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SRS Geology/Hydrogeology Environmental Information Document

by
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Aiken, South Carolina 29808

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DISCLAIMER

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Chapter 1—Introduction

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Overview

The purpose of the Savannah River Site Geology and Hydrogeology Environmental Information Document (EID) is to provide geologic and hydrogeologic information to serve as a baseline to evaluate potential environmental impacts. This EID is based on a summary of knowledge accumulated from research conducted at the Savannah River Site (SRS) and surrounding areas.

This EID is divided into six chapters, including this introduction. The subdivision of the material covers six major geological subdisciplines: geomorphology, stratigraphy, structural geology and seismology, hydrostratigraphy and hydrogeology, water quality, and geochemistry.

Several appendices are included that may be helpful:

Appendix I: a map of the SRS showing the locations of the principal streams and the cultural features such as the major areas and man-made reservoirs and ponds

Appendix II: a geologic time scale

Appendix III: a glossary of technical terms used in the EID

Appendix IV: a compilation of hydrogeologic properties of the principal aquifer and confining units

Appendix V: a U.S. Geological Survey map of the Savannah River Site (Map MF-2300) compiled by Prowell (1996) and explanatory text for the map. To the extent possible, the lithostratigraphic nomenclature used in this EID is consistent with this map and with the nomenclature used by the U.S. Geological Survey and the South Carolina Geological Survey.

Regional Setting and Geologic Background

The Savannah River Site is along the Savannah River in west-central South Carolina. The site occupies approximately 800 km^2 (310 mi^2) in portions of Aiken, Allendale, and Barnwell counties. The site is in the Atlantic Coastal Plain physiographic province approximately 40 km (25 mi) southeast of the Fall Line, the boundary between Coastal Plain and Piedmont provinces (Figure 1-1). The Coastal Plain is underlain by a seaward-dipping wedge of unconsolidated and semiconsolidated sediments. This wedge extends from the contact at the Fall Line with the exposed metamorphic and igneous bedrock, which characterizes the Piedmont province, to the edge of the continental shelf. The wedge thickens from zero at the Fall Line to greater than 1.2 km (0.7 mi), locally, at the South Carolina coast. Piedmont rocks and Triassic-Jurassic sedimentary rocks form the basement for the Coastal Plain.

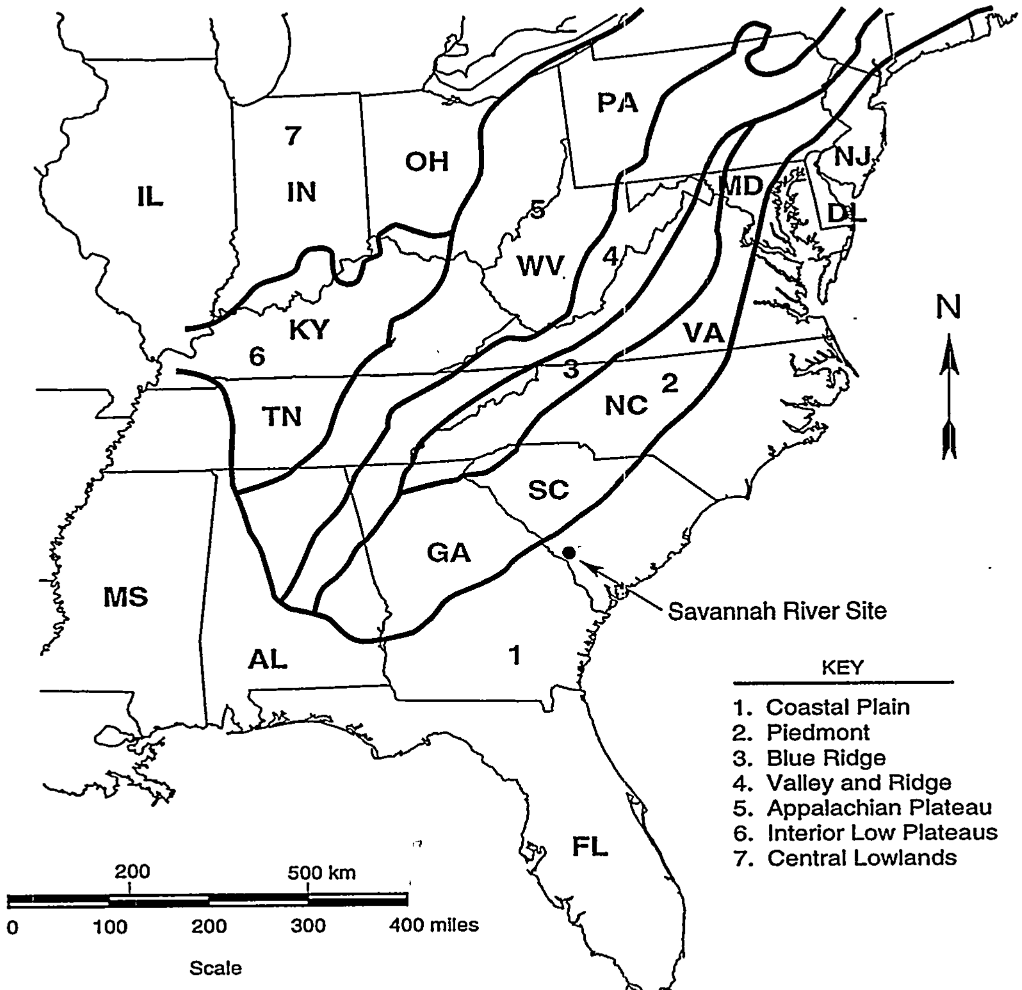

Figure 1-1. Physiographic Provinces of the Southeastern United States (Source: WSRC 1991).

Colquhoun and Johnson (1968) divided the South Carolina Coastal Plain into three physiographic belts: the Upper, Middle, and Lower Coastal Plains (Figure 1-2). The Upper Coastal Plain slopes from a maximum elevation of 200 m (650 ft) at the Fall Line to about 75 m (250 ft) on its southeastern boundary. Erosion has obliterated primary depositional topography of the Upper Coastal Plain. The Orangeburg Scarp separates the Upper and Middle Coastal Plains. The scarp has approximately 30 m (100 ft) of relief over a distance of a few kilometers. Lower elevations and subtle depositional topography that has been modified significantly by erosion, characterize the Middle Coastal Plain (Siple 1967). The Surry Scarp divides the Middle and Lower Coastal Plain belts. Cooke (1936) divided the Upper Coastal Plain of South Carolina into the Aiken Plateau and Congaree Sand Hills. SRS is on the Aiken Plateau (Figure 1-2).

The Aiken Plateau is bounded by the Savannah and Congaree Rivers and extends from the Fall Line to the Orangeburg Scarp. Broad interfluvial areas with narrow, steep-sided valleys characterize the plateau surface. Local relief is as much as 90 m (300 ft) (Siple 1967). The plateau is typically well drained, although many poorly drained sinks and depressions exist, especially in topographical high areas (above 80 m mean sea level [msl]). The Aiken Plateau also contains elliptical depressions called Carolina bays. These features are common throughout the Atlantic Coastal Plain, but are most numerous in North and South Carolina. The Carolina bays on the Aiken Plateau have southeast-trending major axes up to 1800 m (6000 ft) long (Siple 1967).

Chapter 2, Geomorphology, describes the evolution of landforms and surface geological features at the SRS, including the Aiken Plateau, formation of the scarps and stream terraces, the Savannah River floodplain, and Carolina bays.

A series of transgressions and regressions of the sea laid the sediments of the Atlantic Coastal Plain. The character of the sediments indicates a variety of depositional environments ranging from fluvial, to deltaic, to shallow marine. This broad range of depositional conditions has created a complex system of sedimentary units.

Chapter 3, Stratigraphy, provides details of the Atlantic Coastal Plain sedimentary wedge. This chapter also covers the lithology and characteristics of the underlying basement geology beneath the Coastal Plain sedimentary sequence at SRS. Two older geologic terranes are present. The first is the Dunbarton basin, a Triassic-Jurassic rift basin filled with lithified terrigenous and lacustrine sediments with minor amounts of mafic volcanic and intrusive rock (Marine 1974; Marine and Siple 1974). The second is a crystalline terrane of metamorphosed sedimentary and igneous rocks that may range in age from late Proterozoic to late Paleozoic. Erosion leveled the Paleozoic rocks and the Triassic-Jurassic sediments that make up the basement complexes prior to deposition of the Coastal Plain sediments.

Chapter 4, Structural Geology, discusses the structural features, particularly faults, identified in the SRS subsurface. Chapter 4 also addresses some of the seismic history of the region and the larger area of the southeastern United States.

The groundwater of SRS is an important environmental resource; therefore, understanding the complexities of the hydrogeologic processes and parameters that govern the flow of groundwater and transport of contaminants in the subsurface is equally important. The variety of depositional environments represented in the Atlantic Coastal Plain section underlying SRS has created a complex system of sedimentary units, some of which are highly

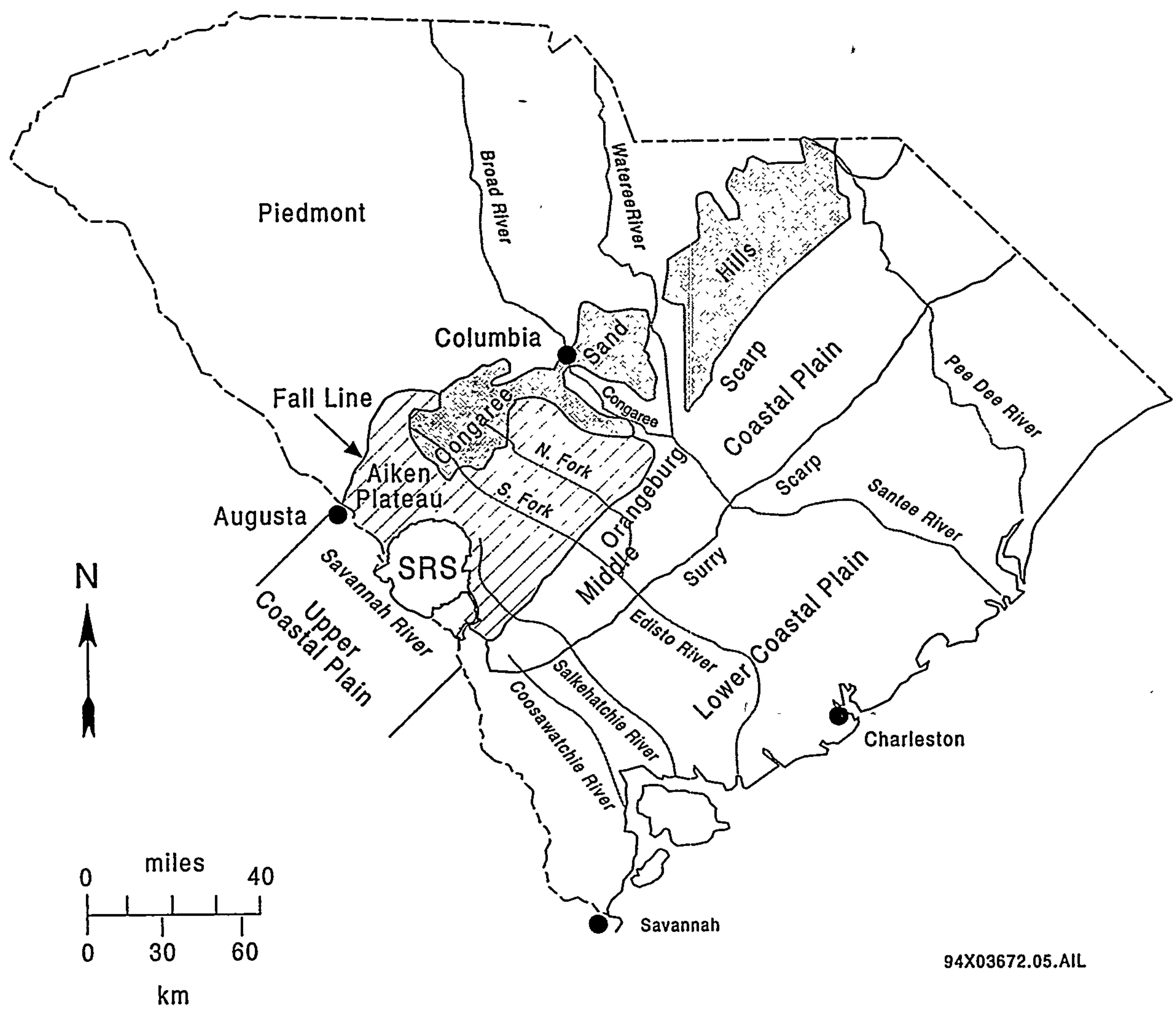

Figure 1-2. Location of the SRS and the Physiography of the Surrounding Region (modified after Siple 1967 and Cooke 1936).

permeable to water flow (aquifers) and others that strongly impede the flow of water (aquitards). These hydrogeologic characteristics have been studied and correlated to present a new synthesis of hydrostratigraphy for SRS (Aadland et al. 1992; Aadland and Bledsoe 1990a and b). This topic is covered in Chapter 5, Hydrogeology.

Chapter 6, Groundwater Quality, is a summary and synthesis of numerous hydrogeologic investigations conducted on SRS over the past four decades. Topics covered include background information on the groundwater geochemistry of the site and surrounding areas, microbiology of the subsurface, and data on factors governing the transport of contaminants on the site.

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Chapter 2—Geomorphology

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Introduction

In a modern view of geomorphology, the earth's surface represents the intersection of the atmosphere, hydrosphere, lithosphere, and biosphere (Ritter 1978). The drive towards equilibrium (from a geologic perspective) between geologic forces and the resistive media on which they act results in observed landforms. The driving forces, which include climate, gravity, heat transfer, and internal heat within the earth (which is the driving force for tectonic activity), control the processes that change the landscape. The resistive media are the land surfaces on which the forces are operating. In this view, landforms can be considered as part of an open system in which mass and energy are constantly supplied and removed (Ritter 1978). Thus SRS landforms are modified or were formed in order to balance gains and losses of mass and energy. Understanding these surface processes is therefore important for evaluating the forces that created the modern landforms and in predicting future changes to the landscape.

The primary driving forces governing landscape changes are the climate and tectonic activity. Climate, as defined by mean annual temperature and precipitation, plays a major role in determining the dominant geomorphologic processes that operate in an area (Wilson 1968). At SRS, the mean annual temperature is 18°C (64°F) and the average annual precipitation is 122 cm (48 in.). In such a climate, the dominant geomorphic processes are running water, weathering (both mechanical and chemical), and creep or slow mass movements (Wilson 1968). The resistive framework on which these processes operate at SRS is the Coastal Plain sediments, which underlie SRS (Chapter 3, Stratigraphy). These unconsolidated sediments are generally less resistant to geomorphic processes than other media such as igneous or metamorphic rock.

The region that includes the SRS has been above sea level since at least the late Miocene (i.e., about 6-10 million years). During this time, erosion of stream valleys, formation of soils by weathering, regional tilting of the crust beneath the site, and migration of the Savannah River all have sculpted the land surface. The combined action of these processes has created the variety of landforms observed at SRS. These landforms and the inferred processes responsible for their formation are described below.

Regional Setting

Introduction

SRS is in the Atlantic Coastal Province along the Savannah River in west-central South Carolina (Figure 2-1). The Atlantic Coastal Province differs from most other geomorphic provinces in North America in that it has a large suboceanic area, the Atlantic Continental Shelf, in addition to its subaerial segment, the Atlantic Coastal Plain (Walker and Coleman

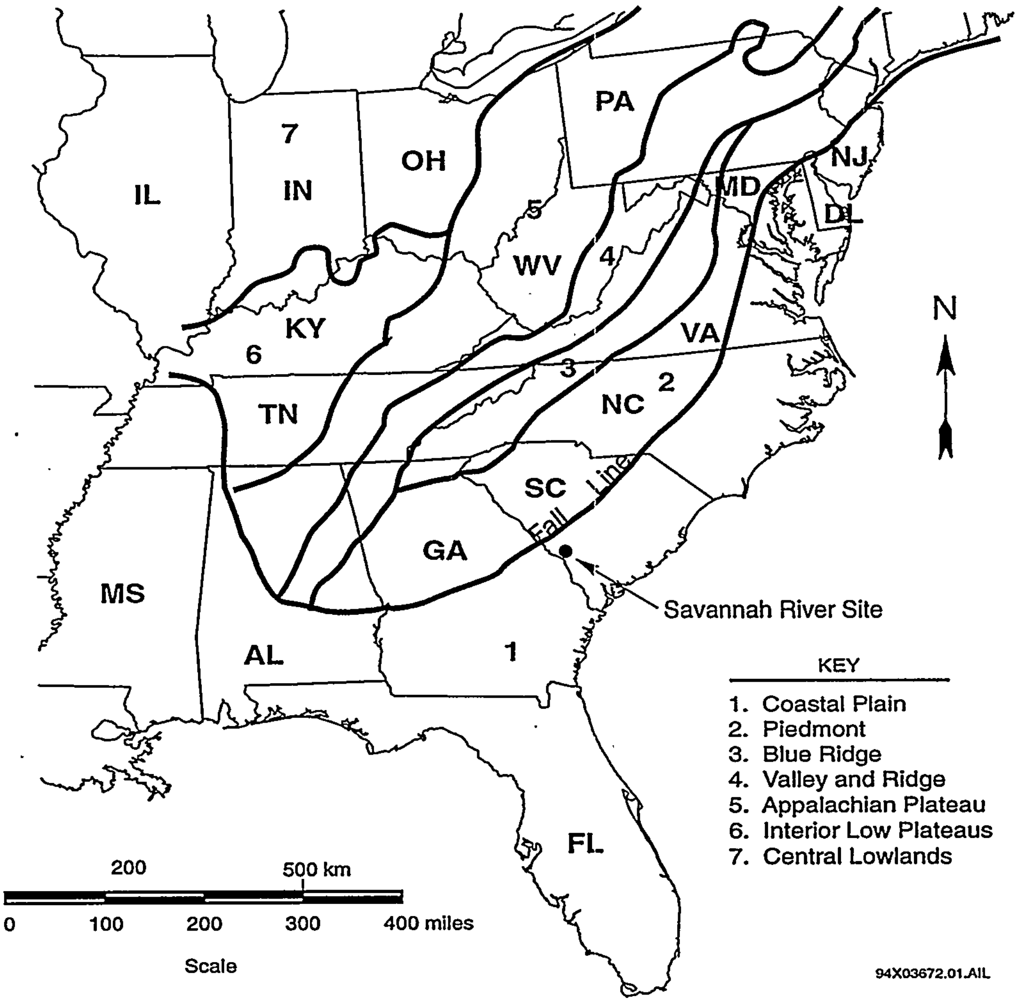

Figure 2-1. Physiographic Provinces of the Southeastern United States (Source: WSRC 1991).

1987). The Atlantic Coastal Plain extends from Long Island in New York (with outliers in Martha's Vineyard and Cape Cod) through the Atlantic coast of Florida.

The Coastal Plain is underlain by a seaward-dipping wedge of unconsolidated and semi-consolidated sediments ranging in age from Cretaceous to Holocene. The Coastal Plain sedimentary wedge extends from the contact at the Fall Line with the exposed metamorphic and igneous bedrock, which characterize the Piedmont Province, out to the edge of the continental shelf. The wedge thickens from zero at the Fall Line to greater than 1.2 km (0.7 mi), locally, at the South Carolina coast.

The unifying character of this province stems mainly from a geologic history that has recorded alternating periods of submergence and emergence (Walker and Coleman 1987). Thus, all parts of the province have experienced coastal processes, usually several times. Over many parts of the province, however, erosion or burial has extensively modified or destroyed the surface expression of coastal processes. Most of the Atlantic Continental

Shelf was subaerial as recently as 18,000 years ago, during the last glacial maximum; whereas parts of the Atlantic Coastal Plain have not been submerged since the Cretaceous (Walker and Coleman 1987). The interface between these two divisions, submerged and subaerial (i.e., the coastline), has been near its present position for only about 5000-6000 years (Walker and Coleman 1987).

Geomorphic processes have operated on the gently sloping surface of the Atlantic Coastal Plain sediments. These exposed sediments generally increase in age upslope. These older sediments have been subjected longer to subaerial geomorphic forces (Walker and Coleman 1987). In addition to slope and rock type, the effectiveness of processes within the province has varied mainly with tectonic activity, climate, time, and, more recently, human activity.

The major drainage pattern of the Atlantic Coastal Plain may be categorized as parallel. This pattern is characterized by relatively narrow, elongated drainage basins, with major tributaries having long stretches parallel to the primary branch of the river (Figure 2-2) (Walker and Coleman 1987).

South Carolina Coastal Plain Subprovinces

Upper Coastal Plain

Colquhoun and Johnson (1968) divided the South Carolina Coastal Plain into three physiographic belts: the Upper, Middle, and Lower Coastal Plains (Figure 2-3). The Upper Coastal Plain slopes from a maximum elevation of 200 m (650 ft) at the Fall Line to about 75 m (250 ft) on its southeastern boundary. It is underlain by sediments varying in age from Cretaceous to early or middle Miocene (Colquhoun and Johnson 1968). Subaerial erosion has obliterated primary depositional topography of the Upper Coastal Plain. The Orangeburg Scarp separates the Upper and Middle Coastal Plains. The scarp has approximately 30 m (100 ft) of relief over a distance of a few kilometers.

Cooke (1936) divided the Upper Coastal Plain of South Carolina into the Aiken Plateau to the southwest and Congaree Sand Hills toward the northeast. The Savannah River Site is on the Aiken Plateau, which is bounded by the Savannah and Congaree Rivers and extends from the Fall Line to the Orangeburg Scarp (Figure 2-3). Broad interfluvial areas with narrow, steep-sided valleys characterize the plateau surface. Local relief is as much as 90 m (300 ft) (Siple 1967). The plateau is usually well drained, although many poorly drained depressions exist, especially in topographical high areas. Many of these depressions are elliptical in outline and exhibit features common to Carolina bays. These bays are common throughout the Atlantic Coastal Plain, but are most numerous in North and South Carolina. The Carolina bays on the Aiken Plateau have southeast-trending major axes up to 1800 m (6000 ft) long (Siple 1967).

Middle Coastal Plain

Lower elevations, approximately 75-43 m (250-140 ft), characterize the Middle Coastal Plain (Colquhoun and Johnson 1968). Subtle remnants of the depositional topography remain, but the plain has been modified significantly by subaerial erosion (Siple 1967). At shallow depths, the Middle Coastal Plain is underlain predominantly by sediments ranging in age from late Miocene to Pliocene (Colquhoun and Johnson 1968). The Surry Scarp divides the Middle and Lower Coastal Plain subprovinces.

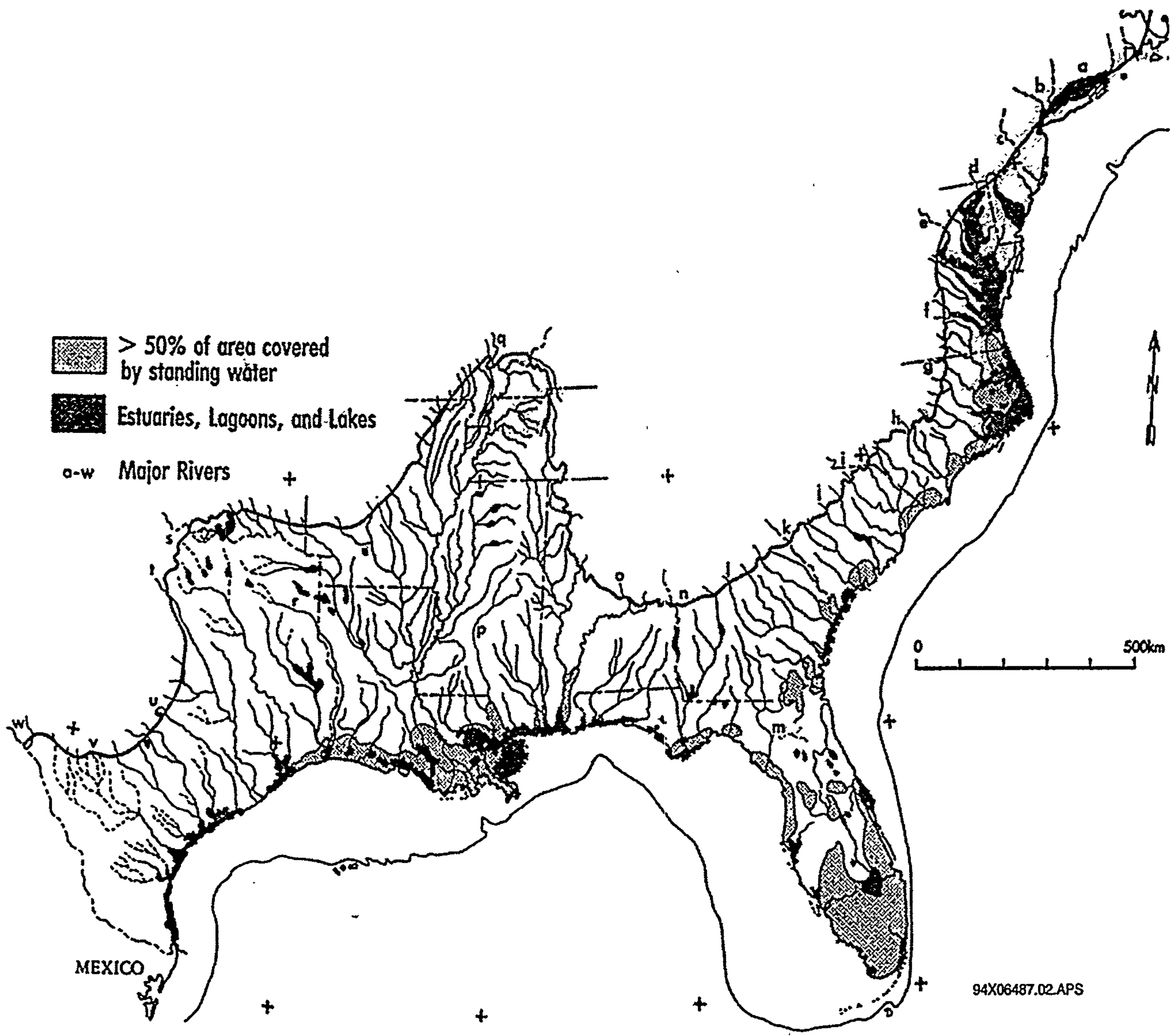

Figure 2-2. Primary Drainage Systems in the Coastal Plain Physiographic Province (Source: Walker and Coleman 1987).

