt solution containing low-level radioactivity. The sludge component will be transported through a pipeline to the vitrification facility at the DWPF (S Area), where it will be eventually mixed into a molten, borosilicate glass matrix. The molten glass will be poured into stainless-steel canisters, and once the glass has solidified, these canisters will be welded shut. The radioactive waste will be retained in this immobilized state on-site until a national respository for high-level radioactive waste is available for final storage. The concentrated salt solution will be transported through a separate pipeline to a disposal facility known as Z Area, a site of approximately 200 acres located north of S Area (fig. 2). Current plans are to mix the salt solution with a pulverized furnace slag and concrete before pouring the mixture into near-surface concrete vaults at Z Area. The resultant mixture, known as saltstone, will be solidified and permanently stored in these vaults.

In September 1984 the U.S. Geological Survey entered into an agreement with the Department of Energy to conduct a reconnaissance investigation of the hydrogeology in the vicinity of the DWPF at the Savannah River Plant.

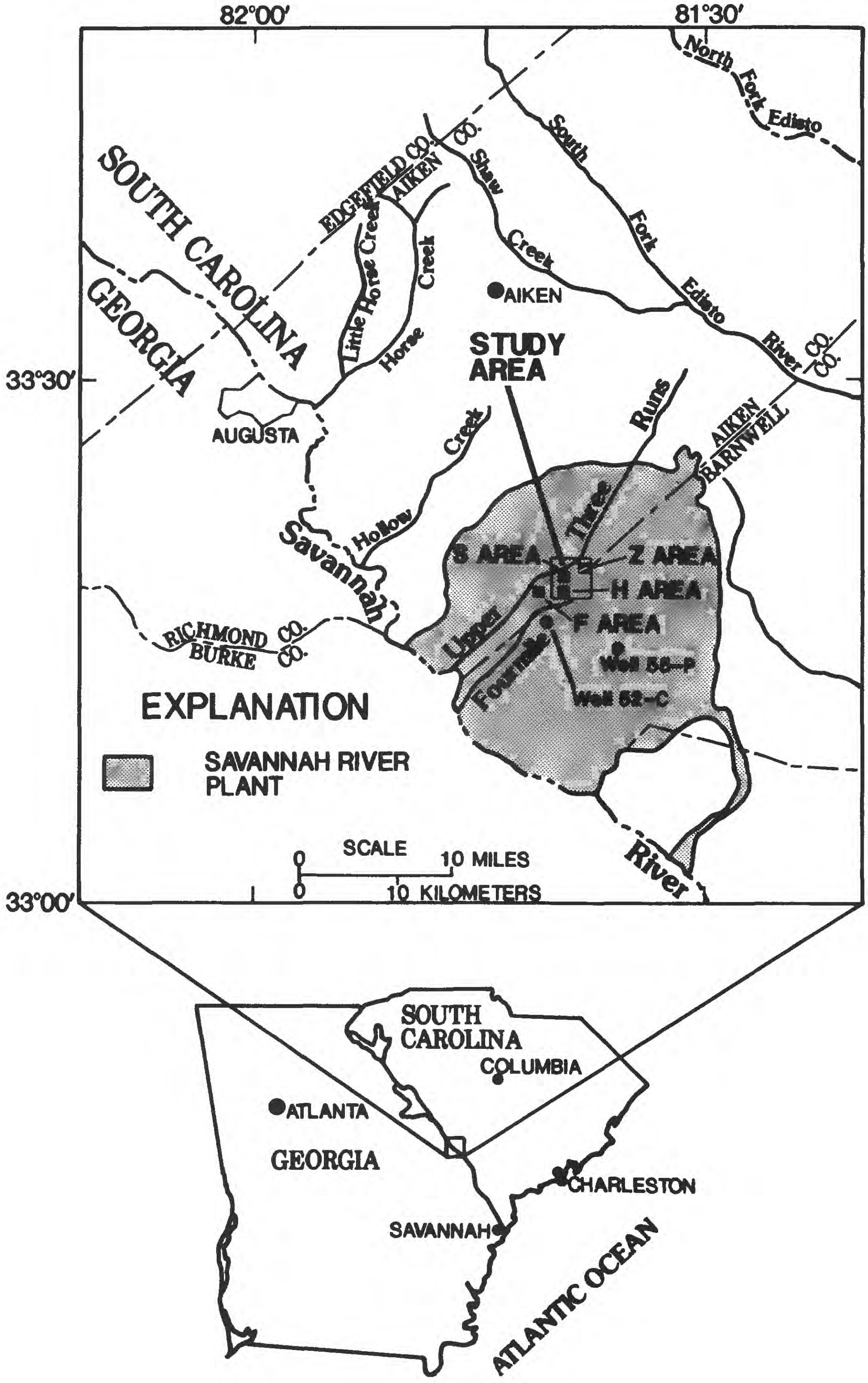


Figure 1.--The study area within the Savannah River Plant.

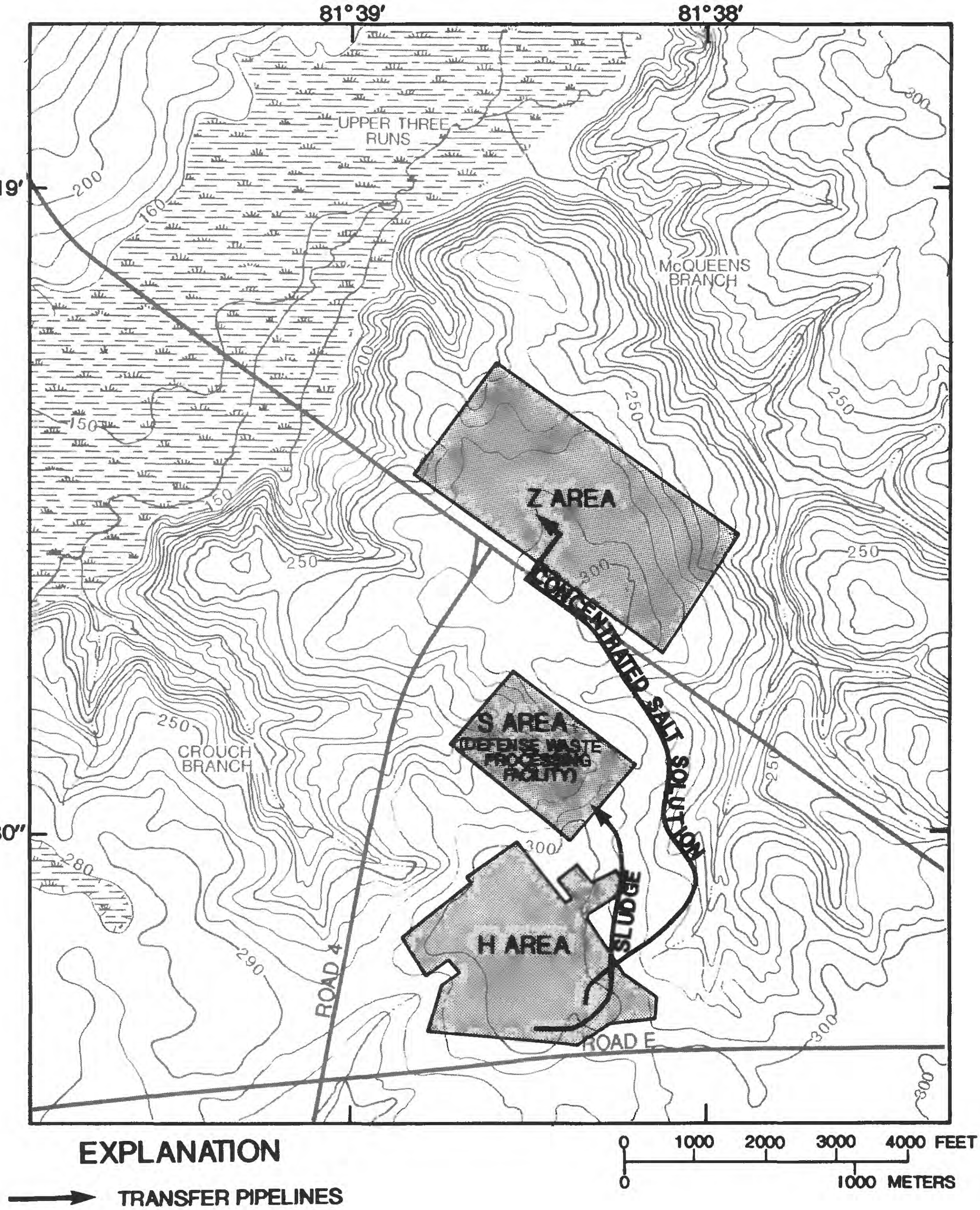


Figure 2.--H, S, and Z Areas within the study area.

Purpose and Scope

The purposes of this report are two-fold: (1) to define the hydrogeologic conditions in the vicinity of the DWPF and, (2) to evaluate the potential for movement of a concentrated salt-solution waste if released at or near the DWPF.

These purposes were accomplished by assembling and evaluating existing hydrogeologic data; collecting additional geologic, hydrologic, and water-quality data; developing a local geologic framework; developing a conceptual model of the local ground-water flow system; and by performing laboratory experiments to determine the mobility of salt-solution waste in surface and near-surface sediments.

Although the unconsolidated sediments are about 1,000 ft thick in the study area, only the Tertiary age sediments, or upper 300 ft are discussed in this report. The top of the Ellenton Formation acts as the major confining unit between the overlying aquifers in Tertiary sediments and the underlying aquifers in Cretaceous sediments; therefore, the Ellenton Formation is the vertical limit of our hydrogeologic investigation..

The majority of the hydrologic data for this study came from monitoring wells at the saltstone disposal site (SDS) in Z Area (fig. 3). No recent water-level data were collected in S Area owing to the removal of S Area monitoring wells prior to construction at the DWPF.

General Description of Study Area

The SRP is located in the Coastal Plain physiographic province of South Carolina. Both the S and Z Areas (fig. 2) are located on the relatively flat Aiken Plateau at an altitude of approximately 300 ft above sea level. A number of streams dissect the study area and incise the land surface, greatly influencing the local ground-water system. The study area is bordered on three sides by streams that cut into the surficial sediments to varying degrees. Upper Three Runs lies about a mile northwest of DWPF at an altitude of about 150 ft above sea level (fig. 2). Upper Three Runs discharges to the Savannah River about 9 miles to the southwest at an altitude of about 80 ft. McQueens Branch forms the northeastern boundary of the study area at an altitude ranging from 160 to 250 ft (fig. 2). Crouch Branch, a smaller tributary of Upper Three Runs, lies west of S Area at an altitude ranging from approximately 150 to 250 ft (fig. 2).

Topography at the DWPF site, as well as the saltstone disposal area, is relatively flat. The water table generally ranges between 64 and 77 ft below land surface in the interstream area. However, closer to the streams, the water table slopes sharply where the land surface is incised.

The geology of the study area is typical of the Atlantic Coastal Plain. The sediments, which range in age from Cretaceous to Holocene, generally are unconsolidated and are composed of stratified gravel, sand, silt, and clay. Limestone occurs in isolated areas.

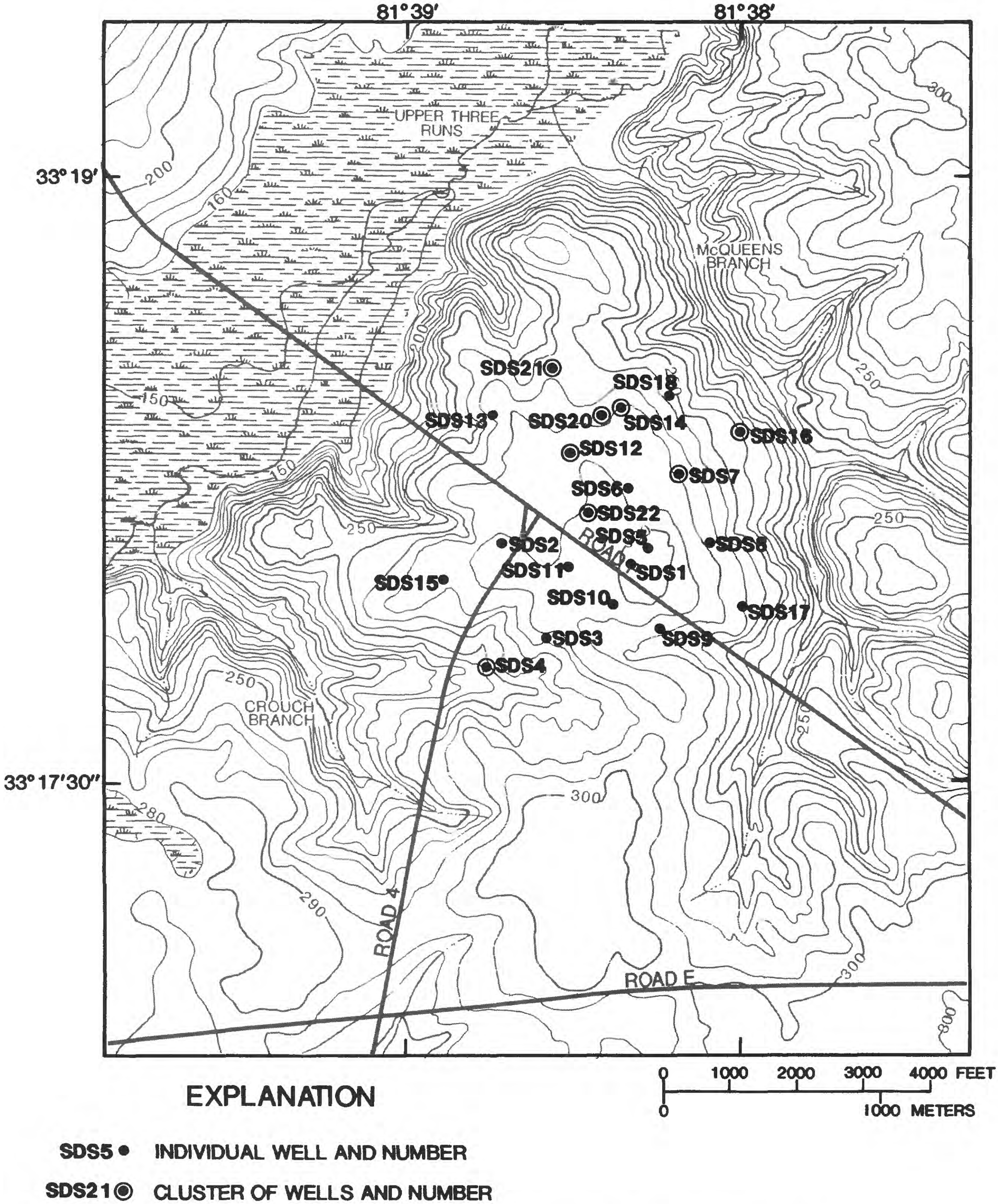


Figure 3.--Saltstone Disposal Site monitoring wells.

The climate of the area is relatively temperate with warm humid summers and mild winters. Meteorological data have been collected at the SRP since 1961. Currently, wind speed and direction are monitored at seven towers located adjacent to each production area on the SRP, and a television tower located 9 miles northwest of the SRP boundary (Hoel, 1983). Additionally, daily temperature, relative humidity, precipitation, and air pressure are recorded about 5 miles from the study area by SRP (Hoel, 1983).

Average annual air temperature at SRP was 64 °F (Hoel, 1983) for the period 1961 through 1981. Temperature has reached a low of 4 °F in January and February to a high of 106 °F in July. Average monthly temperatures recorded during 1961-1981 are presented in figure 4. The average daily relative humidity ranged from 43 to 90 percent, with higher readings occurring in the morning than in the afternoon.

Average annual precipitation at the SRP was about 48 in. (Hoel, 1983) for the period 1952 through 1982. Monthly precipitation for the period of record ranged from a low of 2.33 in. in November to a high of 5.08 in. in March (fig. 4). Snow very rarely occurs at the SRP. The summer months of June, July, and August generally are the wettest (29 percent of total precipitation), followed closely by the winter months of January, February, and March.

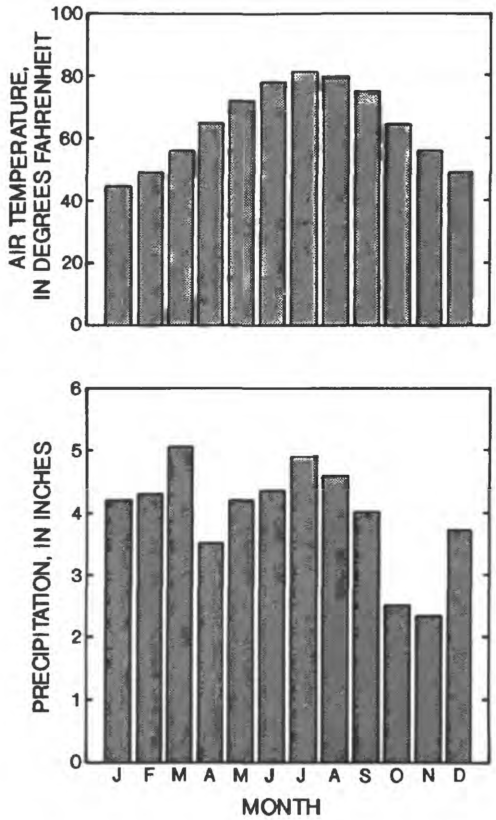


Figure 4.--Average monthly temperature and precipitation at the Savannah River Plant during 1961-1981.

Overland runoff at the SRP was not observed in areas of generally flat topography where forest litter and surface sand are present, but overland runoff is likely in areas of steep slope. In a U.S. Geological Survey study at a commercial low-level radioactive waste disposal site adjacent to SRP, 11 miles east of the study area, 70 percent of the precipitation was estimated to return to the atmosphere by evapotranspiration (Dennehy and McMahon, 1987). In that same study, using a water balance technique, recharge was estimated to be approximately 30 percent of precipitation in areas where surface sediments remain undisturbed.

Previous Investigations

The geology and hydrology at the SRP are discussed in a variety of site-specific reports. Summaries of the local geology are presented in Siple (1967), Christl (1964), Petty and others (1965), Bechtel Corporation (1972, 1973, 1982), Daniels (1974), Marine and Siple (1974), Marine and Root (1978), Marine (1979), Faye and Prowell (1982), and Prowell and others (1985b). In addition, regional geologic investigations including the Savannah River Plant area have been authored by Sloan (1908), Cooke (1936), Cooke and MacNeil (1952), and Prowell and others (1985a). Only a few reports are related directly to S and Z Areas. D'Appolonia (1982) completed the most comprehensive investigation to date of the DWPF that included information on climate, geology, and hydrology at S Area. One year earlier, D'Appolonia (1981) reported geologic and hydrologic data from an early site characterization of Z Area in which 25 monitoring wells were installed. Additional work at Z Area included another site assessment by INTERA (1986) in which the geology and hydrology of the area were examined with the primary emphasis directed to the development of ground-water flow and transport models of nitrate movement below the proposed saltstone disposal facility (Z Area).

GEOLOGY

The stratigraphic nomenclature at the SRP has remained relatively unchanged since the publication of Siple (1967). A better understanding of the geology in areas adjacent to the plant, however, has evolved with time, and the geologic units within the plant boundaries now need revision to fit the modern stratigraphic concepts of the region. Local refinements of the geologic framework of Siple (1967) have been necessary to accommodate various geohydrologic studies at the SRP. The most significant modification to that report is the delineation of the "tan" and "green" clay layers by Root (1980). He recognized these two lithologic horizons as zones of low permeability in his evaluation of ground water in the vicinity of the DWPF study area. Special attention will be given to these two lithofacies and their stratigraphic positions because they are also of significance to this study.

Stratigraphy

Siple (1967, fig. 3) recognized five regional Coastal Plain formations of Tertiary age near the center of the SRP and referenced these to well 55-P (fig. 1). This well is located about 6 miles southeast of the DWPF study area. The five formations that he reported are: (1) the Ellenton Formation, (2) the Congaree Formation, (3) the McBean Formation, (4) the Barnwell Formation, and (5) the Hawthorn Formation. Except for the name "Hawthorn", these names are still in use in areas immediately outside of the SRP. Therefore, these names (except Hawthorn) are used in this report (table 1) for consistency with published literature; however, some modifications have been made to Siple's stratigraphic framework to conform to present geologic knowledge.

To evaluate these formations at the DWPF, samples were examined from eight core holes (fig. 5) and numerous exposures in a large area around the DWPF. The following descriptions are based on these observations in conjunction with data from other reports. In addition, data from these core holes were used to construct two geologic sections, figure 6 (fig. 5, A-A') and figure 7 (fig. 5, B-B'), to better define the geology at the DWPF.

Ellenton Formation

Nomenclature

The Ellenton Formation is named after the abandoned town of Ellenton, SC which was located near the center of the SRP property prior to Federal acquisition of the land. Siple (1967) proposed the name Ellenton Formation to denote lithologically distinct strata of unknown age situated above sand and clay of presumed Cretaceous age and below fossil-dated Eocene strata; however, the name Ellenton is not widely used outside the SRP boundaries. Siple (1967, p. 28-31) established the type section in SRP test well 52-C, located near the center of the plant about 4 miles southwest of the DWPF study area (fig. 1). This well was drilled in 1952, and cuttings and geophysical logs from it were used to describe the lithologic character of the Ellenton Formation. The Ellenton Formation is not known to crop out on the SRP, and has only recently been recognized (see Prowell and others, 1985b) in stream cuts north of the SRP boundary near the community of Hollow Creek, S.C. (fig. 1).

Lithology

The Ellenton Formation on the SRP is approximately 50- to 80-ft thick and generally can be divided into a lower clayey-sand phase and an upper clay phase as described in Prowell and others (1985b). The lower Ellenton phase is composed of medium to coarse sand consisting of subangular quartz in a light-gray to off-white clay matrix. Light-gray to blue-gray quartz forms the majority of the sand fraction and gives the formation a characteristic pale-gray appearance. Finely disseminated carbonaceous debris and fragments of lignite are common. Secondary minerals include muscovite, feldspar, sillimanite, iron-bearing minerals (typically pyrite, marcasite, and siderite), garnet, rutilated quartz, and various unidentified dark, heavy minerals.

The upper Ellenton phase is largely sandy to silty kaolinitic clay with some thin beds of clayey coarse sand. Mica is typically abundant in the clay layers, and X-ray analysis of sandy-clay samples indicates significant amounts of cristobalite. Some clay and clayey-silt beds in the upper

Table 1.--Correlation chart of geologic units

SERIES	EUROPEAN STAGE	PROVINCIAL STAGE	WESTERN GEORGIA	EASTERN GEORGIA	THIS REPORT	SOUTH CAROLINA (W–E)
MIOCENE	Undifferentiated	Undifferentiated		Hawthorn Fm.	Upland Unit	Hawthorn Fm.; Edisto Fm.
OLIGOCENE	Chattian ?——?	Chickasawhayan		Suwanee Limestone		Chandler Bridge Fm.; Cooper Fm. (Ashley Member)
OLIGOCENE	Rupelian	Vicksburgian				
EOCENE	Priabonian	Jacksonian	Ocala Limestone	Barnwell Fm.	Barnwell Group	Barnwell Fm. / Cooper Fm. (Parkers Ferry Harleyville Members) ?
EOCENE	Bartonian		Moody's Branch	? ?		?
EOCENE	Lutetian	Claibornian	Lisbon Fm.	Lisbon/McBean Fm.	McBean Fm.	McBean Fm. / Santee Limestone
EOCENE	Ypresian		Tallahatta Fm.; Hatchetigbee/Bashi Fms.	Huber Fm.	Congaree Fm. ? ?	Congaree Fm.; Fishburne Fm.
PALEOCENE	Thanetian	Sabinian	Tuscahoma Fm.; Nanafalia/Baker Hill Fm.			Black Mingo Fm. / Black Mingo Group (of Van Nieuwenhuise and Colquhoun)
PALEOCENE	Danian	Midwayan	Porters Creek Fm.; Clayton Fm.		Ellenton Fm.	Ellenton Fm.