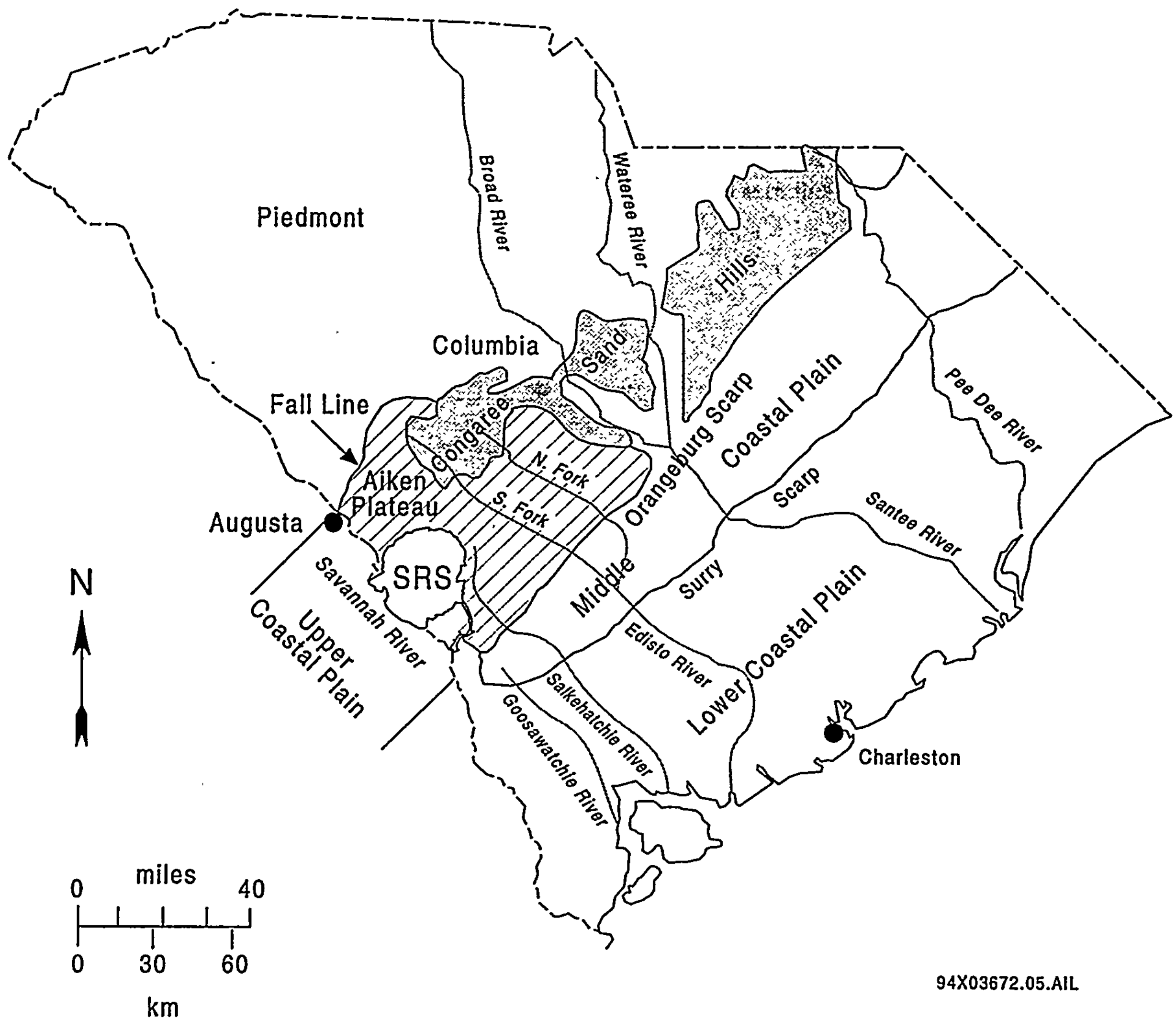

Figure 2-3. Location of the Savannah River Site and the Physiography of the Surrounding Region (Source: modified after Siple 1967 and Cooke 1936).

Lower Coastal Plain

The Lower Coastal Plain (Figure 2-3) surface is dominantly one of primary topography (Colquhoun and Johnson 1968). Effects of fluvial and eolian erosion are most apparent in the landward part of the subprovince. Larger landforms, such as barrier-island chains and marsh surfaces, can be observed in the landward areas. Individual storm beach ridges can be recognized on aerial photographs, topographic maps, and soil maps in the seaward part of the subprovince (Colquhoun and Johnson 1968). The Lower Coastal Plain is underlain at shallow depths by Pleistocene and Holocene sediments lying at elevations ranging from zero at the coast to approximately 43 m (140 ft).

Regional Drainage Pattern

A parallel drainage pattern is prevalent in South Carolina as in other portions of the Atlantic Coastal Province (Figure 2-3) (Howard 1967). This pattern tends to form on parallel, elongated landforms that have a low to moderate uniform regional dip. These conditions are characteristic of the South Carolina Coastal Plain sediments, which form parallel, elongated landforms bounded by the major scarps: Surry Scarp and Orangeburg Scarp.

Landforms

Aiken Plateau

The network of tributaries of the Savannah River heavily dissects the surface of the Aiken Plateau at SRS. The broad interfluvial areas have gently rolling hills with relatively shallow slopes. The major geomorphologic process operating on these surfaces is likely to be soil creep due to the shallow slope. On the eastern half of SRS, late Miocene to middle Pliocene dune sands cover some of the plateau areas (Nystrom and Willoughby 1992; Prowell 1994). Recognizable dunes appear on topographic maps. The areas covered by dune-sands are conspicuous because they appear to be less dissected by stream tributaries. One potential explanation for this is that the dune-sands are quite permeable, and rainfall infiltrates readily rather than forming runoff to streams.

The streams generally have steeply sloping banks along one side and more gentle slopes along the opposite bank. This is notable particularly along Upper and Lower Three Runs and along the Savannah River. The origin of this cross-sectional asymmetry has not been resolved. Potential explanations include control by regional or local tilting of SRS strata (Geomatrix Consultants 1993; Stieve et al. 1993; Chapter 3, Stratigraphy) and Ferrel's law (Ferrel 1859), which states that moving bodies in the Northern Hemisphere are deflected to the right (Siple 1967).

Carolina Bays

Introduction

Most of the upland areas of the Aiken Plateau are well drained, but numerous poorly drained depressions are present. Many of the depressions have the characteristic features of Carolina bays, which were described from areas further east on the Coastal Plain. These depressions are generally elliptical or oval, with their major axes aligned northwest-southeast. On the SRS, the common association of Carolina bays to underlying calcareous sediments lead Siple (1967) to attribute their formation to a collapse of partially dissolved calcareous units. More recent studies (e.g., Kaczorowski 1976 and 1977) suggest that surficial processes are responsible for the development of Carolina bays.

The SRS has 194 confirmed or suspected Carolina bays that have been identified and cataloged by Schalles et al. (1989). Their work showed that Carolina bays are distributed in clusters or broad bands across the site (Figure 2-4). The lowest densities occur in the northeastern section of the site. The bays occur at elevations ranging from 36-104 m (120-340 ft). The surface areas of SRS bays range from less than 0.1 hectare (ha) (0.25 acre) to about 50 ha (125 acres). The Savannah River Site also has small wetlands with circular outlines. These areas, which may be small Carolina bays, are especially numerous near the floodplain of the Savannah River in the southwestern portion of the Site. Schalles et al. (1989) excluded up to a dozen small wetlands because they lacked the characteristic elliptical shape or a northwest-to-southeast orientation of their long axes. They noted from a review of 1940s aerial photography that Sites 96, 97, and 98 may be remnants of a very large bay covering approximately 220 ha (540 acres). The median size of SRS bays is about 0.8 ha (2 acres) (Table 2-1). Only about 15 of the bays exceed 4 ha (10 acres) in area. Although some of the SRS Carolina bays are in proximity to one another (e.g., Sites 124 and 125, Sites 91 and 92), no examples of the overlapping bay depressions reported by previous workers were found (Johnson 1942; Prouty 1952).

In a more recent study, Kirkman et al. (1996) identified 299 Carolina bay and bay-like structures on the SRS by examining 1951 aerial photographs. The difference between the number identified in this study and that of Schalles et al. 1989 is a result of the interpretation of what constitutes a Carolina bay or bay-like structure. The size range and size frequency distribution of Carolina bays is very similar in both studies.

Carolina bays on SRS have mineral soils with little or no peat accumulation; many are underlain by a low permeability clay (Schalles et al. 1989). Most of the bays contain water, at least seasonally or in some years. Frey (1950) observed that such "hard-bottomed" bays in North Carolina occur primarily on the upper Coastal Plain terraces. Surface inflow channels are generally absent (Schalles et al. 1989). Drainage channels occur with some frequency; although many appear to be man- made or modified. Today, through disuse, most of these channels are partially filled with sediments, and surface discharge occurs only during periods of extremely high water (Schalles et al. 1989).

Carolina Bay Hydrology

All SRS Carolina bays dry out periodically (Schalles et al. 1989). Many of the smaller bays contain surface water only during wet seasons; whereas some of the larger depressions dry up only during prolonged drought. These conditions suggest that water in the bays is in continuous or temporary connection with near-surface groundwater. Schalles et al. (1989) proposed that most groundwater-surface water interactions occur laterally, around the margins of the depressions, and that these connections often are lost during periods of low water levels. In some cases, the underlying clay can form a perched water table. In contrast, a detailed study by Lide et al. (1995) of the hydrology of Thunder Bay near the eastern border of the Savannah River Site showed that water in that bay was in constant contact with the water table. Thus, this Carolina bay is not the result of water perched upon a clay layer above the water table.

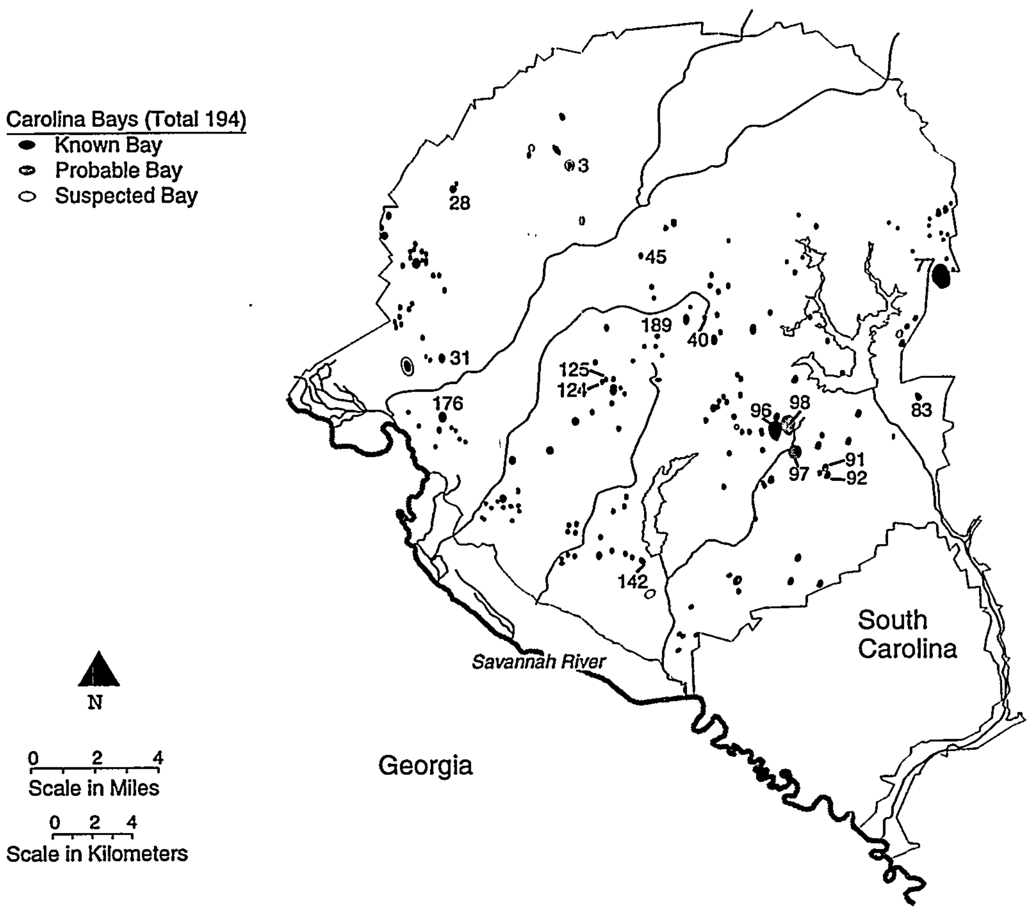

Figure 2-4. Known and Suspected Carolina Bays of the Savannah River Site. They Appear in Northeast-Southwest Trending Bands or in Clusters (modified after Schalles et al. 1989). Numbers refer to sites specified by Schalles et al. (1989).

Table 2-1. Carolina Bays

Bay Size (Hectares)	No. of Bays
<0.2	22
0.40-0.81	60
1.2-2.0	69
2.4-4.1	27
4.4-5.7	8
8.5	1
11.3	2

Fluvial Landforms

Introduction

The majority of SRS is drained by the Savannah River and its tributaries. The principal tributaries are Upper Three Runs, Four Mile Branch, Pen Branch, Steel Creek, and Lower Three Runs (Figure 2-5). All of these tributaries flow southwest at approximately right angles to the Savannah River and approximately parallel to the strike of the sedimentary units. A small portion of the eastern edge of SRS drains to the Salkehatchie River. At the smaller scale of the tributary basins, the drainage networks are dendritic. This type of network tends to develop on horizontal or nearly horizontal sediments (Howard 1967), which is characteristic of the sediments underlying SRS.

Savannah River Valley

Introduction

The Savannah River is the local base level for surface drainage from the SRS. It occupies a broad valley that has been cut into the Aiken Plateau. Incision of the river has produced an 85-m (280-ft)-deep valley. The valley varies from approximately 10-17 km (6-10 mi) wide in the vicinity of SRS. The river meanders through the valley both upstream and downstream of the site. Adjacent to SRS, however, the river is relatively straight, especially where it has migrated to the southwestern side of the valley. The average gradient of the river through the SRS area is about 0.2 m/km (1.0 ft/mi).

Development of the Savannah River Valley

In the past, the Savannah River valley has been more deeply incised than is evident by the modern river channel. In recent geologic time, the valley has been partially back-filled with alluvial sediments. The initial stages of the drainage basin formation likely were established by late Miocene time (Newell et al. 1980). Fluctuations in sea level occurred due to waxing or waning of glaciation during the Plio-Pleistocene reaching a low sea-level stand during late Wisconsinan time approximately 18,000 years ago (Milliman and Emery 1960).

The Savannah River has deepened and widened since the late Miocene. The river, above and below SRS, has a broad floodplain across which the channel meanders. The main reach of river along the southwestern margin of the site is anomalously straight, and the river channel runs along the southern side of the floodplain.

On the northeastern side of the valley, two prominent terraces have formed (Figure 2-6). The older and higher terrace has been variously named the Ellenton Plain, Terrace II (Stevenson 1982), and the Ellenton Terrace (Geomatrix Consultants 1993). The younger and lower terrace has been called Terrace I (Stevenson 1982) and the Bush Field Terrace (Geomatrix Consultants 1993). This report uses the nomenclature of Geomatrix Consultants (1993).

Preservation of older, unpaired terraces northeast of the modern floodplain suggests westward migration of the river occurred during incision below the general elevation of the broad upland surfaces of the Aiken Plateau (Figure 2-7). In the SRS area, tributaries entering the Savannah River from the northeast are considerably longer and have larger drainage

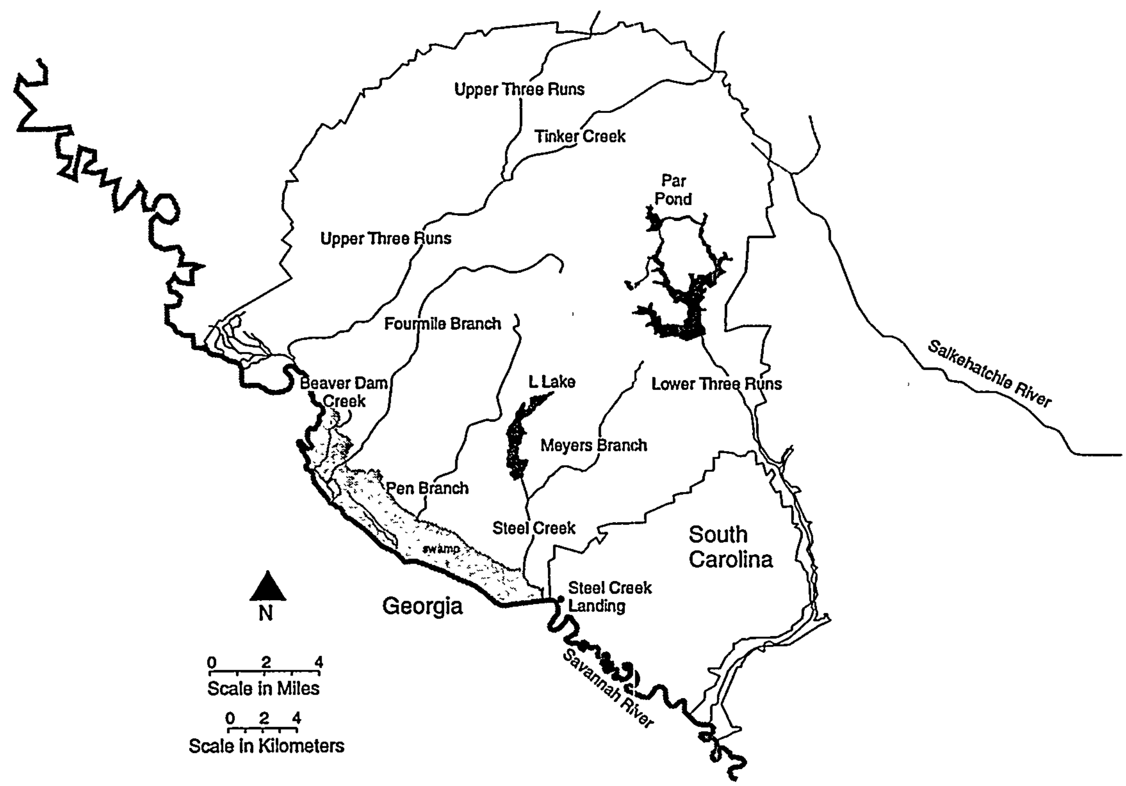

Figure 2-5. Surface Drainage Systems of the Savannah River Site.

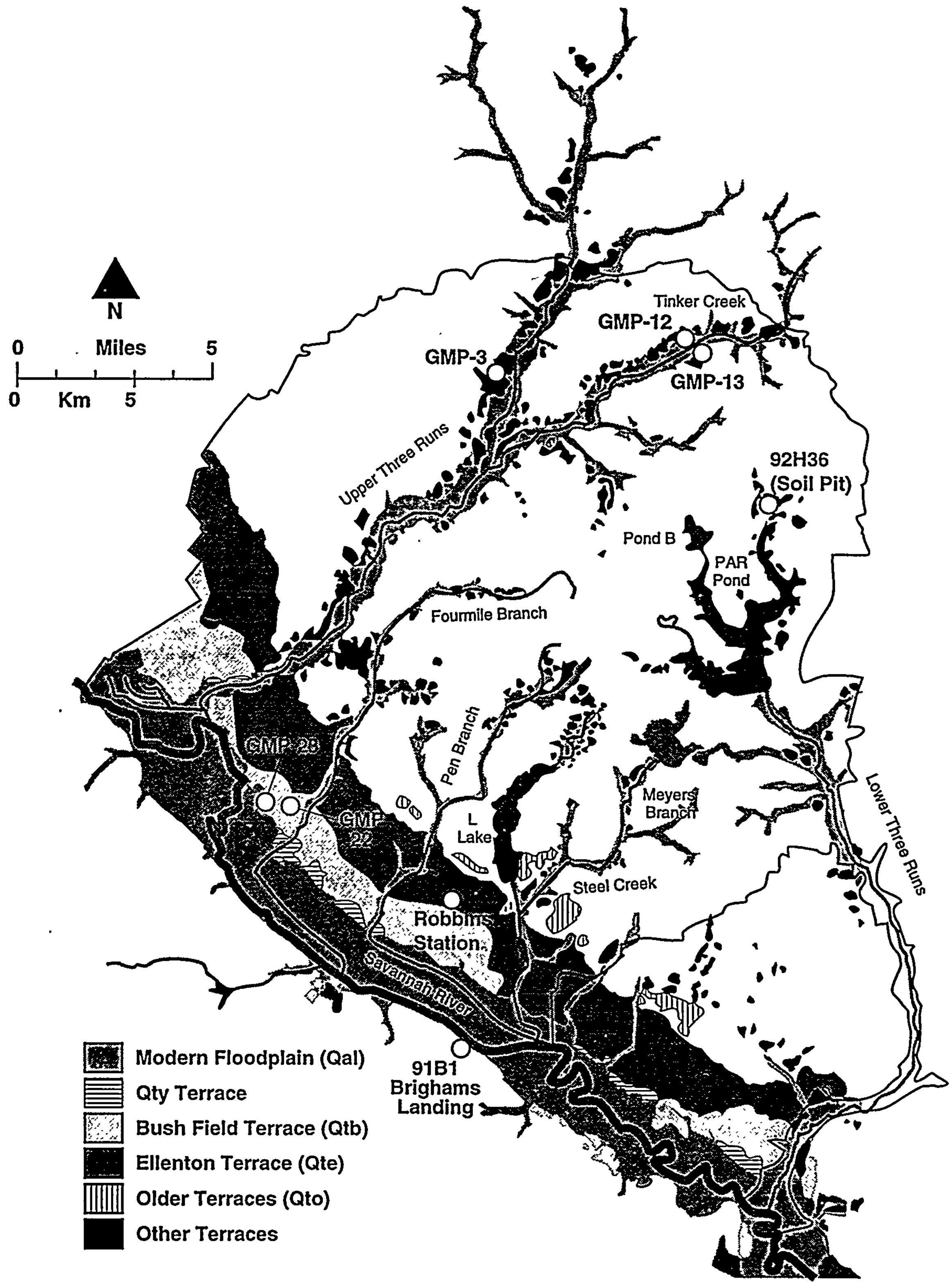

Figure 2-6. Terraces of the Savannah River and its Tributaries. Labeled Circles Identify Locations of Drill Holes or Soil Profiles (Source: Geomatrix Consultants 1993).

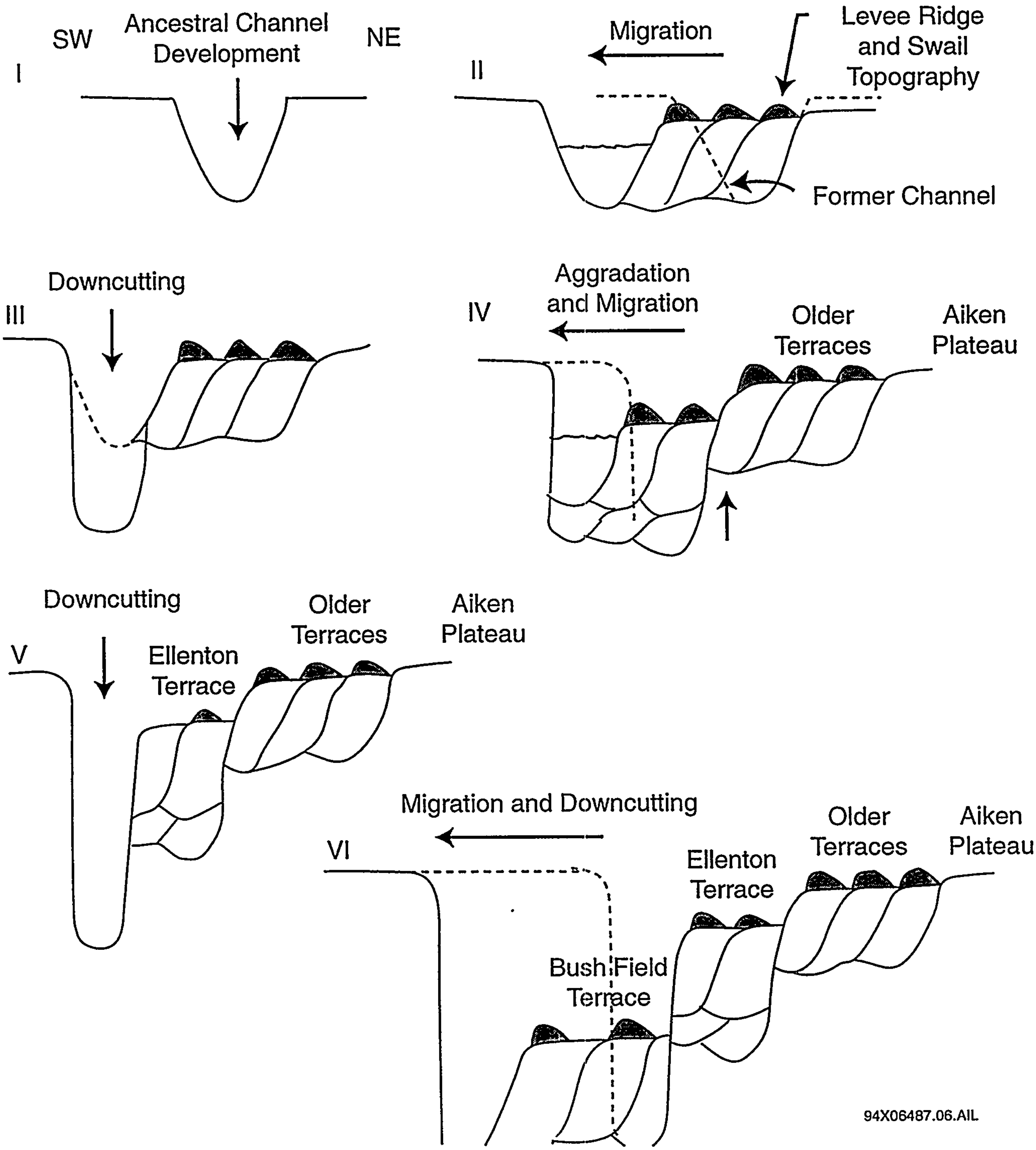

Figure 2-7. Reconstruction of Terrace Formation along the Savannah River on the Savannah River Site (The Ellenton Terrace was dated by Hanson et al. [1993] at 0.35-1Ma. The Bush Field Terrace was dated by Hanson et al. [1993] to be between 100-250 ka years old [modified from Stevenson 1982]).

basins than tributaries to the southwest. This pattern also suggests stream capture and erosion related to a general westward migration of the river. The position of the Savannah River appears to have shifted less in the areas north and south of the SRS area, where paired terraces (i.e., terraces at the same elevation on both sides of a stream) indicate that the river has maintained a similar location, particularly since development of the Bush Field terrace. More detailed descriptions of these fluvial terraces are below.

Modern Floodplain

The Savannah River incised into underlying tertiary sediments during the late Pleistocene. This downcutting was a result of lower sea level during periods of glaciation and the establishment of lower base levels for the rivers draining the Piedmont and Atlantic Coastal Plain. Ongoing studies by the U.S. Geological Survey, earlier studies by Stevenson (1982), and seismic profiling of the river indicate that the erosion surface developed during the last glacial period lies approximately 10-15 m (33-49 ft) below the present river channel and floodplain.

During the last 10,000 years, as the glaciers melted and sea level rose, the principal geomorphic process taking place has been aggradation (i.e., filling of the river valley with sediment) to form a wide floodplain. The cause of the aggradation is still uncertain. Stevenson (1982) suggested that the aggradation resulted from sea level rise and a general landward migration of the shoreline. Alternatively, Geomatrix Consultants (1993) suggests that climatic change associated with the melting of the glaciers increased sediment supply and hence aggradation.

Trimble (1975) estimated soil erosion on the southern Piedmont since the start of European occupation based on U.S. Department of Agriculture (USDA) erosion surveys conducted between 1936 and 1967. The most severe erosion occurred on the Piedmont of South Carolina and eastern Georgia (Figure 2-8). The estimated average depths of soil erosion were 7.6 in. from the Georgia Piedmont and 9.6 in. from the South Carolina Piedmont. A portion of this erosion made up the sediment supply being carried downstream by the Savannah River. This sediment is what sustains or builds the modern floodplain.

The modern Savannah River floodplain generally consists of extensive broad alluvial surfaces at heights ranging from 2-3 m (7-10 ft) above the modern river channel. The relief on these broad surfaces is generally less than 1 m (3 ft) over short distances; the total relief may be as much as 3 m (10 ft) over large distances that encompass meander scrollwork, meander cutoffs, oxbow lakes, and abandoned meanders. Terraces or surfaces of intermediate height that form from channel migration can be found within the modern floodplain. Reconstruction of paleochannels (Stevenson 1982) indicates that, although the river at the present time maintains a relatively straight course in the reach south of Four Mile Branch, it meandered across the floodplain during the Holocene (Figure 2-9).

Stevenson (1982) devised a detailed sequence of the migration trends of the Savannah River in its present valley based upon the direction of the channel migration trends and course direction transitions (smooth, parallel boundaries or cross-cutting relationships). The reconstruction indicates that the river generally has migrated laterally from the northeast to the southwest. The sequence of remnant channels is illustrated in Figure 2-9 with "A" representing the oldest and "H" the youngest.

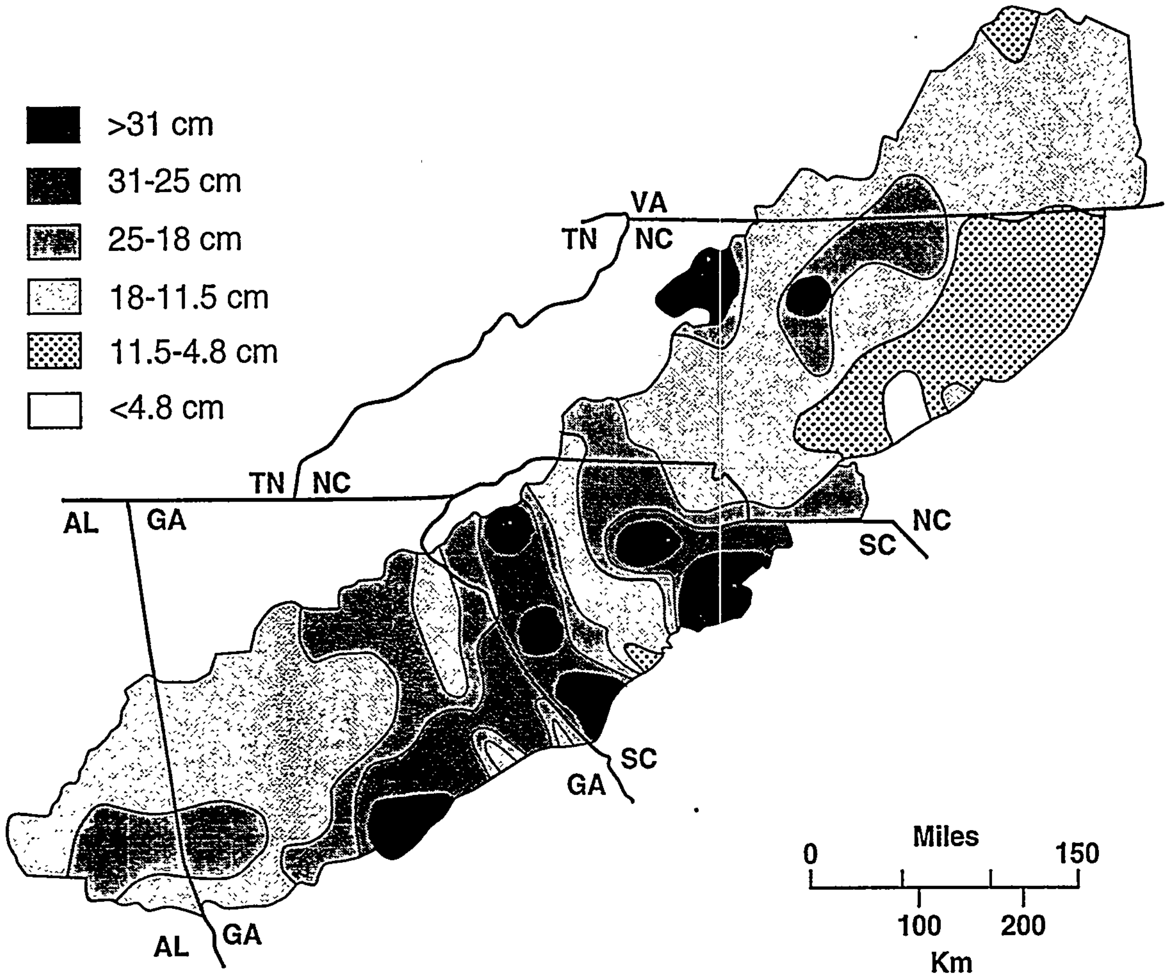

Figure 2-8. Estimated Total Soil Removal in the Piedmont Physiographic Province (after Trimble 1975).

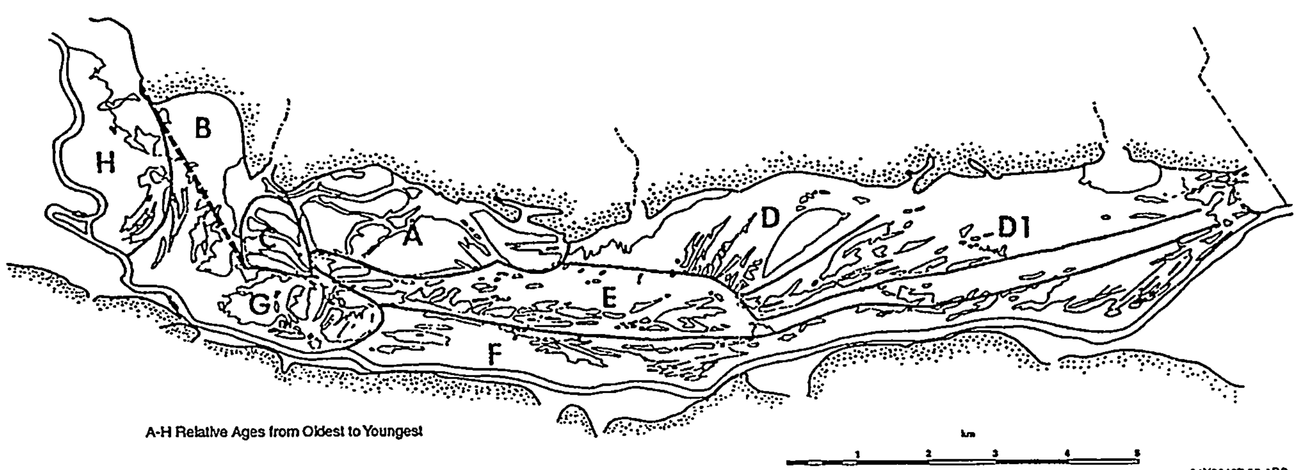

Figure 2-9. Inferred Reconstruction of the Migration History of the Savannah River Within the Modern Floodplain Adjacent to the Savannah River Site (The oldest trend is "A." A radiocarbon date from trend D suggests that this portion of the floodplain was deposited approximately 4000 years ago.).

Stevenson (1982) also examined geomorphic changes during historical times by comparing a series of navigation charts and maps of the Savannah River created since 1818. Three changes were noted: changes in the meander pattern, cutoff of an oxbow lake in the upstream portion of the study area, and diversion of the Pen Branch tributary (Figure 2-10).

Fluvial Terraces

Two prominent fluvial terraces of the Savannah River have been recognized and studied in detail on SRS: the Bush Field Terrace and the Ellenton Terrace (Geomatrix Consultants 1993). Geomatrix also identified minor fluvial terraces, including younger terraces of intermediate elevation between the modern floodplain and the Bush Field Terrace, and remnants of older terraces at elevations higher than the Ellenton Terrace.

Geomatrix Consultants (1993) estimated ages for the terraces using different approaches: it correlated the terraces to other dated fluvial terraces and to regional soil chronosequences and it estimated ages using uplift and incision models. The results indicate the terraces were formed during the Pleistocene with the age of the Ellenton Terrace estimated between 350 ka and 1 Ma and the age of the Bush Field Terrace estimated between 100 and 250 ka. This sequence is illustrated schematically in Figure 2-7. The terraces are asymmetrical, lacking pairs along the southwest bank of the river (Figure 2-6). This pattern is particularly noticeable in the stretch between the confluence of Upper Three Runs and the Barnwell County and Allendale County line south of Steel Creek, where the present river channel is eroding and forming high, steep bluffs on the Georgia side (southwest) of the river.

<u>Younger Terrace Surfaces</u>. Geomatrix Consultants (1993) recognized terrace surfaces (Qty in Figures 2-6, 2-11, and 2-12) approximately 5-6 m (16-20 ft) above the present channel, slightly higher than the modern heights.

These surfaces of intermediate height are not easily distinguished from the modern floodplain or the next higher terrace, the Bush Field Terrace (Qtb). Subsurface data near Fourmile Branch, however, suggest that the elevation of the erosional unconformity underlying the 6-m (20-ft) terrace surface at this location differs from the underlying strath surfaces associated with either the Bush Field Terrace or the modern floodplain (Figure 2-12) (Geomatrix Consultants 1993).

<u>Bush Field Terrace</u>. The Bush Field Terrace (Qtb in Figures 2-6, 2-11, and 2-12, the lower of the two prominent terraces along the Savannah River, is comparable in width to the modern floodplain and, like the modern floodplain, includes terrace surfaces of slightly differing heights above local base level. The Bush Field Terrace includes surfaces ranging from approximately 8-13 m (26-43 ft) above the Savannah River (Figures 2-11 and 2-12). Subsurface data for this terrace near Fourmile Branch suggest that some of these surfaces are fill-cut terraces (Geomatrix Consultants 1993).

Within SRS, the Bush Field Terrace is preserved primarily on the northeast side of the river (Figures 2-6, 2-11, and 2-12). Northwest of the site boundary, broad terrace remnants are well preserved on the southwest side of the river, where they are occupied by the Bush Field airport buildings and runways (Geomatrix Consultants 1993). Bush Field Terrace remnants are on both sides of the river near the confluence of Lower Three Runs and the Savannah River at the southern margin of the study area (Geomatrix Consultants 1993).

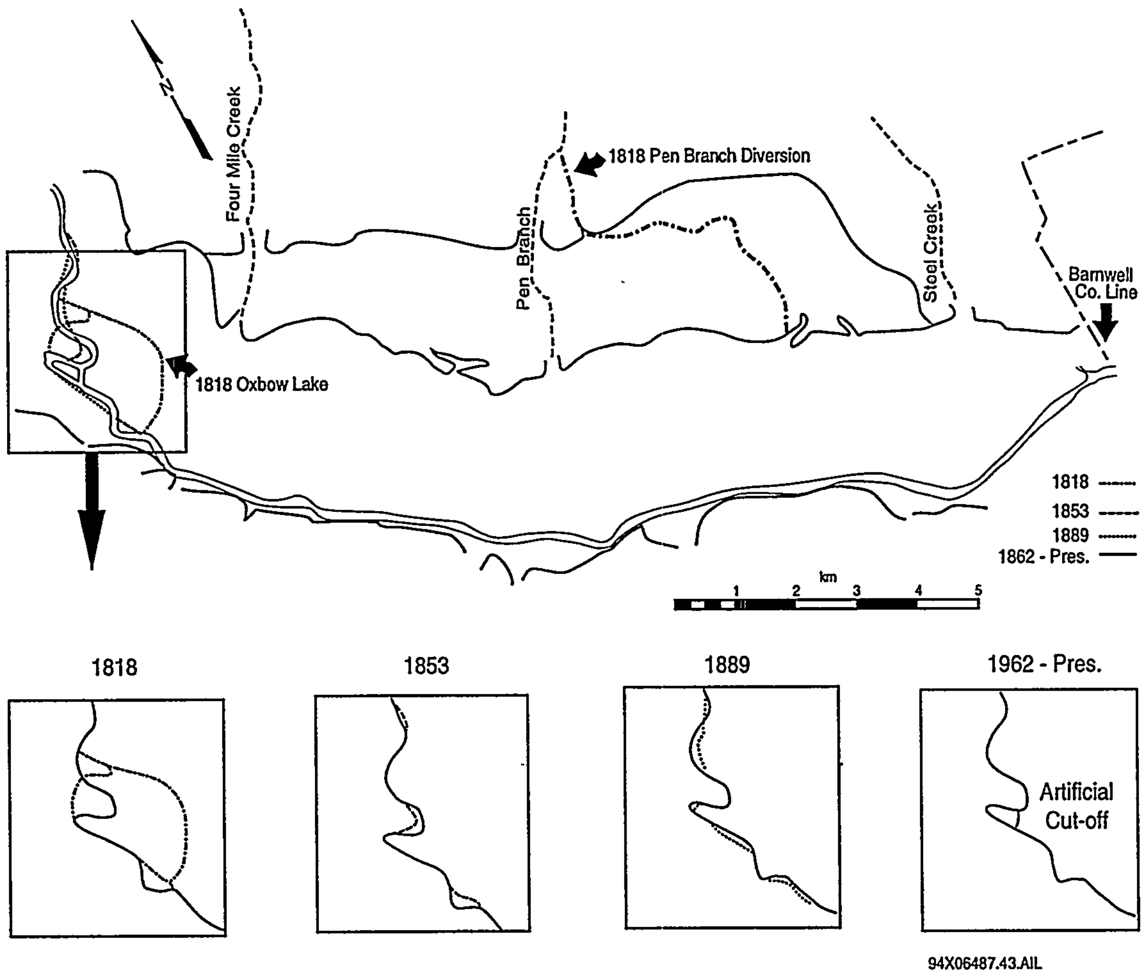

Figure 2-10. Changes in the Flow of the Savannah River and its Tributaries During the Last 200 Years (Source: Stevenson 1982).

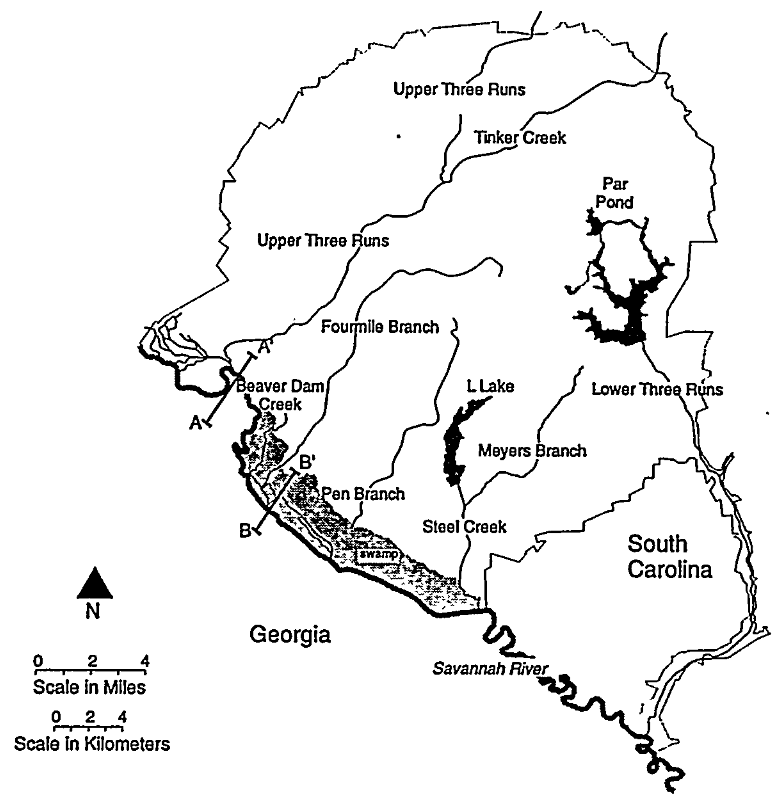

Figure 2-11. Location of Cross-Valley Profiles Showing Fluvial Terraces Along the Savannah River Near the Confluence of Upper Three Runs (Profile A-A[1]) and Fourmile Branch (Profile B-B[1]) (Source: Hanson et al. 1993).

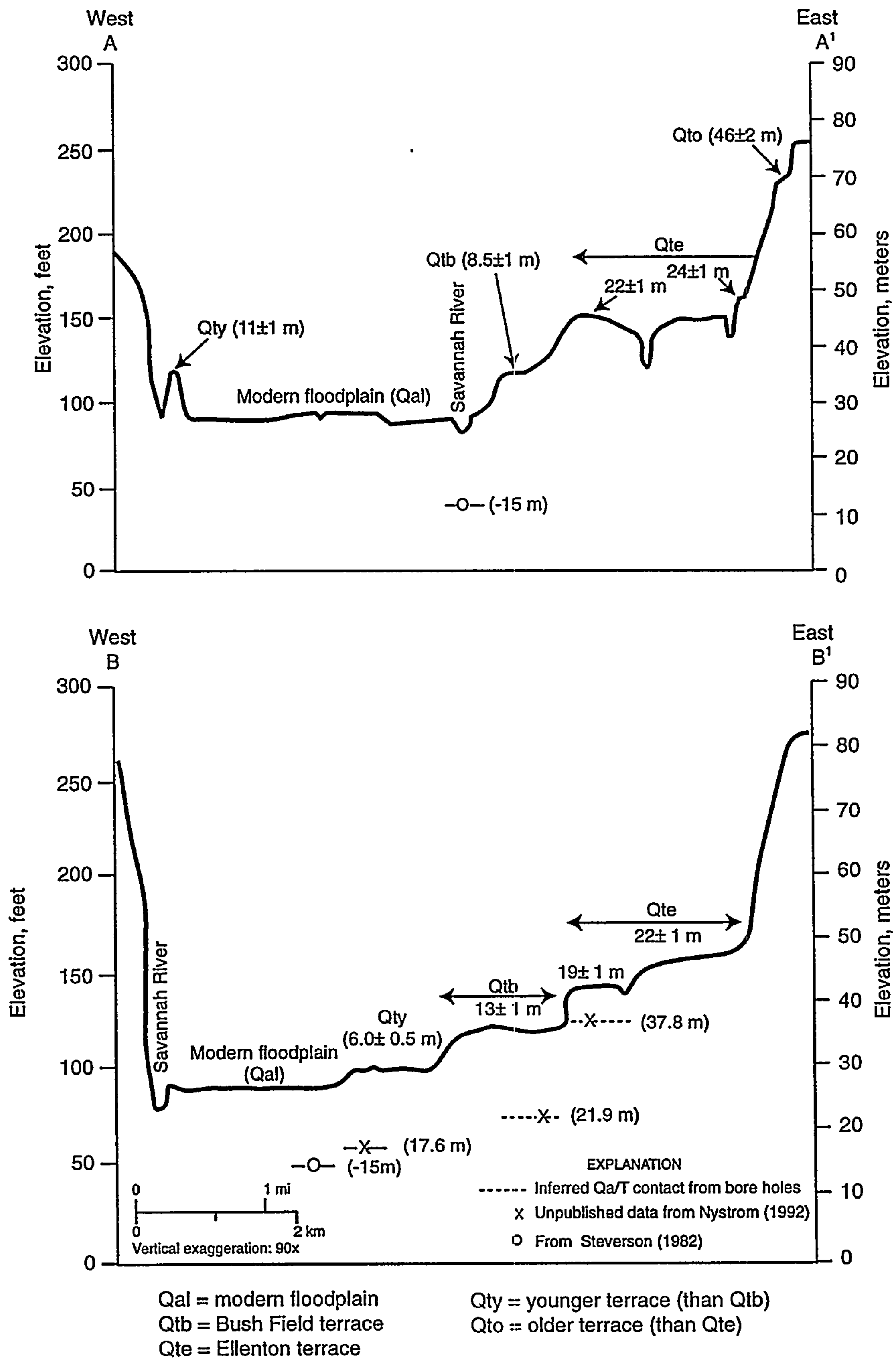

Figure 2-12. Cross-Valley Profiles Showing Fluvial Terraces Along the Savannah River Near the Confluence of Upper Three Runs (Profile A-A[1]) and Fourmile Branch (Profile B-B[1]) (Source: Hanson et al. 1993).

Thicknesses of alluvium underlying Bush Field Terrace surfaces are similar to those of modern floodplain alluvium (Geomatrix Consultants 1993). Based on limited subsurface data from auger holes drilled on the Ellenton and Bush Field terraces near Fourmile Branch, these are fill terraces underlain by alluvium 9-15-m (29-49-ft) thick, which is comparable to that of the modern floodplain near the mouth of Upper Three Runs (Geomatrix Consultants 1993). Like the upper surfaces of the terraces, the erosional unconformity at the base of the alluvium is inferred to rise in discrete steps away from the river (Figure 2-12).