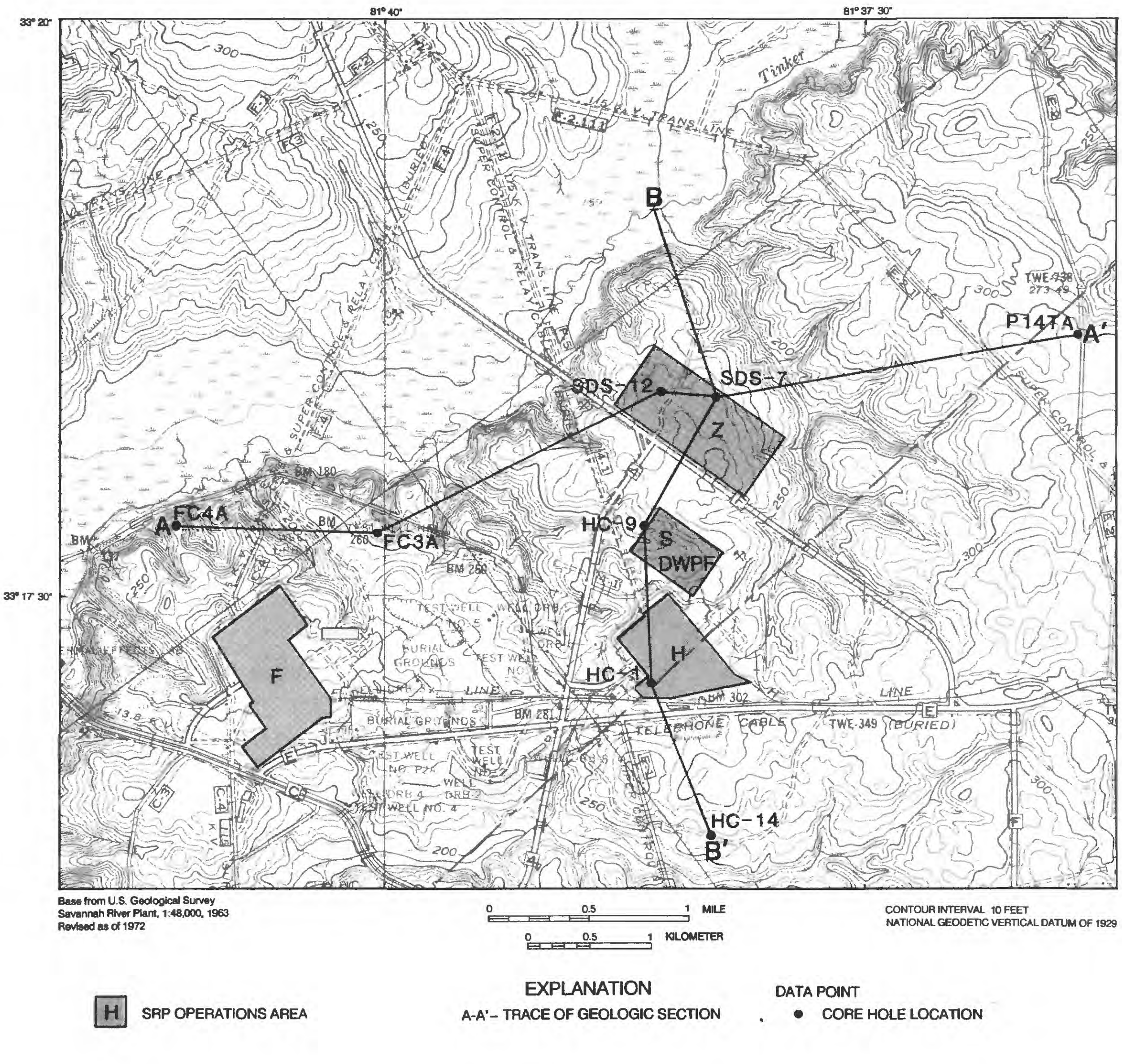


Figure 5.--Location of wells used in Defense Waste Processing Facility geologic investigation and geologic section along A-A' and B-B'.

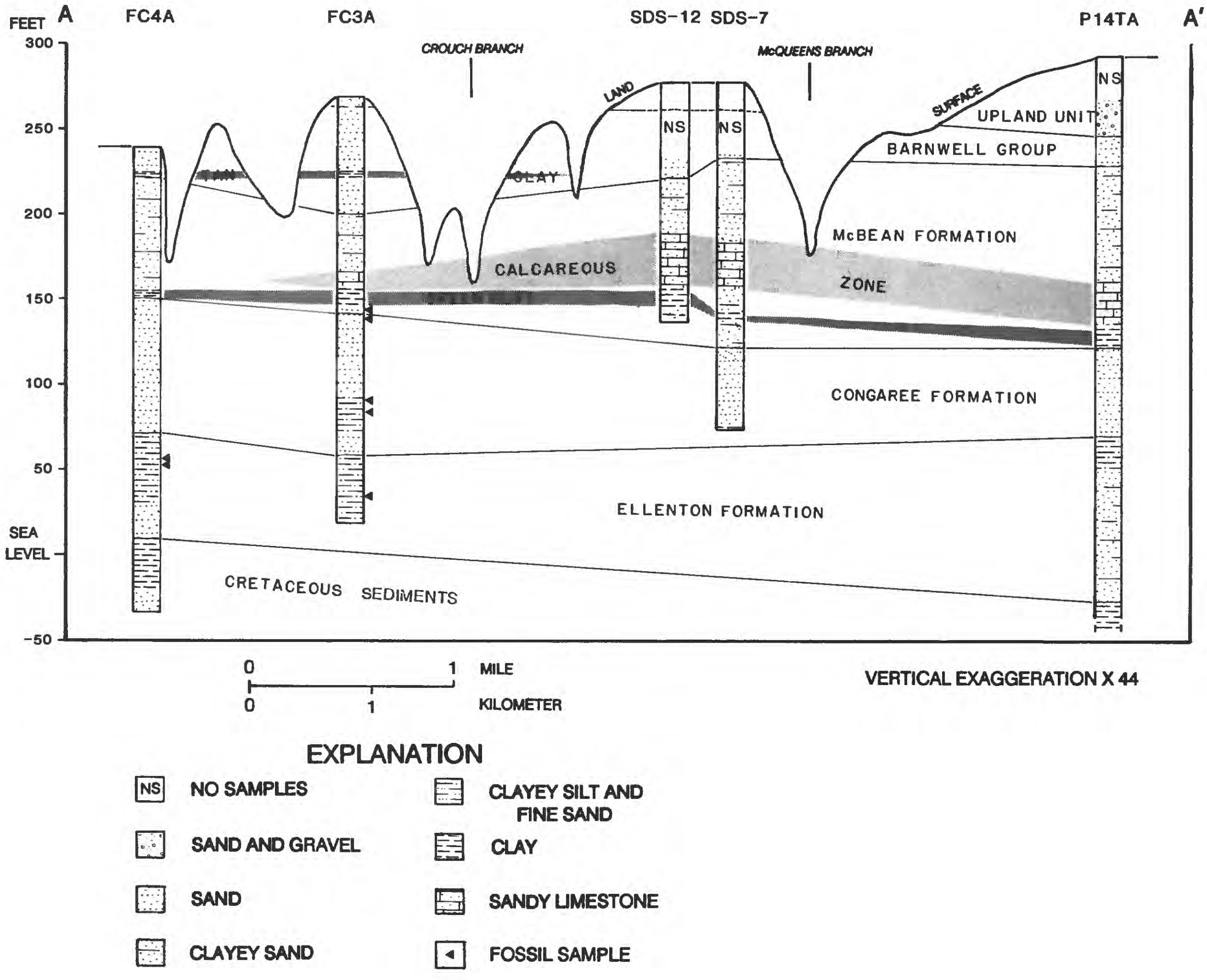


Figure 6.--Geologic section along line A-A'.

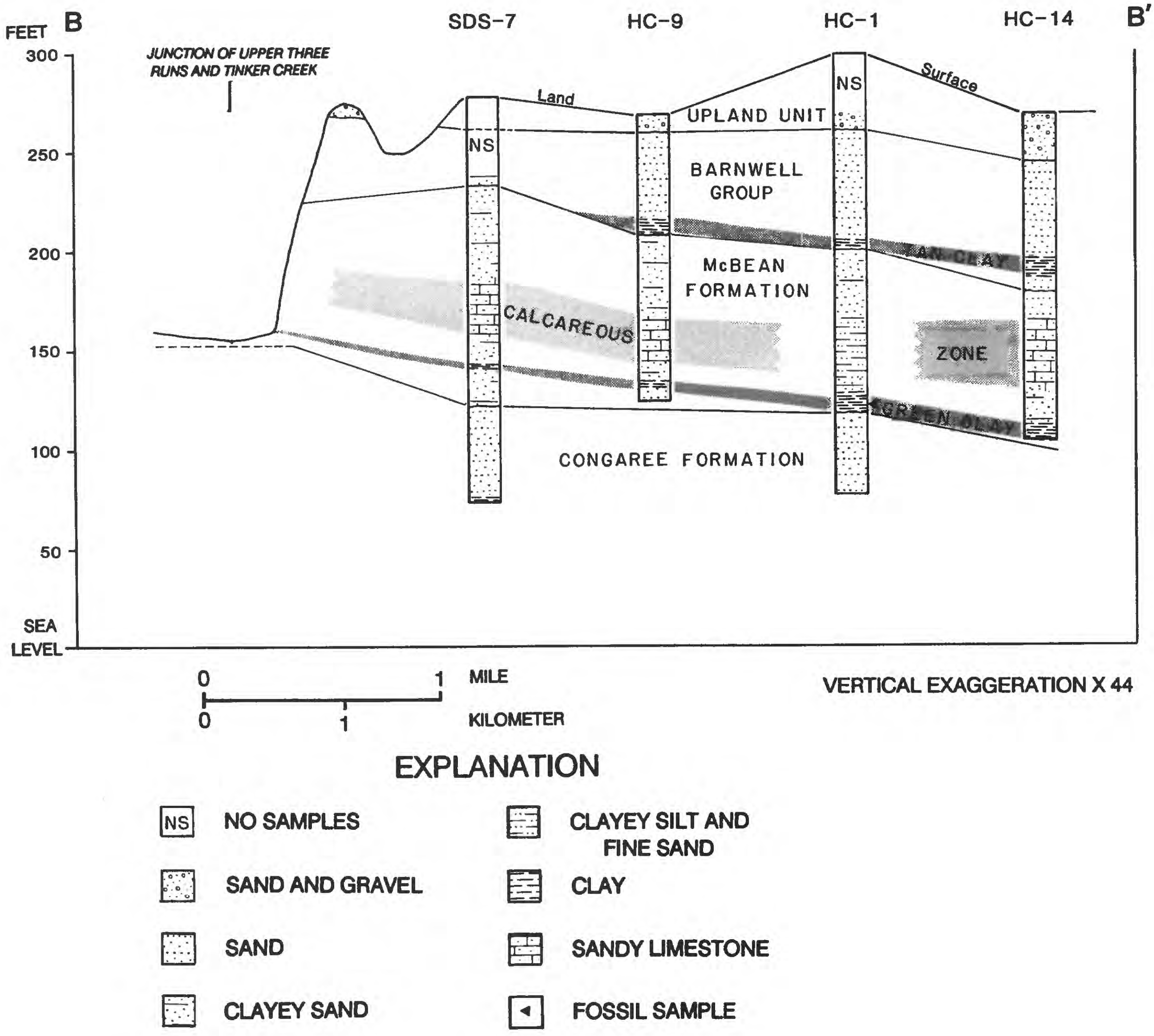


Figure 7.--Geologic section along line B-B'.

Ellenton are highly carbonaceous and are dark gray to black. These carbonaceous clay beds are typically less than 5-ft thick and are well-laminated. Some sandy beds contain fragments of lignite in the coarse size fraction, but these beds are not very common. Finely disseminated carbon probably contributes to the characteristic pale-gray color of the upper Ellenton described by Siple (1967). The Ellenton is typically off white in the absence of carbonaceous material, but it is light green or yellowish green in layers where cristobalite is abundant.

The unconformity at the base of the Ellenton is typically marked by a thin bed of very coarse sand and (or) gravel, but it is most easily recognized on the basis of the appearance of the underlying Cretaceous section defined by Prowell and others (1985a). Commonly, the top of the Cretaceous is characterized by red- to orange-stained clay, but where this oxidized clay is absent, the basal sands of the Ellenton can be difficult to distinguish from underlying Cretaceous sand. In areas where the stained clays are absent, Cretaceous sand is commonly reworked into the lowermost Ellenton, obscuring any abrupt change in lithology. The presence of sillimanite, feldspar, and cristobalite is the best indication that the sand is part of the Ellenton Formation and not the underlying Cretaceous strata.

The lithologic character of the formation and the presence of a marine palynoflora with abundant carbonaceous material suggest that the Ellenton was deposited in a marginal-marine, deltaic environment. The lithology and depositional environment of the Ellenton are most like those of the lower part of the Huber Formation (table 1) in east-central Georgia, which suggests that the Midwayan (Paleocene) fluvio-marine, deltaic deposition described by Prowell and others (1985a) extends across the SRP.

Age

Siple (1967) implied that the Ellenton Formation was probably Late Cretaceous on the basis of lithologic similarity to underlying Cretaceous strata. He also suggested that the Ellenton might be Paleocene, as did Colquhoun and others (1982, 1983), but neither offer paleontologic evidence to support their assumptions. This age designation was first proven and refined by Prowell and others (1985b) from samples on the SRP. Prowell and others (1985b) sampled the carbonaceous clay layers of the Ellenton Formation from well FC-3A (fig. 5) (U.S. Geological Survey Paleobotanical Locality R3038) at altitudes of 34 and 37 ft above sea level to analyze the dinoflagellate and pollen assemblages. The cored holes at the DWPF were not deep enough to reach the Ellenton section, so we extrapolated the stratigraphic information of Prowell and others (1985b) into the area on the basis of lithologic continuity (fig. 5).

The diverse, well-preserved floral assemblages reported by Prowell and others (1985b) indicate that deposition of the Ellenton was in the middle part of the Midwayan Provincial Stage. This suggests a correlation with the Clayton, and (or) Porters Creek Formations in Georgia and Alabama and the Naheola Formation in Alabama (Edwards, 1980), the Brightseat Formation in Maryland, the Rhems Formation of the Black Mingo Group in coastal South Carolina (Van Nieuwenhuise and Colquhoun, 1982), the lower part of the Huber Formation in central and eastern Georgia (Buie, 1978, 1980), and the P_1 unit of Prowell and others (1985a) in westernmost South Carolina and eastern Georgia.

Congaree Formation

Nomenclature

The name "Congaree" was first used by Sloan (1908) to describe sands and clays in central South Carolina near the Congaree River. Veatch and Stephenson (1911) extended the use of the term to "Congaree Clay", which was the basal member of their McBean Formation. Cooke and MacNeil (1952) established the "Congaree Formation" to define "shale," "brittle siltstone," and "well- to poorly-sorted sand" that resembled the Tallahatta Formation of Alabama and Mississippi and was separated from the overlying McBean Formation by an erosional contact. The different application of the name Congaree Formation by various authors is described by Huddlestun (1982). Siple (1967) recognized the differences between the strata at McBean Creek (McBean Formation) along the Savannah River and the underlying moderately-sorted clayey sand (Congaree Formation), and he also recognized the need to place an erosional contact between the two formations. Siple, apparently realizing the confusion in nomenclature, combined the two formations for his discussion of the SRP. Siple (1967) was clear, however, in his definition of the Congaree Formation on the SRP, and it is not the Twiggs Clay (of the Barnwell Formation) as suggested by Huddlestun (1982). Through geologic mapping and paleontological control, Siple's SRP Congaree Formation is interpreted to be the downdip equivalent of the Eocene part of the Huber Formation of Buie (1978) mapped in outcrop immediately north of the SRP by Nystrom and Willoughby (1982).

Lithology

The Congaree Formation in the vicinity of the DWPF is about 50- to 70-ft thick and is comprised of moderately-sorted quartz sand in a buff to light-gray clay matrix. The sand is largely fine to coarse, subangular to subrounded quartz with small quantities of very fine, dark, heavy minerals and mica. The heavy-mineral assemblage of the sand is characterized by sillimanite, ilmenite, staurolite, rutile, garnet, and magnetite. The mica is present throughout the formation, but is generally more prevalent in the clay-rich intervals. Mica grains are generally small, but some individual flakes are quite large. The sand occurs in thin beds, a few inches to a few feet thick, and bedding is generally flat to weakly cross bedded. The sand is enclosed in a slight to moderate clay matrix, which is largely off-white kaolin. Oxidation of iron-bearing, heavy minerals can stain the matrix pale orange, or more commonly, the clays may be light gray owing to finely disseminated carbonaceous matter. Field observations of this formation in tributaries to Upper Three Runs show that thin (0.25 in.), clay-enriched, silty laminae are present in at least the upper part of the unit. In addition, the clay-coated walls of burrows of marine organisms can also be seen in local outcrops.

The clay-enriched laminae seen in outcrop are not readily visible in cores in the vicinity of the DWPF, but thicker clay layers are present and more prominent. Throughout the cored Congaree section, thin, distinct beds of clay, 0.5- to 2-ft thick, are found every 10 to 20 ft. These beds are typically well-laminated, silty clay and may be very carbonaceous. The medium to dark-gray color of these clay beds is a dramatic contrast to the white clayey sands of the formation.

Lithologically, the Congaree Formation of the SRP most closely resembles the Eocene part of the Huber Formation as described by Nystrom and Willoughby (1982), and lithologic unit E_3 of Prowell and others (1985a) at the southern end of the SRP. The moderate number of marine microflora and evidence of burrowing in outcrops indicates that the Congaree was deposited in a shallow open-marine environment. The correlation of the Congaree strata at the SRP with the Eocene part of the Huber Formation provides important information about depositional environment. Nystrom and Willoughby (1982, p. 144, beds 4a-5a) report Congaree lithologies immediately updip of the SRP in the lower part of their Huber section. The Huber strata consist of poorly sorted, cross bedded to thinly laminated clayey sands and massive kaolin beds deposited in a delta plain environment. The thin laminations, slight cross bedding, and marine biologic activity in the Congaree strata downdip of the Huber outcrop imply that the Congaree was deposited in the shallow-water marine delta front of this Eocene delta.

Age

Siple (1967) placed the Congaree Formation of the SRP in the middle Eocene (Claiborne) on the basis of work by Cooke and MacNeil (1952) in central South Carolina. Megafossils are not present in the Congaree at the SRP and Siple (1967) had no direct way of dating any of the strata. Core samples from well FC-3A (fig. 5) at 141 and 91 ft above sea level were collected to help establish an exact age of the strata. The dinoflagellate flora places these samples low in the middle Eocene or in the lower two thirds of the Claibornian Stage (L. E. Edwards, U.S. Geological Survey, written commun., 1983). This age determination correlates the Congaree Formation at the SRP with the upper part of the Tallahatta Formation and the lower part of the overlying Lisbon Formation of western Georgia and eastern Alabama. The Congaree is also correlative with the Eocene part of the Huber Formation (Buie, 1978; 1980) in eastern Georgia and updip western South Carolina, and the lower part of the Santee Limestone in eastern South Carolina.

McBean Formation

Nomenclature

The McBean Formation was named by Veatch and Stephenson (1911) for exposures of marine strata along McBean Creek, a tributary of the Savannah River, in Burke County, Georgia. Sloan (1908) recognized the calcareous and fossiliferous McBean lithologies as being correlative with the upper middle Eocene Santee Limestone and Warley Hill Formation in South Carolina, but Veatch and Stephenson (1911) applied the new formation name (McBean Formation) because of inconsistencies in regional correlations. Shearer (1917) and Cooke and Shearer (1918) recognized that part of the section originally included in the McBean Formation was actually late Eocene and should be included in the Barnwell Formation (Group). Cooke and Shearer (1918) generally restricted their usage of McBean Formation to the typically calcareous and fossiliferous outcrops along McBean Creek and at Shell Bluff on the Savannah River, but they did not exclude the noncalcareous, unfossiliferous sands and clays that accompany the calcareous deposits. As a result of the progressive loss of calcareous strata in the McBean from Georgia into South Carolina, Cooke (1936) extended the use of the name McBean well into South Carolina and included sands and clays of parts of the Barnwell Formation (Group) and Congaree Formation. Therefore, his stratigraphic relations made it difficult to distinguish and map the Barnwell, McBean, and Congaree into central South Carolina. Cooke and MacNeil (1952) tried to correct the stratigraphic misconceptions by restricting the McBean Formation to age-equivalent sediments of the Cook Mountain Formation in Texas and Mississippi. Cooke and MacNeil (1952), however, failed to recognize the problem of overlapping lithofacies and again included sediments (Twiggs Clay) from the basal Barnwell strata in the McBean.

Siple (1967) must have realized the confusion concerning the definition of the McBean strata and chose to combine the McBean and Congaree Formations on the basis of the water-bearing properties for the purpose of his report. Siple (1967, p.45), however, identified five lithologies (1. polished quartz sand, 2. glauconitic marl, 3. laminated montmorillonitic clays, 4. soft, fossiliferous limestone, and 5. lenses of silicified limestone) that are found in sediments of Claibornian age on the SRP. These lithologies are generally confined to the McBean Formation of this report. Huddlestun (1982), however, describes the McBean Formation as a single lithology on the basis of one remaining outcrop at the type locality. Huddlestun (1982, p.29) states of Siple (1967) that "only lithology (4), impure beds of soft fossiliferous limestone or marl is consistent with McBean lithology," but we regard the McBean as a sedimentary sequence of several lithologies marked above and below by depositional unconformities.

Lithology

An examination of the McBean Creek area shows many of the same lithologies described by Siple (1967). The base of the McBean sequence is marked by a thin bed of coarse, angular sediment containing nodular iron concretions. Borings of marine organisms have carried the overlying polished quartz sand down into kaolinitic clays of the Congaree Formation (Huber). The basal part of the McBean is characterized by beds of moderately-sorted, cross-bedded quartz sand and fine gravel, and well-laminated beds of green montmorillonitic clay and orange sand. Some sandy layers contain glauconite and phosphate and polished blue quartz grains. Where carbonate cementation is extensive, the McBean contains sandy limestones and marls that commonly include preserved shell molds of mollusks. The upper part of the McBean is composed of thinly laminated green clays and coarse sands containing shell ghosts, and is easily confused with the basal sediments of the overlying Barnwell Formation (Group). The base of the Barnwell, however, does not contain shell ghosts and oxidation spots from weathering glauconite, and is clearly marked by a thin lag bed on the basal unconformity. The McBean strata in the vicinity of the type section are so similar to the age-equivalent strata at the SRP that we retained use of the formation name in this report.

The base of the McBean Formation in the vicinity of the DWPF is marked by a 12-in. thick lag bed of poorly-sorted, coarse quartz sand, gravel, and other marine debris. This contact is well exposed in a tributary to Upper

Three Runs located immediately east of well FC-4A (fig. 5). Above this lag bed is typically 4 to 8 ft of moderately-sorted, subrounded quartz sand in a matrix of dark-green clay. Glauconite and highly polished grains of blue quartz are common in this sand. In the vicinity of the DWPF, a 2- to 6-ft thick layer of dense, dark-green, illite/smectite clay overlies this basal sand. This clay is the "green clay" reported by Root (1980) and forms a more or less continuous confining bed beneath the DWPF and H Area (figs. 6 and 7). The green clay is not a discrete clay bed, but rather a series of thin clays interlayered with sandy clays. Hence, the green clay zone may thin and thicken, and grade laterally into the McBean sands. This occurs between wells SDS-12 and P14TA (fig. 6). The irregularity of the green clay zone near well SDS-7 (fig. 6) must be the result of deposition due to the uniformity of other contacts above and below.

Above the green clay is about 30 ft of fine-grained, well-sorted white quartz sand containing significant amounts of white mica and fine, dark, heavy minerals. The typical heavy minerals in the McBean are ilmenite, leucoxene, zircon, sillimanite, kyanite, monazite, and magnetite. West and south of the DWPF (in wells HC-1A, FC-4A, and area outcrops), the fine, white sand has a matrix of pale-green clay, whereas east of the F Area (in well FC-3A) the matrix is largely calcium carbonate (calcareous zone of figs. 6 and 7). In the areas where the matrix is clay, the sand is light green and is commonly burrowed. Fine glauconite may be present in small amounts. Where the matrix is calcium carbonate, the sand is very white and moderately to well cemented. Sandy limestone is present in this interval in the SDS wells and well P14TA (fig. 5), and this lithology commonly contains the fossilized shells of mollusks and pelecypods.

The calcareous beds in the McBean have lost their calcium carbonate cement in outcrop exposures along Upper Three Runs Creek and in well HC-1A (fig. 7). These strata commonly crop out as clayey sands and are typically less cemented by silica. In the case of surface exposures, the carbonate was probably removed during weathering of the bluff along Upper Three Runs Creek and the replacement silica derived from alteration of the montmorillonitic green clay to kaolinite. The absence of calcium carbonate in well HC-1A, however, is more difficult to explain. Possibly the influx of clayey silt and fine sand in HC-1A prohibited the precipitation of limestone, or possibly the limestone was eroded by channel currents and the old channel refilled with sand. The limestone also may have been removed by post-depositional migration of ground water, but this process is seldom so selective.

The fine white sand and (or) sandy limestone is overlain by 30 to 40 ft of fine to coarse, angular to subangular, quartz sand in a medium-green to ochre-colored clay matrix. Larger quartz grains tend to be polished and well-rounded, and are commonly associated with large mica flakes. This sand contains the same suite of heavy minerals discussed in the previous paragraph, and commonly has moderate amounts of glauconite as well. The upper sands of the McBean are poorly sorted and are characterized by dark-brown to black spots probably caused by the weathering of glauconite or phosphate grains. The matrix clays are largely illite/smectite and are devoid of calcium carbonate. In outcrops just east of F Area, the upper sands contain shell ghosts, and the bedding in this area is laminar to slightly cross bedded. The top of the McBean Formation is present in the large roadcut immediately east of F Area on SRP road "C" about one-third of the way up from the road base. The uppermost McBean beds are truncated by a 2-ft fossiliferous lag bed marking the unconformity at the base of the Barnwell Formation (Group).

The marine megafossils and microfossils, glauconite, burrows of marine organisms, illite/smectite clays in thin but extensive layers, and sandy limestone indicate that the McBean was deposited in a near-shore, marine environment. The variability of facies and lithology, however, suggests that local changes in water depth and other characteristics of deposition were not uncommon. The various McBean lithofacies can be taken to reflect shallow-shelf to restricted marine deposition. The green clay and sand at the base of the formation could reflect back-barrier and tidal channel deposits during transgression of a late Eocene sea. The fine, white sand and sandy limestone above these deposits are probably shallow-shelf, open-marine deposits, and the fine to coarse, clayey sands at the top of the sequence are probably shoreface deposits left during regression. The upper shoreface and foreshore deposits were probably removed by the late Eocene (Barnwell Group) transgression.

Age

Siple (1967) placed the combined McBean and Congaree Formations in the middle Eocene (Claiborne) based on work by Cooke and MacNeil (1952). Cooke and MacNeil (1952, p. 24) restricted the McBean to the late Claiborne, making it equivalent to the Cook Mountain Formation in Texas and Mississippi. Siple (1967), however, did not report any age determinations from the megafossils found in outcrops at the SRP. A core from the "green clay" in well FC-3A at an altitude of 145 ft above sea level (fig. 6), had a moderate dinoflagellate assemblage. The assemblage is indicative of the upper part of the middle Eocene (late Claibornian) (L. E. Edwards, U.S. Geological Survey, written commun., 1983). This age assignment indicates that the McBean Formation at the SRP is the equivalent of the McBean Formation at the type locality, unit E_5 (see table 1) of Prowell and others (1985a) in western South Carolina, the upper part of the Santee Limestone of eastern South Carolina, the Castle Hayne Formation of North Carolina (Prowell and others, 1985b), and the upper part of the Lisbon Formation of western Georgia.

Barnwell Group

Nomenclature

Sloan (1907, 1908) first used the name "Barnwell Phase" to describe sands, glauconites, and ferruginous sandstones overlying middle Eocene carbonates in South Carolina. Cooke (1936) adopted the term "Barnwell Formation" to describe the updip Eocene sands in western South Carolina that overlie his McBean Formation, but did not establish a type locality and was vague about the formation lithologies. This was probably because the Barnwell as defined by Sloan (1908) and Cooke (1936) included strata now assigned to the McBean Formation. Cooke considered the Barnwell Formation to be late Eocene and this age assignment has been followed by subsequent workers such as Cooke and MacNeil (1952), Siple (1967), Colquhoun and Johnson (1968), Nystrom and Willoughby (1982), and Huddlestun and Hetrick (1979, 1986). Huddlestun and Hetrick (1979) suggested that the Barnwell Formation be changed to Barnwell Group to accommodate various new upper Eocene units and eliminate some problems in lithostratigraphy. Presently, their Barnwell Group in the outcrops at the SRP consists of two units: (1) the Tobacco Road Sand and (2) the underlying Dry Branch Formation of Huddlestun and Hetrick (1986). Their Dry Branch Formation consists of the Twiggs Clay Member and the Irwinton Sand Member of the Barnwell Formation of LaMoreaux (1946) (also the usage of the U.S. Geological Survey) in eastern Georgia. We are herein, using Huddlestun's and Hetrick's rank of Barnwell Group and associated nomenclature for the purpose of this report in the study area.

The Barnwell Group at the SRP is not difficult to subdivide in outcrop, but it is extremely difficult to differentiate in drill cores described in this report. The recovery of the Barnwell sands is fair in drill cores, but the differentiation of the two formations depends on depositional characteristics as well as lithology. The contact between the Tobacco Road Sand and the underlying Dry Branch Formation is well exposed near the top of the large outcrop immediately east of F Area, but this contact could not confidently be traced through the available drill cores. Therefore, for the purpose of this report the Barnwell Group is shown on illustrations as one geologic unit, but it contains the differing lithologies as described in the following text.

Lithology

The base of the Barnwell Group at the SRP is marked by a 2-ft thick unconformable lag bed consisting of very coarse, angular quartz sand, quartz gravel, perforated shell fragments, carbon fragments, and other debris remaining after the transgressive erosion of the underlying geologic formations by a late Eocene sea. The shell fragments are derived from the McBean Formation, whereas the coarse sand and gravel are probably from updip Cretaceous and Paleocene beds. This contact is well exposed in the large outcrop on SRP Road "C" immediately east of F Area, and at the base of a large erosional ditch about 500 ft west of this road cut. Above this basal unconformity is about 4 ft of moderately-sorted, fine to medium, orange to brown sand that is generally massive. Atop this sandbed is a 2- to 10-ft thick bed of laminated, tan to pale-green clay that is relatively continuous in the central SRP. This clay is the "tan clay" described by Root (1980, 1981). Unlike the "green clay", the tan clay is largely kaolinite and tends to be sticky and plastic rather than slick and brittle. The tan clay also tends to be oxidized (by weathering or ground water), and any fossils or organic matter have been destroyed.

The tan clay grades upward into interbedded sands and very thin clays. The fine to medium quartz sand is moderately to well sorted, and occurs in thin, flat beds about 0.5 to 6 in. thick. The sand is angular to subangular and contains mica and dark heavy minerals. The heavy mineral suite is characterized by brown ilmenite, zircon, brown hornblende, biotite(?), staurolite, sillimanite, kyanite, and magnetite. The thin clay beds are very thinly laminated and irregular. The clay in these beds, as well as the matrix clay in the sand, is almost entirely kaolinite. This sequence of interbedded sands and clays is commonly 10- to 30-ft thick and the average grain size coarsens upward. Outcrops of this lithology show little or no evidence of burrowing organisms or remnants of shells. This lithology is correlative with the Dry Branch Formation of Huddlestun and Hetrick (1979).

The laminated sands and clays of the Dry Branch Formation are overlain by poorly to moderately sorted, fine to very coarse, quartz sand. Several layers of ovoid-shaped gravel commonly mark the transition between the two lithologies. These upper sands typically have angular to subangular grains in a slight clay matrix. Mica and dark heavy minerals are also present in the quartz sand. Brown ilmenite and sillimanite are very abundant in the typical heavy-mineral assemblage along with zircon, rutile, brown hornblende, and staurolite. Cross bedding, white kaolin clasts, and thin wisps of white clay are characteristic of this lithofacies. Unlike the sands and clays below, these upper sands are typically burrowed, commonly to the point of obscuring bedding.

The base of the Tobacco Road Sand of Huddlestun and Hetrick (1979) is placed at the first gravel bed separating the interbedded sands and clays from coarse, highly burrowed, poorly sorted sands above; therefore, these upper Barnwell sands are considered to correlate with the Tobacco Road Sand. This basal gravel is interpreted to represent a depositional unconformity of unknown age range. Huddlestun and Hetrick (1979) considered this contact to be of little time significance, but its importance can change with the interpretation of the age of the Tobacco Road strata.

The sorting and bedding in the Barnwell strata and the evidence of burrowing organisms suggest that these sediments were deposited in a shallow, near-shore marine environment. The tan clay and the interbedded sands and clays in the base of the Barnwell are most easily interpreted as tidal flat and back-barrier deposits at the edge of a transgressing sea. The tan clay could be a back barrier accumulation and the interbedded sands and clays from a tidal flat. This would explain the sedimentary characteristics of the strata and the lack of bioturbation. The gravel beds at the base of the Tobacco Road strata probably reflect the unconformity produced as the transgressing beach environment overlapped the barriers and tidal flats. The highly burrowed and cross-bedded sands of the Tobacco Road reflect an open marine shoreface environment that was preserved by subsequent regression of the sea. However, depending on the age of the Tobacco Road Sand, these shoreface deposits may be remnants of a post-Eocene invasion of the sea.

Age

The age of the Barnwell Group could not be established in the vicinity of the DWPF because of the absence of datable samples. The two formations at the SRP, however, are the lithologic equivalents of units E_7 and E_8 (see table 1) of Prowell and others (1985a) in western South Carolina. Huddlestun and Hetrick (1986) report that the age of the lower Barnwell strata in Georgia is late Eocene. This age determination correlates the Barnwell with the Ocala Limestone of southern Georgia and Florida and the Eocene part of the Cooper Formation of eastern South Carolina. The upper formations of the Barnwell Group, particularly the Tobacco Road Sand, are difficult to date and therefore could be younger than late Eocene. Prowell and O'Connor (1978), Zullo and others (1982), and Nystrom and others (1986) offered inconclusive evidence that the Tobacco Road Sand may be as young as late Oligocene or Miocene. Although the late Oligocene age would correspond with the deposition of the upper part of the Cooper Formation in eastern South Carolina, we favor the age of the Barnwell Group being shown as late Eocene until better biostratigraphic evidence is available.

Upland Unit

Nomenclature

Sloan (1907, 1908) noted the extensive fluvial deposits in Aiken and Barnwell Counties, S.C., and included them in his Lafayette phase deposits of presumed Pleistocene age. These deposits were not reported by Cooke (1936), but were noted by Lang (1940) and Siple (1967). Siple equated these deposits with the Hawthorn Formation of Cooke (1936), but states, "The designation of the deposit herein described as the Hawthorn Formation has been subject to as much difference of opinion as that concerning the Barnwell Formation." Thus, he had almost no direct lithologic or paleontologic evidence of the association of his "Hawthorn" with other strata in the Southeast. In addition, he recognized that the type-Hawthorn Formation was composed of phosphatic marl and sandy limestone; nevertheless, he chose to assign the name to the fluvial deposits at the SRP. In 1982, regional mapping by Nystrom and Willoughby (1982) and Kite (1982) showed the widespread distribution of these fluvial deposits updip of the SRP in Aiken County, S.C. They informally referred to their fluvial deposits as the "upland unit." However, Nystrom and Willoughby (1982, p. 106) mistakenly correlated their upland unit with "alluvial deposits of late Tertiary age" described by Siple (1967, p. 62, 63), and discussed later in this report. In fact, the upland unit on their maps projects directly into the "Hawthorn Formation" mapped by Siple (1967, pls. 1 and 3). We choose to use the informal term "upland unit" in this report, to avoid the stratigraphic and lithologic connotations of the name "Hawthorn."

Lithology

The upland unit was deposited in a high-energy, highly variable fluvial depositional environment. The deposits conform to the shapes of large stream and river channels with extensive cross cutting and refilling. The lithologic variability of fluvial deposits makes a singular description difficult, and the scour and fill structure eliminates any vertical stratigraphy. The upland unit at the SRP is characterized by three predominant lithofacies: (1) beds of gravel, cobbles, and poorly-sorted, cross-bedded sand, (2) beds of cross-bedded, fine to very coarse sand and grit containing clay clasts and in-situ-weathered feldspars, and (3) brightly colored, massive beds of sandy clay. These lithofacies are described in this order in the following text, but they can occur in any vertical or horizontal sequence in local outcrops and drill holes.

The coarser lithofacies of the upland unit is characterized by gravels and cobbles ranging in diameter from 0.5 to 4 in. These cobbles consist almost exclusively of Piedmont polycrystalline vein quartz, whereas almost all of the gravel in older units is crystalline clear and smokey quartz. The gravels are typically found in a matrix of fine to very coarse, clayey, quartz sand containing abundant mica and white clay balls. The gravels outline the shapes of old fluvial channels with the larger cobbles nearer the base. The clayey sands are generally cross bedded and are best developed between the beds of finer gravel. This lithology is best developed on the north end of the SRP with a decrease in the number of cobbles to the south.

The most common lithofacies in the upland unit is highly cross-bedded, fine to very coarse sand and grit containing large micas and weathered feldspars. The sand and grit generally consists of angular to subangular quartz found in a matrix of kaolinitic clay and large mica flakes. White kaolinitic clay balls are also common in this lithology and may range from coarse sand to cobble size. The sands also contain iron-bearing heavy minerals that have oxidized and given the upland unit a distinctive red-on-white color. This lithology is characterized by small (0.2 in.) square to rhombohedral white clay clasts formed by the in-situ weathering of feldspars. These clasts give the typically pale to medium-red sands an unusual spotted appearance and were reported by Siple (1967, p. 57, 58) as features of his Hawthorn Formation. Siple (1967, p. 60) also reported large clay-lined noded burrows in this unit on the southeastern end of the SRP. We found similar burrows in this unit southeast of the DWPF outside of the SRP boundary, which have been interpreted to suggest an estuarine environment for parts of the upland unit.

The last lithofacies in the upland unit is massive sandy clay that typically fills channels south of the DWPF. The clay shows very little evidence of bedding and surprisingly little lithologic variation. The small percentage of sand in the clay is generally coarse, angular quartz evenly dispersed throughout the surrounding clay. This unit has a characteristic hackly fracture probably owing to cyclic hydration and dessication. Very fine, dark, heavy minerals within the clay apparently have oxidized and stained the unit intense shades of red, orange, yellow, and purple.

The strong cross bedding, poor sorting, and channel-form deposits of the upland unit reflect fluvial deposition in a large river system. Regional mapping by Nystrom and Willoughby (1982), Nystrom and others (1986), and Prowell (unpublished data) indicates that the upland unit is present in Aiken, Barnwell, and Allendale Counties, S.C., and in Burke and Screven Counties, Ga. The map patterns suggest that a large ancient river system may have existed along a north-south axis near the present Savannah River drainage basin. The angular in-situ-weathered feldspars suggest that this drainage system quickly eroded fresh rock sources in the Piedmont. The burrows present in the upland unit immediately southeast of the SRP indicate that this river network flowed into a nearby sea and formed estuaries as far north as Dunbarton. This observation explains the decrease in the amount of coarse gravel in the upland unit on the south end of the SRP because of the lower stream gradients and current velocities in a fluvio-estuarine environment.

Age

The age of the upland unit is the subject of considerable controversy because of the total absence of fossils in the various lithofacies. Siple (1967) tentatively assigned this unit (his Hawthorn Formation) a Miocene age through downdip correlation with Hawthorn deposits exposed along the Savannah River in Effingham County, Ga. This is consistent with Cooke and MacNeil's (1952) reference to Hawthorn strata in a railroad cut near Dunbarton at the SRP. The true Hawthorn, however, is a carbonate-rich open marine deposit unlike any of the lithologies in the upland unit. Colquhoun and Steele (1985) considered the upland unit as a regressive phase of the Barnwell Group deposition, and by association, applied a late Eocene age. Nystrom and others (1986) favor downdip correlation with the middle Miocene Altamaha Formation (post-Hawthorn) of Huddlestun (1985), whereas McCartan and others (1984) offer evidence that the upland unit may be as young as Pliocene. At the present time, the age of the upland unit is best classified as Miocene or younger.

Colluvium and (or) Alluvium

Nomenclature

A variety of surficial deposits present in the vicinity of the DWPF can generally be classified as colluvium and(or) alluvium. In addition, part of the material mapped as colluvium on top of interfluvial areas can be called residuum. Siple (1967) recognized these deposits throughout the SRP and termed them "alluvial deposits of late Tertiary age." Newell and others (1980) extensively studied similar deposits updip of the SRP and concluded that they were the result of weathering, mass wasting, and aqueous transport of high-level strata down to local drainages. Where the sediment exhibited fair sorting, bedding of sands and clays, and flow-induced features such as cross bedding, the deposits were classified as alluvium. Where the sediments were massive to poorly stratified, poorly sorted, and devoid of clay layers, the deposits were called colluvium. The colluvial deposits mapped by Newell and others (1980) were largely confined to hill tops and sides, whereas alluvial deposits were typically in valley bottoms. We found the same general distribution of alluvium and colluvium in the DWPF study area.

Lithology

The colluvium and (or) alluvium in the DWPF study area is not one large sedimentary deposit but rather numerous small remnants left by progressive mass-wasting of the land surface. Hence, they are discontinuous masses and their lithology is directly determined by the lithology of the older strata being eroded. Generally, the lithologies of the colluvial deposits are correlative with the strata in the Barnwell Group (Huddlestun and Hetrick, 1986), whereas the alluvium also contains materials from upland deposits and the McBean Formation. Most of the colluvium and the older alluvial deposits can be distinguished from the regional Coastal Plain strata on the basis of plinthites. Plinthites are well-rounded, iron-cemented sand nodules formed by the erosion and transport of iron-rich layers from modern soil profiles. They are not present in regional geologic formations, but are typically abundant in local surficial deposits (Newell and others, 1980).

The alluvium is largely confined to the valley bottom of Upper Three Runs and local tributaries such as McQueens Branch (fig. 2). These deposits consist of fine to medium quartz sand that has fair to moderate sorting. Small amounts of mica are present in the sand but dark, heavy minerals are generally absent. Thin layers of clay occur in swampy areas and small-scale cross bedding is present in old channel fills. Older channel deposits may contain well-rounded to ovoid, quartz gravels from either the upland deposits or the Tobacco Road Sand, whereas younger sand deposits contain rounded, blue quartz grains from the McBean Formation.

The colluvium is best developed on the sides of stream interfluves and is relatively thin on hill tops. Modern downcutting in local drainages has truncated the toes of the old colluvial deposits providing good exposures 5- to 10-ft above present stream level. The colluvium in the DWPF study area largely consists of unsorted to poorly sorted, fine to very coarse, quartz sand in a matrix of dense red clay. The deposits are characteristically massive to very weakly stratified in a downslope direction. Mica is present in the intervals lacking clay, and dark heavy minerals are absent. Distinct clay layers and clay clasts are absent and the deposits are highly oxidized (red). Colluvial deposits generally conform to the shape of old stream valleys but some have eroded into positive topographic features. Newell and others (1980) noted that weathering and oxidation of colluvial strata can "harden" the deposits so that they are more resistant to erosion than surrounding materials. Hence, post-oxidation erosion can result in a topographic reversal due to the stability of the resistant colluvium. In general, most of the natural hillsides along Upper Three Runs and its major tributaries are covered with colluvium that vary in thickness from a few feet to as much as 20 ft. Only the thickest deposits were included on the surface geologic map in this report (fig. 8).

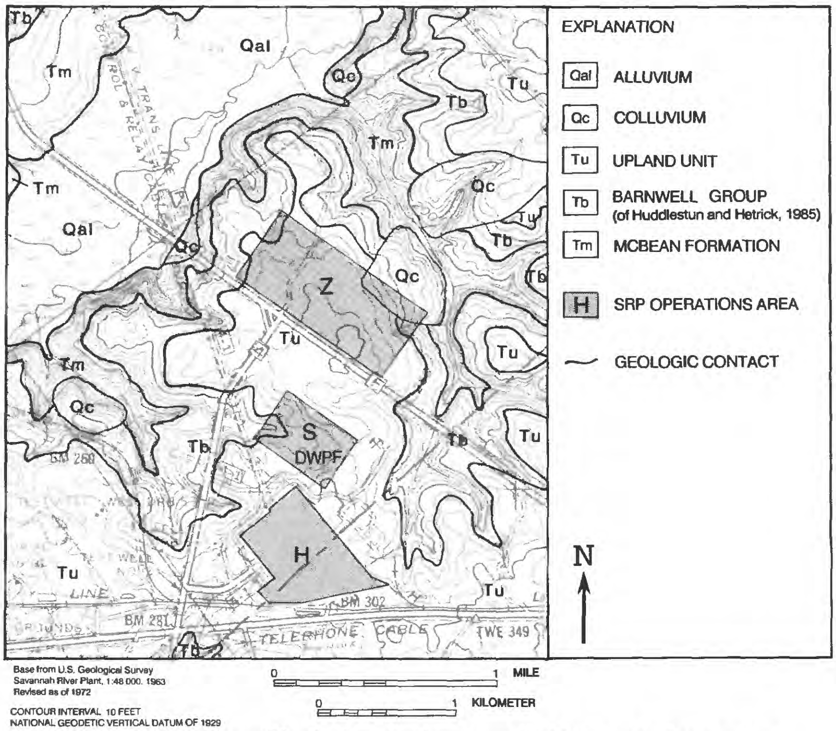


Figure 8.--Surficial geology of the study area.

Age

The age of the colluvium and (or) alluvium in the DWPF study area is unknown and very likely varies from one deposit to the next. The deposits, however, are clearly related to the present drainage morphology, which is considered to be post-Miocene, and probably range in age from Pliocene to early Holocene.

Distribution of Strata

Geologic Map

The surface geology was mapped in a 7-mi^2 area around the DWPF (fig. 8) to determine the extent of stream dissection of the geologic formations and the tan and green clay confining zones. Three of the Coastal Plain stratigraphic units, the McBean Formation, the Barnwell Group (Huddlestun and Hetrick, 1986), and the upland unit, are present in outcrop above the base level of Upper Three Runs. The Congaree Formation is exposed in stream cuts west of the map area near well FC-4A, projection of outcrop altitudes to the east suggests that Upper Three Runs probably flows on the uppermost Congaree strata. The green clay has apparently been completely cut by Upper Three Runs and crops out just at the top of the stream valley alluvium. The remaining strata of the McBean Formation crop out as clayey sand and silicified sand and silt in man-made exposures along the southern bluffs of Upper Three Runs and Tinker Creeks. The tan clay, present about 10 ft above the basal Barnwell unconformity, crops out on the Upper Three Runs valley walls in the eastern part of the study area. Outcrop and borehole (wells SDS-7, SDS-12, and P14TA) information suggests that the tan clay is not present northeast of the DWPF.

The alluvium shown on the geologic map is largely in the Upper Three Runs valley, but thin deposits of alluvium are also present in the valleys of major tributaries such as McQueens Branch. The smaller alluvial deposits are not shown on figure 8 because of scale. At places where the alluvium is highly dissected by local streams, it is between 3- and 10-ft thick.

Only the largest deposits of colluvium are shown on figure 8 and the colluvium is mapped only where good outcrops define the extent of the deposits. Colluvium probably covers most of the steep slopes along Upper Three Runs and its major tributaries, but this could not be verified for inclusion on the geologic map. Similarly, small patches of colluvium are present in old depressions on the upland unit, but they are too small to portray on the geologic map.

Geologic Sections

The lack of core-hole samples in the DWPF required that we examine samples from cored holes in adjacent areas to determine the geologic configuration of the subsurface. A sequence of five cored holes was used to construct an east-west geologic section (fig. 6) from F Area to the area east of McQueens Branch, and four cored holes in conjunction with outcrops along Upper Three Runs were used to construct a north-south geologic section (fig. 7) from Upper Three Runs to Fourmile Branch. The two sections share a common point in Z Area (well SDS-7), and the north-south section passes through the DWPF and H Area. Well HC-1 in H Area is the type section for the tan and green clay confining zones of Root (1980).

The geologic sections show some important features of the tan and green clays and the "calcareous zone" in the McBean Formation. The tan clay is relatively continuous in the western and southern parts the study area, increasing in thickness to the south; however, available samples suggest that the tan clay is not present as a discrete layer east of the DWPF. The loss of the tan clay in the stratigraphic section seems related to a topographic high on the top of the McBean Formation between S and Z Areas. The green clay is relatively continuous throughout the study area, and probably is the most consistent impermeable layer in the Tertiary geologic section. Where it is not a discrete clay layer, the green clay interval is characterized by a thick sandy clay that has similar confining properties according to Root (1980).

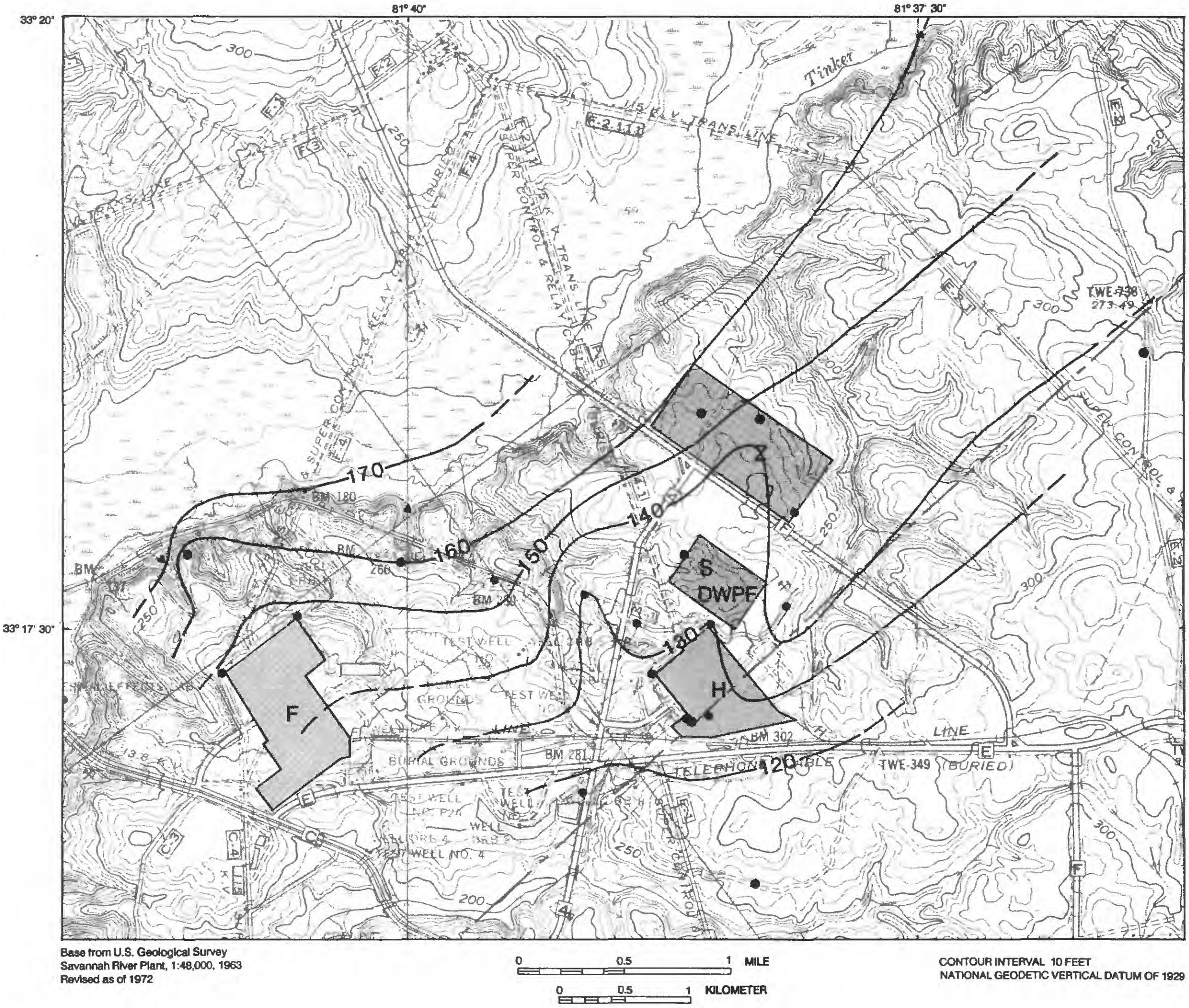
The calcareous zone is best developed in the vicinity of the DWPF and diminishes to the west (wells FC-3A and FC-4A). The zone continues south from the DWPF but is locally absent in well HC-1. Although no calcium carbonate was found in well HC-1, a sequence of clay and fine sand occupies the same stratigraphic interval. Carbonate may have been present during deposition but subsequently removed by circulating ground water, which seems to be the case in outcrop exposures.