Ellenton Terrace. The Ellenton Terrace (Qte in Figures 2-6, 2-11, and 2-12) is the higher of the two prominent terraces that are well preserved along the Savannah River. This terrace, as mapped at the present time (Geomatrix Consultants 1993), includes surfaces that range from approximately 17 M (56 ft) to as much as 25 m (82 ft) above local base level (Figures 2-11 and 2-12). Surfaces at heights of approximately 24-25 m (79-82 ft) above the present channel are observed on only the northeast side of the river. Here, they are relatively continuous except between Fourmile Branch and Steel Creek, where the higher part of the terrace appears to have been eroded during the formation of the lower 17- to 22-m (56- to 72-ft) surfaces (Geomatrix Consultants 1993).

Alluvium underlying the Ellenton Terrace surface is well exposed in railroad cuts adjacent to and south of both Fourmile Branch and Upper Three Runs (Geomatrix Consultants 1993). These cuts provide good exposures of the upper 6-7 m (20-30 ft) of the alluvium and soil developed on the terrace deposits. The upper 2-2.5 m (7-8 ft) consists of a massive, loose, light-colored sand to loamy sand (E horizon) that overlies a 2.8-m (9-ft)-thick argillic horizon developed on poorly sorted, fine- to coarse-grained sand. Increased accumulations of iron and aluminum compounds that form a reticulate mottled plinthite (Btv) horizon characterizes the approximate upper 0.6 m (2 ft) of argillic horizon.

The base of the alluvium underlying the Ellenton Terrace is not exposed at either the Fourmile Branch or Upper Three Runs railroad cut localities (Geomatrix Consultants 1993). Subsurface data from drill sites near the Fourmile Branch exposures suggest that the strath underlying the alluvium is probably 2-3 m (7-10 ft) below the exposed deposits. The thickness of the alluvium is similar to that of the modern floodplain alluvium.

Older Terraces. The oldest terraces along the Savannah River in the SRS area (Qto in Figures 2-6, 2-11, and 2-12) are represented by isolated remnants preserved only on the northeast side of the valley (Geomatrix Consultants 1993). These terrace remnants, at heights that range from approximately 30-50 m (98-164 ft) above local base level, were delineated by Geomatrix Consultants (1993) entirely by geomorphic expression. Because adequate exposures are lacking, the thickness and nature of terrace deposits associated with these surfaces are unknown. The remnants are not extensive or numerous enough to allow determination of original terrace width. Correlation of the highest terrace remnants in the region between Upper Three Runs and Pen Branch suggests a near-horizontal to relatively low-stream gradient (< 0.3 m/km [< 1.7 ft/mi]) for the Savannah River at this location during formation of the older (Qto) terraces.

Terrace Ages. The relative ages of the terraces follow the topographic lowering of the Savannah River Valley during the late Tertiary and Quaternary periods. The oldest terraces are scattered remnants at elevations of 30-50 m (98-164 ft) above the present river level. The terraces become progressively younger as the terrace elevations decrease. Table 2-2 shows the terrace elevations and age estimates.

Table 2-2. Elevations and Ages of Fluvial Terraces of the Savannah River at SRS (after Geomatrix Consultants 1993 and Stevenson 1982)

			Dating Method and Age Ranges			
Terrace	**Elevation above River Channel**	**Radiocarbon (ypb)**	**Regional Correlation**	**Soil Chronostratigraphy**	**Uplift/Incision Models**
Older Remnants	30-50 m (98-164 ft)	NA	>2 Ma		
Ellenton (Terrace II)	17-25 m	NA	200 ka to ≥ 760 ka	400 ka to >1 Ma	360 ka to 1.1 Ma
Bush Field (Terrace I)	8-13 m (26-43 ft)	NA	90 ka	100 to 200 ka	77 to 345 ka
Younger Terraces	5-6 m (16-20 ft)	NA			
Modern Floodplain	0-3 m (0-10 ft)	<12 ka			

ybp = years before present.
Ma = about 1,000,000 years ago.
ka = about 1,000 years ago.

Tributaries

Introduction

The principal Savannah River tributaries of the SRS, listed in downstream order, are Upper Three Runs, Fourmile Branch, Pen Branch, Steel Creek, and Lower Three Runs (Figure 2-5). Table 2-3 summarizes the drainage characteristics of these principal tributaries. They generally flow southwest to south, approximately parallel to the strike of the underlying sedimentary units, and at approximately right angles to the Savannah River. They are classified as subsequent streams (Siple 1967); that is, tributaries that have developed by headward erosion along belts of underlying weak strata and formed subsequent to the first-order stream (here, the Savannah River), of which they are tributaries.

Table 2-3. Drainage Data for the Major SRS Tributaries to the Savannah River

Tributary	Drainage Area[a] (km^2)	Length[a] (km)	Average Stream Gradient[a]	Mean Discharge[b] m^3/sec (cfs)
Upper Three Runs	557.1	49.2[c]	0.0026	6.7 (240)
Fourmile Branch	41.2	11.3	0.0032	3.7 (130)
Pen Branch	27.9	9.4	0.0058	7.2 (250)
Steel Creek	24	10.7	0.0063	5.1 (180)
Lower Three Runs	467.5	40.0	0.0023	NA

[a]Geomatrix Consultants (1993).
[b]Estimated from USGS Stream Gauging Data (Bennett et al. 1992). SRS operations included in discharges.
[c]Length includes Cedar Creek, the master stream.
cfs = cubic feet per second.

The tributaries on the north side of the Savannah River (i.e., those in South Carolina, including those on SRS) are noticeably longer than the tributaries on the south side in Georgia, opposite SRS.

Two of the streams on the SRS have been dammed to create cooling water reservoirs for reactors. Steel Creek was dammed to form L Lake as a cooling reservoir for L Reactor (Figure 2-5). Lower Three Runs was dammed to form Par Pond (an acronym for P and R Reactors).

Asymmetry of Stream Valley

The pronounced asymmetry of the stream valley is apparent in cross sections (Figures 2-13 and 2-14). The southeastern banks of the valleys are generally much steeper than the northwestern banks. There has been considerable speculation on the underlying causes of the asymmetry. Siple (1967) pointed out that the down-dip banks are steeper than the up-dip banks where the streams parallel the strike of the underlying sediments. Based on this observation, he suggested that stream cutting progresses in the direction of the regional dip of the sedimentary units. Regional tilting of the land surface by flexing of the lithospheric crust in the seaward direction is widely observed in the Coastal Plain (Beaumont 1978, 1979; Pazzaglia and Gardner 1992; Pavich 1985; Sykes 1978; Prowell 1988) and is consistent with the observed asymmetry in most of the tributary streams. Neither of these possible mechanisms is consistent with the asymmetry of the Savannah River valley in the reach between Upper Three Runs and Steel Creek, where the asymmetry is towards the southwest rather than southeast. Multiple factors may be operating independently to create the patterns of stream valley asymmetry observed in the SRS area.

Tributary Terraces and Alluvium

Like the Savannah River, the principal tributaries on the site occupy valleys that were once more deeply cut, then partially backfilled with alluvium during the Quaternary. Fluvial terraces are likewise found in the tributary stream valleys, though they are usually of small areal extent. Geomatrix Consultants (1993) indicated the correlation of some of the higher

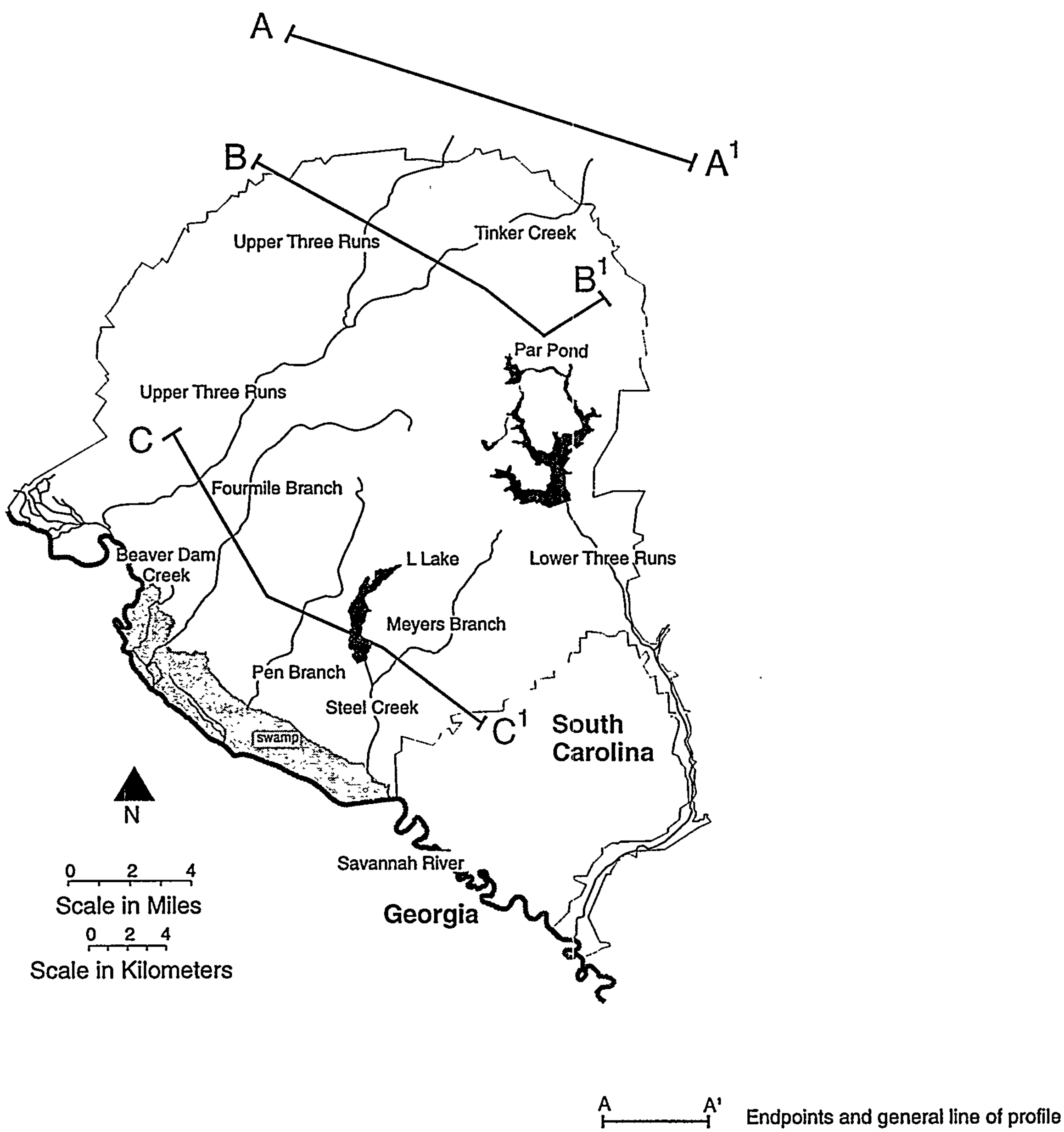

Figure 2-13. Location of Cross-Basin Profiles for the Savannah River Site Tributaries (Source: Geomatrix Consultants 1993).

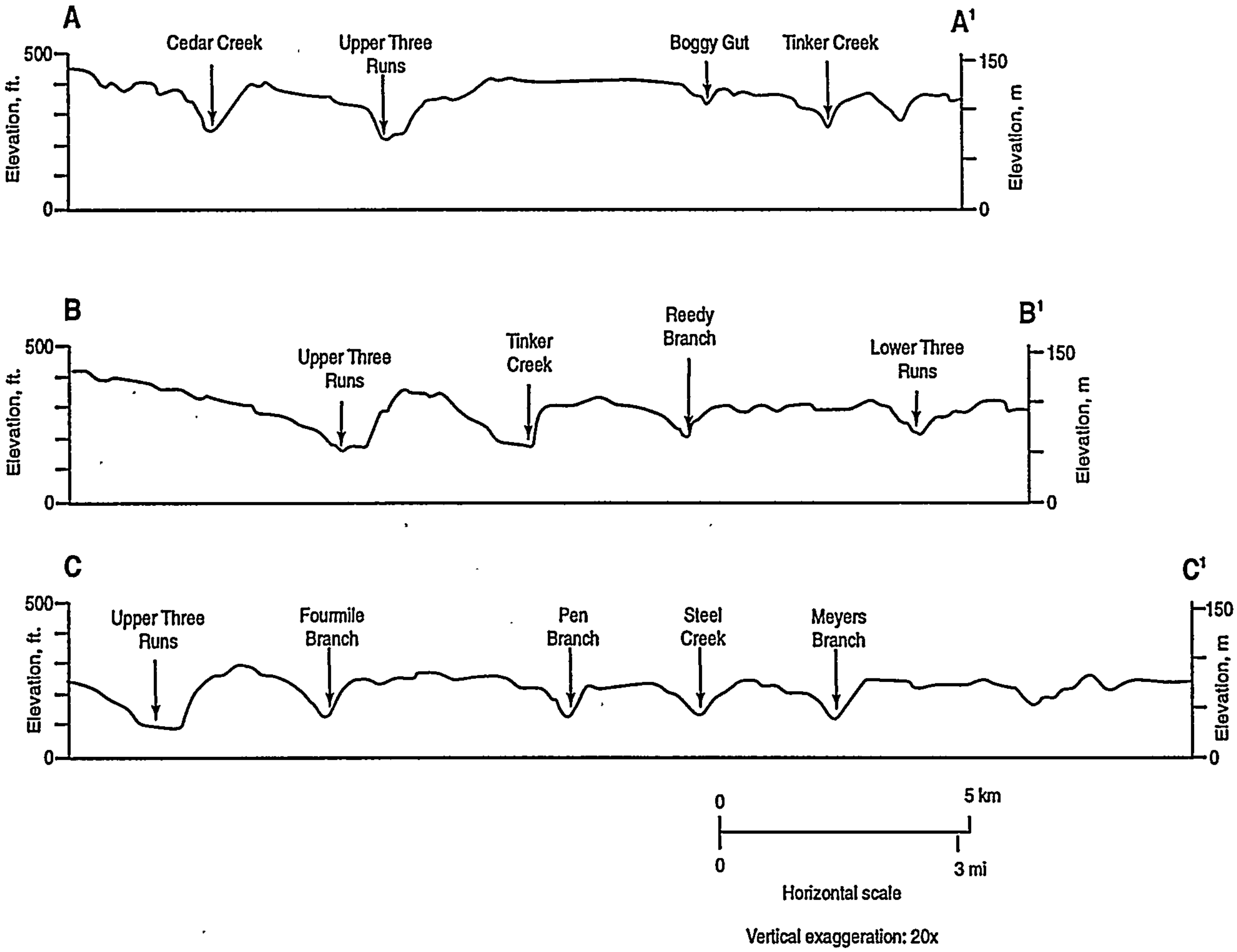

Figure 2-14. Cross-Basin Profiles for the Savannah River Site Tributaries (A-A[1]; B-B[1]; C-C[1]) (Source: Geomatrix Consultants 1993).

remnant terraces along Upper Three Runs to major terrace sequences along the Savannah River may be possible.

The lower terraces in the tributary stream valleys are likely of late Pleistocene or early Holocene age and represent aggradational or filling stages in the stream valleys following earlier incision.

Nystrom (1992) obtained radiocarbon dates of peat from several boreholes drilled in Quaternary alluvial deposits along Upper Three Runs and Tinker Creek in the northern portion of SRS. Five dates were reported, ranging from 11,110 years before present (ybp) in one of the boreholes in the Tinker Creek floodplain to greater than 46,800 ybp near the base of the alluvial sediments in a different Tinker Creek borehole. The older dates are approaching the limit of the radiocarbon technique and must be interpreted with care (Stone and Brown 1981) due to potential contamination by younger carbon. Nystrom (1992) interpreted these data, combined with the character of the sediments above the 11,110 ybp peat, to indicate that the aggradation of the Savannah River valley floor during the Holocene sea level rise did not extend into the upper stretches of Tinker Creek.

Quantitative Morphometric Analysis

Quantitative morphometric analysis refers to the detailed measurement of landscape components such as drainage basins and stream networks, stream and terrace gradients, hillslopes, and relief. Quantification of various drainage basin variables and landscape components provides important information for evaluating the interrelationships between independent (e.g., time, climate, tectonics, bedrock) and dependent (e.g., vegetation, relief, runoff and sediment yield) variables. Though more frequently applied to tectonically active areas, Geomatrix Consultants (1993) recently completed an extensive morphometric analysis of the Savannah River Site.

Geomatrix Consultants (1993) included a local slope map for SRS, topographic profiles of the site area, longitudinal stream and terrace profiles of larger tributary basins, and topographic residual maps. Analyses focused on tributary basins within SRS and adjacent regions and on geomorphic elements thought to be the most revealing and sensitive to long-term tectonic influences. The residual map for the site area (Figure 2-15) indicates that the greatest amounts of stream incision, hence long-term uplift, occur in a north-northeasterly trend along Upper Three Runs and Tinker Creek. The study concluded that the incision due to uplift, in combination with dip-slope migration of Upper Three Runs, is probably the primary factor responsible for the asymmetry of the Upper Three Runs valley and basin, the anomalous high drainage density and relief in the Tinker Creek and Boggy Gut area, and the narrow interfluvial divides in this area.

The residual map analysis does not identify clear structural features expressed in the landscape. Some alignments of larger residuals are weakly apparent, but are not consistently associated with known geologic structures. The large residuals are best explained as the result of long-term tectonic uplift and southeast tilting, local variation in relief and lithology, and geomorphic responses to those two factors (Geomatrix Consultants 1993).

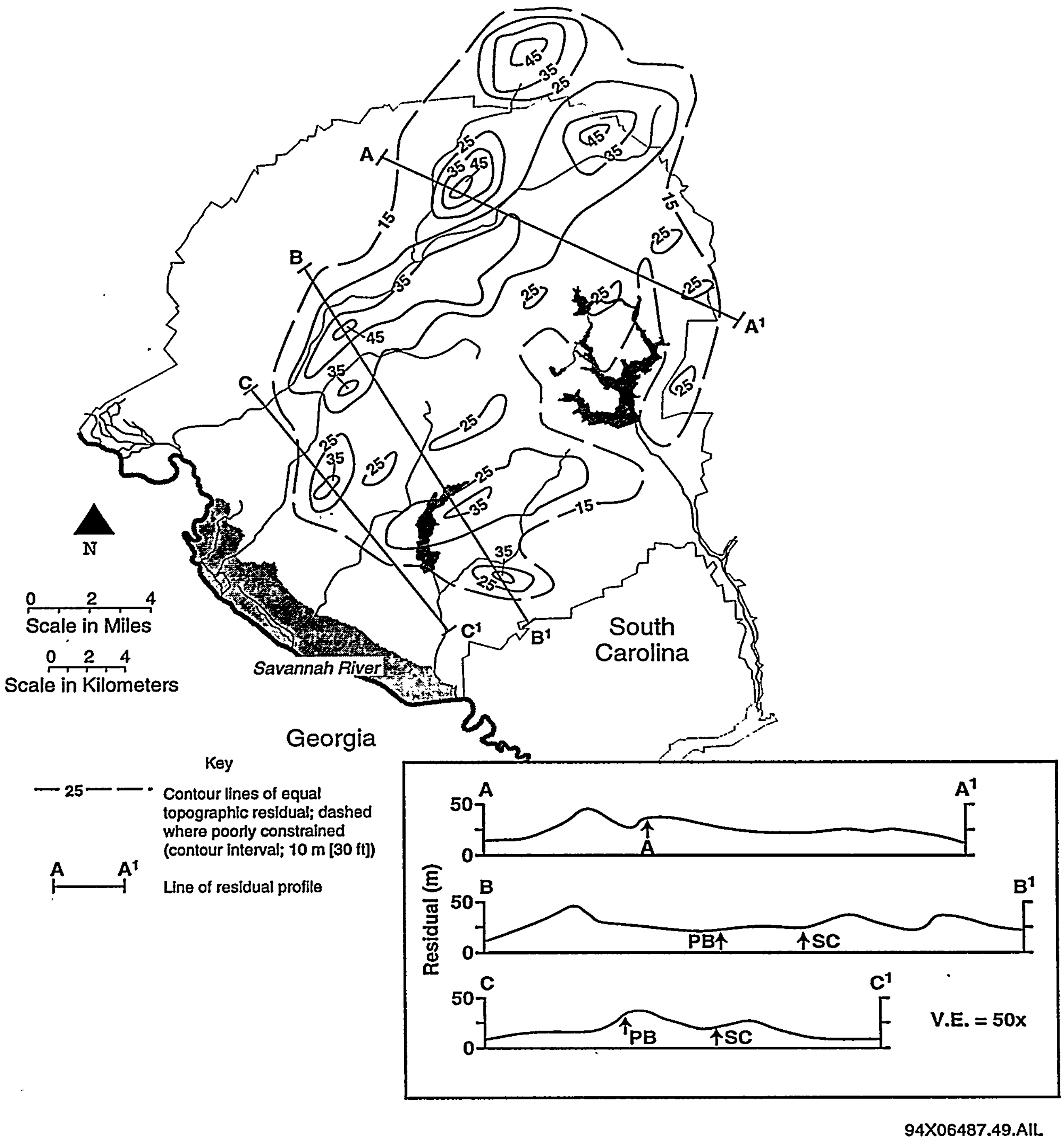

Figure 2-15. Generalized Contour Map of Topographic Residuals Derived from Analysis of Envelope and Subenvelope Maps.

Summary

The Savannah River Site lies on the Aiken Plateau, a deeply dissected upland plain at the western margin of the Atlantic Coastal Plain. Erosion, tectonic uplift, tilting of the region, and base level changes have sculpted the landscape since at least the Pliocene. Unlike the Middle and Lower Coastal Plain physiographic subprovinces, all landscape remnants of the last high sea stand to cover the area have been obliterated on the Aiken Plateau. Aside from fluvial deposits, remnant sand dunes of Pliocene age are the last major depositional unit preserved on the site. They form especially prominent landscape features on the eastern margin of the site.

The Aiken Plateau slopes gently to the southeast and is generally well drained except where poorly drained elliptical depressions, Carolina bays, dot the landscape. Nearly 200 Carolina bays have been identified on the site, the majority of which are 0.4-2 ha (1-5 acres).

The Savannah River on the southwestern margin of the site is the principal regional drainage basin. It serves as the local base-level for SRS tributaries that drain the site and enter the Savannah River at almost right angles. Of the major tributaries on site, only Upper Three Runs has it headwaters upgradient from the site. The remaining major tributaries, Fourmile Branch, Pen Branch, Steel Creek, and Lower Three Runs, have their origins on the 775 km^2 (300 mi^2) SRS.

The Savannah River adjacent to SRS and the principal tributaries on the site are markedly asymmetrical in cross section. Steep escarpments are on the southwestern side of the Savannah River and on the southeastern or eastern sides of the tributary streams. A single cause for the pronounced asymmetry of the valleys has not been identified. Coriolis effects, erosion of the dip-slope banks, tilting or flexing of the lithosphere, or a combination of these factors have all been evoked as potential mechanisms to produce the asymmetry.

Several fluvial terraces have been identified in the Savannah River valley and the tributary stream valleys. Two principal terraces of the Savannah River are evident on the site: the Ellenton Terrace, which stands about 17-25 m (56-82 ft) above the river, and the younger terrace, the Bush Field Terrace, which stands about 8-13 m (26-43 ft) above the river. The modern floodplain of the Savannah River is approximately 2-4 km wide (1.2-4.0 miles) at the site boundary. The river is confined by natural causes to the southwestern side of its valley as it passes the site.

Detailed studies of the terraces and other landforms on the site have not shown a clear indication of geologic structures controlling the distribution or elevation of the terraces. Long-term regional uplift and tilting of the lithosphere during the Quaternary, however, have undoubtedly influenced terrace formation during the stream valley development.

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Chapter 3—Regional Geology and Stratigraphy

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Regional Setting

The Savannah River Site is along the Savannah River in west-central South Carolina. The site occupies approximately 800 km^2 (310 mi^2) in portions of Aiken, Allendale, and Barnwell counties. The site is in the Atlantic Coastal Plain physiographic province approximately 40 km (25 mi) southeast of the Piedmont province (Figure 3-1). A seaward-dipping wedge of unconsolidated and semiconsolidated sediments lies under the coastal plains. This wedge extends from the contact at the Fall Line with the exposed metamorphic and igneous bedrock, which characterizes the Piedmont province, out to the edge of the continental shelf. The wedge thickens from zero at the Fall Line to greater than 1200 m (4000 ft) at the South Carolina coast. Piedmont rocks and Triassic-Jurassic sedimentary rocks form the basement for the Coastal Plain.