Structure Contour Maps

Root (1980) recognized that the most important geohydrologic units immediately south of the DWPF are the tan and green clay layers. The position and continuity of these confining units has a major effect on the subsurface ground-water system. We were able to use Root's (1980) data concerning the tan and green clays from H Area in combination with our geologic investigation to construct structure contour maps (figs. 9 and 10) that show the configuration of the two layers in the vicinity of F Area, H Area, S Area (DWPF), Z Area (SDS), and Upper Three Runs. The maps indicate the altitude of the top of the clay layers. The thickness of the layers is not shown because they are consistently only 2- to 10-ft thick. In addition, the layers have gradational boundaries and mapping their thicknesses is a matter of interpretation.

The structure contour map of the top of the green clay (fig. 9) shows that the layer is gently sloping to the southeast with one anomaly just south of the DWPF. An open depression about 10-ft deep starts in H Area and extends north into the vicinity of the DWPF. This feature is probably depositional because no easily dissolved rocks are known to exist below the green clay in this area, and the structure is not duplicated in the tan clay.

The structure contour map of the top of the tan clay (fig. 10) indicates that the layer is relatively flat in the DWPF area, but more importantly it is absent in areas north and east of the DWPF. The tan clay is also less well defined than the green clay in many drill holes and



EXPLANATION

H SRP OPERATIONS AREA

—160— STRUCTURE CONTOUR -- Shows altitude of top of green clay of the McBean Formation. Dashed where approximately located. Contour interval 10 feet. Datum is sea level.

DATA POINT

● CORE HOLE LOCATION

▲ OUTCROP

Figure 9.--Altitude of the top of the green clay.

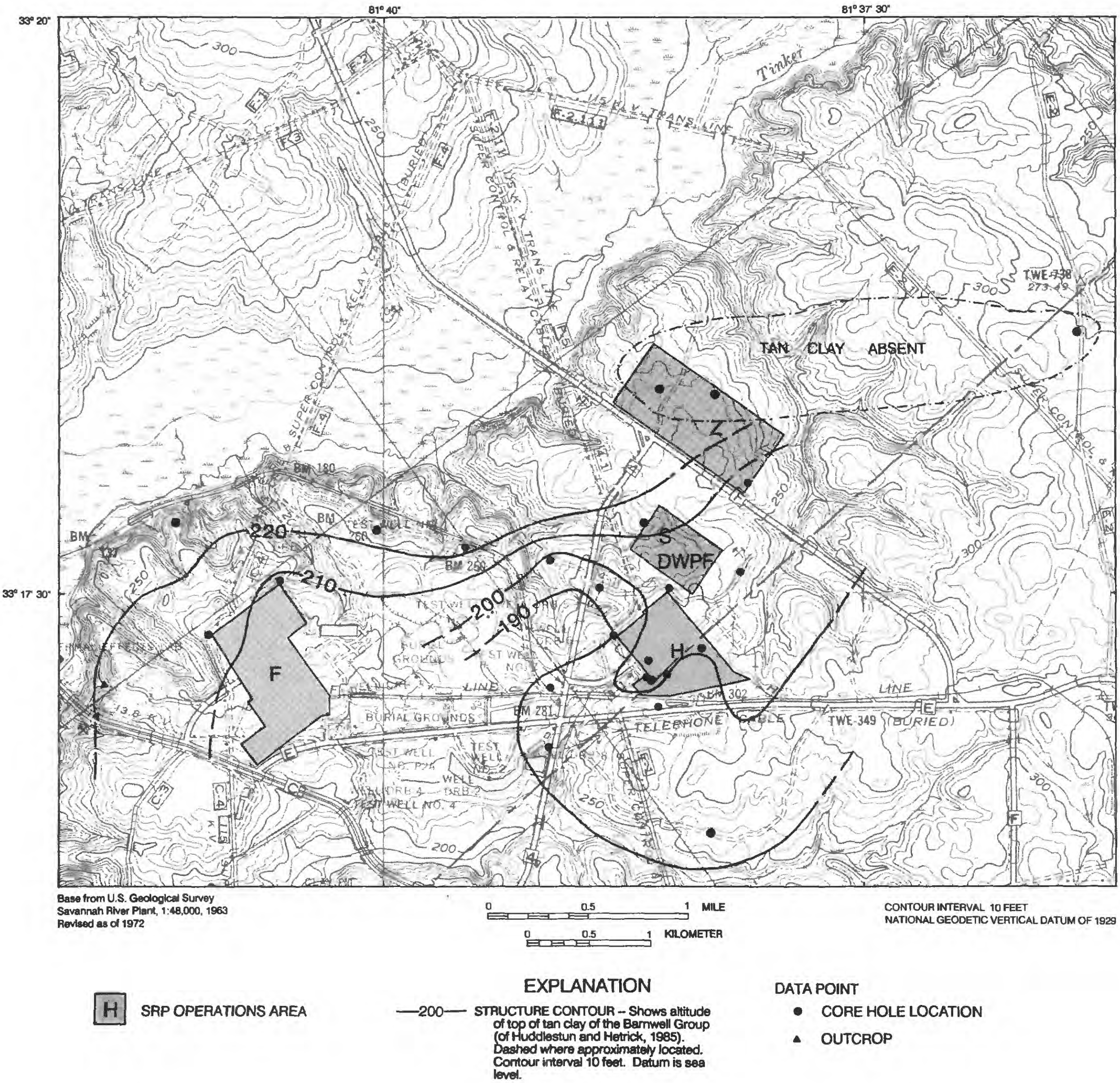


Figure 10.--Altitude of the top of the tan clay.

probably has less continuity. The tan clay is more likely to be laterally continuous in downdip areas (for example, F and H Areas) and more localized and discontinuous in updip areas (for example S and Z Areas) due to expected downdip thickening.

GROUND WATER

In the geology section of this report, the stratigraphy, nomenclature, lithology, age, and distribution of the sediments are described. The names given to units with similar characteristics are based on lithostratigraphy (rock strata) and biostratigraphy (fossil strata). In this section, hydrogeologic characteristics are considered and the major hydrogeologic units (strata designated by their hydrologic characteristics as either aquifers or confining units) are defined. Figure 11 illustrates the relation between geologic and hydrogeologic units at the site. This figure is generalized and may vary depending on the location in the study area. For example, in areas where the tan-clay confining unit is absent, the Barnwell and McBean aquifers become the Barnwell-McBean aquifer.

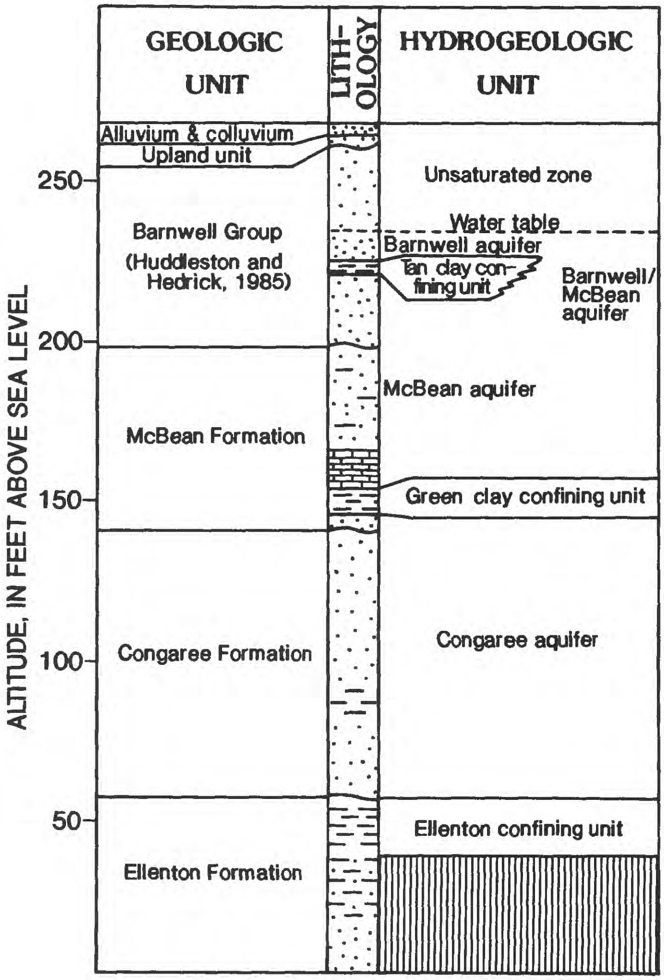


Figure 11.--Correlation chart for geologic and hydrogeologic units.

Description of Aquifers and Confining Units

An aquifer is a water-bearing interval of rock or sediment that is capable of yielding water in usable quantities to wells or springs. It may consist of a group of formations, a formation, or part of a formation, and it may include material of different ages.

Aquifers in the study area generally are separated by confining units that are composed of material having low permeability such as clay. Confining units do not yield significant amounts of water to wells. They also may be composed of material of different ages.

Three aquifers and three confining units are delineated in the Tertiary sediments beneath the study area (fig. 11). Figures 12 and 13 are section diagrams that illustrate the sequence of aquifers and confining units that are of concern to this investigation.

The unsaturated zone at the study area extends vertically from land surface through the colluvium and (or) alluvium where present, the upland unit, and into part of the Barnwell Group (fig. 11). The thickness of the unsaturated zone varies with topography and depth to the water table. The thickness of the upland unit alone averages 18 ft. Near the center of the study area (Well SDS-10) the unsaturated zone is approximately 60 ft thick. Moving away from the center of the topographic high to the southwest (Well SDS-4A), the unsaturated zone thins to approximately 25 ft. Values for the saturated hydraulic conductivity for the colluvium and (or) alluvium are not available. The geometric mean for the saturated hydraulic conductivity of the upland unit was determined from five laboratory measurements to be 4×10^{-5} ft/s (table 2).

The water-table aquifer, referred to as the Barnwell aquifer, consists of the saturated material of the Barnwell Group above the tan-clay confining unit (figs. 12 and 13). The areal extent of the aquifer over the study area is limited by the areal extent of the tan-clay confining unit. The tan-clay confining unit is absent in the northeastern part of the study area (figs. 6 and 10); therefore, the Barnwell aquifer appears as a separate hydrogeologic unit only south and west of Z Area. Within the study area, the Barnwell aquifer has been incised substantially by streams on three sides, which further limits its continuity and areal extent. Overall, where present, the aquifer is relatively thin.

The Barnwell Group seems to be quite heterogeneous. Laboratory and field measurements of hydraulic conductivity range from 10^{-8} to 10^{-5} ft/s (table 2). Included in table 2 is the geometric mean of eight different tests conducted as part of the waste/sediment interaction studies, which yielded a value of 4×10^{-6} ft/s.

Underlying the Barnwell aquifer is what is known at the SRP as the "tan clay." The tan clay is a semi-confining unit between the Barnwell and McBean aquifers (fig. 11). It ranges in thickness from 0 to 10 ft, and slopes to the southeast. Having a low hydraulic conductivity (table 2), this unit impedes the downward flow of water from the Barnwell aquifer to the McBean aquifer. Of course where the tan clay confining unit is not present, vertical movement of water is not impeded (figs. 12 and 13).

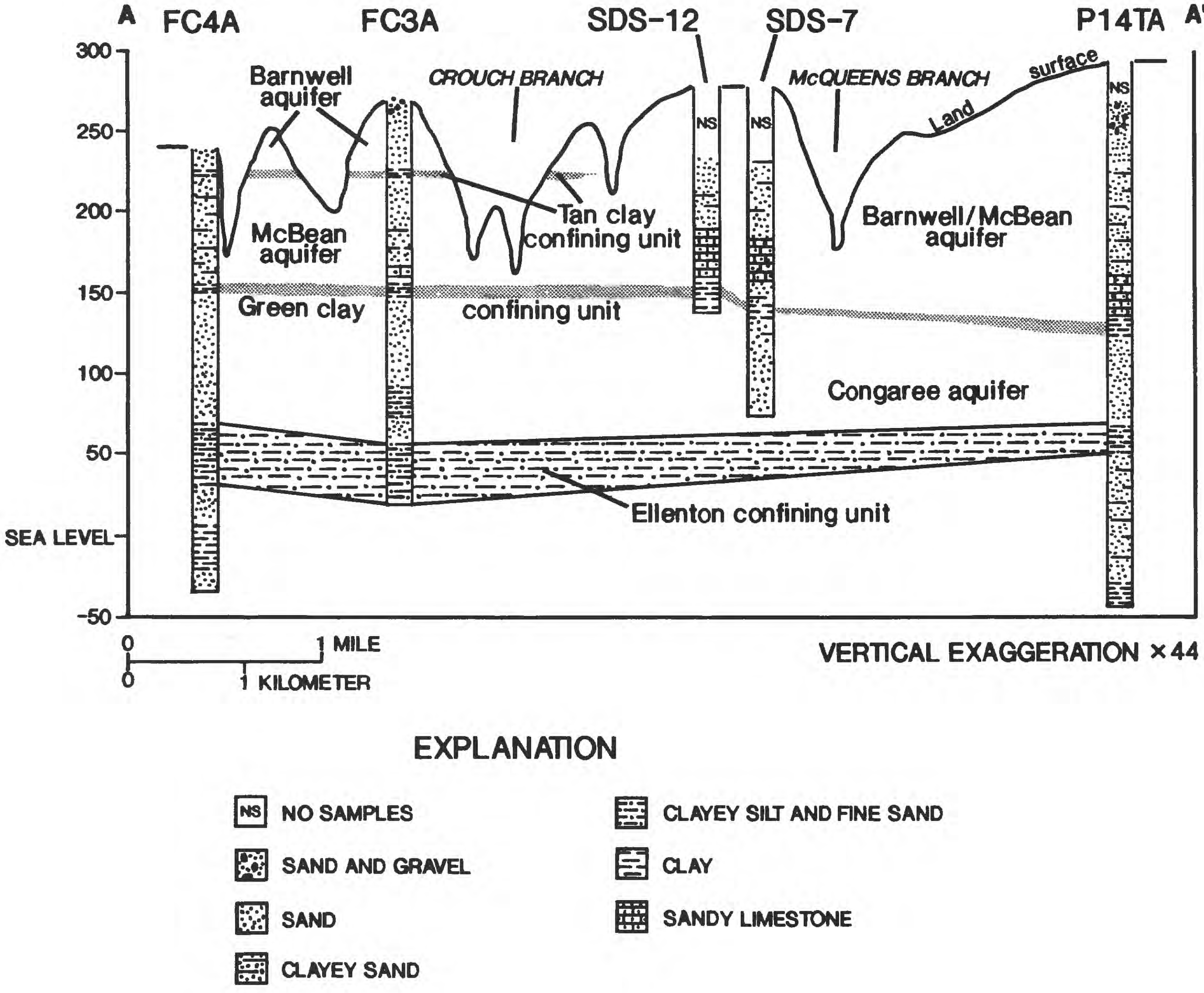


Figure 12.--Hydrogeologic section along line A-A'.

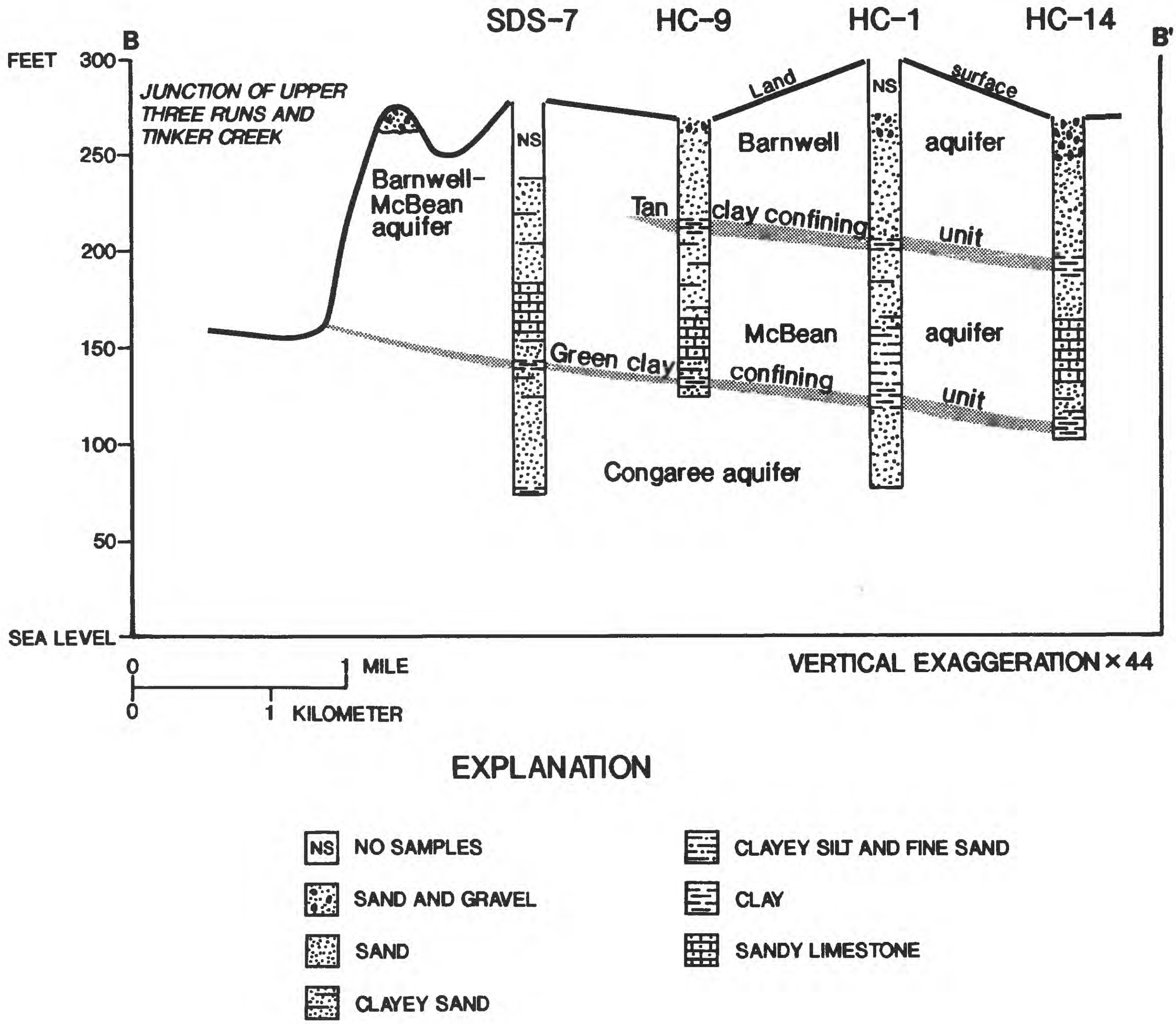


Figure 13.--Hydrogeologic section along line B-B'.

Table 2.--Summary of hydraulic conductivity data

[ft/s, feet per second; --, data not available]

Geologic unit	Regional data (Christensen and Gordon, 1983) (ft/s)	Laboratory data (D'Appolonia, 1981) (ft/s)	Field data (Parizak and Root, 1984) (ft/s)	Field data (INTERA, 1985) (ft/s)	U.S. Geological Survey laboratory data (ft/s)
Upland	--	--	--	--	4×10^{-5}
Barnwell Group[e]	10^{-7} to 10^{-5}	[a] 3.9×10^{-6} [b] 2.7×10^{-8}	2×10^{-5}	--	[c] 4×10^{-6}
Tan clay of of the Barnwell Group[e]	--	[b] 4.6×10^{-8}	10^{-6} to 10^{-5}	--	--
McBean Formation	10^{-7} to 10^{-5}	--	--	10^{-8} to 10^{-4}	--
Green clay of the McBean Formation	--	--	--	[d] 10^{-10} to 10^{-8}	--
Congaree Formation	7×10^{-5}	--	3.6×10^{-5}	10^{-7} to 10^{-4}	--

[a] Sandy facies

[b] Clayey sand facies

[c] Geometric mean of 8 tests

[d] Model-determined data (INTERA, 1986)

[e] Of Huddlestun and Hetrick, 1986

In the northeastern part of the study area, where the tan clay is absent, water levels in wells indicate that the Barnwell and McBean aquifers are hydraulically connected. Therefore, for discussion in this report these aquifers are considered as a single composite aquifer which is referred to as the Barnwell-McBean aquifer.

The McBean aquifer consists of the Barnwell Group sediments beneath the tan-clay confining unit and the McBean Formation sediments above the green-clay confining unit. Hydraulically, the McBean aquifer can be considered one aquifer, even though it has two, and possibly three, distinct stratigraphic zones: (1) an upper sandy zone (2) a middle transition zone, and (3) a lower calcareous zone. Hydrologic data pertaining to individual zones are not available. The lower zone has been found to contain large cavities. While drilling in that zone, instances occurred when drill pipe fell in free-fall and drilling fluids were lost (INTERA, 1986). The drilling fluid losses and cavities in the McBean suggest that this zone is quite permeable. To examine this possibility, aquifer tests were conducted on the calcareous zone, and results indicated a lower hydraulic conductivity in this zone than in the upper (sandy zone) McBean aquifer (INTERA, 1986). It seems that cavities found during drilling are not interconnected. Additionally, Christensen and Gordon (1983) suggest that the regional permeability of the calcareous zone is lower than the drilling activities suggest. Hydraulic conductivities of the aquifer range from 10^{-8} to 10^{-4} ft/s (table 2).

The McBean aquifer also has been incised by local streams. In the southern half of the study area, east and west of DWPF, McQueens and Crouch Branches down cut into the aquifer to varying degrees (fig. 12). To the north and northwest, Upper Three Runs down cuts through the Barnwell-McBean aquifer. As a result, the McBean aquifer is continuous only south of S Area (figs. 12 and 13).

The Barnwell-McBean aquifer is restricted to the northern half of the study area (figs 12 and 13). It is assumed that hydraulic properties of this aquifer are similar to the Barnwell and McBean aquifers. Upper Three Runs down cuts deeply into the aquifer, and in the northwestern part of the study area, completely through the aquifer.

The McBean or the Barnwell-McBean aquifers are hydraulically separated from the Congaree aquifer by a low-permeability unit known as the "green clay." The green-clay confining unit (fig. 9) seems to be continuous throughout the study area, and is the only competent confining unit within the Tertiary sediments. The thickness of this unit averages approximately 10 ft (figs. 12 and 13) and the slope is to the southeast, similar to that of the tan-clay confining unit. The only stream to down cut into and through the green-clay confining unit is Upper Three Runs in the western part of the study area (fig. 13). We were unable to find any measurements of vertical hydraulic conductivity for the green-clay confining unit in the literature of the study area. However, a range of possible values (10^{-10} to 10^{-8} ft/s) was estimated from sensitivity analyses performed by INTERA (1986) while calibrating their ground-water flow model of Z Area (table 2). These estimated values indicate that the green-clay confining unit has a lower hydraulic conductivity than the tan-clay confining unit.

The Congaree aquifer is the deepest aquifer considered in this report. The aquifer consists of sediments of the McBean Formation beneath the green clay and of the Congaree Formation. The aquifer is incised only by Upper Three Runs in the northwestern part of the study area. Within the study area, the Congaree aquifer generally is considered to be the most productive aquifer. The hydraulic conductivity is variable; an average value, based on reported values in other studies, probably is on the order of 10^{-5} ft/s (table 2).

The Ellenton confining unit is the lower limit of our investigation at the DWPF and vicinity. Few geohydrologic data have been reported for the Ellenton Formation in the study area. The Ellenton Formation is composed of an upper clay section (confining unit) and a lower clay-sand section (aquifer). The upper clay seems to be the major confining unit between the overlying Congaree aquifer and the underlying Cretaceous aquifers. No streams in the study area incise the Ellenton confining unit or the Cretaceous aquifer. We were unable to find any vertical hydraulic conductivity data on either the confining unit or aquifer.