Colquhoun and Johnson (1968) divided the South Carolina Coastal Plain into three physiographic belts: the Upper, Middle, and Lower Coastal Plain (Figure 3-2). The Upper Coastal Plain slopes from a maximum elevation of 200 m (650 ft) at the Fall Line to about 75 m (250 ft) on its southeastern boundary. Erosion has obliterated the primary depositional topography of the Upper Coastal Plain. The Orangeburg Scarp separates the Upper and Middle Coastal Plains. The scarp has approximately 30 m (100 ft) of relief over a distance of a few kilometers. The Middle Coastal Plain is characterized by lower elevations and subtle depositional topography that erosion has modified significantly (Marine 1967). The Surry Scarp divides the Middle and Lower Coastal Plain belts. Cooke (1936) divided the Upper Coastal Plain of South Carolina into the Aiken Plateau, where SRS is located (Figure 3-2), and the Congaree Sand Hills.

The Aiken Plateau is bounded by the Savannah and Congaree Rivers and extends from the Fall Line to the Orangeburg Scarp. Broad interfluvial areas with narrow, steep-sided valleys characterize the plateau's surface. Local relief is as much as 90 m (300 ft) (Siple 1967). The Aiken Plateau is typically well-drained, although many poorly drained sinks and depressions exist, especially in topographically high areas (above 80 m [250 ft] mean sea level [msl]). The Aiken Plateau also contains elliptical depressions called Carolina bays, which are common throughout the Atlantic Coastal Plain, but are most numerous in North and South Carolina.

Sediments of the Atlantic Coastal Plain were laid down during a series of transgressions and regressions of the sea. The character of the sediments indicates depositional environments ranging from fluvial, to deltaic, to shallow marine. This variety of depositional conditions has created a complex system of sedimentary units, some of which are highly permeable to water flow and others that strongly impede the flow of water.

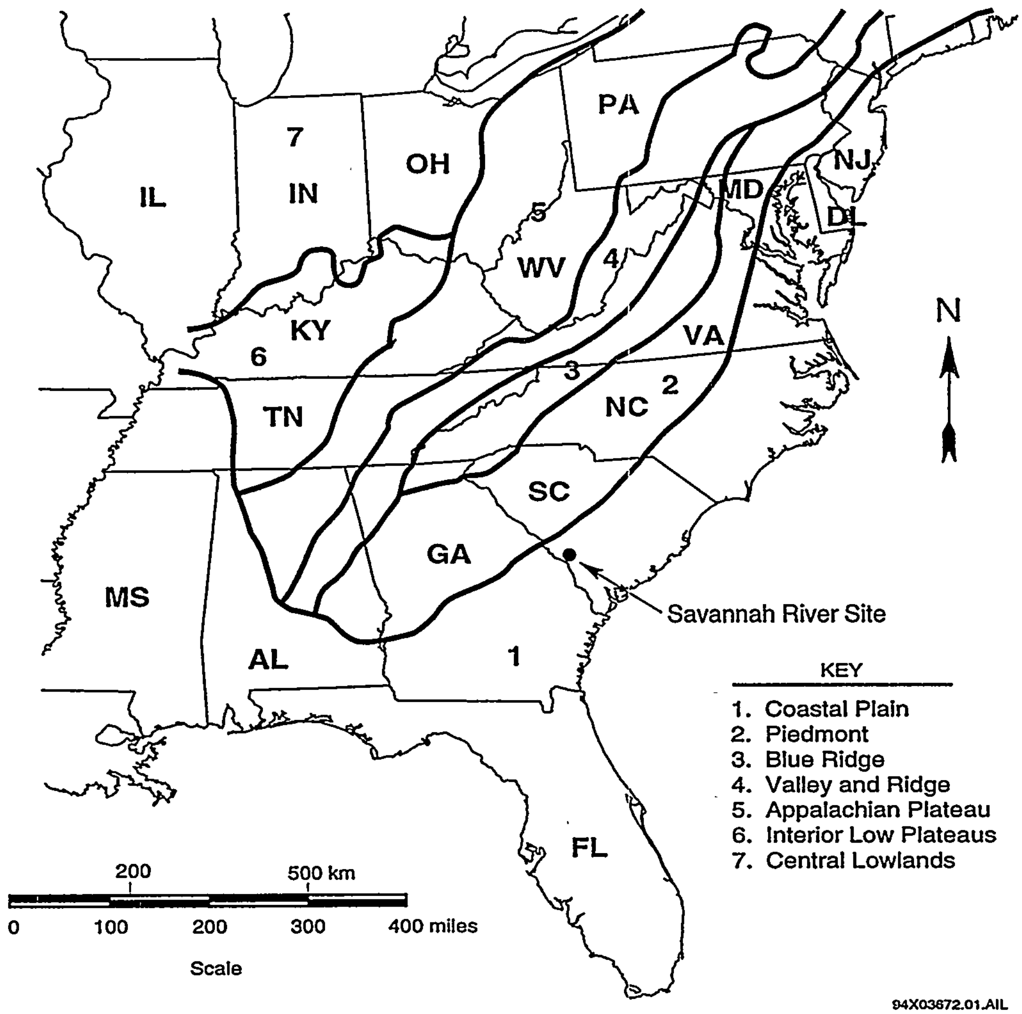

Figure 3-1. Physiographic Provinces of the Southeastern United States (Source: WSRC 1991).

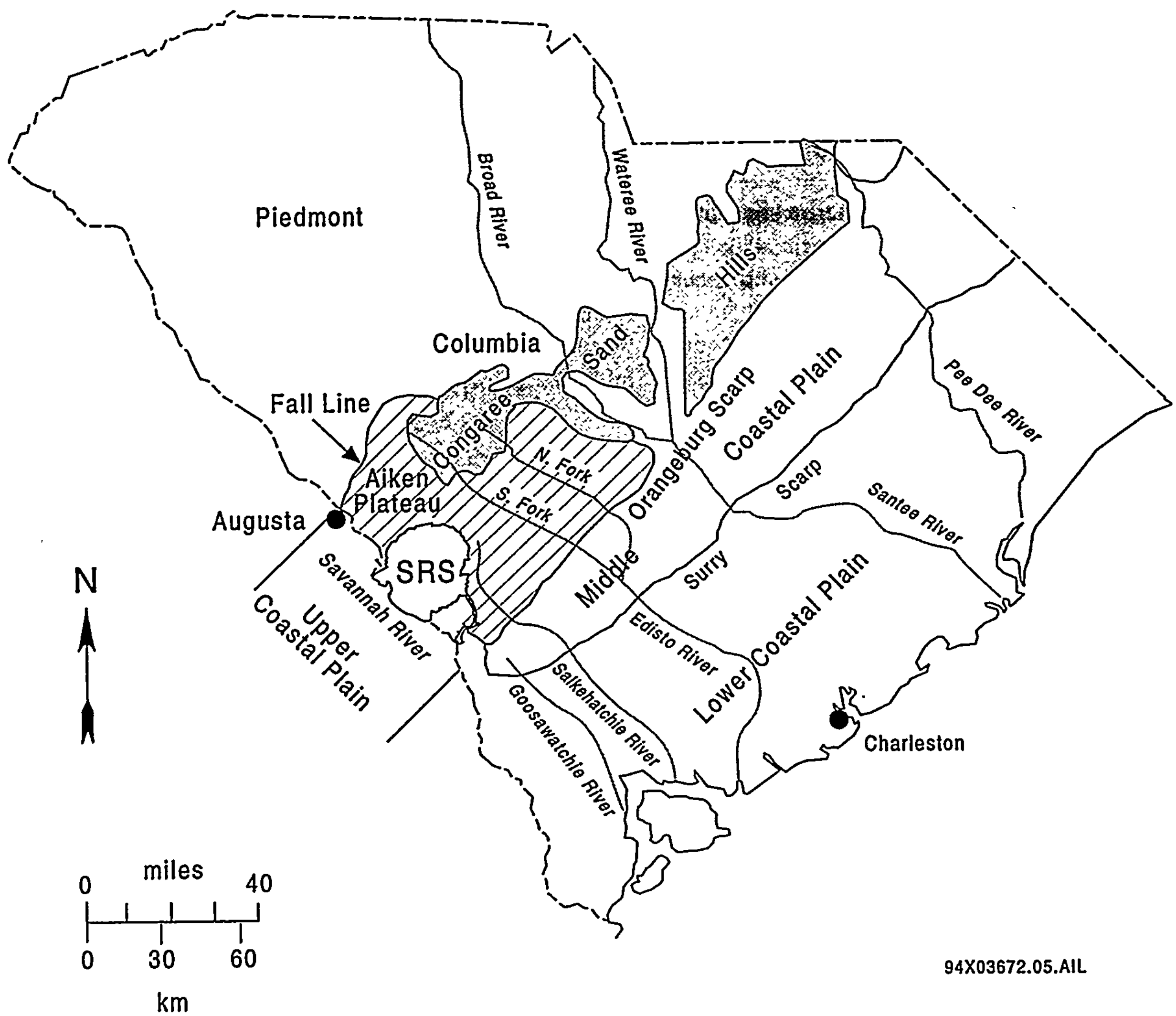

Figure 3-2. Location of the Study Area and Physiography of the Surrounding Region (modified after Siple 1967 and Cooke 1936).

Regional Geology

Introduction

The region, as defined by the area within a 330-km (200-mi) distance of SRS, includes the Atlantic Coastal Plain, Piedmont, Blue Ridge, and Valley and Ridge provinces (Figure 3-1). The Valley and Ridge province consists of thrust-faulted and folded sedimentary rocks and is characterized by a series of parallel ridges and valleys that have resulted from differential erosion of the tilted sedimentary layers. To the east, the Blue Ridge province consists of a folded, faulted, and metamorphosed basement and cover sequence. The Piedmont province is the eastern most physiographic and geologic province of the Appalachian Mountains and consists of gneiss, schist, phyllite, and slate rock units that have been intruded by plutonic rocks of granitic to ultramafic composition.

Two different basement rock types underlie the Coastal Plain sedimentary sequence at SRS. The basement in the northern portion of SRS consists of Precambrian to late Paleozoic, metamorphosed sedimentary and igneous rock that correlate with the exposed Piedmont rocks to the north of the site by age and rock type. Basement rocks in the southern and eastern portions of SRS consist of Triassic terrigenous sediments that fill the Dunbarton Basin (Marine 1974; Marine and Siple 1974) (Figure 3-3).

Valley and Ridge Province

The Valley and Ridge province (Figures 3-1 and 3-4) has a thick sequence of sedimentary rocks that range in age from Cambrian through Pennsylvanian. The Cambrian-to-Lower Ordovician section was deposited on the passive continental shelf; whereas the Middle Ordovician to Pennsylvanian section records the effects of mountain building to the east, including uplift, erosion, and deposition of clastic sediments shed from uplands. In the Middle Ordovician, carbonate deposition ended shortly thereafter with the influx of clastic sediments derived from the Taconic highlands to the northeast. Sedimentation continued intermittently throughout the remainder of the Paleozoic Era. Rocks of Silurian, Devonian, and Mississippian ages are thin and consist mostly of limestone and shale, with local dolostone, sandstone, and chert. Strata of the Pennsylvanian age are thick and consist primarily of shale and sandstone, with numerous coal and sparse limestone beds.

Blue Ridge Province

The Blue Ridge province consists of a series of thrust sheets composed of metamorphosed Precambrian to early Paleozoic sediments and Paleozoic igneous plutons. The thrust sheets have been transported northwestward over younger Paleozoic sedimentary rocks. The boundaries of the province usually are marked at the Blue Ridge thrust on the northwest and the Brevard fault zone on the southeast.

Due to the complexity and fragmented nature of the province, the stratigraphic correlations of many units are not well documented. In general, however, the rocks in the western portions of the Blue Ridge consist of continental basement rocks and late Precambrian to early

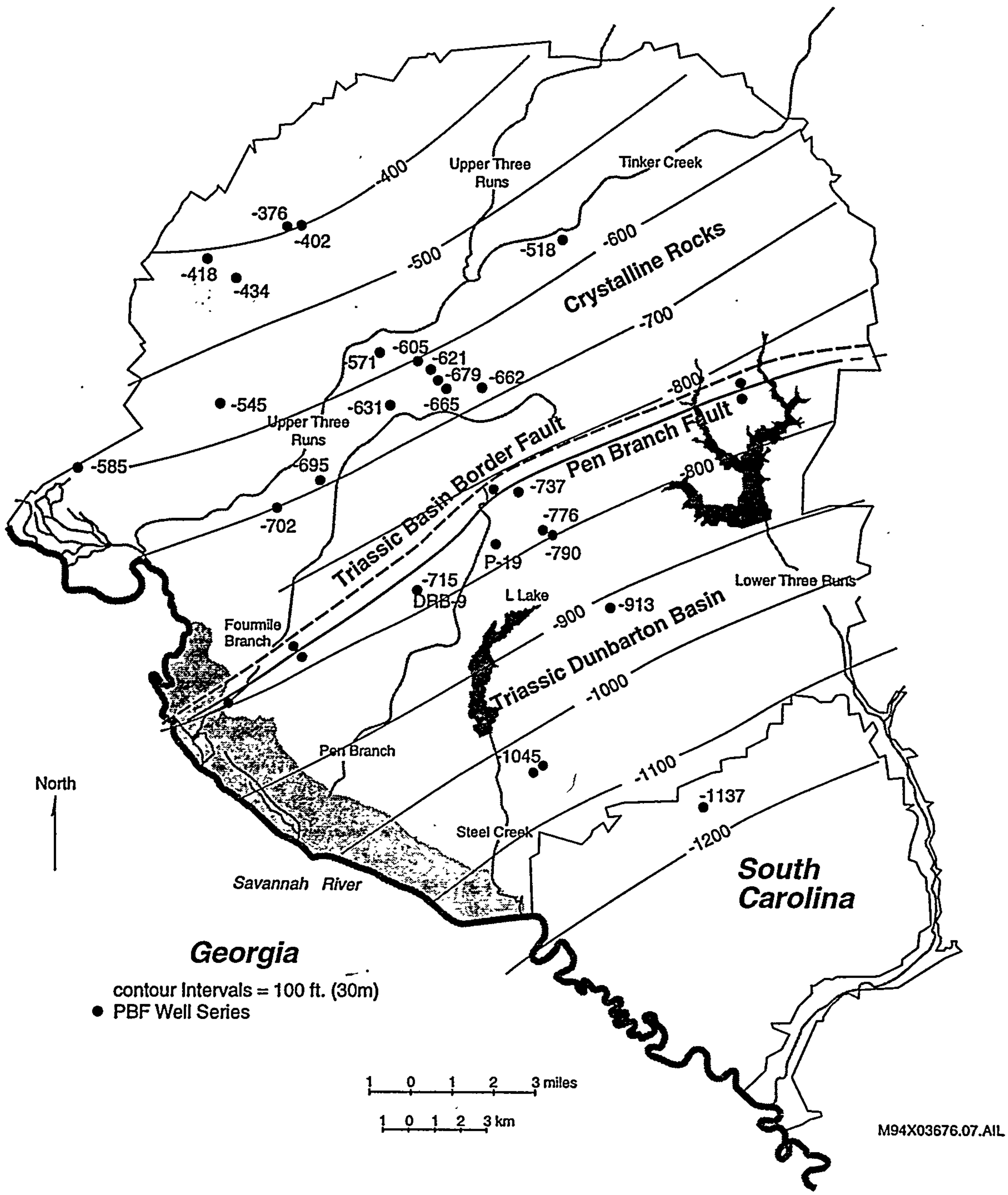

Figure 3-3. Contour Map of the Top of the Pre-Cretaceous Basement Surface Near SRS (Source: Marine and Siple 1974).

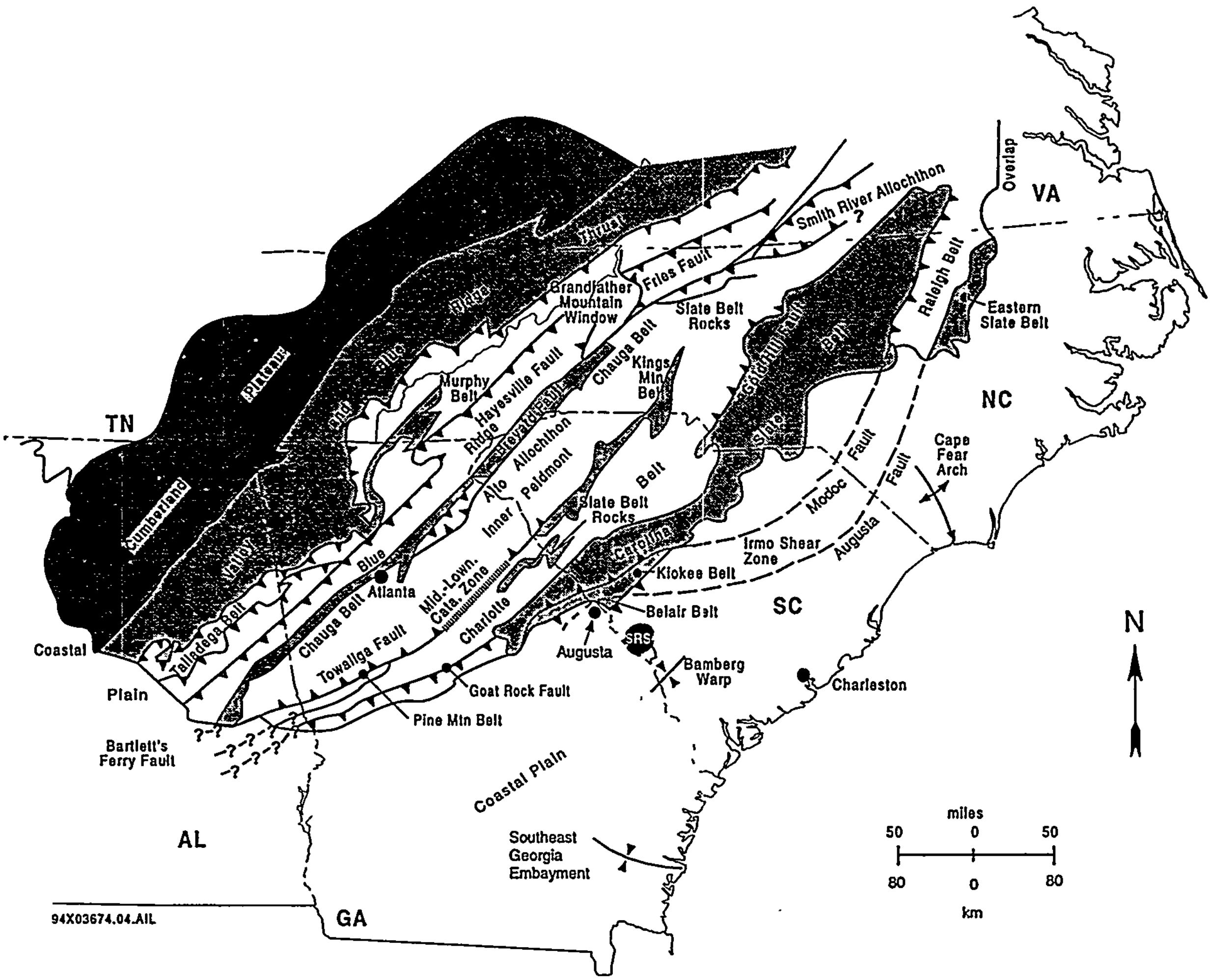

Figure 3-4. Regional Physiographic-Geologic-Tectonic Map of the Southern Appalachians (Source: WSRC 1991, modified after Hatcher 1972).

Paleozoic, rifting-related clastic sequences, metavolcanics and plutons. The clastic sedimentary sequences reflect a continental platform depositional environment. In contrast, the eastern Blue Ridge units contain oceanic basement rocks, such as ophiolites, and deep water clastics and metasediments, suggestive of a continental slope or rise, depositional environment. The Hayesville-Fries fault marks the boundary between western Blue Ridge and eastern Blue Ridge (Hatcher 1978) and has been inferred to be a major terrane boundary by Williams and Hatcher (1983).

Piedmont Province

Introduction

The Piedmont province consists of northeast-trending tectonic belts that are defined by tectonic history, metamorphic grade, and structural relationships (Figure 3-4) (Hatcher 1972). The province is subdivided into seven distinctive tectono-stratigraphic belts, separated by major faults, contrasts in metamorphic grade, or both. From northwest to southeast, these are the Chauga, Inner Piedmont, Kings Mountain, Charlotte, Carolina Slate, Kiokee, and Belair belts (Figure 3-4). The metamorphic grade of these belts alternates between low grade (Chauga, Kings Mountain, Carolina Slate, and Belair) and medium to high grade (Inner Piedmont, Charlotte, and Kiokee). The rocks of the Piedmont have been deformed into isoclinal recumbent and upright folds, which have been refolded and contained by several thrust sheets or nappes.

These metamorphic rocks extend beneath the Coastal Plain sediments in central and eastern South Carolina. The southeastern most extent of the Piedmont province underneath the Coastal Plain is unknown. The crystalline basement beneath SRS consists of Late Proterozoic to Paleozoic metamorphic and igneous rocks that are similar to those found in the Kiokee and Carolina Slate belts of the Piedmont (Marine and Siple 1974). Cores collected from wells drilled at SRS that penetrated crystalline basement rocks suggest that the crystalline basement rocks contain gneiss, schist, granite, and metamorphosed volcanic rock, including tuff, rhyolite, andesite, and breccia.

Inner Piedmont Belt

The Inner Piedmont belt (Figure 3-4) contains rocks with the highest metamorphic grade found in the southern Appalachian Piedmont (Griffin 1971), including volcanic and sedimentary rocks metamorphosed to upper amphibolite and granulite facies. These rocks consist of amphibolite, granitic gneiss, paragneiss, metasandstone, and schist. Structures generally converge toward the northwest (Hatcher 1978). Recumbent to reclined folds are overturned to the northwest and form large nappes in the northwestern Inner Piedmont (e.g., Six Mile nappe) that overlie the Chauga belt (Griffin 1974; Hatcher 1987). The eastern Blue Ridge and Inner Piedmont contain stratigraphically equivalent rocks (Hatcher et al. 1986).

Chauga Belt

The Chauga belt (Figure 3-4) east of the Blue Ridge by the Brevard fault zone, is part of the Inner Piedmont and is recognized by either a thrust fault or a pronounced metamorphic gradient (Hatcher and Acker 1984). The rocks within the Chauga belt are stratified, low- to medium-grade (upper greenschist-middle amphibolite) metasedimentary rocks assigned to the Late Proterozoic to Early Cambrian Chauga River Formation and the stratigraphically equivalent Poor Mountain Formation (Hatcher 1970). The Chauga River and Poor Mountain Formations are overlain by the Henderson Gneiss (Hatcher 1970) and Alto allochthon (Edelman et al. 1987; Hatcher 1987). The Henderson Gneiss is a granitic augen gneiss with U-Pb zircon crystallization ages of 535 million years (Hatcher 1987) and 600 million years (Odom and Fullagar 1973). The Alto allochthon consists of migmatitic amphibolite facies rocks transported northwest from the Inner Piedmont (Hatcher 1987).

Kings Mountain Belt

The Kings Mountain belt (Figure 3-4), which extends southwestward from central North Carolina into northeast Georgia, lies between the Inner Piedmont and Charlotte belts and is separated from the Inner Piedmont by the Kings Mountain shear zone-Towaliga fault (Horton, et. al 1981). The oldest unit in the Kings Mountain belt is a volcanic-intrusive complex intruded by metatonalite of Late Proterozoic age (Horton et al. 1981). This complex grades upward into a metasedimentary sequence. The western part of the Kings Mountain belt consists of a sequence containing marble, amphibolite, and calc-silicate rocks with sedimentary protoliths. The metamorphic grade (greenschist facies) of the Kings Mountain belt is generally lower than that of the adjacent Inner Piedmont and Charlotte belts, although parts of the Kings Mountain belt are in the sillimanite zone of the Upper Amphibolite facies (Horton et al. 1981; Horton and Butler 1977). The major structures within the Kings Mountain belt are gently plunging folds and faults.

Charlotte Belt

The Charlotte belt (Figure 3-4) consists of amphibolite, biotite gneiss, hornblende gneiss, and schist, derived from volcanic, volcaniclastic, or sedimentary protoliths, that exhibit moderate- to high-grade metamorphism. Much of the belt was metamorphosed to amphibolite facies during the Taconic orogeny (Butler 1983), although retrograde metamorphism is widespread.

Plutons with diverse compositions intrude the rocks of the Charlotte belt. Plutons of the oldest group (530-550 million years) are generally highly deformed (Fullagar 1971; Gilbert et al. 1982) and are genetically related to the volcanic rocks of the Carolina Slate belt (Fullagar 1971; Weisenfluh and Snoke 1978). Late syntectonic gabbroic to granitic intrusions were emplaced in the Charlotte belt from 430 to 355 Ma (Butler and Ragland 1969; Butler and Fullagar 1978). A final group of postectonic granite plutons was emplaced in the Charlotte belt from 325 to 265 Ma (Fullagar 1971; Secor and Snoke 1978; Fullagar and Butler 1979; Sinha and Zeitz 1982; and Dallmeyer et al. 1986). The Charlotte belt also is characterized by the intrusion of numerous early sheets and dikes of granitic intrusive rocks (Secor et al. 1982), which are probably the intrusive equivalents of some of the volcanic rocks of the Carolina Slate belt (Overstreet and Bell 1965).

Carolina Slate Belt

Thick sequences of volcaniclastic rocks and sequences of felsic to mafic metavolcanic rocks characterize the Carolina Slate belt (Figure 3-4). The belt was subjected to low-to-medium-grade regional metamorphism from 500 to 300 Ma and was intruded subsequently by granitic and gabbroic plutons about 300 Ma (Carpenter 1982). The Charlotte and Carolina Slate belts are correlative and differ mostly in metamorphic grade. The Charlotte belt has been interpreted as a tectonic infrastructure of the Carolina Slate belt (Secor et al. 1986).

The oldest stratigraphic units in the Carolina Slate belt consist of intermediate to felsic ash-flow tuff and associated volcaniclastic rocks. These rocks are called the Persimmon Fork Formation (3.3 km [2.0 mi] thick) in South Carolina (Secor and Snoke 1978; Secor and Wagener 1968), the Uwharrie Formation (10 km [6.2 mi] thick) in North Carolina (Secor and Wagener 1968; Conley and Bain 1965), and the Lincolnton Metadacite (5 km [3.1 mi] thick) in Georgia (Whitney et al. 1978; Carpenter et al. 1982). These formations are overlain by a sequence of mudstone, siltstone, sandstone, graywacke, with some interbedded volcanic tuffs and flows. In South Carolina, this sequence is divided into the Richtex (>3.3 km [2.0 mi]) and the Asbill Pond (>5 km [3.0 mi]) Formations (Secor et al. 1983; Secor et al. 1986; Secor and Wagener 1968; Secor 1987). Structural relationships indicate that the Richtex Formation overlies the Persimmon Fork Formation, although it is uncertain if the contact is stratigraphic or tectonic (Secor 1987). Sedimentary structures suggest that the Asbill Pond formation was deposited on a tidal shelf (Secor and Snoke 1978).

The age of the Carolina Slate belt rocks in South Carolina may be as young as Ordovician (about 465 million years) (Fullagar 1971; Dallmeyer et al. 1986; Carpenter et al. 1982; Hills and Butler 1969; Butler and Fullagar 1975; Wright and Seiders 1980; LeHuray 1987). The Richtex and Asbill Pond formations were deposited during the Middle Cambrian (525 Ma), based on occurrences of sponge spicules and Acado-Baltic trilobites (Paradoxides) (Secor et al. 1983; Bourland and Rigby 1982).

The oldest deformation seen in the Carolina Slate belt is post middle-Cambrian and is characterized by tight to isoclinal folding and greenschist facies regional metamorphism. Rocks of the Charlotte belt were metamorphosed to amphibolite facies during this event. The deformational event postdates Cambrian strata in the Carolina Slate belt and occurred before intrusion of Silurian-to-Devonian-age plutons in the Charlotte belt. Several large granitic plutons intruded the Carolina Slate belt during the late Paleozoic. These plutons generally are undeformed, although those along the Fall Line and adjacent to the Kiokee Belt developed a mylonitic foliation during the Alleghenian orogeny (Secor et al. 1986; Secor and Snoke 1978; Dallmeyer et al. 1986; Secor 1987).

Kiokee Belt

The Kiokee belt (Figure 3-4) is between the Carolina Slate belt and the Atlantic Coastal Plain in central Georgia and South Carolina. The interior of the Kiokee belt is a migmatitic complex of paragneiss, leucocratic paragneisses, sillimanite schist, amphibolite, ultramafic schist, serpentinite, metaquartzite, and granitic intrusions of late Paleozoic age (Secor 1987). The high-grade (amphibolite facies) Kiokee belt comprises midcrustal rocks of an Alleghenian infrastructure exposed in regional antiforms produced by the ramping of underlying thrust faults (Secor et al. 1986; Secor 1987). Structural evidence suggests that the migmatitic rocks in the interior of the Kiokee belt were at least 10 km (6 mi) north-northeast of their present position relative to the Carolina Slate belt, before the Alleghenian orogeny (Noel et al. 1988). These rocks may be stratigraphically equivalent to similar units in the Charlotte belt or may represent a separate exotic terrane (Secor 1987). The boundary between the Kiokee belt and Carolina Slate belt is a poorly characterized fault in the Modoc shear zone (Sacks and Dennis 1987), although continuity of rock units across the boundary has been suggested (Bramlett 1980; Snoke et al. 1980). The Augusta fault forms the southeast boundary between the Kiokee and Belair belts and exhibits polyphase, ductile, and brittle deformation (Maher 1987).

Belair Belt

The Belair belt (Figure 3-4), near Augusta, Georgia, is a small belt of greenschist facies metasedimentary and metavolcanic rocks (Maher 1987; Hatcher et al. 1977; Maher 1978; Prowell and O'Connor 1978). Geophysical and well data indicate that the Belair belt extends beneath the Atlantic Coastal Plain (Daniels 1974). The ages of the principal metamorphic and deformational events are uncertain but may be similar to those in the Carolina Slate belt (580-385 million years) (Dallmeyer et al. 1986; Secor et al. 1986).

Regional Geology of Early Mesozoic Rift Basins

Introduction

Opening of the Atlantic Ocean during the early Mesozoic produced extensional faults that cut the crystalline rocks of the Piedmont and extensional basins in the crust (Figure 3-5). Sediments within the basins consist mainly of nonmarine sandstone, conglomerate, siltstone, and shale. Carbonate rocks and coal are found locally in several basins. The sediments within the various basins are so similar that they have been lumped together in a single stratigraphic unit: the Newark Supergroup. Paleontological evidence reported by Travese (1986) indicates that the Newark Supergroup beds include late Triassic to early Jurassic strata in the northern basins but only late Triassic (Carnian) strata in the southern basins.

Igneous rocks of basaltic composition occur as flows, sills, and stocks within the basins and as extensive dike swarms within and outside the basins (King 1971). Generally, the basins are elongated in a northeast-southwest direction and are bounded by extensional faults on one or both sides. Southeast of the Fall Line, Triassic-Jurassic basins have been buried beneath the Atlantic Coastal Plain sediments (Figure 3-5). These buried basins have been identified from both geophysical and well data (Milton and Hurst 1965; Milton and Grasty 1969; Ackerman 1983; Peterson et al. 1984; Behrendt 1985; McBride et al. 1988), and may be more extensive than their exposed counterparts (Rodgers 1970; Steele and Colquhoun 1985).

Recent seismic refraction studies suggest subcoastal plain rocks in southern South Carolina are composed of basalt flows or sills, or both, intercalated with Mesozoic sediments; these unconformably overlie Paleozoic crystalline rocks (Smith and Talwani 1987; Smith et al. 1988). In southern Georgia, drill hole and geophysical data, including regional Consortium for Continental Reflection Profiles (COCORP) seismic reflection data, show a similar basement complex beneath Coastal Plain strata. The Riddleville basin is a half graben with a major south-dipping extensional fault at its northern boundary that merges into the Augusta fault to the south (Petersen et al. 1984). The South Georgia Rift basin covers an expanse beneath the southeastern Coastal Plain (Figure 3-5). It comprises a complex system of interconnected basins containing variable thicknesses of Mesozoic strata (Chowns and Williams 1983; Daniels et al. 1983; Nelson et al. 1985; McBride et al. 1988).

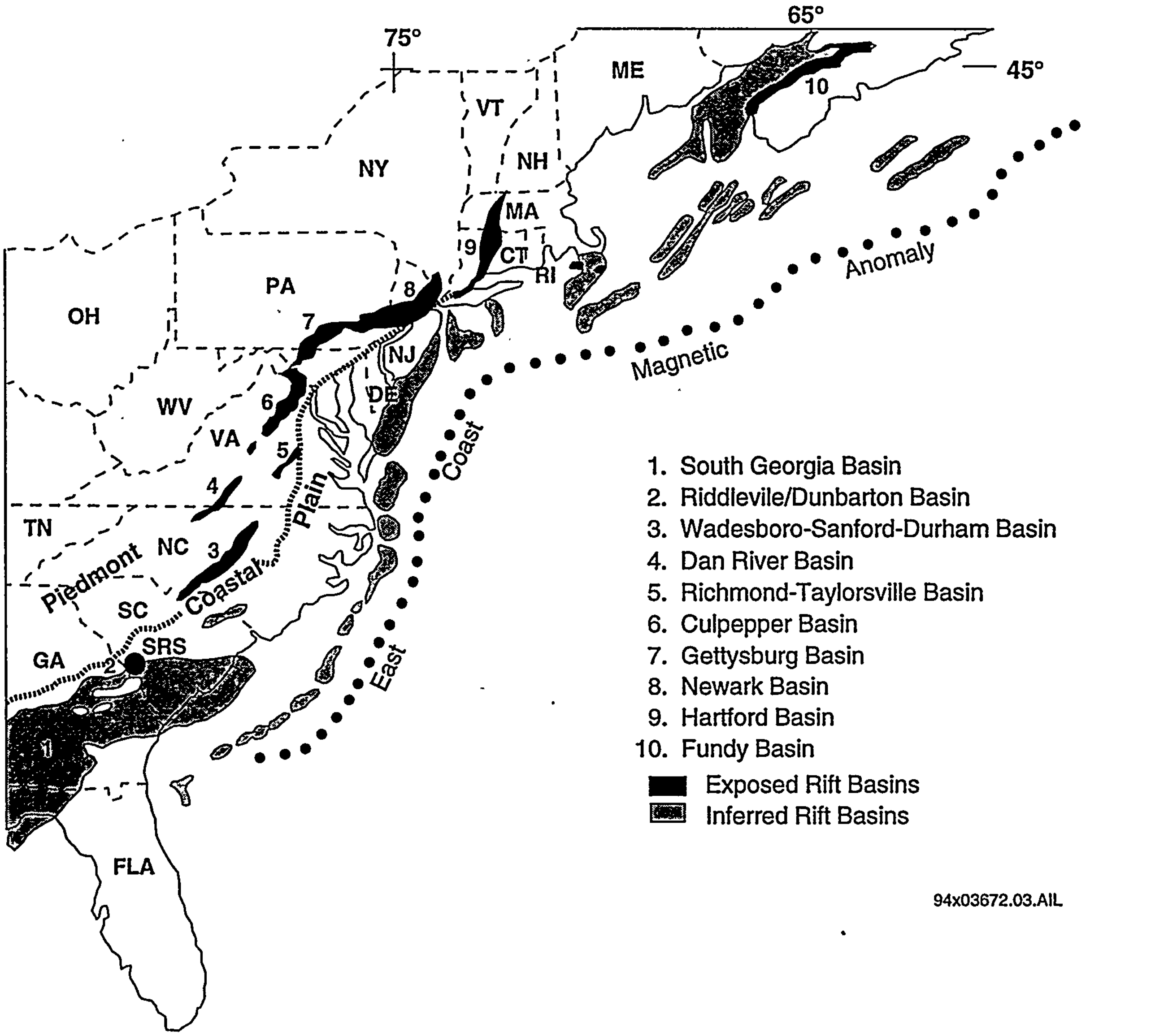

Figure 3-5. Triassic-Jurassic Rift Basins of Eastern North America (Source: Heck 1989).

Dunbarton Basin

A Triassic rift basin, the Dunbarton basin, lies beneath coastal plain cover in the southeastern part of SRS (Figure 3-6). The axis of the basin strikes N 63° E, that is, parallel to the regional strike of structures in the crystalline basement (Figure 3-6) (Marine and Siple 1974). The basin extends 15 km (25 mi) to the northeast of SRS and terminates abruptly about 8 km (5 miles) southwest of the Savannah River (Figure 3-7) (Siple 1967; Marine 1974).

Most of the evidence collected to date suggests that the basin is half graben with a steeply dipping normal fault on the northwest border. The vertical displacement on this fault is uncertain. The thickness of fill in the graben has been estimated by different studies to be 1.7 km (1.0 mi) (Cumbest et al. 1992), 2.5 km (1.5 mi) (Stieve and Stephenson 1995), and 3.7 km (2.3 mi) by Domoracki (1994). Sediments filling the basin dip northwest toward the fault except for some drag folding of strata adjacent to the fault (Stephenson and Stieve 1992). A steep magnetic gradient (250-600 gamma in 4.82 km [3 mi]) that crosses the southeast part of SRS (Figure 3-7) has been interpreted as the southeast border of the Dunbarton basin, although well data have not confirmed this basin margin (Siple 1967; Marine 1974; Marine and Siple 1974).

Core samples of Dunbarton basin sediments were collected as part of a bedrock waste storage exploratory program (Marine 1974; Bradley and Corey 1976). The lithologies of these cores show coarse grained (proximal) alluvial fan facies adjacent to the fault and finer grained sediments characteristic of distal fans and fan fringe facies further to the southeast, away from the fault.

In appearance, color, and texture, the sediments are similar to other Newark Supergroup sediments. Rock fragments, feldspars, and occasional caliche nodules (formed in desert-like soils) all indicate rapid erosion of a nearby source and deposition under relative dry climatic conditions. Lake deposits and basalt sills are conspicuous in their absence from the core materials.

Coastal Plain Sediments

Introduction

Subsurface Paleozoic and lower Mesozoic rocks at the SRS have been eroded and are unconformably overlain by unconsolidated to semiconsolidated coastal plain sediments (Colquhoun and Johnson 1968; Siple 1967; Cooke 1936). The erosional subcoastal plain surface (Figure 3-3) dips approximately 6.6 m/km (35 ft/mi) to the southeast (Colquhoun and Johnson 1968). The coastal plain sediments overlying the unconformity form a clastic wedge that thickens and dips toward the southeast (Figure 3-8). This southeastern dipping wedge of unconsolidated and consolidated sediments extends from the contact with the crystalline Piedmont province at the Fall Line to the edge of the continental shelf. Sediment thickness increases from zero at the Fall Line to more than 1.2 km (0.7 mi) near Savannah, Georgia.

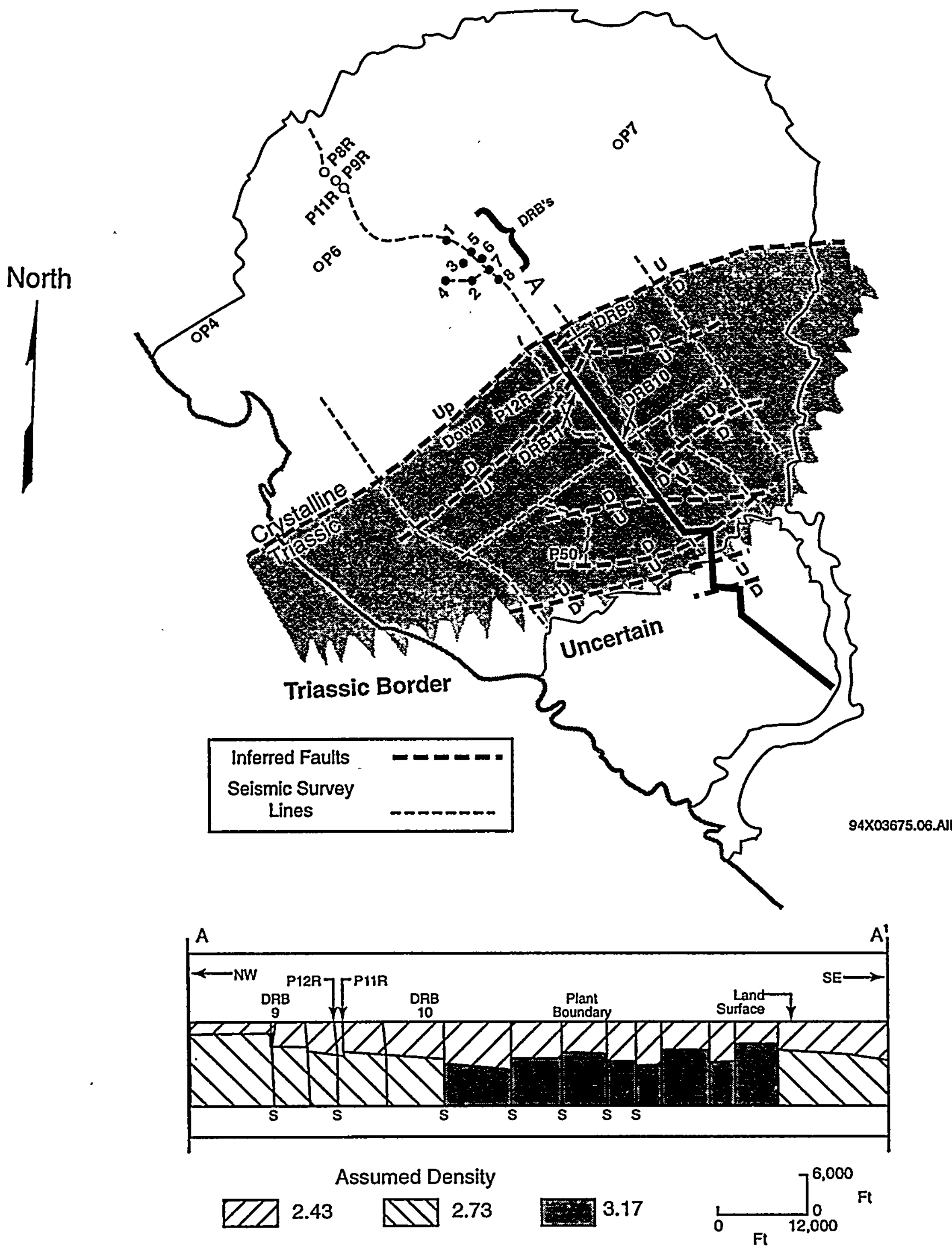

Figure 3-6. Structure Within Durbarton Basin Based on Seismic Reflection and Gravity Survey at the Savannah River Site (Source: Marine 1974).

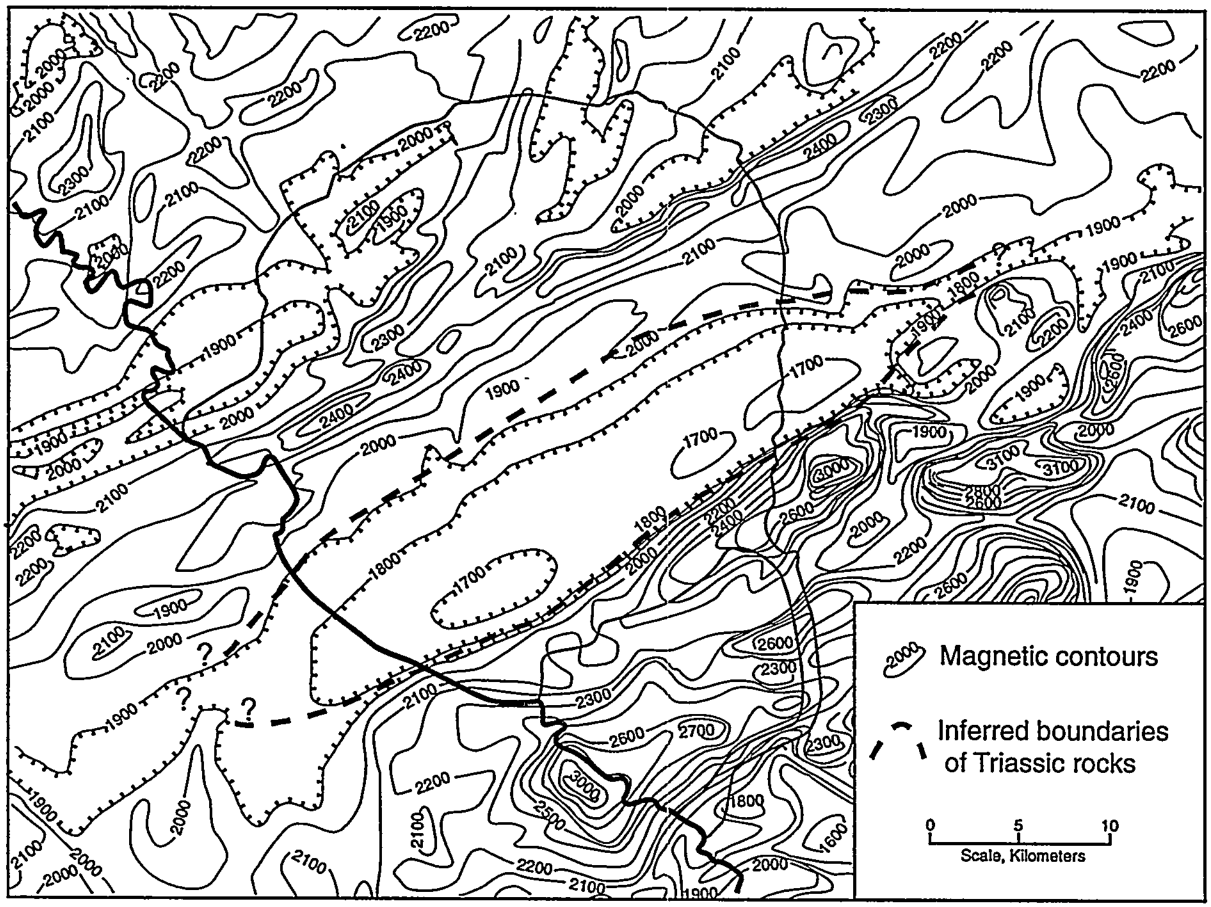

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Figure 3-7. Aeromagnetic Map Showing the Outline of the Dunbarton Triassic Basin Underlying the Savannah River Site (Source: Marine and Siple 1974).

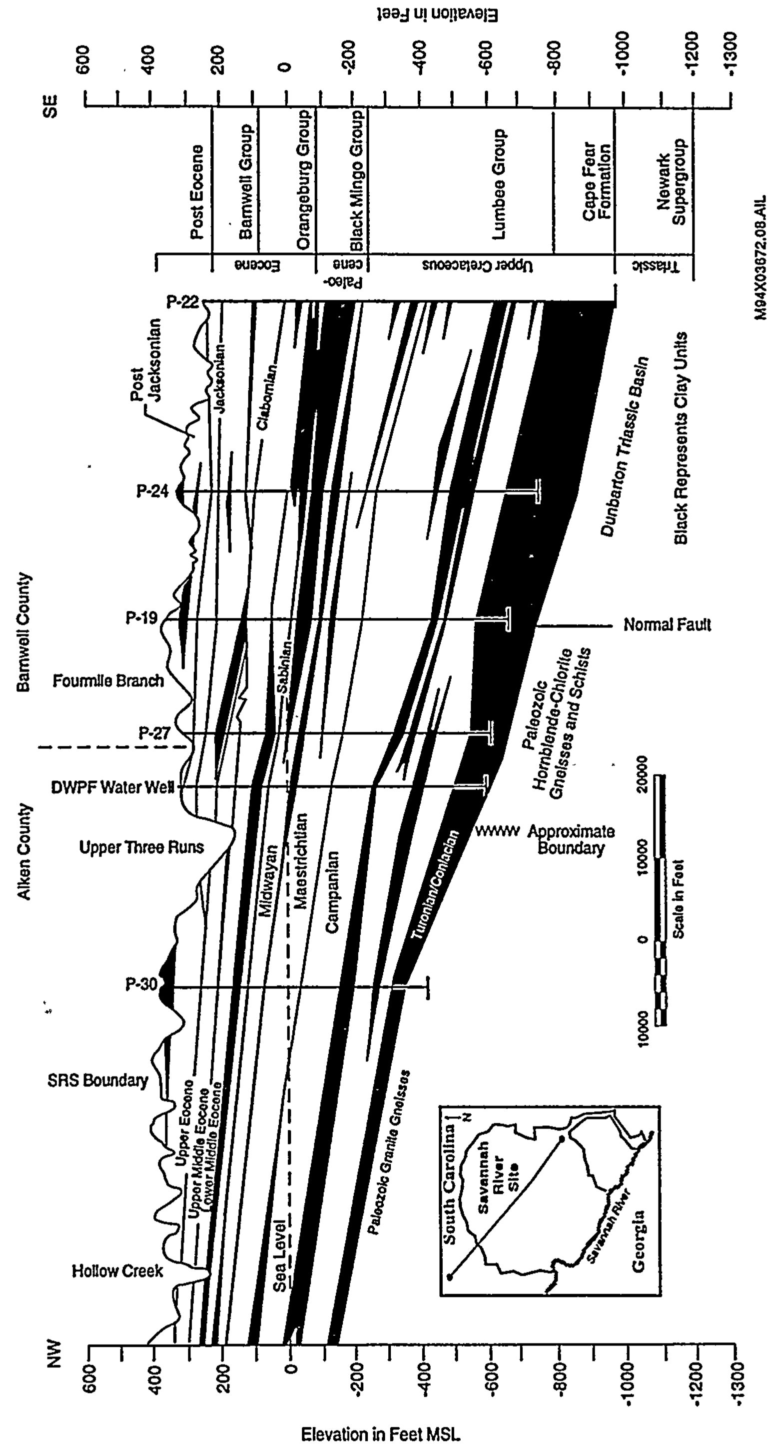


Figure 3-8. Stratigraphic Cross-Section of the Savannah River Site Region (Source: Aadland et al. 1992).