Water Levels and Ground-Water Movement

The water levels that define the potentiometric surfaces and directions of flow within and between aquifers and confining units are examined in this section. The ground water that saturates the aquifers and confining units beneath the DWPF and vicinity moves through the intergranular spaces within these units in response to differences in hydraulic head. The rate and direction of movement is controlled by the hydraulic conductivity of the units (a measure of their ability to transmit water) and by the hydraulic gradient (the difference in the hydraulic head within and between the units).

Water levels were measured in 34 SDS wells (fig. 3) during August and September 1986 (table 3). Well construction information was obtained from various SRP publications (table 3). The reader should note that the accuracy of the hydrologic interpretation based on water-level data is entirely dependent upon the integrity of the well construction and the accuracy of the various pertinent construction measurements. Some inconsistencies were recognized and attempts were made to minimize their impact. We were unable to collect water-level data in S Area to supplement concurrent SDS monitoring well data because of the removal of S Area monitoring wells prior to construction of the DWPF. Therefore, potentiometric maps developed by Christensen and Gordon (1983) are used to aid in the understanding of ground-water movement throughout the entire study area. Additionally, Cook (1986) presents water-level measurements in the 34 SDS wells beginning in 1982 and ending in early 1986.

The potentiometric surface of the Barnwell-McBean aquifer during September 1986 is shown in figure 14. This potentiometric surface represents the top of the zone of saturation, which, by definition is the water table. Also shown in figure 14 is the area in which the tan-clay confining unit is present.

Table 3.--Well construction information and water levels for selected wells in study area

[--, not determined]

Well number	Aquifer screened	Altitude of screen bottom* above sea level (feet)	Screen length* (feet)	Altitude top of casing* above sea level (feet)	Altitude of water levels above sea level (feet)		Remarks
					August 1986	September 1986	
SDS-1	Barnwell-McBean	214.4	20	295.1	227.0	227.5	
SDS-2	Barnwell-McBean	215.6	20	289.6	227.7	227.7	
SDS-3A	Barnwell-McBean	210.5	20	292.5	233.5	233.7	
SDS-4	McBean	185.4	20	257.4	229.7	230.1	
SDS-4A	Barnwell	228.4	5	257.6	--	232.2	
SDS-5	McBean	218.2	20	289.8	233.7	234.2	
SDS-6	Barnwell-McBean	216.9	20	290.0	227.4	227.7	
SDS-7A	Congaree	75.0	5	278.8	170.3	170.0	
SDS-7B	McBean	135.3	5	278.0	205.7	206.1	
SDS-7C	Barnwell-McBean	184.2	5	277.2	212.5	212.9	
SDS-7D	Barnwell-McBean	205.6	20	277.2	214.2	214.6	
SDS-8	Barnwell-McBean	201.9	20	272.1	216.4	217.0	
SDS-9	Barnwell	223.1	20	295.7	236.0	236.1	
SDS-10	Barnwell	225.7	20	295.2	235.0	235.2	
SDS-11	Barnwell-McBean	219.3	20	291.9	232.7	233.1	
SDS-12A	Congaree	136.4	5	278.7	164.2	164.0	
SDS-12B	Barnwell-McBean	186.7	5	278.7	216.0	216.2	
SDS-12C	Barnwell-McBean	206.1	20	279.1	216.7	216.9	
SDS-13	Barnwell-McBean	204.4	20	277.4	208.0	207.9	
SDS-14	Barnwell-McBean	200.9	20	271.0	223.0	222.4	Perched
SDS-14A	--	252.8	5	271.0	Dry	259.0	Perched
SDS-15	Barnwell-McBean	212.0	5	284.9	223.8	223.7	
SDS-16A	Congaree	--	5	233.6	172.0	171.7	
SDS-16B	Congaree	--	5	233.6	169.9	169.6	
SDS-17	McBean	196.6	20	271.3	222.0	222.2	
SDS-18A	Barnwell-McBean	206.0	20	258.6	202.6	203.1	
SDS-20A	Congaree	101.4	5	263.8	165.3	166.0	
SDS-20B	Barnwell-McBean	165.4	5	263.8	212.5	212.8	
SDS-20C	Barnwell-McBean	190.6	20	264.1	213.9	214.2	
SDS-21A	Congaree	97.7	5	253.7	162.1	161.9	
SDS-21B	Barnwell-McBean	153.4	5	252.5	208.1	208.3	
SDS-21C	Barnwell-McBean	175.7	20	252.5	207.3	207.5	
SDS-22B	Barnwell-McBean	189.1	5	290.2	222.8	223.2	
SDS-22C	Barnwell-McBean	213.2	20	289.9	229.1	229.4	

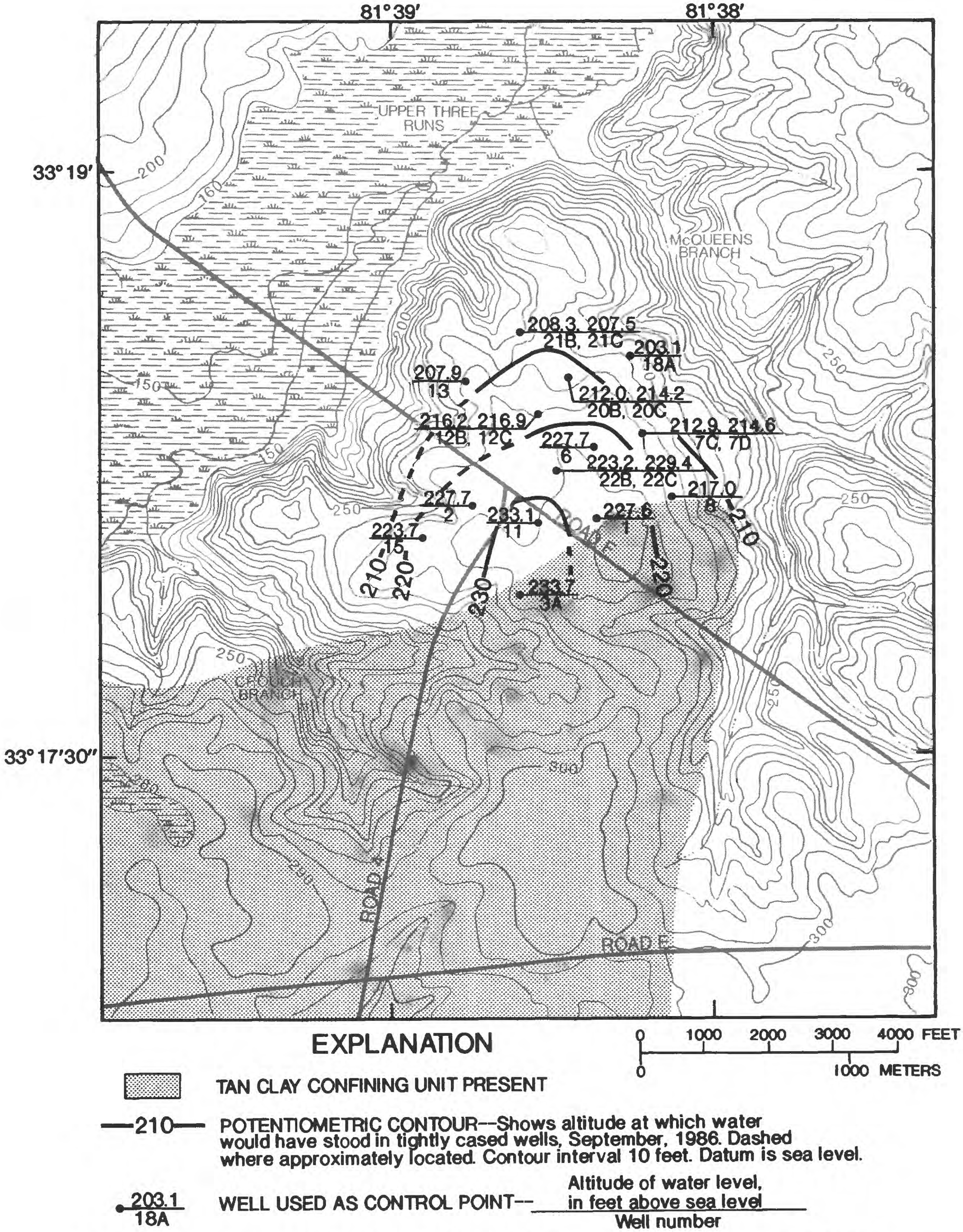


Figure 14.--Potentiometric surface of the Barnwell-McBean aquifer in vicinity of study area.

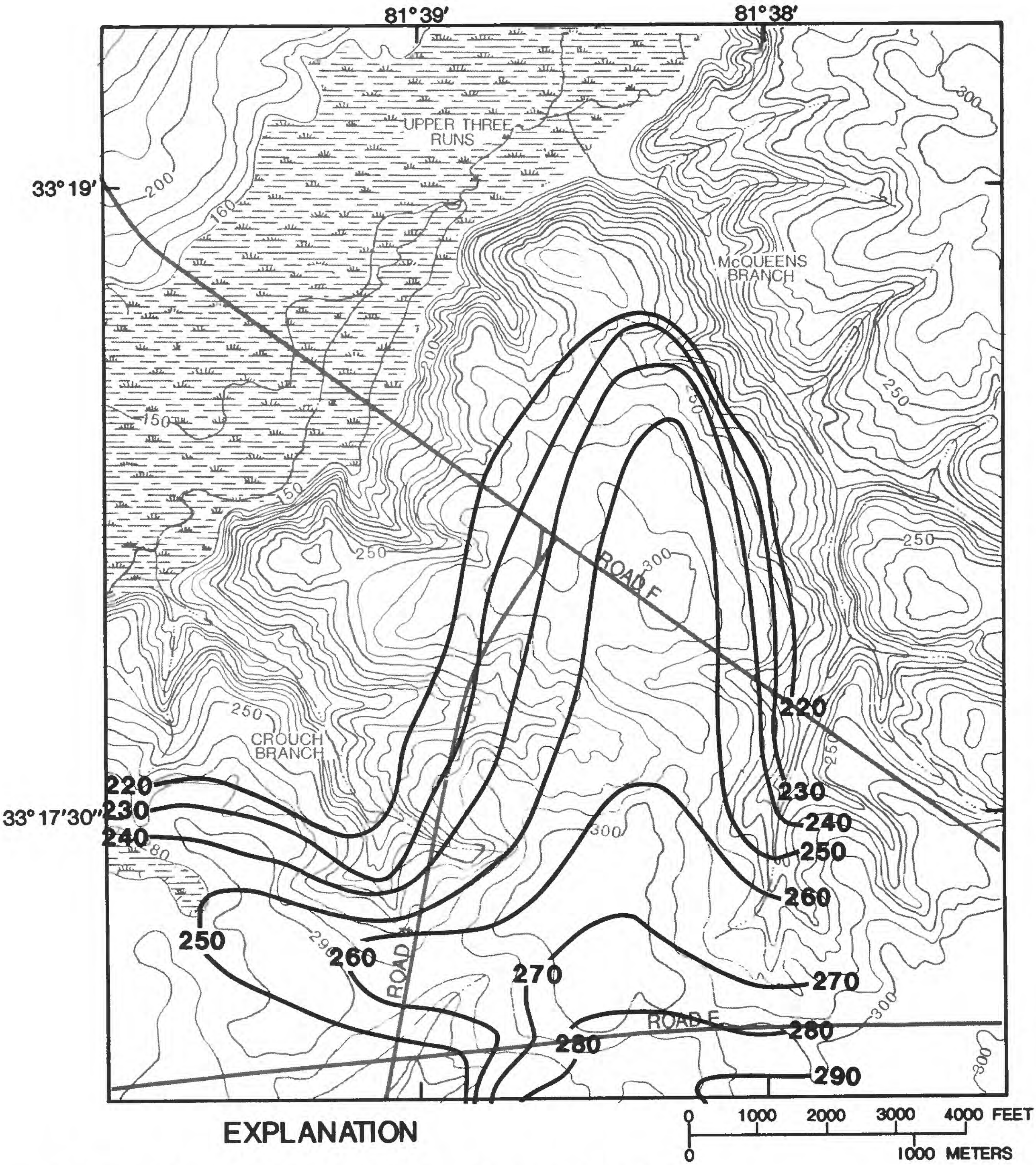
In Z Area the altitude of the water table is estimated to range from 208 to 229 ft above sea level. Perched water can be found within this composite aquifer (SDS-14A, -14), where discontinuous clay lenses impede the downward migration of percolating water (Sargent, 1984).

The direction of ground-water flow in the Barnwell-McBean aquifer is perpendicular to the potentiometric contours (fig. 14), and is influenced substantially by the incised streams surrounding the study area. Because the streams lower the hydraulic head, ground-water flow is from the interstream area towards the bounding streams.

For comparison purposes a potentiometric surface map of the water table presented by Christensen and Gordon (1983) based on 1968 data has been modified, and is presented in figure 15 to illustrate the direction of ground-water flow over the entire study area. The map is based mainly on the shape of the topography, with very little well control (J.L. Steele, DuPont, written commun., 1988). Individual data points are not indicated on the map; however, the contour patterns are similar (figs. 14 and 15). The direction of ground-water flow in the southern part of the study area is northward. From our present geologic knowledge of the area, it seems that figure 15 represents water levels from wells completed in the Barnwell-McBean aquifer north of Road F (where the tan-clay confining unit is absent), whereas south of Road F, (where the tan-clay confining unit is present) the map reflects water levels from wells completed in the Barnwell aquifer. However, because water levels (contour patterns) of both aquifers are thought to approximate the water table, figure 15, even though based on minimal data, is useful for determining the direction of the water-table gradient, and for inferring the direction of lateral flow over a wider area than our data (SDS wells) permit. On this basis, it seems that the lateral component of ground-water flow in the Barnwell below the DWPF is to the northwest and west.

Inflow to the Barnwell-McBean aquifer comes from infiltrating precipitation and from lateral flow of water from the south. The water-table aquifer primarily discharges to local streams. Because of the vertical gradient, the potential exists for water to leak through the green-clay confining unit into the deeper Congaree aquifer. Where the tan-clay confining unit is present, the Barnwell aquifer leaks water to the underlying McBean aquifer.

The altitude of hydraulic head at three wells open to the McBean aquifer during September 1986, is shown in figure 16. Also shown is the area in which the tan-clay confining unit is present. Water-level altitudes range from a high of 234 ft at SDS-5 to a low of 222 ft above sea level at SDS-17. Water in the three wells shown on figure 16 are under confined conditions. Water-level altitudes of other wells in the area, such as SDS-15, -2, -11, and -1 might also be influenced by a discontinuous tan-clay confining unit, but without additional data we cannot presently confirm this possibility.



EXPLANATION

—230— POTENTIOMETRIC CONTOUR--Shows altitude at which water would have stood in tightly cased wells, 1968. Contour interval is 10 feet. Datum is sea level.

Figure 15.--Potentiometric surface of the water table in vicinity of study area.

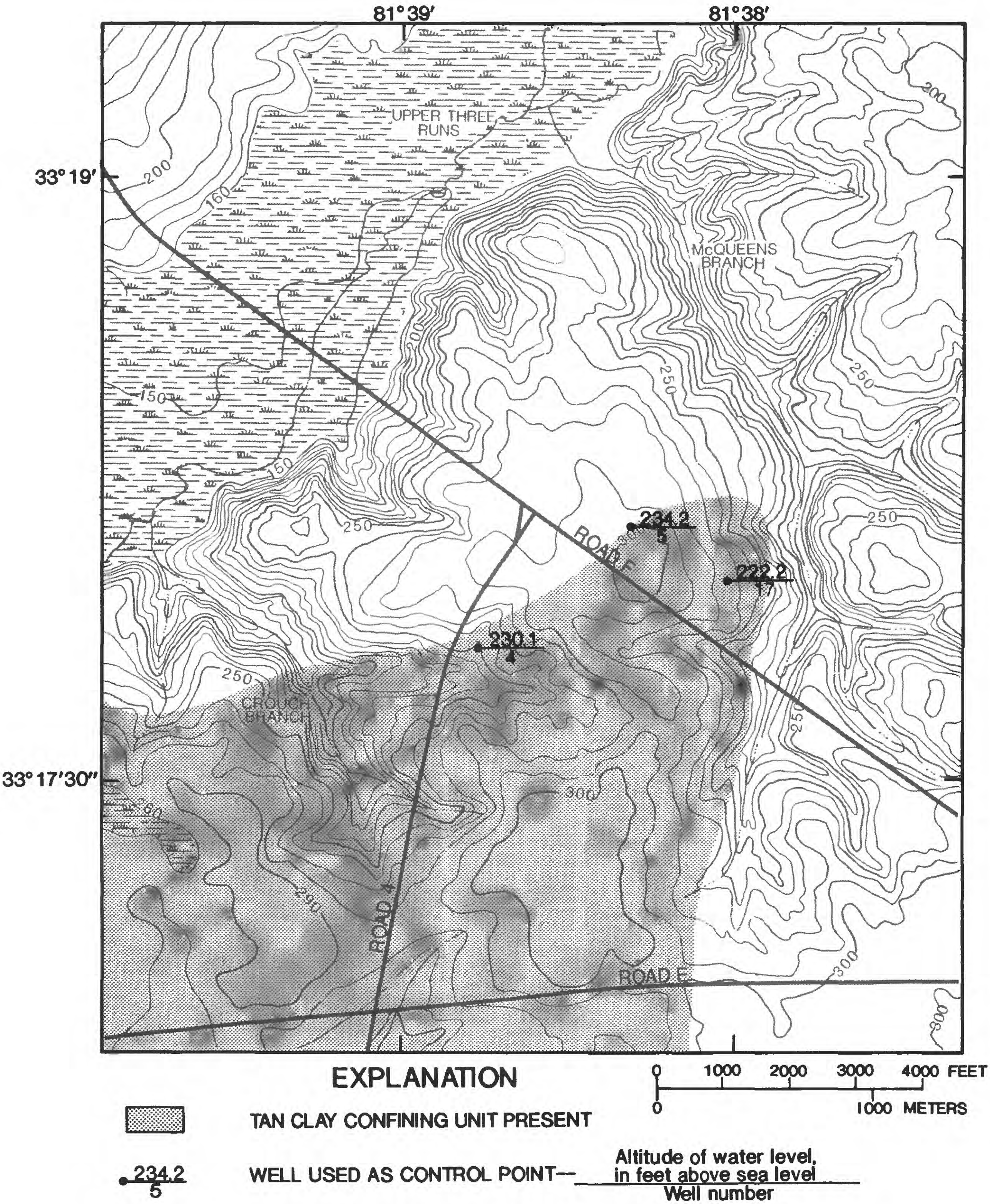


Figure 16.--Hydraulic head measurements of the McBean aquifer in vicinity of study area.

Figure 17 is a potentiometric surface map of the upper McBean aquifer in the vicinity of the study area (modified from Christensen and Gordon, 1983). The map was constructed using a minimal number of data points within the study area, and probably was based primarily on the shape of the topography. This map apparently reflects both confined (McBean aquifer) and unconfined (Barnwell-McBean aquifer) conditions in the McBean Formation owing to the presence or absence of the tan-clay confining unit. It is difficult to determine with certainty the direction of ground-water flow in the McBean aquifer from figure 16. Nevertheless, with the aid of figure 17 and the water-table map (fig. 14), an inference can be made that ground water in the McBean aquifer generally flows to the north and then moves radially from the interstream area to the bounding streams.

Inflow to the local section of the McBean aquifer is laterally from the south, and from vertical leakage through the overlying tan-clay confining unit. Discharge from the McBean aquifer occurs either as seeps along stream cuts, or as seepage through the streambeds and leakage to the underlying Congaree aquifer.

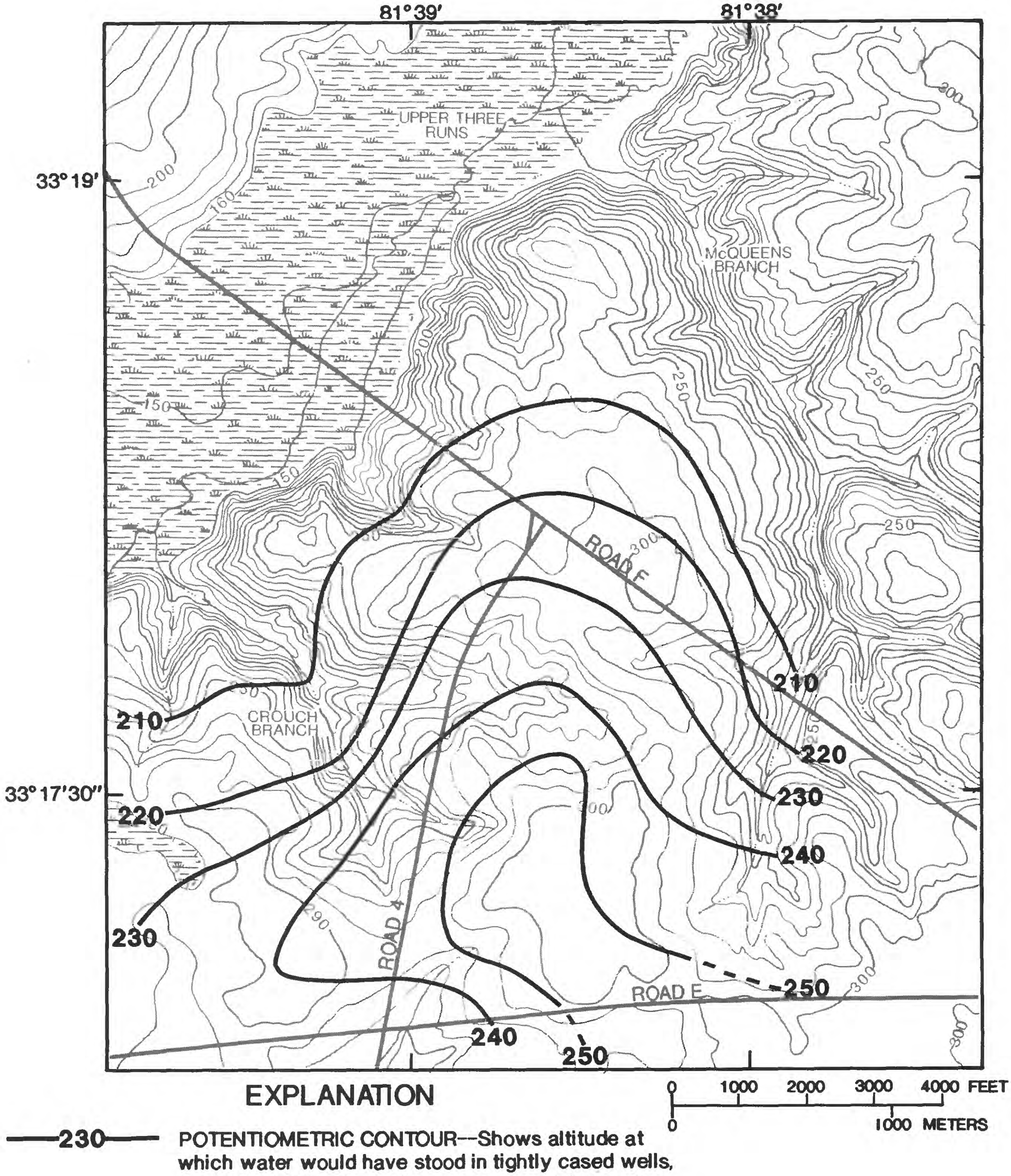
The vertical gradient between the Barnwell and McBean aquifers is downward. This is demonstrated in wells SDS-4A completed in the Barnwell aquifer and SDS-4 completed in the McBean aquifer. The head difference across the confining unit is approximately 2 ft in this part of the study area. However, where the tan-clay confining unit is absent, no head difference is observed.

The green-clay confining unit separating the Congaree aquifer from the overlying aquifers is continuous throughout the study area (figs. 12 and 13). The hydraulic head in the Congaree aquifer is approximately 50 ft lower than in the overlying Barnwell-McBean aquifer, indicating a significant downward gradient between these two aquifers.

Figure 18 shows the estimated potentiometric surface of the Congaree aquifer. The approximate altitude of the potentiometric surface was constructed from water-level measurements made in 5 wells during September 1986. The altitude of the potentiometric surface in the Congaree aquifer ranges from 162 to 172 ft (fig. 18). The direction of ground-water flow seems to be toward the northwest. The top of the aquifer near Upper Three Runs is at an altitude of approximately 160 to 170 ft. Upper Three Runs has incised the aquifer where the streambed altitude is approximately 150 ft. We believe, therefore, that near these facilities, the Congaree aquifer discharges to Upper Three Runs. A map of the potentiometric surface of the Congaree aquifer at the Savannah River Plant prepared by Christensen and Gordon (1983, figs. 3-19) shows that Upper Three Runs acts as a drain for the Congaree aquifer in the study area (fig. 19).

SURFACE WATER

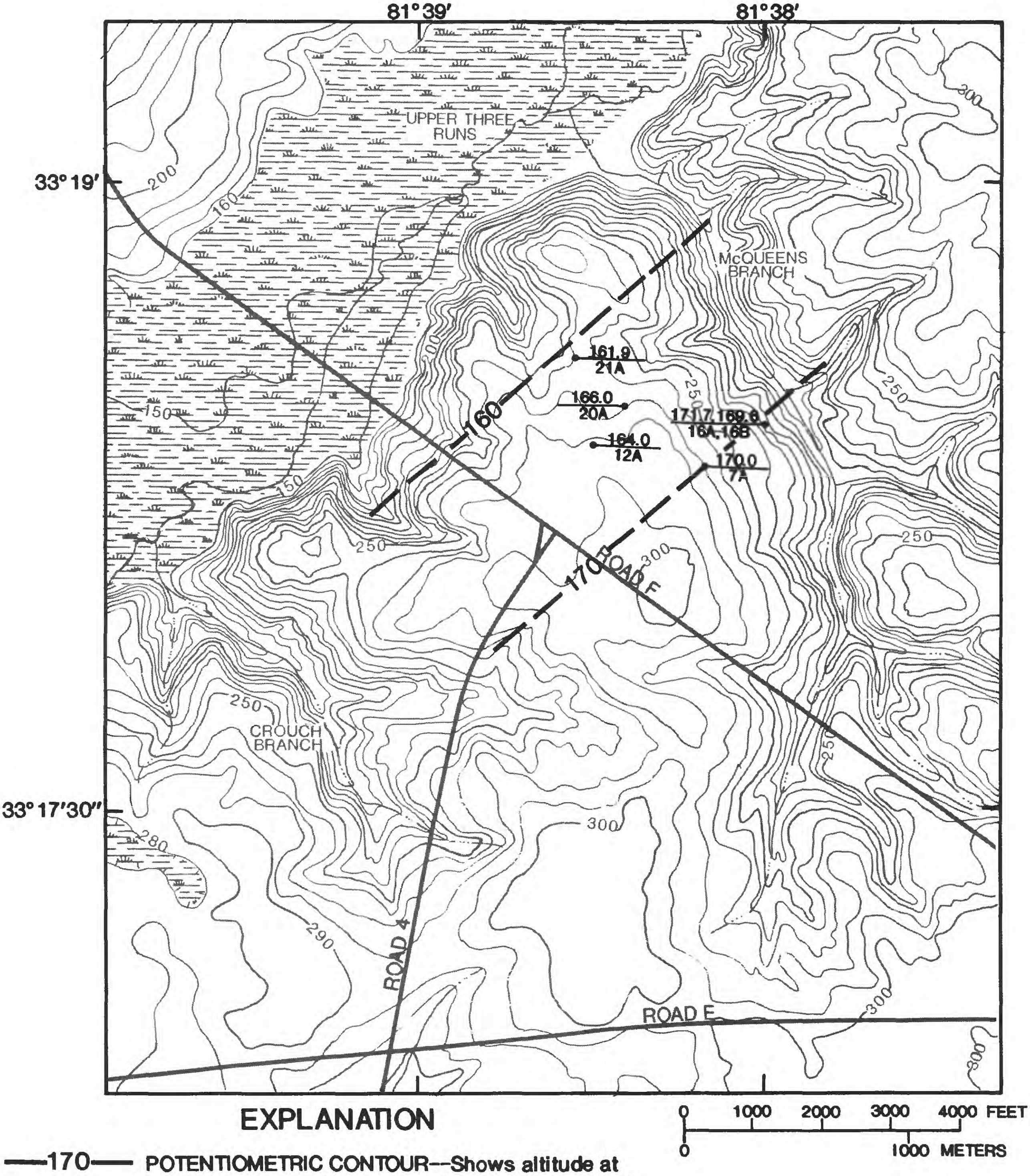
Three streams pertinent to this study are Upper Three Runs, McQueens Branch, and Crouch Branch. Upper Three Runs, which is the northwestern limit of our study area, originates outside the boundary of the Savannah River Plant. The U.S. Geological Survey maintains a streamflow gaging



EXPLANATION

—230— POTENTIOMETRIC CONTOUR--Shows altitude at which water would have stood in tightly cased wells, August, 1977. Dashed where approximately located. Contour interval is 10 feet. Datum is sea level.

Figure 17.--Potentiometric surface of the upper McBean aquifer in vicinity of study area.



EXPLANATION

—170— POTENTIOMETRIC CONTOUR--Shows altitude at which water would have stood in tightly cased wells, September, 1986. Dashed where approximately located. Contour interval is 10 feet. Datum is sea level.

•164.0/12A WELL USED AS CONTROL POINT-- Altitude of water level, in feet above sea level / Well number

Figure 18.--Estimated potentiometric surface of the Congaree aquifer in vicinity of study area.

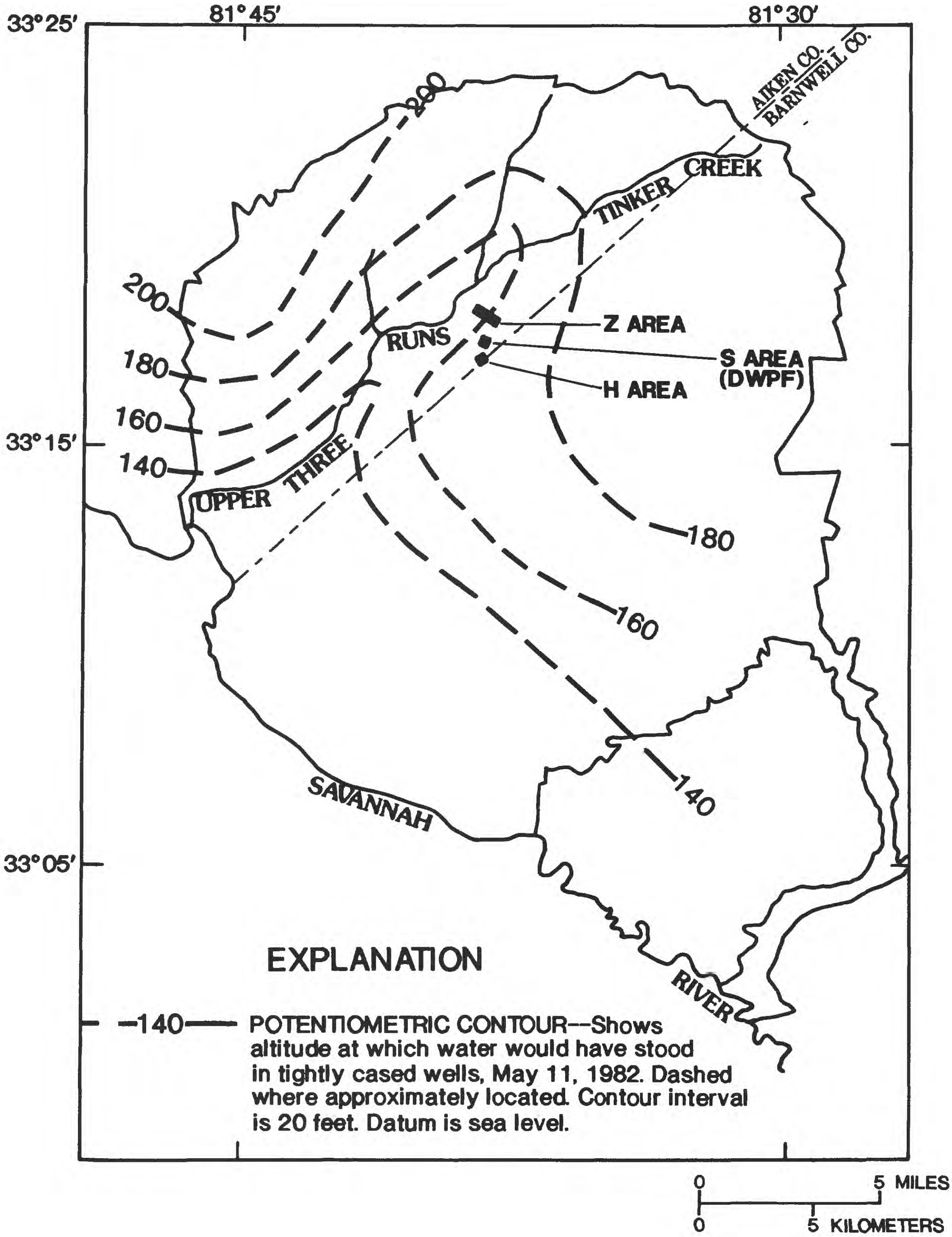


Figure 19.--Potentiometric surface of the Congaree aquifer at the Savannah River Plant.

station inside the Plant area on Upper Three Runs near New Ellenton, South Carolina (fig. 20). The drainage area above this station is 87 mi^2. Average discharge over 19 years of record is 107 ft^3/s, with extremes in discharge ranging from 49 to 472 ft^3/s (U.S. Geological Survey, 1986). Upper Three Runs has eroded valleys with steep southeastern banks and gently sloping northwestern banks owing to the southeasterly dip of the rock. It seems that Upper Three Runs is eroding predominantly in a downdip direction.

A second station maintained by the U.S. Geological Survey on Upper Three Runs is located above Road C approximately 9 river miles downstream from the gage near New Ellenton (fig. 20). This gage has a drainage area of 176 mi^2. The gage has been in service since 1974 and the average discharge is 206 ft^3/s (U.S. Geological Survey, 1986). Extremes for period of record range from 113 to 962 ft^3/s (U.S. Geological Survey, 1986). A number of tributaries discharge into Upper Three Runs between these two gaging stations; therefore, a direct determination of gain/loss along the stream channel is not possible with the current streamflow gaging-station network. Nevertheless, the two gaging stations can be compared by taking the average discharges measured at each gage for equivalent periods and normalizing them to their own drainage areas. The average discharge measured at Upper Three Runs above Road C was presented above for an 11-year period (1974-1985). The same 11-year period was used to determine an average discharge at Upper Three Runs near New Ellenton. For that period, the average discharge at Upper Three Runs near New Ellenton and above Road C are 104 and 206 ft^3/s, respectively. After dividing the discharges by their respective drainage areas, the normalized values are 1.20 and 1.17 $(ft^3/s)/mi^2$, respectively, indicating similar streamflow characteristics between the upper and lower drainage basins.

Two tributaries of Upper Three Runs in the study area are McQueens Branch and Crouch Branch. Both tributaries receive surface runoff from S and Z Areas. Figure 20 shows the outline of these two drainage basins. McQueens Branch and Crouch Branch basins have drainage areas of 4.3 and 1.1 mi^2, respectively. Streamflow gaging stations were installed as part of this project on McQueens Branch and Crouch Branch as shown in figure 20. Data collection began at each site on February 25, 1986. By May 14, 1986, however, the gaging station on McQueens Branch was disrupted owing to beavers damming the creek upstream from the gaging station. At Crouch Branch, streamflow data were collected until November 17, 1986, just prior to project termination.

During the period of data collection, the area was in a drought condition. The streamflow measured at the gages represents a low-flow condition in which all streamflow results from ground-water discharge (baseflow) into the stream. Because these low flows persisted throughout the period of data collection, meaningful stage-discharge rating curves could not be developed for either stream. Tables 4 and 5 show measured gage heights for the period of record. The gage heights have been included because they are indices of streamflow prior to large scale development at S and Z Areas. These data could be used for future comparison if a stage-discharge relation is developed for each tributary.

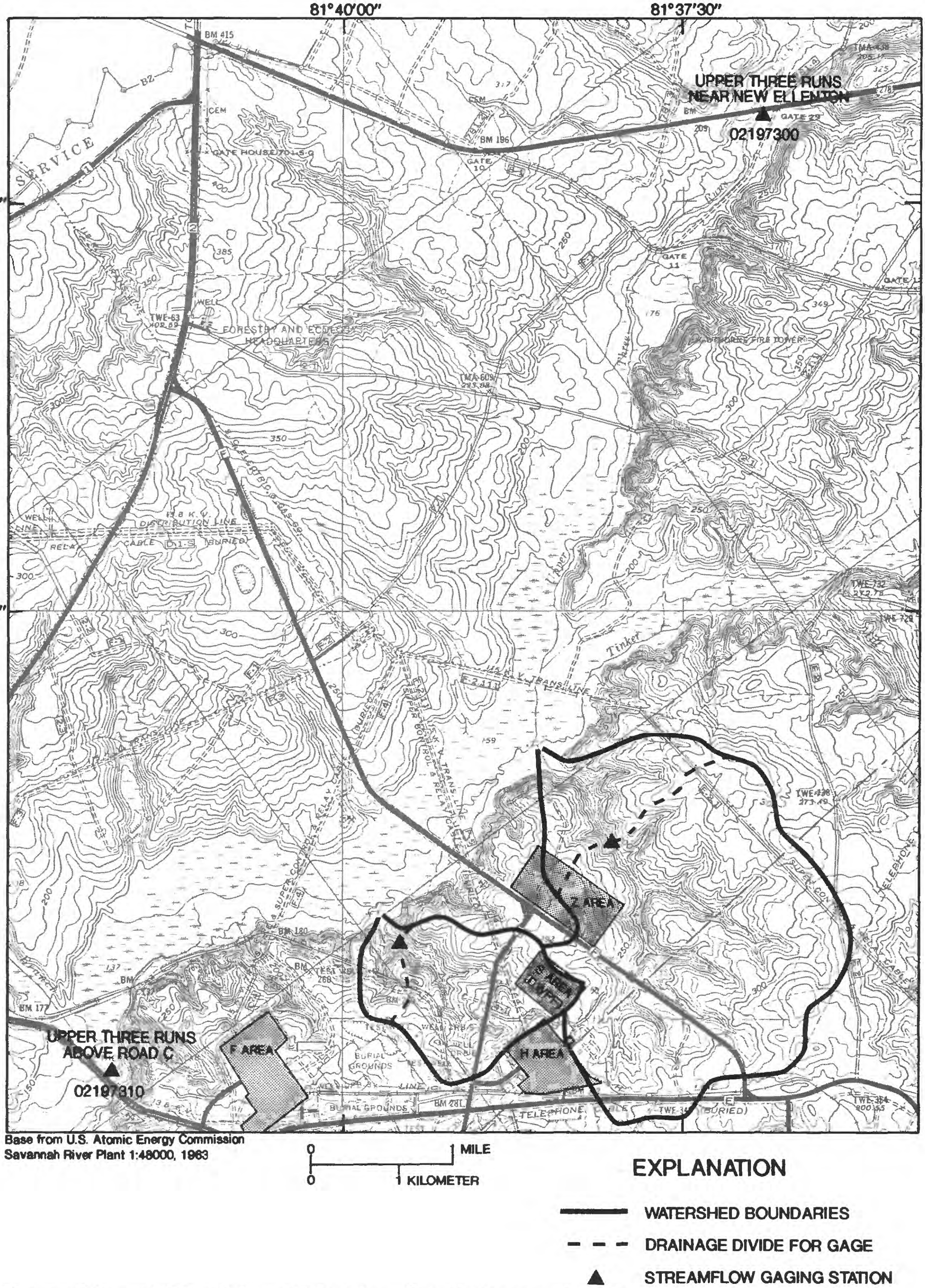


Figure 20.--Delineation of basins for McQueens Branch and Crouch Branch tributaries to Upper Three Runs.

Table 4.--Gage height data collected at McQueens Branch near S Area at Savannah River Plant, S.C. (021973010) for the period of record

[---, not determined or missing data]

Location:--Lat 33°18'34", long 81°38'02", Aiken County, on left bank, 0.75 mile northeast of intersection of Savannah River Plant Roads F and 4.
Drainage area:--3.6 square miles
Period of record:--February 25, 1986 to June 27, 1986
Gage:--Digital water-stage recorder. Elevation of gage is 168 feet above sea level (from topographic map).
Remarks:--No other gages have operated on this stream. Gage heights after May 14 show effects of beaver dam.

	Gage height during 1986 (feet) mean values				
Day	Feb.	Mar.	Apr.	May	June
1	---	1.28	1.74	1.85	1.97
2	---	1.29	1.80	1.84	1.96
3	---	1.28	1.85	1.85	1.98
4	---	1.26	1.86	1.86	2.04
5	---	1.28	1.90	1.85	2.00
6	---	1.29	1.88	1.87	1.97
7	---	1.29	1.89	1.86	1.97
8	---	1.31	1.96	1.93	1.99
9	---	1.34	1.92	1.91	1.96
10	---	1.32	1.86	1.85	2.31
11	---	1.24	1.84	1.82	1.98
12	---	1.10	1.87	1.87	1.67
13	---	1.23	1.81	1.95	1.56
14	---	1.48	1.81	1.87	1.58
15	---	1.22	1.80	1.79	1.61
16	---	1.17	1.80	1.91	1.57
17	---	1.32	1.79	1.96	1.55
18	---	1.32	1.80	1.95	1.58
19	---	1.53	1.82	1.97	1.78
20	---	1.54	1.78	1.95	1.56
21	---	1.40	1.79	1.95	1.42
22	---	1.38	1.81	1.96	1.45
23	---	1.42	1.83	1.96	1.42
24	---	1.41	1.85	1.96	1.43
25	1.31	1.41	1.83	1.97	1.43
26	1.32	1.44	1.85	1.95	1.42
27	1.35	1.43	1.87	1.97	1.45
28	1.25	1.42	1.85	1.99	---
29	---	1.43	1.85	2.00	---
30	---	1.57	1.86	1.96	---
31	---	1.72	---	1.98	---
Mean	---	1.36	1.84	1.91	---
Maximum	---	1.72	1.96	2.00	---
Minimum	---	1.10	1.74	1.79	---

Table 5.--Gage height data collected at Crouch Branch near H Area at Savannah River, S.C. (021973012) for the period of record

[---, not determined or missing data]

Location:--Lat 33°17'57", long 81°39'34", Aiken County, on left bank, 1.0 mile northwest of H Area, 1.0 mile northeast of F Area, 1,500 feet from confluence with Upper Three Runs Creek.
Drainage area:--0.9 square mile.
Period of record:--February 25, 1986 to November 17, 1986
Gage:--Digital water-stage recorder. Elevation of gage is 150 feet above sea level (from topographic map).
Remark:--No other gages have been operated on this stream.

					Gage height during 1986 (feet) mean values					
Day	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.
1	---	0.47	0.35	0.32	0.30	0.38	0.38	0.57	0.54	0.73
2	---	.47	.35	.32	.30	.38	.37	.56	.51	.57
3	---	.47	.35	.32	.32	.37	.37	.55	.51	.54
4	---	.48	.35	.32	.33	.37	.74	.55	.53	.52
5	---	.48	.35	.32	.33	.37	.41	.58	.53	.53
6	---	.48	.35	.31	.31	.38	.54	.59	.52	.53
7	---	.48	.35	.31	.30	.37	.61	---	.52	.53
8	---	.48	.41	.41	.30	.37	.54	---	.54	.55
9	---	.49	.40	.39	.30	.36	.40	---	.73	.55
10	---	.48	.35	.36	.78	.36	.38	---	.97	.55
11	---	.49	.35	.36	.81	.46	.37	.52	.62	.55
12	---	.49	.34	.50	.47	.39	.37	.54	.56	.55
13	---	.58	.34	.60	.43	.38	.44	.51	.56	.55
14	---	.70	.34	.38	.41	.39	.77	.50	.57	.55
15	---	.44	.34	.33	.41	.40	.46	.50	.56	.55
16	---	.43	.34	.32	.42	.38	.43	.50	.55	.55
17	---	.40	.34	.32	.41	.38	.43	.49	.53	.55
18	---	.40	.34	.32	.41	.37	.42	.49	.52	---
19	---	.60	.33	.32	.52	.36	.75	.49	.52	---
20	---	.52	.33	.32	.43	.36	.53	.50	.52	---
21	---	.41	.34	.31	.39	.38	.85	.50	.51	---
22	---	.40	.34	.31	.38	.52	.71	.50	.51	---
23	---	.38	.34	.31	.38	.42	.63	.50	.51	---
24	---	.36	.33	.30	.38	.41	.60	.50	.51	---
25	0.44	.36	.33	.30	.38	.40	.60	.51	.56	---
26	.45	.36	.32	.30	.39	.41	.59	.52	.53	---
27	.54	.36	.32	.31	.39	.39	.67	.54	.51	---
28	.48	.36	.32	.32	.38	.39	.72	.53	.51	---
29	---	.36	.33	.37	.38	.39	.63	.65	.51	---
30	---	.36	.32	.32	.37	.38	.63	.58	.51	---
31	---	.36	---	.31	---	.37	.62	---	.60	---
Mean	---	.45	.34	.34	.40	.39	.58	---	.55	---
Maximum	---	.70	.41	.60	.81	.52	1.53	---	.97	---
Minimum	---	.36	.32	.30	.30	.36	.37	---	.51	---

Seepage investigations were conducted on all three streams during a low flow period on March 19, 1986, to determine variations in stream discharge over several reaches along these streams. The last recorded precipitation occurred in the area 5 days prior to making these measurements. Station locations for these measurements are shown in figure 21.

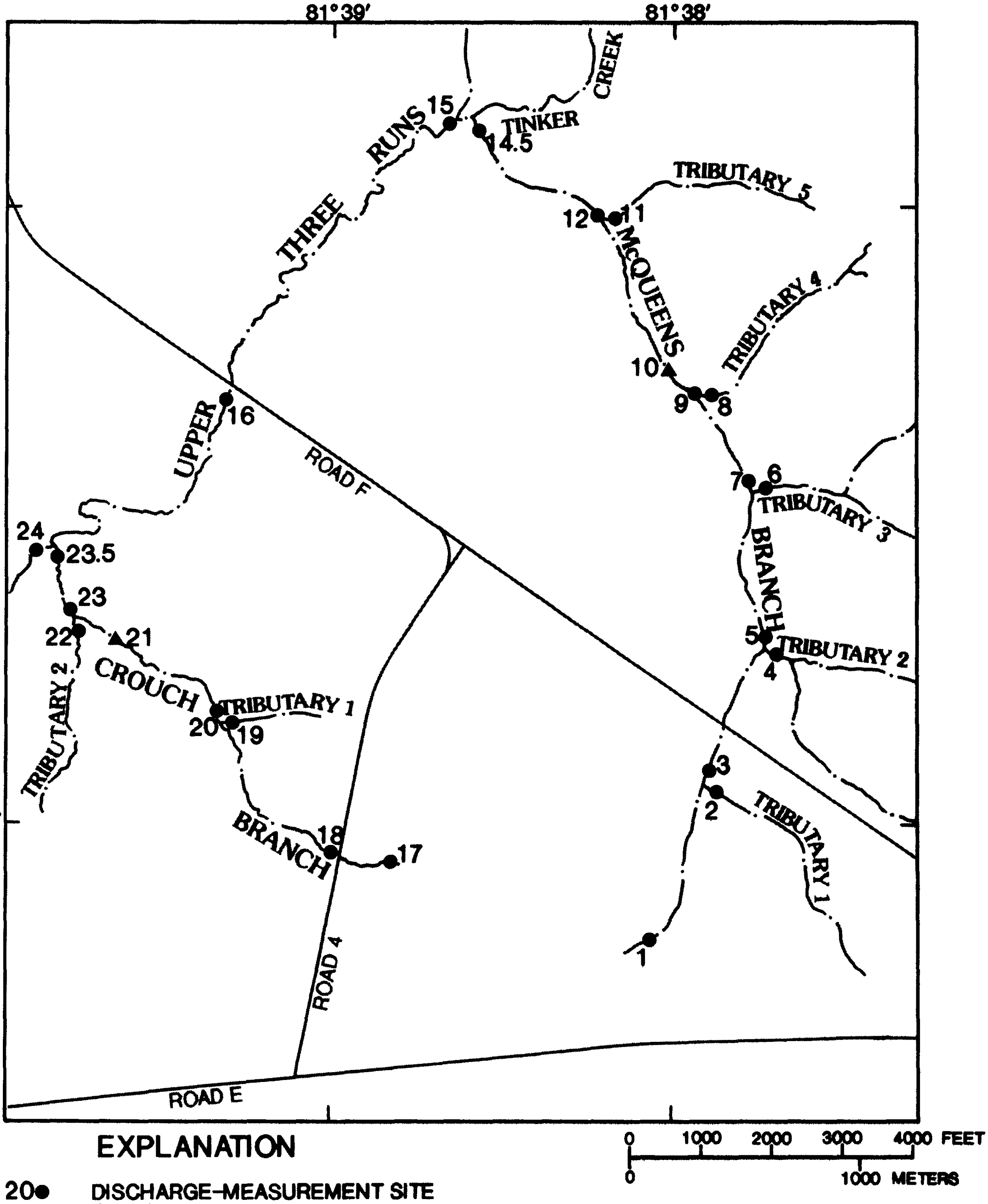
The results of the seepage investigation for that part of Upper Three Runs within the study area indicate that the average gain in streamflow was 9.3 $(ft^3/s)/mi$ of stream channel. The seepage data are presented in this form because it is directly transferable to future ground-water flow modeling of this study area. The contribution of ground water was constant throughout the length measured.

The results of the seepage investigation for McQueens Branch and Crouch Branch are shown in figure 22. The plots illustrate the cumulative flow measured at various points from the streams' origins to their most downstream point. Abrupt increases in flow represent contributions of small tributaries along the length of the streams. Every tributary that contributed flow to the main channel was measured. McQueens Branch, the larger of the two tributaries, gained ground water at an average rate of 0.65 $(ft^3/s)/mi$ of stream length. Crouch Branch gained ground water at an average rate of 0.56 $(ft^3/s)/mi$ of stream length. Note that the rate of inflow in different reaches differs along each stream's length. For example, there seems to be a measurable increase (steeper slope) in ground water discharge to streamflow between tributaries 4 and 5 of McQueens Branch (fig. 22a).