The Coastal Plain sequence near the center of SRS consists of about 167 m (600 ft) of Upper Cretaceous quartz sand, pebbly quartz sand, and kaolinitic clay, overlain by about 18 m (100 ft) of Paleocene clayey and silty quartz sand, glauconitic sand, and silt. The Paleocene beds are in turn overlain by about 91 m (250 ft) of Eocene sediments that grade from quartz sand, glauconitic quartz sand, clay, and limestone into calcareous sand, silt, and clay. In places, especially at higher elevations, deposits of pebbly, clayey sand, conglomerate, and clay of probable Miocene age cap the sequence. Lateral and vertical facies change over relatively short distances are characteristic of most of the Coastal Plain sequence.

Figure 3-9 shows several recently employed or proposed stratigraphic columns for the site region. The stratigraphic column defined by Lewis and Aadland (1992) has been used in this document. It is a compromise between well-established unit names used by geologic mapping projects (e.g., Prowell 1994a and b; Nystrom 1993; Willoughby 1993; and Willoughby et al. 1994) and unit names established at SRS from subsurface stratigraphic and hydrostratigraphic investigations.

Cretaceous System

Upper Cretaceous sediments of Santonian through Maestrichtian age overlie Paleozoic crystalline rocks and lower Mesozoic sedimentary rocks throughout SRS. The Upper Cretaceous sequence includes the Cape Fear Formation and the formations of the overlying Lumbee Group. Cooke (1936) and Siple (1967) assigned the beds of the Lumbee Group to the Tuscaloosa Formation, but the Tuscaloosa has not been traced into the SRS area from its type locality in Alabama. The Upper Cretaceous section is about 213 m (600 ft) thick near the center of the site.

Cape Fear Formation

The Cape Fear Formation rests directly on a thin veneer of saprolitic bedrock. The saprolite varies from less than 1.8 m (6 ft) to more than 12 m (40 ft) in thickness and defines the surface of the crystalline basement rocks and the Triassic-aged sedimentary rocks of the Newark Supergroup (Figure 3-9). The thickness of the saprolite reflects the degree of weathering of the basement prior to deposition of the Cape Fear Formation. The Cape Fear Formation pinches out north of the site boundary, but thickens to more than 55 m (180 ft) near the southeastern boundary of SRS (Lewis and Aadland 1992). Microfossil data from samples in down-dip wells at SRS are consistent with assignment of the Cape Fear to pollen zone V (Prowell et al. 1985a), indicating an early Late Cretaceous age for the Cape Fear Formation (Figure 3-10).

The Cape Fear Formation consists of poorly sorted, silty to clayey, gravelly quartz sand and interbedded clays. Bedding thickness of the sands, silts, and clays varies from about 1.5 to 6 m (5 to 20 ft), with the sand beds being thicker than the clays. The sands are locally arkosic in composition, with rock fragments common in pebbly zones. These characteristics and the paucity of marine fossils are indicative of a high-energy environment close to a sediment source area, possibly fluvial-deltaic environments on the upper parts of a delta plain (Prowell et al. 1985b).

The Cape Fear Formation is more indurated than other Cretaceous sediments because of the abundance of silica cement in the matrix (Siple 1967) and is more indurated in the northern part of the area than to the south. The transition from the more indurated clayey sand in the

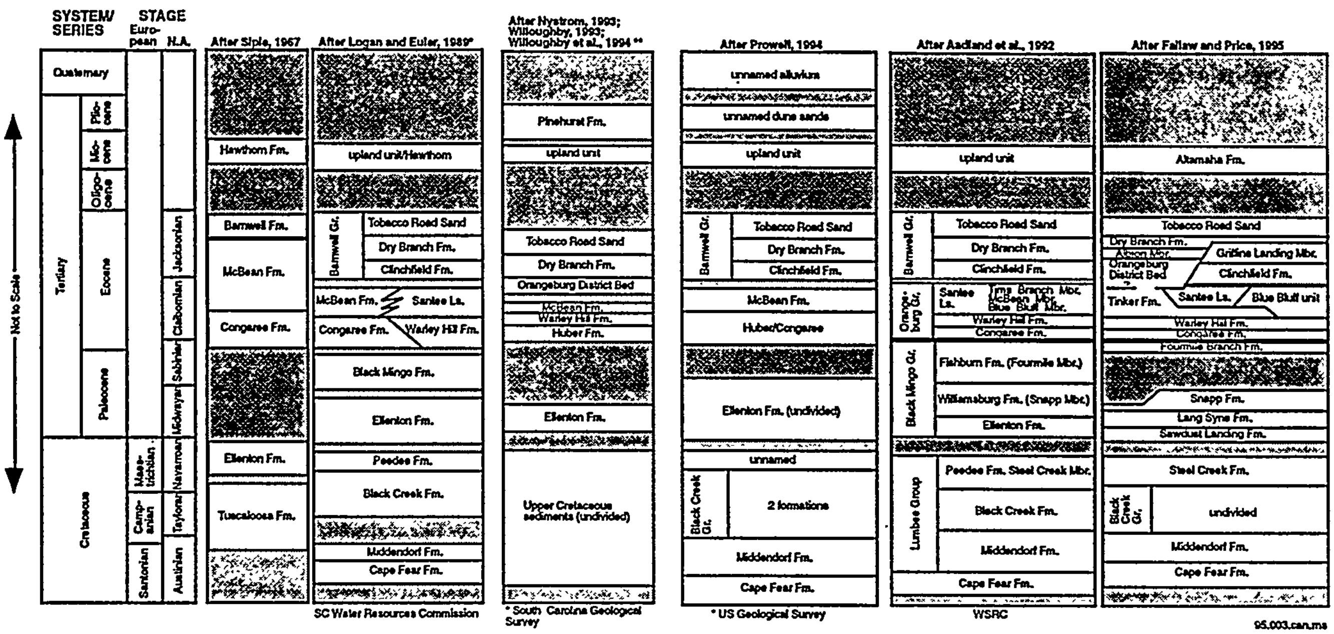


Figure 3-9. Comparison of Selected Stratigraphic Columns Used in Reports Relevant to Site Geology and Hydrogeology.

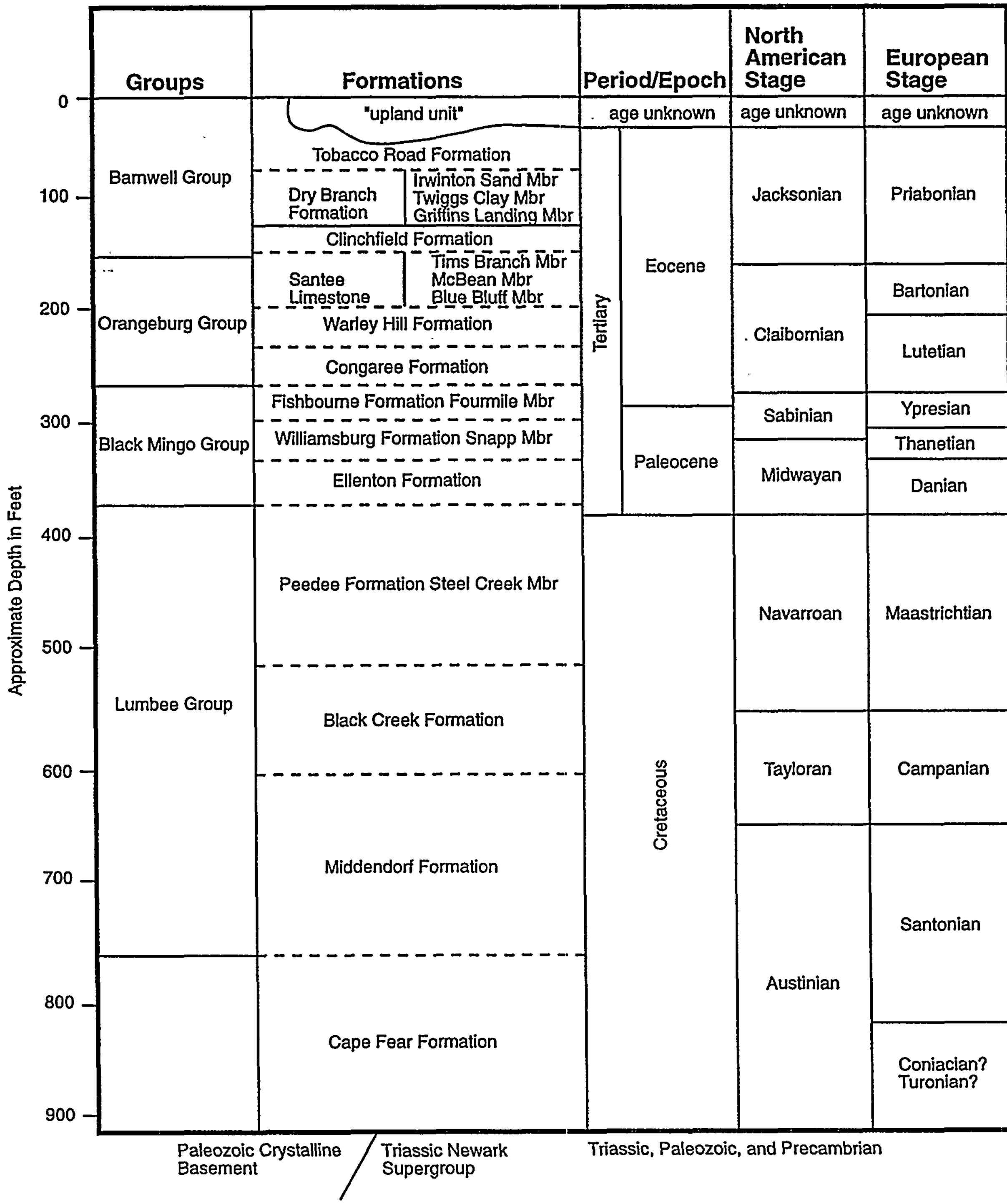


Figure 3-10. Stratigraphic Column for the Savannah River Site (Source: Aadland et al. 1992).

north to the poorly consolidated cleaner sand in the south may be due to lithologic changes during deposition or may reflect the southern limit of silica cementation (Clarke et al. 1985).

Lumbee Group

The SRS area has three formations of the Late Cretaceous Lumbee Group (Swift and Heron 1969; Faye and Prowell 1982). From oldest to youngest, these are the Middendorf, Black Creek, and Peedee Formations (Figure 3-10).

The Lumbee Group in the SRS area consists of fluvial and deltaic quartz sands, pebbly sands, and clays. The sedimentary sequence is more clayey and fine-grained down-dip from the SRS area, reflecting shallow to deep marine shelf sedimentary environments. Thickness varies from about 106 m (350 ft) near the northwestern boundary of SRS to about 230 m (750 ft) near the C-10 well south of the site (Figure 3-11). The individual formations are difficult to distinguish and were thus mapped as undifferentiated Upper Cretaceous (Nystrom and Willoughby 1982). The upper surface of the Lumbee Group dips to the southeast at approximately 4.0 m/km (21 ft/mi) across SRS (Figure 3-8).

Middendorf Formation

The Middendorf Formation overlies the Cape Fear Formation with a sharp, distinct contact. Sloan (1908) first named this formation, but Cooke (1936) assigned these sediments to the Tuscaloosa Formation. Swift and Heron (1969) resumed use of the name Middendorf. The Middendorf is marked by an abrupt change from the moderately indurated clays and clayey sands of the underlying Cape Fear to the slightly indurated sands and less clayey sands of the Middendorf. The basal zone is often pebbly. The formation thickness ranges from approximately 40 m (130 ft) in the north to 55 m (180 ft) in the south (Lewis and Aadland 1992). The Middendorf is not well dated here, but pollen samples from clay zones in the unit indicate a Santonian (early Late Cretaceous) age for the unit (Prowell, 1994a). Regional studies by Prowell et al. (1985b) also suggest a Santonian age for the unit.

The sands of the Middendorf Formation are medium- to very coarse-grained, typically angular, slightly silty, and tan and light gray to yellow. The sands are much cleaner and less indurated than the underlying Cape Fear sediments. Sorting is generally moderate to poor. Pebble and granule zones are common in up-dip parts of SRS, whereas clay layers up to 3 m (10 ft) thick are more common down-dip. Clay clasts are abundant in places. Some parts of the unit are feldspathic and micaceous. Lignitic zones are also common.

Black Creek Formation

Sloan (1908) first described the Black Creek Formation as "Black Creek Shales," which crop out in Darlington and Florence counties. Swift and Heron (1969) assigned it formational status. Prowell et al. (1985a), citing Christopher (1982) and Sohl and Christopher (1983) suggested a late Cretaceous age (late Campanian to early Maestrichtian) for the Black Creek Formation as indicated by various palynomorphs from the unit. Sediments assigned to the Black Creek Formation in SRS yield Campanian (middle Late Cretaceous) to Maestrichtian (late Cretaceous) paleontological ages and unconformably overlie the Middendorf Formation (Logan and Euler 1989).

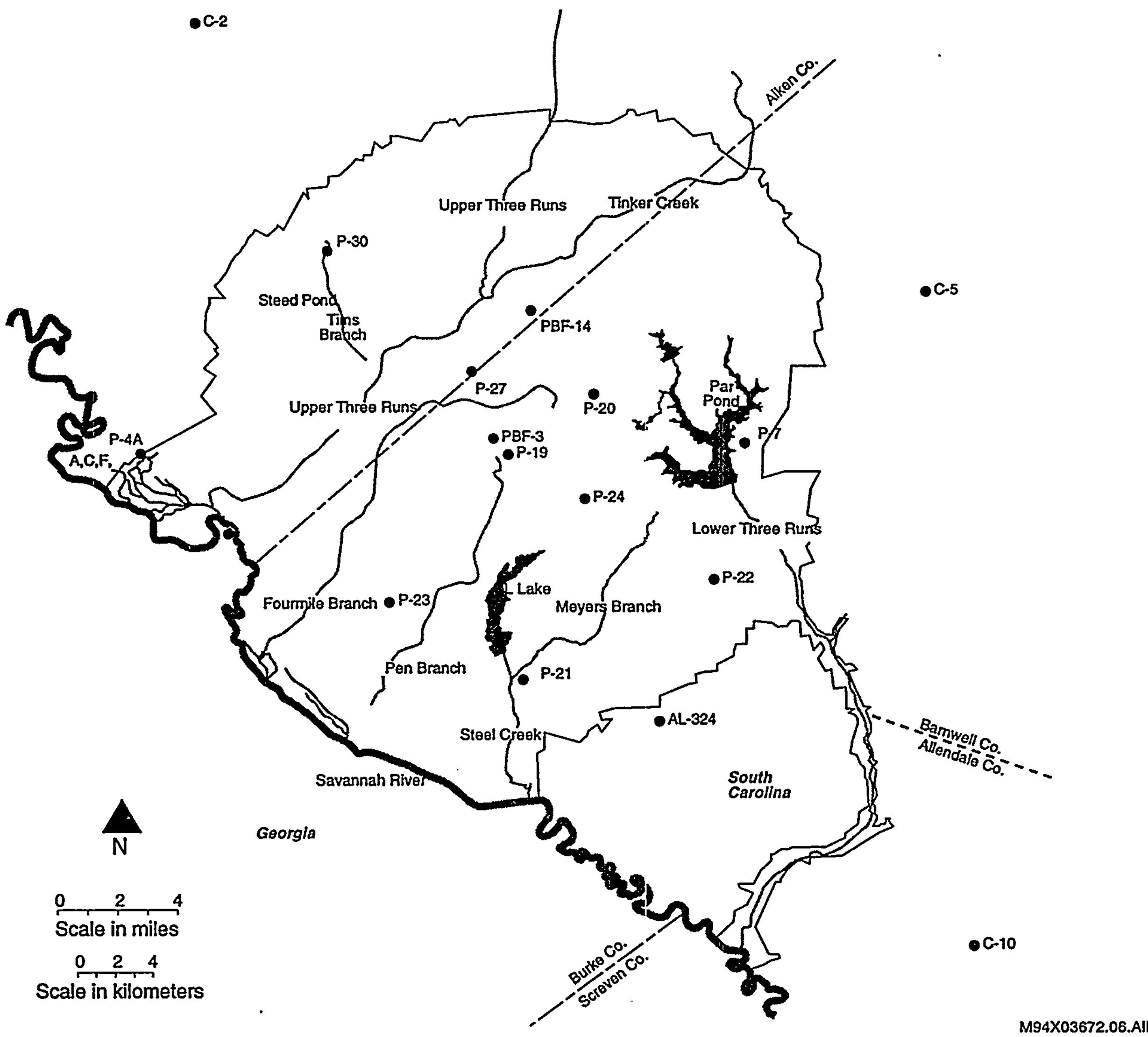


Figure 3-11. Location of Some Well Clusters in and Around the Savannah River Site (Source: Aadland et al. 1992).

At SRS, the Black Creek Formation is penetrated at all P-well cluster sites with the exception of P-20. The unit varies in thickness from approximately 77 m (255 ft) in the north to 106 m (350 ft) in the south, and dips approximately 4.2 m/km (22 ft/mi) to the southeast. The Black Creek is distinguished from the overlying and underlying Cretaceous units by its uniform fine-grained silty-sands and relatively high clay content. It is generally darker and more lignitic and micaceous than other Cretaceous units, especially in the up-dip part of the section. The Black Creek is composed of two thick, fining-upward sequences, each capped by thick clay beds. Throughout much of SRS, the lower one-third of the formation is mostly sand that is separated from the more clayey and silty upper two-thirds of the unit by clay beds often 6-12 m (20-40 ft) thick. In general, the top of the Black Creek Formation is picked at the top of a clay bed that varies from 3-7.5 m (10-25 ft) thick.

Peedee Formation - Steel Creek Member

Ruffin (1843) named the Maestrichtian Peedee Formation in his description of beds cropping out along the PeeDee River in Florence county, South Carolina. Previous investigators considered the Peedee Formation to be absent in SRS. However, recent palynological evidence indicates sediments that occur in the same age range as the Peedee do occur in the southern portion of the SRS (Logan and Euler 1989). Because there is a considerable difference in lithology between the type Peedee (Heron 1958) and the sediments in the SRS region, Peedee-equivalent sediments in SRS are referred to as the "Steel Creek Member of the Peedee Formation." This phase of the unit is well displayed in well P-21, near Steel Creek (Figure 3-11). The top of the Steel Creek Member is picked at the top of a massive clay that varies from 1.0 m to more than 9.1 m thick (3 ft to more than 30 ft).

The Steel Creek Member varies in thickness from approximately 18 m (60 ft) in the north to 53 m (175 ft) at well C-10 in the south. The unit consists of yellow, tan and gray, medium to coarse grained, moderately sorted sand, and interbedded sand and variegated clay. The lower part of the unit consists of medium to coarse-grained, poorly to well-sorted, quartz sand, silty sands, and off-white to buff clay that contains thin beds of micaceous and carbonaceous clay. Pebbly zones and layers with clay clasts are common. Fining-upward sands are interbedded with the clay and silty clay beds in some areas. It is difficult to differentiate the Steel Creek from the underlying Black Creek in the northwestern part of SRS. The unit appears to have been deposited in fluvial environments in the northern part of SRS and upper to lower delta-plain environments to the south. The massive clays that cap the unit suggest lower delta-plain to shallow-shelf depositional environments. The presence of dinoflagellates indicates some marine influence in parts of the Steel Creek (Prowell et al. 1985b). A pebble-rich zone at the base of the unit suggests a basal unconformity. The Steel Creek section thins dramatically between the AL-324 and the P-22 wells at the southeastern edge of SRS due to truncation by erosion at the overlying Cretaceous-Tertiary unconformity.

Tertiary System

Black Mingo Group

In west-central South Carolina, the Black Mingo Group consists of the lower Paleocene (Midwayan, Danian-lower Thanetian) Ellenton Formation, the upper Paleocene (lower Sabinian, upper Thanetian) Williamsburg Formation (Colquhoun et al. 1983), and the lower Eocene (upper Sabinian-Ypresian) Fishburne Formation (Gohn et al. 1983) (Figure 3-10).

The Black Mingo Group consists of quartz sands, silty clays and clays which suggest upper and lower delta-plain environments of deposition generally under marine influences (Prowell et al. 1985b). In the southern part of SRS, massive clay beds predominate, and are often more than 15.2 m (50 ft) thick. The upper surface of the group dips to the southeast at approximately 3.0 m/km (16 ft/mi) and thickens from about 21 m (70 ft) at the northwestern site boundary to about 48.8 m (160 ft) near the southeastern boundary.

Ellenton Formation

The Ellenton Formation (Siple 1967) unconformably overlies the Cretaceous sediments and consists of two fining-upward sand-to-clay sequences. The Ellenton is approximately 12 m (40 ft) thick at the northwestern boundary of SRS and thickens to about 30 m (100 ft) near the southeastern boundary. The formation is mostly dark gray to black, moderately to poorly sorted, fine- to coarse-grained, micaceous, lignitic, silty and clayey quartz sands interbedded with dark gray clays and clayey silts. Pebbly zones, muscovite, feldspar, and iron-sulfide are common. Individual clay beds up to 6 m (20 ft) thick are in the unit. Clay and silt beds make up approximately one-third of the unit in SRS. The dark, fine-grained sediments represent lower delta plain, bay-dominated environments.

Williamsburg Formation - Snapp Member

The sediments at SRS that are time-equivalent to the Sabinian (mid-late Thanetian) Williamsburg Formation differ from the Williamsburg type and are designated as the "Snapp Member" of the Williamsburg Formation (Fallaw et al. 1990) (Figure 3-10). The unit is encountered in well P-22 in the southeast part of SRS near Snapp Station (Figure 3-11). The basal contact with the underlying Ellenton Formation is probably unconformable. The Snapp Member appears to pinch out in the northwestern part of SRS and thicken to about 15 m (50 ft) near the southeastern boundary of the site.

In and near SRS, the Williamsburg sediments are typically silty, medium- to coarse-grained quartz sand interbedded with clay. Dark, micaceous, lignitic sands also occur here. These sediments suggest a delta-plain depositional environment (Lewis and Aadland 1992). In the southernmost part of SRS, the Williamsburg consists of gray-green, fine to medium, well-rounded, calcareous, quartz sand and interbedded micritic limestone and limy clay that is highly fossiliferous and glauconitic (Clarke et al. 1985). This lithology suggests deposition in open, shallow-shelf environments somewhat removed from clastic sediment sources.

Fishburne Formation - Fourmile Member

Overlying the Williamsburg Formation is the basal Eocene Fourmile Member of the Fishburne Formation. Early Eocene ages, derived from palynological assemblages, indicate that the sands immediately overlying the Williamsburg Formation are equivalent to the Fishburne Formation (Gohn et al. 1983), a calcareous unit that occurs down-dip near the coast.

The Fourmile Member of the Fishburne Formation crops out northwest of the SRS, where it has been mapped as part of the Huber Formation; but it has been traced in the subsurface into the northwestern portion of the site (Fallaw 1991). Fourmile Member sand beds are variable in color, fine- to coarse-grained, moderately to well sorted, and usually unconsolidated. A few pebbly zones occur near the base of the unit. A clayey zone of varying thickness may be interbedded with the sand sequence. Based on lithologic characteristics, the Fourmile Member sand was probably deposited in a shallow marine environment, and the clay units formed in bays or lagoons (Fallaw 1991).

Orangeburg Group

The Claibornian (Lutetian-Bartonian) Orangeburg Group consists of the lower middle Eocene Congaree Formation (Tallahatta equivalent), the upper middle Eocene Warley Hill Formation, and the Santee Limestone Formation (Lisbon equivalent). Over most of SRS, these Eocene units are more marine in character than the underlying Cretaceous and Paleocene units. They consist of alternating layers of sand, limestone, marl, and clay (Brooks et al. 1985). The group crops out at lower elevations in many places within and in the vicinity of SRS. Sediments thicken from approximately 27 m (90 ft) at the northwestern SRS boundary to about 48 m (160 ft) near the southeastern boundary.

From the base upward, the Orangeburg Group sequence changes from clean shoreline sands characteristic of the Congaree Formation to shelf marls, clays, sands, limestones, and various mixed clastic-carbonate lithologies typical of the Warley Hill Formation and the Santee Limestone. The sequence is transgressive with the middle Eocene sea reaching its most northerly position during the deposition of the Santee.

Congaree Formation

The lower middle Eocene Congaree Formation has been traced from the Congaree valley in east-central South Carolina into SRS. Fallaw et al. (1990) correlated it paleontologically with the lower Claibornian or lower (and middle) Eocene Tallahatta Formation in neighboring southeastern Georgia; Lewis and Aadland (1992) mapped it as the Huber Formation northwest of the SRS, where the unit is more micaceous and is more poorly sorted. At the SRS, the Congaree Formation consists of yellow, orange, tan, gray, green, and greenish gray, well-sorted, fine to coarse quartz sands with granule and small pebble zones common. Thin clay laminae occur throughout the section. The quartz grains tend to be better rounded here than in the rest of the stratigraphic column. The sands are locally glauconitic. The sediments indicate deposition in shoreline to shallow shelf environments.