Ground water entered the stream at an equivalent rate of 1.68 $(ft^3/s)/mi$ of stream length. The approximate altitude of the stream bed in this reach is 165 ft. This is about the same altitude as the base of the calcareous zone in the McBean aquifer. Conceivably, the higher rate of discharge could be attributed to a more permeable interval in the calcareous zone. A sharp increase (steeper slope) in the contribution of ground water to streamflow also is evident in the reach between the gage and tributary 2 on Crouch Branch. The altitude of the gage, based on the topographic map, is 150 ft. The top of the Congaree aquifer is at an altitude of approximately 160 ft in this area (fig. 12). Between the gaging station and tributary 2 (fig. 22b), the stream probably has intercepted the more permeable Congaree aquifer which discharges ground water at a greater rate than the overlying strata.

WATER QUALITY AND GEOCHEMISTRY

Water samples from the Barnwell-McBean and Congaree aquifers were collected to determine background water quality in each aquifer. Cluster wells SDS-12 and SDS-20 were sampled (fig. 3). Wells in these clusters are screened in the Barnwell-McBean (SDS-12B, C, and SDS-20B, C) and Congaree aquifers (SDS-12A, SDS-20A).

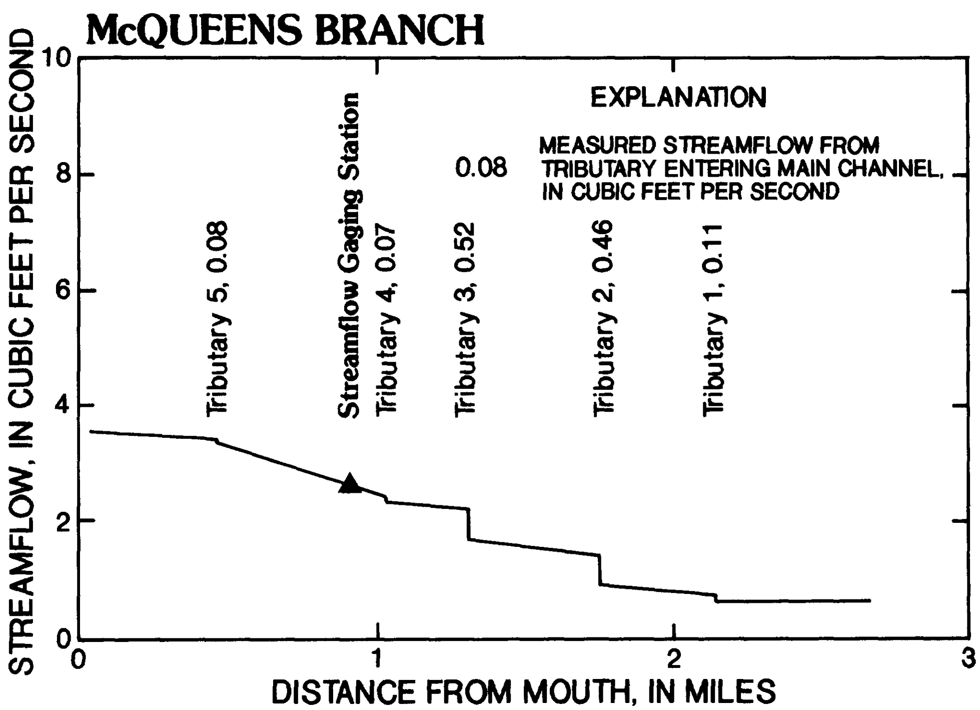


EXPLANATION

20● DISCHARGE-MEASUREMENT SITE AND SITE NUMBER

10▲ STREAMFLOW GAGING STATION AND STATION NUMBER

Figure 21.--Location of seepage investigation stations in the vicinity of the study area.



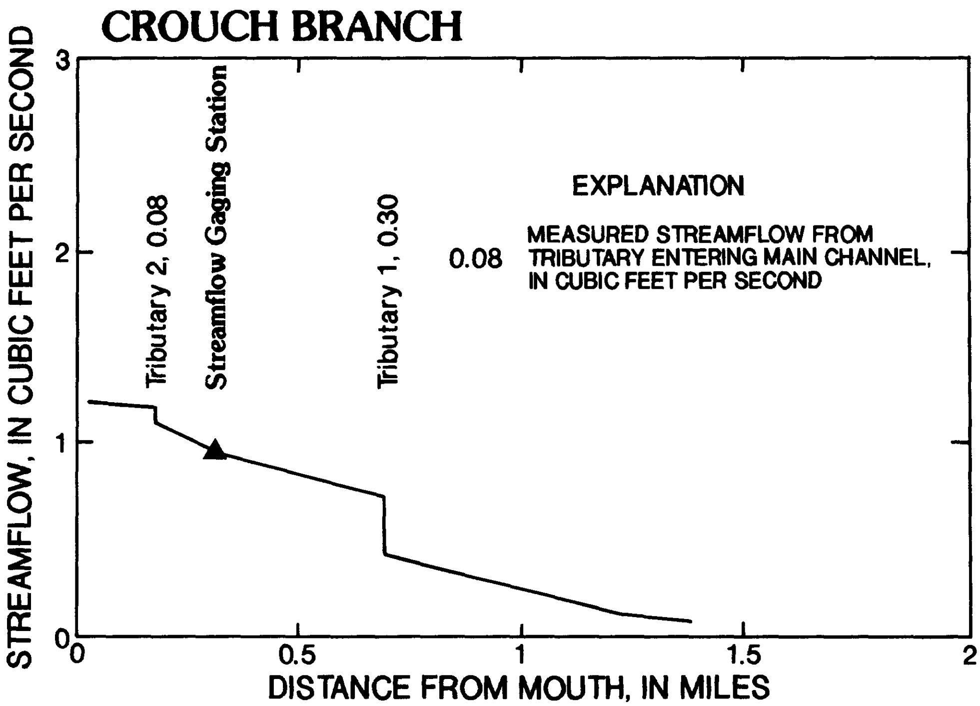


Figure 22.--Measured streamflow changes along reaches during seepage study; (a) McQueens Branch and (b) Crouch Branch.

Sample Collection and Analysis

Grout contamination in the SDS wells (Cook, 1986), and the low ionic strength of the shallow ground water necessitated that care be taken to obtain water samples representative of the aquifer. A significant effect of grout contamination is to increase the pH of water in the well and adjacent sections of the aquifer. For example, measured values of pH in samples from SDS-20A were reported to range from 10.49 to 11.15 (Cook, 1986), whereas pH measured in this study, after purging the well and adjacent aquifer, was 7.81 (table 6). In addition to grout contamination, waters of low ionic strength tend to be poorly buffered, making stable field measurements of pH difficult to obtain.

Prior to sampling, each well was pumped with a submersible pump until conductance, pH, and temperature, taken at one-half well-volume increments, had stabilized. A minimum of 4.5 well volumes were evacuated at each well before stability was reached. Alkalinity, conductance, pH, and temperature were measured in the field according to the methods of Wood (1976). Dissolved oxygen was measured titrametrically in the field (American Public Health Association 1981, p. 390).

In accordance with established procedures, samples were filtered through 0.45-micrometer pore size membrane filters and shipped on ice to the U.S. Geological Survey National Water Quality Laboratory in Arvada, Colorado for analysis (Fishman and Friedman, 1985). Samples for cation analysis were acidified with nitric acid.

Results and Analysis

Chemical analyses of water samples obtained from five wells in clusters SDS-12 and SDS-20 are presented in table 6. Well SDS-12B yielded insufficient quantities of water to obtain stable conductance, pH and temperature readings, therefore, it was not sampled. Charge balance differences between anions and cations were five percent or less for all analyses. The temperature of water from well SDS-20A may be artificially high owing to the heating action of the submersible pump used to collect the sample. Thermodynamic calculations made with the computer program WATEQF (Plummer and others, 1976) indicate that the relative equilibrium relations of the water do not change appreciably if a more likely temperature (such as that measured at SDS-12A) is used for the sample, therefore, the temperature measured at SDS-20A does not influence the interpretation of the data.

Water at these wells can be divided into three types (fig. 23, table 6): (1) an acidic mixed-ion type of water (SDS-20C); (2) an alkaline calcium-bicarbonate water (SDS-12A, SDS-20A, SDS-20B); and (3) a water intermediate between these two types of water (SDS-12C).

The mixed-ion water at SDS-20C is from the upper part of the Barnwell-McBean aquifer. No cation contributes more than 50 percent of the total cations and silica is a major part of the dissolved solids. Chloride and bicarbonate each contribute about half of the total anions. Acidity is

Table 6.--Concentrations of dissolved major and minor elements in waters from the Barnwell-McBean and Congaree aquifers

[T (°C), temperature in degrees Celsius; µs/cm, microsiemens per centimeter; <, less than specified value]

Sample	Calcium Ca	Magnesium Mg	Sodium Na	Potassium K	Chloride Cl	Sulfate SO_4	Bicarbonate HCO_3	pH (units)	Temperature T (°C)	Conductance (µS/cm)	Residue at 180 °C, dissolved
	Concentrations in milligrams per liter (mg/L)										
12A	38.0	1.6	2.7	1.3	1.7	12.0	123.0	8.09	21.2	184.0	175
12C	4.8	1.2	1.1	.4	.85	.2	18.0	6.85	21.5	35.0	35
20A	31.0	.57	1.8	1.7	2.2	10.0	85.0	7.81	22.7	153.0	120
20B	19.0	.52	1.9	.70	1.8	5.5	62.0	8.40	20.7	91.0	92
20C	1.6	.42	1.5	.42	2.1	.2	6.0	6.04	20.9	19.0	21

Concentrations in micrograms per liter (µg/L) unless otherwise specified

Sample	Aluminum Al	Barium Ba	Bromide Br (mg/L)	Cadmium Cd	Copper Cu	Dissolved oxygen O_2 (mg/L)	Fluoride F (mg/L)	Iron Fe	Lead Pb	Lithium Li	Manganese Mn
12A	<10.0	7.0	<0.01	<1.0	<10.0	0.6	<0.10	36.0	<10.0	12.0	8.0
12C	<10.0	20.0	.03	<1.0	<10.0	6.8	.07	6.0	<10.0	7.0	109.0
20A	<10.0	46.0	<.01	<1.0	<10.0	<.1	<.10	25.0	<10.0	15.0	82.0
20B	20.0	17.0	<.01	<1.0	<10.0	8.4	<.10	4.0	<10.0	8.0	<1.0
20C	20.0	10.0	.03	<1.0	20.0	8.8	.01	10.0	<10.0	6.0	12.0

Concentrations in micrograms per liter (µg/L) unless otherwise specified

Sample	Molybdenum Mo	Nitrite and nitrate NO_2 and NO_3 (mg/L as N)	Ortho phosphate PO_4 (mg/L as P)	Silica SiO_2 (mg/L)	Strontium Sr	Vanadium V	Zinc Zn	Beryllium Be	Boron B	Cobalt Co
12A	<10.0	<0.10	<0.01	40.0	390.0	<6.0	140.0	<0.5	20.0	<3.0
12C	<10.0	.89	<.01	5.7	17.0	<6.0	290.0	<.5	<10.0	<3.0
20A	<10.0	<.10	.08	24.0	269.0	<6.0	19.0	<.5	<10.0	<3.0
20B	<10.0	1.20	.06	24.0	91.0	<6.0	5.0	<.5	<10.0	<3.0
20C	<10.0	.65	<.01	6.4	14.0	<6.0	46.0	<.5	<10.0	<3.0

relatively high with a pH of 6.04, dissolved oxygen is relatively high (8.8 mg/L), and dissolved solids are relatively low (21 mg/L). Water of this type is characteristic of recharge waters in sediments of the Atlantic Coastal Plain (Baedecker and Back, 1979).

The calcium bicarbonate water is from the Congaree aquifer and the lower part of the Barnwell-McBean aquifer. Calcium and bicarbonate range from 19 to 38 mg/L and 62 to 123 mg/L, respectively, and contribute at least 83 percent of the ions in solution. This water is more alkaline than the mixed-ion water, with measured values of pH ranging from 7.81 to 8.40. Concentrations of dissolved silica are higher than in the mixed-ion water. Dissolved oxygen is high (8.4 mg/L) in the lower Barnwell-McBean aquifer at SDS-20B, but it is nearly depleted in the waters from the Congaree aquifer. Dissolved solids are at least three times higher in the calcium-bicarbonate water (92 to 175 mg/L) than in the mixed-ion water.

The intermediate water (well SDS-12C) also is from the upper part of the Barnwell-McBean aquifer. Like the mixed-ion water, it is low in dissolved solids (35 mg/L). However, dissolved calcium and bicarbonate are slightly higher and comprise 68 percent of the ions in solution. At 6.85, pH also is higher. Dissolved oxygen (6.8 mg/L) is slightly lower than the other water types from the Barnwell-McBean aquifer.

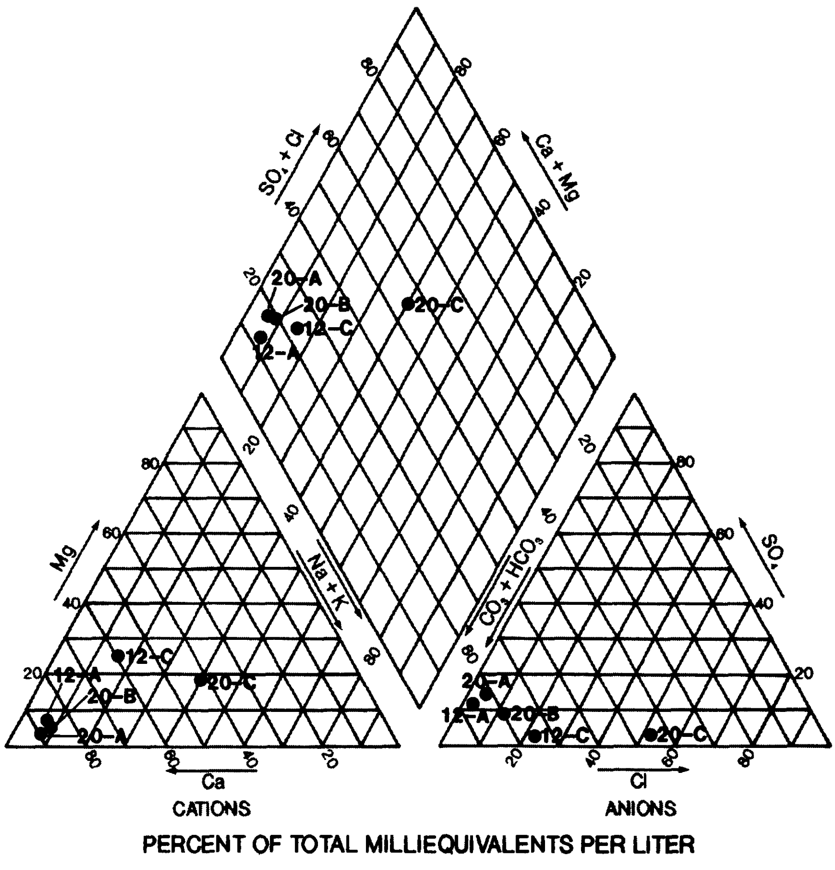


Figure 23.--Major-ion composition of water samples from the Barnwell-McBean and Congaree aquifers.

It is important to document the present concentrations of nitrate in the water-bearing units, because nitrate is a major constituent in the salt-solution waste that will be stored at Z Area. The highest measured concentration of dissolved nitrate plus nitrite, as nitrogen, was 1.20 mg/L (table 6). These nitrogen species were detected only in the unit containing measurable dissolved oxygen (Barnwell-McBean aquifer), indicating that nitrate/nitrite reducing bacteria may be active in the green clay and/or Congaree aquifer. This is important information with respect to following the movement of potential nitrate contaminants. Depending on the availability of required nutrients and organic substrates, the concentrations of nitrate contaminants could be lessened or eliminated in a zone of nitrate reduction.

The relatively high levels of dissolved zinc found in water samples from SDS-12 probably are due to contamination by the galvanized steel well casing. Wells at SDS-20 are made of PVC; therefore, similar contamination is unlikely. Relatively high levels of strontium were measured in waters from the Congaree aquifer. The strontium may be from the dissolution strontium-carbonate (strontianite) or strontium-sulfate (celestite) minerals. However, little is known about the occurrence of these minerals in sediments of the Congaree aquifer. It may also occur as a trace element in calcite and be released as calcite dissolves.

The major differences in water chemistry between the upper Barnwell-McBean aquifer and the lower Barnwell-McBean and Congaree aquifers can be summarized as follows: (1) dissolved calcium and bicarbonate concentrations are nearly ten fold greater in the lower Barnwell-McBean and Congaree aquifers; (2) dissolved silica concentrations are about five fold greater, and (3) pH is higher. Because there is a horizontal hydraulic gradient in each aquifer, in addition to a downward hydraulic gradient directed through the Barnwell-McBean aquifer and across the green clay into the Congaree aquifer, wells sampled in this study do not fall along a single flow path, so a strict mass-balance accounting of the dissolved constituents cannot be made. In addition, the limited number and distribution of analyses warrant only a limited interpretation. However, the wells are positioned such that a general discussion of the chemical evolution of the waters can be made.

The large increases in concentrations of dissolved calcium and bicarbonate in the lower Barnwell-McBean aquifer can be attributed to the dissolution of calcite in the calcareous zone in this part of the aquifer. For example, there is little dissolved calcium or bicarbonate in water from the upper Barnwell-McBean aquifer (SDS-20C), and it is undersaturated with respect to calcite, as calculated by WATEQF. This indicates that water from the upper Barnwell-McBean aquifer would tend to dissolve calcite if they were to come in contact. Because of the downward hydraulic gradient in the area, water in the upper Barnwell-McBean aquifer flows downward through the calcareous zone, dissolving calcite, thus increasing pH and increasing concentrations of dissolved calcium and bicarbonate in the lower Barnwell-McBean and Congaree aquifers. This is supported by WATEQF calculations, which indicate water in the lower Barnwell-McBean is in equilibrium with respect to calcite.

The major silica-bearing minerals in the Barnwell-McBean aquifer and the green clay are quartz in the sand fraction and illite/smectite in the clay fraction. Quartz is relatively unreactive at low temperatures, therefore, reactions involving illite/smectite probably are responsible for the large increase in dissolved silica between the upper Barnwell-McBean aquifer and the lower Barnwell-McBean and the Congaree aquifers. Geochemical data from each well were plotted on mineral stability diagrams (fig. 24) to determine which silicate minerals control concentrations of dissolved silica in the water. The composition and structure of illite/smectite mixed-layer clays are so highly variable that choosing accurate thermodynamic data for use in constructing stability diagrams is difficult. To simplify the matter, geochemical data were plotted on diagrams for pure end members of sodium smectite and calcium smectite in an attempt to account for probable compositional variability in the clay. Although the mixed-ion (SDS-20C) and intermediate (SDS-12C) waters plot near the quartz equilibrium line, the trend of the data is to traverse the kaolinite stability field in the direction of the smectite fields. This suggests that as water undersaturated with respect to illite/smectite moves downward it dissolves these clays. In this way, concentrations of dissolved silica increase and the water approachs illite/smectite equilibrium as indicated in figure 24. This reaction also consumes protons, thus increasing pH. Extensive silicification of carbonate material in the lower Barnwell-McBean has been seen in outcrop, suggesting that reactions of this type, which produce silica in excess of quartz saturation, are occurring in the McBean aquifer.

Samples need to be collected from additional wells to provide a better areal and vertical coverage in the study area. Analyses of these samples would allow for a more complete understanding of the geochemical processes and variability in the system.

LABORATORY ANALYSIS OF SEDIMENT/WASTE INTERACTIONS

Hydraulic conductivity is one of the most important hydrologic properties affecting the transport of contaminants in ground water. Although hydraulic conductivity routinely is assumed to remain constant at a point in space, physical and chemical reactions between ground water, sediment, and contaminants may cause it to increase or decrease (Alperovitch and others, 1985; Hayes, 1979). Sediment/waste interactions that might influence the hydraulic conductivity of sediments at the DWPF and vicinity were identified to better evaluate the potential for solute transport at the site. In order to do this, laboratory-scale column experiments were designed to examine the interactions between a laboratory salt solution and sediments with which the waste might come in contact.

Figure 2 shows the proposed location of the buried pipeline which will transport the salt-solution waste from H Area to Z Area. Because of topographic variations between H and Z Areas, the pipeline will pass through sediments of both the upland unit and the Barnwell Group. The sediments within the upland unit generally are more sandy and have a lower clay content than the sediments of the Barnwell Group. Laboratory experiments of

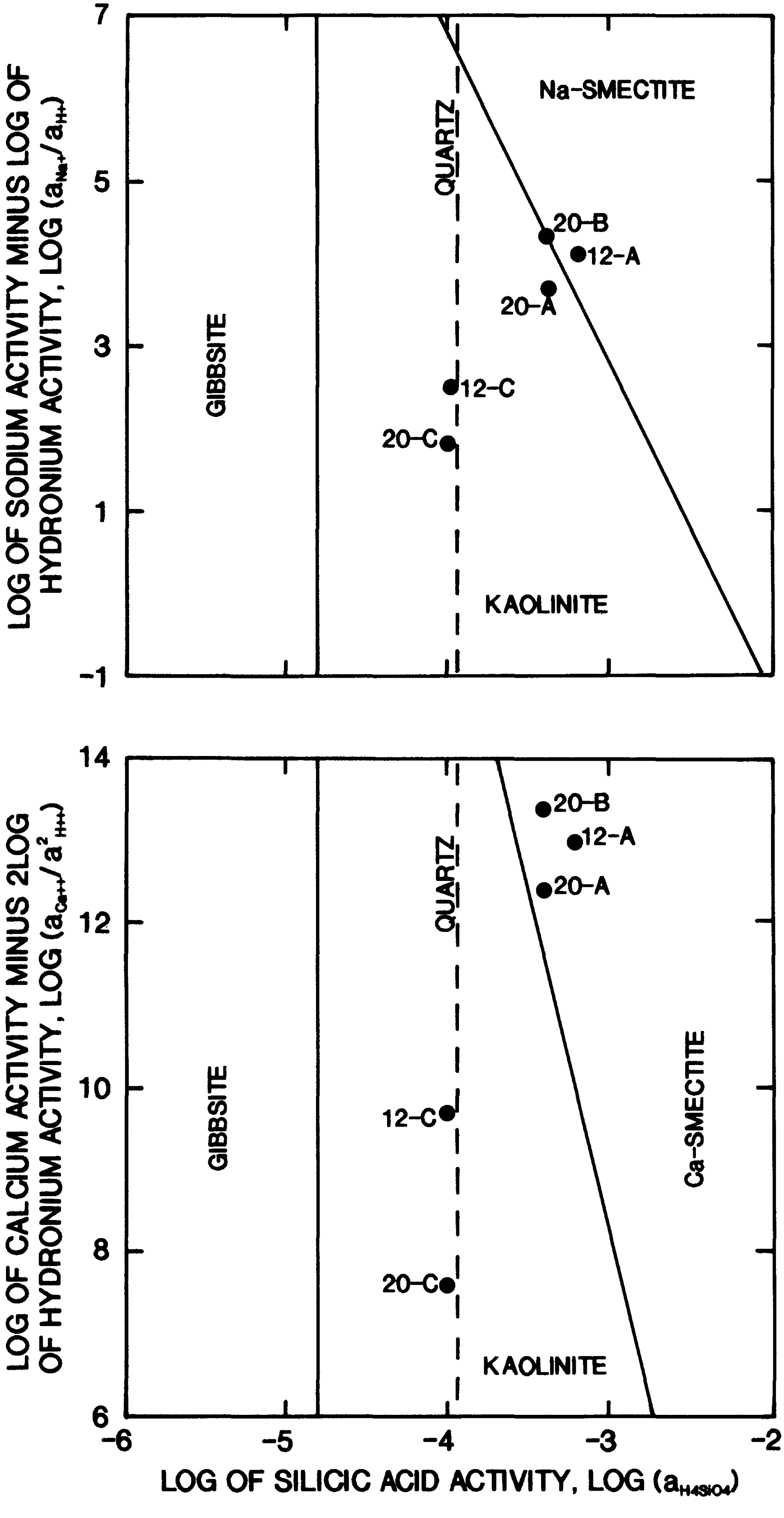


Figure 24.--Stability diagrams for the systems Na-SiO_2-Al_2O_3-H_2O and Ca-SiO_2-Al_2O_3-H_2O,with SDS well waters superimposed.

sediment/waste interactions were performed only on sediments from the Barnwell Group because these are the uppermost saturated sediments at the site.

Material and Method

The salt-solution waste is alkaline and composed largely of $NaNO_3$ (sodium nitrate). Table 7 compares the chemical and physical properties of the salt-solution waste and the solution used in laboratory experiments.

Fresh samples of the Barnwell Group were collected from an excavation for the salt-solution transfer pipeline. Table 8 gives the physical and mineralogic properties of sediments from the Barnwell Group used in the column experiments.

Hydraulic conductivity is a function of both fluid and media properties. Measured hydraulic conductivities were therefore converted to permeabilities (Freeze and Cherry, 1979, p. 27) in order to express the transmissive capability of the medium alone. Hydraulic conductivities obtained with fluids of different density could then be compared.

Oven-dried samples of sediment were sieved through a No. 10 sieve (2 millimeter) and compacted into a PVC cylinder (5.87 in. long by 2.44 in. in diameter) to a bulk density of 93.6 to 96.1 lb. per ft^3, with a porosity of about 0.42. Values obtained in field measurements conducted by D'Appolonia (1981, 1982) are similar; bulk density ranged from 96 to 120 lb. per ft^3 and porosity ranged from 26 to 46 percent. The cylinder was capped at both ends with porous stones and placed into a soil permeameter in order to saturate the sample with tap water and measure hydraulic conductivity using both constant and falling head permeameter tests (Bowles, 1978, p. 97).

The effect of salt solution on the hydraulic conductivity of the sediment samples was measured in three steps. Hydraulic conductivity of the sample was first measured by using tap water in order to establish a baseline value of hydraulic conductivity to compare with values obtained using salt solution. After passing tap water through the sediment for about 12 hours, it was flushed by using salt solution. The effect of the salt solution on the hydraulic conductivity of the sediments was analyzed in three separate tests by passing 2, 4, and 10 pore volumes of solution through the sample. Finally, salt solution was flushed from the sample with tap water to examine changes in hydraulic conductivity due to re-establishing initial solution conditions in the sediment. This sequence of solution applications is equivalent to examining changes in hydraulic conductivity in the Barnwell Group if a slug of the salt-solution waste were to pass through it.

In addition to measuring hydraulic conductivity, the conductance, pH, and concentrations of dissolved aluminum, silica, and sodium in aliquots of the effluent were measured during the tests. Dissolved constituents were analyzed by the South Carolina Department of Health and Environmental Control by using inductively coupled plasma emission spectroscopy.

Table 7.--Comparison of Defence Waste Processing Facility salt solution and solution used in column experiments

DWPF salt solution (approximate)*		Laboratory solution	
Component	Grams per Liter	Component	Grams per Liter
Na^+	117	Na^+	23
NO_3^-	130	NO_3^-	62
NO_2^-	30		
OH^-	20		
$NaB(C_6H_5)_4$	69		
pH ~ 14		pH ~ 12.5	
density	1.26 grams per cubic centimeter	density	1.05 grams per cubic centimeter

* (K. Hayes-White, written commun., 1986)

Table 8.--Properties of Barnwell sediments used in laboratory study

Fraction	Weight percent	Minerals present in order of relative abundance[a]	Cation exchange capacity[b] (milliequivalents (per 100g soil)	Bulk density (lbs/ft^3)	Total porosity percent
Sand (0.0625-2.00 millimeters)	85-90	Quartz, kaolinite (as aggregates), mica, feldspar	1.4 , pH = 6 2.5 , pH = 9 1.9 , pH = 12.5	93.6	42
Silt and clay (<.0625 millimeters)	10-15	Kaolinite, quartz, mica, hematite			

[a]Determined by x-ray diffraction

[b]Hawkins, 1971

Results and Discussion

The changes in relative permeability of the sediment as a function of total pore volumes of salt solution and tap water passed through the column are shown in figure 25. Relative permeability is the ratio of the measured permeability to the baseline value obtained using tap water. Zero pore volumes represents the introduction of salt solution after the initial application of tap water.

Each test (2, 4, 10 pore volumes of salt solution) generally exhibited the same pattern of relative permeability response (fig. 25). Relative permeability decreased sharply immediately upon the entry of salt solution into the sediment. After two pore volumes were introduced, relative permeability stabilized at a value roughly 20-30 percent of the baseline value. In the 4- and 10-pore volume tests relative permeability remained constant as the remaining salt solution was introduced to the sediment. After tap water was reintroduced into the sediments, relative permeabilities did not change until approximately one pore volume of tap water passed through the sediment. At this point, relative permeability decreased steadily, although less rapidly than during the initial introduction of salt solution. The final value of relative permeability for all three tests was about 4 to 10 percent of the baseline value.

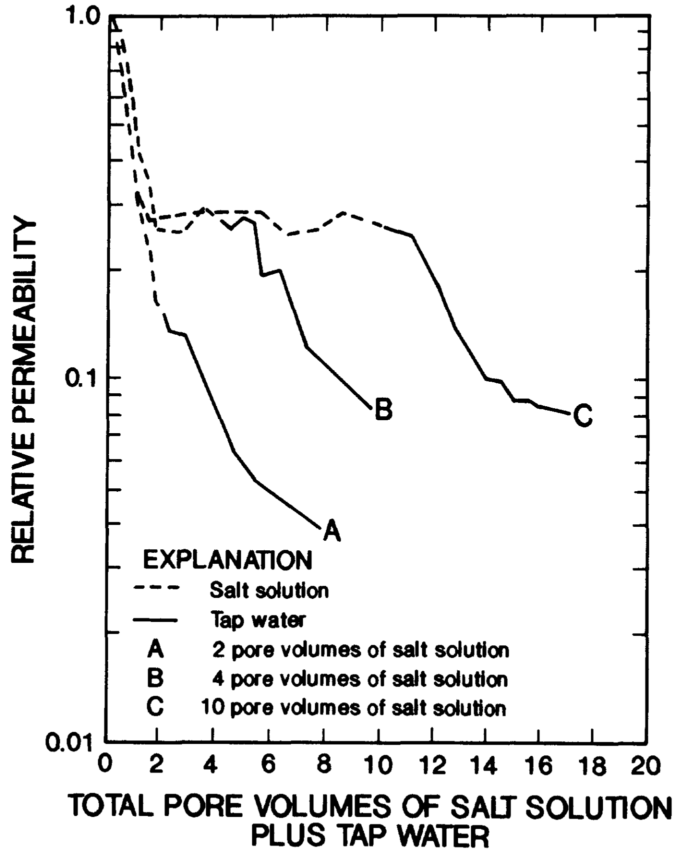


Figure 25.--Relative permeability as a function of total pore volumes of fluid passed through the column for three salt-solution/tap-water flushing sequences.

Permeability-reducing processes can be classified as: (1) mechanical (compaction, grain realignment); (2) chemical (mineral precipitation); and, (3) a combination of (1) and (2) (swelling of clays, dispersion of clays) (Hayes, 1979). Compaction processes can be ignored in the laboratory tests and probably are negligible in a stable tectonic environment like the Upper Coastal Plain of South Carolina (D'Appolonia 1982, p. 3.6.1-70). If smectite or mixed-layer clays were present, clay swelling might be an important process in the reduction of permeability. However, x-ray diffraction analyses of the sediment indicate there is very little, if any, expandable clay in the sediment (table 8). Therefore, precipitation of material from solution and clay dispersion are the only likely mechanisms available to account for the reductions in permeability.

Batch tests of mineral solubility in salt solutions with various alkalinities show that significant mineral dissolution occurred in alkaline solutions, but little dissolution occurred in solutions having values of pH less than about 9.0 (fig. 26a, b). Essentially there were no differences in concentrations of dissolved aluminum and silica between fresh water and 1 molar $NaNO_3$ at a pH less than 7. There were at least two orders of magnitude difference in concentrations between the $NaNO_3$ solution at a pH less than 7 and the solution at pH 12. X-ray diffraction data indicate that dissolution of quartz and kaolinite were the major sources of these solutes. Because of the large concentrations of dissolved silica and aluminum in the alkaline solution it is possible that the equilibrium solubility of one or more aluminum and/or silica-bearing minerals was exceeded, thus providing the potential for mineral precipitation to occur as the alkaline salt solution moved through the column. The data in figure 26c, however, indicate precipitation was not the principal mechanism affecting permeability. Changes in permeability measured during the introduction of salt solution under neutral and alkaline pH conditions show that nearly equal reductions in permeability occurred with both solutions. The slightly greater reductions in permeability produced by the alkaline solution might be a result of mineral precipitation. Examination of sediment exposed to salt solution by X-ray diffraction and scanning electron microscopy gave no evidence of mineral precipitation; although it is possible that very fine-grained, poorly-crystalline aluminum hydroxide species could have formed and gone undetected with these techniques. Furthermore, initial reductions in permeability occurred so rapidly (typically within 1 to 3 hours) that the rates of dissolution and precipitation would have been much greater than those measured in previous investigations (May and others, 1979; Hem and Lind, 1974). A second possible mechanism that might have produced the additional reduction in permeability is dissolution of mineral cements and matrix holding clay aggregates together, thus increasing the amount of mobile grains available to disperse.

The chemical data presented above indicate that the majority of the decreases in permeability were not due to mineral precipitation, therefore, dispersion of clay particles is the most reasonable mechanism. Generally, it is accepted in the soil-science literature that dissolved sodium promotes clay dispersion, and that the amount of clay dispersion is directly related to the amount of dissolved sodium in the pore fluid (Alperovitch and others, 1985; Arora and Coleman, 1979). Dispersion is due to expansion of the electrical double layer (EDL) surrounding a clay particle, which causes clay

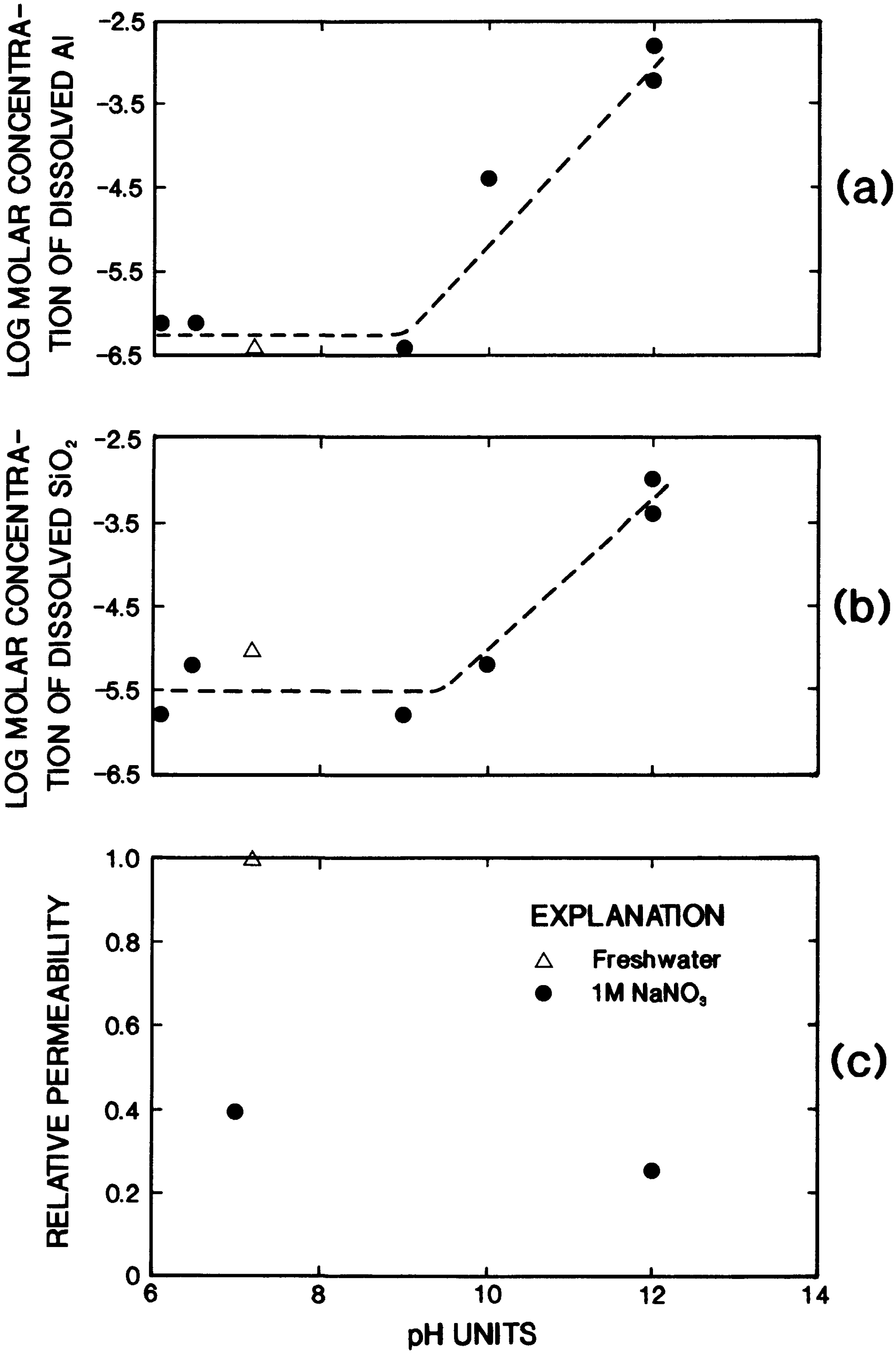


Figure 26.--pH as a function of measured concentrations of dissolved (a) aluminum and (b) silica from batch tests, and (c) relative permeability from column tests.

particles to separate and become mobile. The EDL thickness can be expanded by increasing the number of singly charged hydrated ions, such as sodium, on the clay surface and lowering the ionic strength of the pore fluid (Drever, 1982, p. 81; van Olphen, 1977, p. 34). As clay particles disperse they move through the pores of the sediment until they lodge in pore throats, thus causing a reduction in permeability. Surface-chemistry reactions associated with clay dispersion, proceed rapidly enough to go to completion within the observed period of 1 to 3 hours.

The clay-dispersion mechanism is consistent with the observed patterns of permeability reduction; that is, rapid lowering of permeability upon switching the pore fluid from tap water to salt solution, or the reverse, and no change during maximum salt breakthrough (fig. 25). Introducing salt solution to the column probably resulted in the development of an interface between the solutions, in which sodium concentrations were sufficiently high, and ionic strength sufficiently low, thus promoting clay dispersion. Arora and Coleman (1979) reported that dispersion of soil clay containing kaolinite, mica, and quartz ceased above a critical salt concentration of about 0.22 molar. Above this concentration, the repelling forces between clay particles are overcome by van de Waals forces, which attract clay particles toward each other. One molar sodium nitrate was used in this study, therefore, the critical salt concentration probably was exceeded as the concentration of dissolved sodium in the pore fluids reached maximum breakthrough levels, thereby allowing permeability to remain constant during this time. After freshwater was reintroduced to the column, the ionic strength of the pore fluid was lowered enough to allow clay dispersion, and associated reductions in permeability, to continue. Evidence for clay dispersion includes 1) the appearance of clay in the column effluent and 2) SEM views of pores clogged with grains of clay. Figure 27 shows photomicrographs of pore openings in untreated and treated sediments. The pore in the untreated sediment is relatively free of obstructions, whereas the pore in the treated sediment contains many submicron-sized kaolinite grains (mineral identification was based on morphology and energy dispersive analysis).

Significance Of Permeability Reductions

The reductions in permeability of the Barnwell sediments, owing to the passage of salt solution through them, have important implications with regard to the rate of contaminant transport in the system. The laboratory results indicate that a pulse of a concentrated salt-solution waste would move more slowly through the sediments than would be expected based on pre-spill measurements of hydraulic conductivity. The reduction in permeability, therefore, may act to contain a release of the salt-solution waste near the point of release. By the same token, the reductions in permeability also would make it harder to either flush the waste out of the system or to remove it using recovery wells.

The permeability reductions also have implications with respect to the accuracy of solute transport models that do not account for the changes. August (1986) illustrated the usefulness of incorporating dispersion-related permeability reductions in a computer simulation of an injection/withdrawal cycle of freshwater in a brackish aquifer in Virginia.

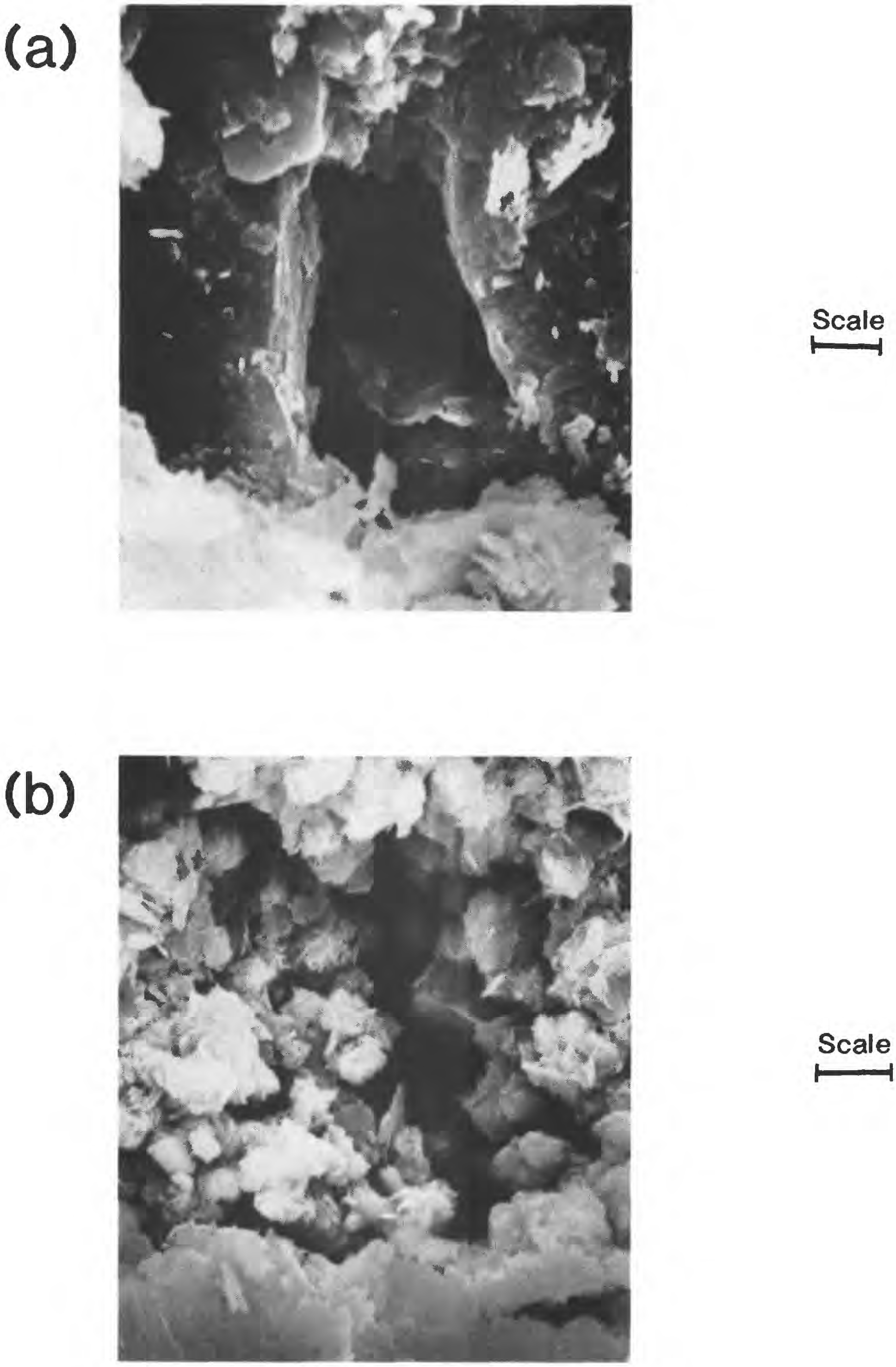


Figure 27.--Photomicrographs of pore openings in sediment samples (a) before and (b) after treatment with alkaline sodium-nitrate solution. Scale is 3.0 micrometers.

SUMMARY

This report presents the results of a preliminary geohydrologic investigation of the DWPF and vicinity in addition to an evaluation of the potential for movement of a concentrated salt-solution waste, if accidentally spilled. The study primarily is concerned with S Area (DWPF) and Z Area. DWPF, currently (1987) under construction, is where the high-level radioactive-sludge component of liquid wastes, generated as a by-product from the production of defense nuclear materials, will be solidified into an immobilized state. Z Area, north of DWPF, is the site for final storage of the other component, a concentrated salt-solution waste.

The report objectives were accomplished by assembling and evaluating existing geohydrologic data, developing a local geologic framework, developing a conceptual model of the local ground-water flow system, documenting present water-quality conditions, and performing laboratory experiments to test mobility of simulated salt-solution waste in surface and near-surface sediments.

A geologic framework was established for the study area. The Ellenton, Congaree, and McBean Formations, and the Barnwell Group were examined in addition to the upland unit and colluvium and (or) alluvium. Specific results from the geologic investigation include two geologic sections through the study area, a surficial geology map of the area, and structure contour maps of the tops of the tan- and green-clay confining units. Other results include the identification of a calcareous zone at the bottom of the McBean Formation. The calcareous zone is present east of F Area (well FC-3A) and has been identified in SDS wells. It was determined that the green-clay confining unit is most likely continuous over the study area, but that the tan clay is not present northeast of the DWPF. The tan clay is relatively continuous in the western and southern parts of the study area, and increases in thickness to the south. The two clay units vary in thickness; the tan clay ranges from 0 to 10 ft while the green clay averages 10 ft. The surfaces of the tan clay and the green clay gently slope to the southeast.

Major hydrogeologic units were delineated by using the assembled hydrogeologic data. The unsaturated zone at the study site consists of the upper part of the Barnwell Group, the upland unit, and colluvium and (or) alluvium. The thickness of the unsaturated zone varies from 60 ft at the center of the study area to 25 ft in the southwestern part. The average thickness of the upland unit is approximately 18 ft. In the northern half of the study area, the Barnwell aquifer is not hydraulically isolated from the McBean aquifer owing to the absence of the tan-clay confining unit. Therefore, in this area the Barnwell and McBean aquifers are considered to be one aquifer, the Barnwell-McBean aquifer. To the south, the aquifers are separated by the tan-clay confining unit and are individually identified. Potentiometric surface maps are presented for the Barnwell-McBean (water table), McBean, and Congaree aquifers for September 1986.

The Barnwell-McBean aquifer is highly dissected by area streams. Water in this aquifer is under water-table conditions and can be perched locally.

Inflow to the aquifer is from infiltrating precipitation and the lateral flow of water from the south. Discharge is to local streams and as leakage through the green-clay confining unit.

The Barnwell aquifer exhibits many of the same hydraulic characteristics as the Barnwell-McBean aquifer. An exception is that the Barnwell aquifer discharges to local streams and leaks through the tan-clay confining unit to the underlying McBean aquifer. The geometric average of laboratory derived hydraulic conductivities is 10^{-6} ft/s.

The McBean aquifer possibly composed up of three different geologic zones (upper sandy zone, transition zone, and lower calcareous zone). However, hydraulically, they tend to respond as a single unit. Hydraulic conductivities range from 10^{-8} to 10^{-4} ft/s and seem to be lower in the calcareous zone than in the upper sandy zone. Local streams incise the McBean aquifer and have a pronounced influence on the direction of ground-water flow. The McBean aquifer discharges lateraly to the northern half of the study area and downward to the underlying Congaree aquifer. The head difference across the tan-clay confining unit, which separates the Barnwell from the McBean aquifer, is about 2 ft.

The Congaree aquifer is the deepest aquifer included in this investigation. Its average hydraulic conductivity is approximately 10^{-5} ft/s. Upper Three Runs is the only stream to incise this aquifer within the study area. The direction of ground-water flow in the Congaree aquifer seems to be to the northwest, based on the potentiometric surface map. The decrease in hydraulic head across the green-clay confining unit, which separates the Congaree aquifer from the McBean aquifer, is approximately 50 ft. The green-clay confining unit has a lower hydraulic conductivity than the tan-clay confining unit.

Two streamflow gaging stations were installed on area streams (McQueens Branch and Crouch Branch). These two streams receive surface drainage from S and Z Areas and drain into Upper Three Runs. Results of seepage investigations indicate that over each reach measured, the stream gains flow and that the rate of gain varies as different geologic units are traversed.

A total of five samples were taken from the Barnwell-McBean and Congaree aquifers (SDS-12 and SDS-20) to document present water quality. It was determined that a minimum of 4.5 well volumes had to be evacuated from each well to obtain a representative sample of the aquifer. Ground water at these wells can be classified as: 1) acidic mixed-cation type (upper Barnwell-McBean); 2) alkaline calcium-bicarbonate type (lower Barnwell-McBean and Congaree); and, 3) a water intermediate between the previous two types (upper Barnwell-McBean). Major differences in water chemistry between waters from the upper part of Barnwell-McBean, the lower Barnwell-McBean, and the Congaree aquifers can be summarized as; 1) dissolved calcium and bicarbonate concentrations increase nearly ten fold with depth, 2) dissolved silica concentrations increase about five fold, and 3) pH increases. Chemical changes in water reflect the influence of lithology as water moves from the upper part of the Barnwell-McBean, to the lower Barnwell-McBean aquifer, and to the Congaree aquifer.

Laboratory column experiments were conducted to examine the potential for movement of a simulated salt solution in sediments from the Barnwell Group. A sequence of solution applications caused changes in hydraulic conductivity simulating changes that would result from a slug of a concentrated salt-solution waste passing through the sediments. Regardless of the number of pore volumes of salt solution passing through the column, the general pattern of decreasing relative permeability was the same, roughly 20 to 30 percent. During the final step of reintroducing tap water to the column, relative permeabilities decreased steadily to about 4 to 10 percent of original values. The physical mechanism responsible for permeability reductions is clay dispersion. Clay dispersion and reductions in permeability are related directly to the concentration of sodium in the pore fluid.

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