To the south, near well AL-324 (Figure 3-11), the Congaree Formation consists of interbedded glauconitic sand and shale, grading to glauconitic, argillaceous, fossiliferous sandy limestone, suggesting a shallow to deep shelf environment of deposition. Further south, beyond the C-10 well (Figure 3-11), the Congaree grades into the platform carbonate facies of the lower Santee Limestone (Colquhoun et al. 1983).

Warley Hill Formation

Unconformably overlying the Congaree Formation are approximately 1.8-3.6 m (6-12 ft) of fine-grained, typical glauconitic sands and green clay beds previously were referred to as the Warley Hill and Caw Members, respectively of the Santee Limestone. The green sand and clay beds were informally referred to as "green clay" in many previous SRS reports (e.g., Siple 1967); Sloan (1908) assigned outcrops of these sediments along Tinker Creek at SRS to his "Warley Hill Phase," correlating them with the type locality in Calhoun County, South Carolina (Sloan 1908; Cooke and MacNeil 1952). Both the glauconitic sand and the clay above the Congaree now are assigned to the Warley Hill Formation (Fallaw et al. 1990). In the up-dip parts of SRS, near the C-2 well (Figure 3-11), the Warley Hill is apparently missing or very thin, and the overlying Santee Limestone rests unconformably on the Congaree Formation.

The Warley Hill sediments at SRS indicate shallow to deep clastic shelf environments of deposition, generally deeper water than the underlying Congaree Formation. This suggests a continuation of the transgressive pulse of the sea during late middle Eocene time. To the south, beyond the P-21 well (Figure 3-11), the green silty sands and clays of the Warley Hill undergo a facies change to the clayey micritic limestones and calcareous clays typical of the overlying Santee Limestone.

Santee Limestone

The upper middle Eocene deposits overlying the Warley Hill Formation consist of moderately sorted yellow and tan sand, calcareous sands and clays, limestones, and clay of the Santee Limestone. The calcareous part of the Santee is much more abundant down-dip, sporadic in the middle of SRS, and missing to the northwest. The limestones represent the most distant northwest advance of the transgressing carbonate platform first developed in early Paleocene time near the South Carolina and Georgia coasts. The terms "McBean Formation" and "Lisbon Formation" often have been applied to these sediments in the past, but the term "Santee" has priority (Sloan 1908). "Santee" was used in many variations by early investigators, but Cooke (1936) was first to use the term "Santee Limestone." Cooke assigned the unit to the upper Eocene; however, in 1952, Cooke and MacNeil (1952) reassigned it to the middle Eocene as the equivalent of the Gulf State's Cook Mountain Formation of the Claiborne Group.

The Santee Limestone is about 21 m (70 ft) thick near the center of SRS, and the sediments indicate deposition in shallow marine environments. The Santee is made up of three members in the SRS area (Fallaw et al. 1990): the Blue Bluff Member, the McBean Member, and the Tims Branch Member (Figure 3-10).

Blue Bluff Member

The Blue Bluff Member of the Santee consists of the gray to green, laminated micritic limestone parts of the Santee. The lithology varies from gray, fissile, calcareous clay to clayey micritic limestone to very thinly layered to laminated, clayey, calcareous, silty, fine sand, with shells and hard, calcareous nodules, lenses, and layers. Blue Bluff cores are glauconitic, up to 30% in some places. This lithology suggests deposition in protected lagoon or bay environments. The Blue Bluff tends to dominate the formation in the southern part of SRS from the P-22 well south (Figure 3-11).

McBean Member

The McBean Member consists of tan to white, consolidated and unconsolidated calcareous sand and clay, shelly limestone, and unconsolidated sand and clay. It is the dominant member of the Santee Limestone in the central part of SRS and represents a shallow-marine shelf deposit. Dissolution of carbonate within the middle to late Eocene carbonate-rich sediments of the Santee Limestone, Utley Limestone, and the lower portions of the overlying upper Eocene Dry Branch Formation formed "soft zones" and/or underconsolidated sands.

Soft zones primarily are recognized during drilling by the drill string sinking under its own weight (or its own weight plus that of the hammer), presumably from the encounter of the rod with vulgar or moldic porosity. Loss of drilling fluid is also an indication of encountering a soft zone or underconsolidated zone. Skinner (1992) related formation of these soft zones in K Area to dissolution of carbonate bioherms. Figure 3-12 illustrates this process schematically.

Patchy carbonate bioherms grew in the shallow seas at the site during deposition of the Santee sediments (Figure 3-12 A). These bioherms then were covered by sand, silt, and clay (Figure 3-12 B). Subsequent movement of groundwater through the sediments replaced and dissolved carbonates (Figure 3-12 C). Collapse of overlying sediments as the grains readjust to partially fill the voids forms underconsolidated intervals above the bioherm and a soft zone in the vicinity of the bioherm interval (Figure 3-12 D). Skinner (1992) found no evidence that these soft zones were connected with surface depressions.

Tims Branch Member

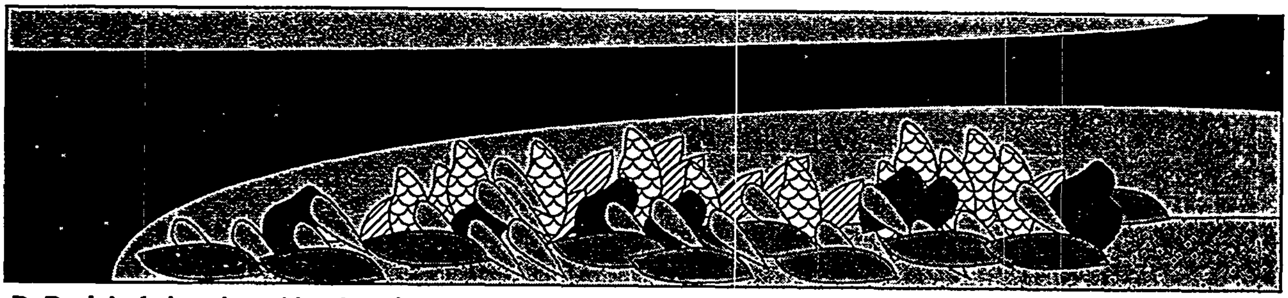
The Tims Branch Member consists of the siliciclastic part of the unit. The sands are fine- and medium-grained, tan, orange, and yellow, poorly to well sorted, and slightly to moderately indurated. They are slightly glauconitic in places, and suggest siliciclastic, shallow marine to shore-face depositional environments. The Tims Branch Member dominates the Santee Limestone in the northern part of SRS. (Fallaw and Price 1992, 1995) have elevated the siliciclastic facies to the Tinker Formation (Figure 3-8).

Barnwell Group

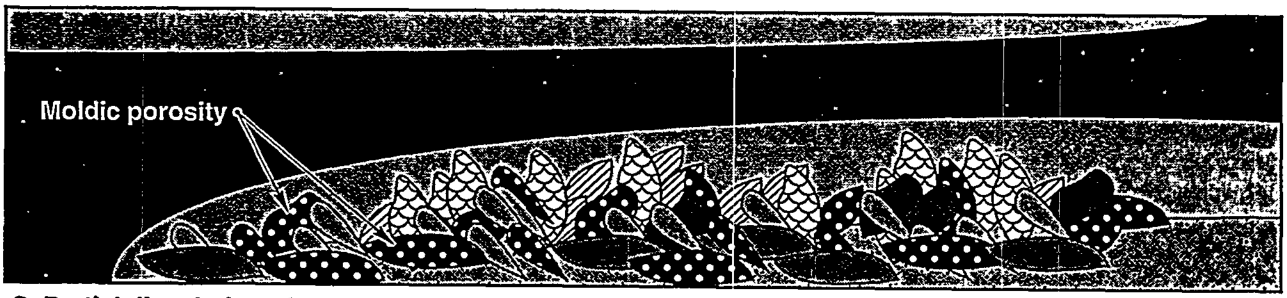
The upper Eocene (Bartonian and Priabonian) sediments of the Barnwell Group represent the Jacksonian Stage in the Upper Coastal Plain of western South Carolina and eastern Georgia (Logan and Euler 1989). They are equivalent in time and stratigraphy to the lower part of the (upper Eocene) Cooper Group of Colquhoun et al. (1983).

Barnwell Group sediments lie unconformably on the Santee Limestone (Figure 3-10) and consist mostly of shallow-marine quartz sands with sporadic clay layers. Huddleston and Hetrick (1985) revised the upper Eocene stratigraphy of the Georgia Coastal Plain, and their approach has been extended into South Carolina (Nystrom and Willoughby 1982; Nystrom et al. 1986). These authors elevated the Eocene (Jacksonian-Priabonian) "Barnwell Formation" to the "Barnwell Group," which in Burke County, Georgia, includes (from oldest to youngest) the Clinchfield and Dry Branch Formations, and the Tobacco Road Sand (Figure 3-10). The group is about 36 m (120 ft) thick near the northwestern boundary of SRS and

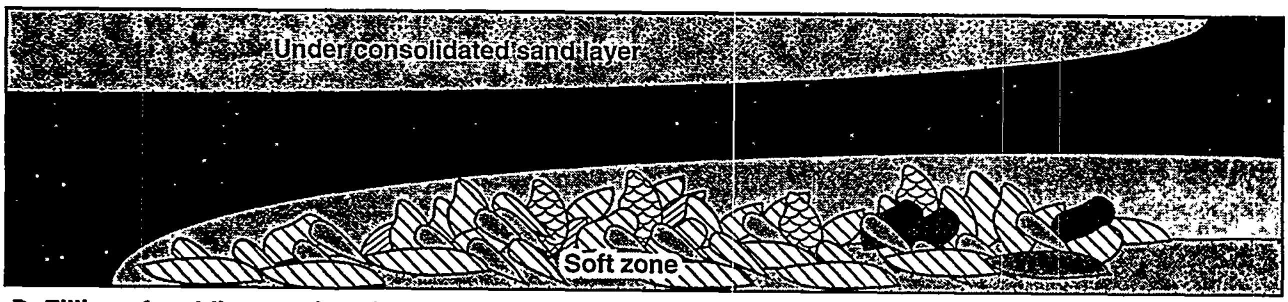
A. Deposition of carbonate by development of oyster banks.



B. Burial of abandoned banks with sand and clay.



C. Partial dissolution of carbonate.



D. Filling of moldic porosity with silts and partial collapse of the mound resulting in the formation of a soft zone.

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Figure 3-12. Mechanism of "Soft Zone" Formation Proposed by Skinner (1992).

about 42 m (140 ft) thick near the southeastern boundary. In the northern part of SRS, the Barnwell Group consists of red to brown, fine- to coarse-grained, well-sorted, massive sandy clays and clayey sands, calcareous sands and clays, and scattered thin layers of silicified fossiliferous limestone. All suggest lower delta plain to shallow shelf environments.

Clinchfield Formation

The basal upper Eocene Clinchfield Formation consists of light-colored quartz sands and glauconitic, biomoldic limestones, calcareous sands, and clays. The sands constitute the Riggins Mill Member of the Clinchfield Formation and comprise medium to coarse, poorly to well sorted, loose and slightly indurated, tan, gray, and green quartz sand. The sands are difficult to identify unless both the Griffins Landing carbonate member of the overlying Dry Branch Formation and the McBean Member of the underlying Santee Limestone are present, with the sand in between. The Clinchfield is about 7.5 m (25 ft) thick in the southeastern part of the site and pinches out or becomes unrecognizable in the center of the site. The sand probably was deposited as the Barnwell sea transgressed over the eroded Santee.

The carbonate sequence of the Clinchfield Formation constitutes the Utley Limestone Member of the formation. It is composed of sandy, glauconitic limestone and calcareous quartz sand with an indurated, biomoldic facies developing in places. In SRS cores, the sediments are tan and white and slightly to well-indurated; however, soft zones as previously discussed, also are found within the Utley Limestone.

Dry Branch Formation

The Jacksonian (upper Eocene) aged Dry Branch Formation is divided into the Irwinton Sand Member, the Twiggs Clay Member, and the Griffins Landing Member. The unit is about 18 m (60 ft) thick near the center of SRS. The top of the Dry Branch Formation is picked on geophysical logs where the gamma-ray count sharply increases from low gamma activity in the Dry Branch sand to the high gamma activity in the more argillaceous sediments of the overlying Tobacco Road Sand.

Twiggs Clay Member

The Twiggs Clay Member is predominant in the Dry Branch Formation west of the Ocmulgee River in Georgia. The member is not mappable in the SRS area (i.e., it is not observed as a single separate unit), but lithologically similar clay is in various stratigraphic intervals within the formation. The tan, light gray, and brown clay beds, usually one to three, are up to 3.6 m (12 ft) thick in SRS wells but are not continuous nor can they be correlated throughout the SRS. These clay beds have been informally referred to in past SRS reports as "tan clay."

Historically, shallow wells drilled in the central portion of SRS to sample the water table aquifer were terminated after encountering the first substantial confining unit, usually the tan to brown clays in the Dry Branch Formation. It was assumed early on that the clay constituted a single, regionally significant confining layer, which was informally referred to as tan clay. Recent detailed lithostratigraphic analysis of drill core and down-hole geophysical data indicated that there are from zero to four 15-cm to 1-m (6-in to 3-ft) thick discontinuous clay beds in the stratigraphic interval, which is approximately 6 m (20 ft) thick where the clays are observed. Thus, there is no single tan clay bed that acts as the first or most shallow regional confining unit; although the clay beds in the Dry Branch are often locally significant. The clay beds often divide the Upper Three Runs aquifer into zones (Chapter 5, Hydrostratigraphy) in the central region of the SRS.

Griffins Landing Member

The Griffins Landing Member is composed mostly of tan to green, slightly- to well-indurated, quartzose micrite and sparite, calcareous quartz sand, and slightly calcareous clay. The unit appears to be widespread in the southeastern part of SRS, where it is about 16 m (50 ft) thick, but becomes sporadic in the center where it pinches out. The carbonate content is highly variable and soft zones are known to occur in the Griffins Landing Member. In places, the unit lies unconformably on the Utley Member of the Clinchfield Formation, which contains much more indurated, moldic limestone. In other areas, it lies on the non-calcareous quartz sand of the Clinchfield. The Clinchfield is difficult to identify or is missing to the northeast, and the unit may lie unconformably on the sand and clay facies of the McBean Member of the Santee Limestone. The Griffins Landing Member appears to have formed in shallow marine to lagoonal environments.

Irwinton Sand Member

The Irwinton Sand Member is composed of tan, yellow, and orange, moderately sorted quartz sand, with interlaminated and interbedded clays that are abundant in places (Twiggs Clay lithology). Pebbly layers and clay clast-rich zones are present. The Irwinton sands have the characteristics of a shallow marine deposit, and the clays may have formed in a lagoon or marsh environment (Smith 1979). The thickness is variable; about 12 m (40 ft) near the northwest site boundary and about 21 m (70 ft) near the southeastern boundary.

Tobacco Road Sand

The upper Jacksonian (upper Eocene) Tobacco Road Sand consists of moderately to poorly sorted, red, brown, tan, purple, and orange fine to coarse quartz sands. Pebble layers are fairly common as are clay laminae and beds. Ophiomorpha, formed in some nonspecific shallow marine environments, are abundant in parts of the formation. The sediments also exhibit other characteristics of a shallow marine deposit. The top of the Tobacco Road is picked where comparatively well-sorted sands are overlain by more poorly sorted sands, pebbly sands, and clays of the "upland unit." The contact is difficult to pick on geophysical logs because the upper surface of the unit is irregular due to fluvial incision that accompanied deposition of the overlying upland unit and later erosion. The lower part of the upper Eocene Cooper Group is the probable down-dip equivalent of the Tobacco Road Sand.

"Upland Unit"/Hawthorn Formation

Deposits of very poorly sorted silty, clayey sand, pebbly sand, and conglomerate of the upland unit cap are present on many of the hills at higher elevations over much of SRS. Weathered feldspar is abundant in places. The color is variable, and facies changes are abrupt. Siple (1967) correlated these sediments with the Hawthorn Formation. Nystrom et al. (1986), who mapped it as the upland unit, discussed evidence for a Miocene age. The environment of deposition appears to be fluvial, and the unit thickness changes abruptly due to channeling of the underlying Tobacco Road Sand during upland deposition and subsequent erosion of the upland unit. Thicknesses of 18 m (60 ft) have been documented (Nystrom et al. 1986).

Lithologies comparable to the upland unit, but assigned to the Hawthorn Formation, overlie the Barnwell Group and the Cooper Group in the southern part of SRS and the equivalent of the Suwannee limestones down-dip toward coastal South Carolina. The up-dip Hawthorn Formation consists of poorly sorted, sandy clay and clayey sand, with lenses of gravel and thin beds of sand similar to the upland unit. Further down-dip, the Hawthorn consists of phosphatic, sandy clay to phosphatic clayey sand and sandy dolomitic limestone interbedded with layers of hard brittle clay, resembling stratified fuller's earth.

Upper Tertiary Dune Sands

Unnamed dune sands unconformably overlie upland unit sediments in many localities on the eastern and southeastern portions of SRS. The sands are generally medium, angular, and moderately sorted quartz with minor mica content. The sands are devoid of clay and of the heavy mineral fraction that is characteristic of underlying units. Prowell (1994a) tentatively has assigned a late Miocene to Pliocene age to these deposits, and the South Carolina Geological Survey maps identify these sands as the "Pinehurst formation."

Quaternary System

Introduction

The Pliocene and dune deposits on the Aiken Plateau are the youngest units with wide lateral extent in the SRS area. Younger deposits are those associated with Holocene streams or with the formation of peat deposits in floodplains or in depressions on the surface of the plateau.

While erosion has clearly been the dominant process in the region, Quaternary alluvial deposits have covered many of the older stratigraphic units. The deposits are mainly poorly sorted, fine to very coarse quartz sands with sparse clay matrix materials (Prowell 1994a). On map scale, the various alluvial deposits are combined and collectively mapped as "Quaternary alluvium." Detailed stratigraphic and geomorphologic investigations, especially those by Stevenson (1982) and by Geomatrix Consultants (1993) have shown, however, that the alluvial deposits are separable and represent distinct depositional episodes during the Quaternary. The principal Quaternary alluvium deposits are associated with the formation of stream terraces in the Savannah River valley, especially the Ellenton and the Bush Field terraces, or with the filling of the Wisconsinan Savannah River channel with alluvium during the Holocene and the formation of the river's modern floodplain.

Savannah River Terrace Deposits

Ellenton Terrace Deposits

The Ellenton Terrace (Qte in Figures 3-13 through 3-15) is the higher of two prominent terraces that are well preserved along the Savannah River (Chapter 2, Geomorphology). The terrace includes surfaces that range from approximately 17 m (56 ft) to as much as 25 m (82 ft) above local base level (Figures 3-14 and 3-15). Surfaces at heights of approximately 24-25 m (79-82 ft) above the present channel are observed only on the northeast side of the river. Here they are relatively continuous except between Fourmile Branch and Steel Creek, where the higher part of the terrace appears to have been eroded while the lower surfaces (17 to 22 m [56 to 72 ft]) were being formed (Geomatrix Consultants 1993).

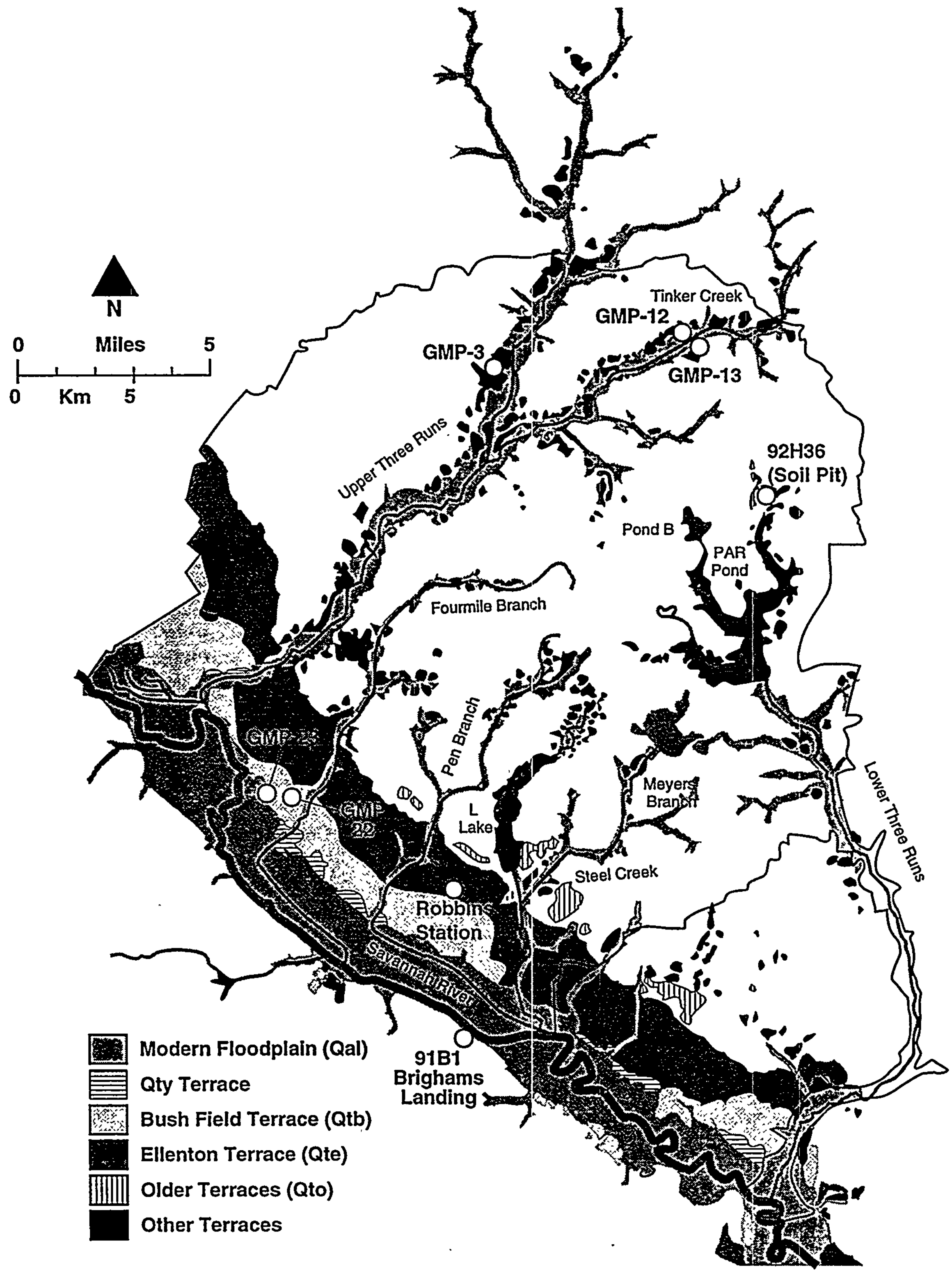

Figure 3-13. Terraces of the Savannah River and its Tributaries (Source: Geomatrix Consultants 1993).

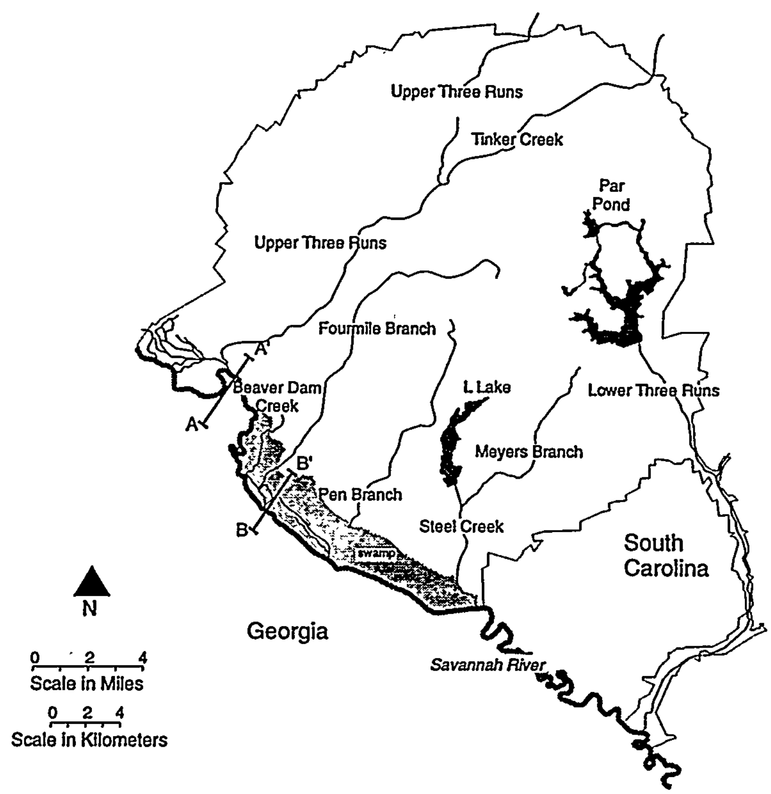

Figure 3-14. Location of Cross-Valley Profile Showing Fluvial Terraces Along the Savannah River Near the Confluence of Upper Three Runs (Profile A-A[1]) and Fourmile Branch (Profile B-B[1]) (Source: Hanson et al. 1993).

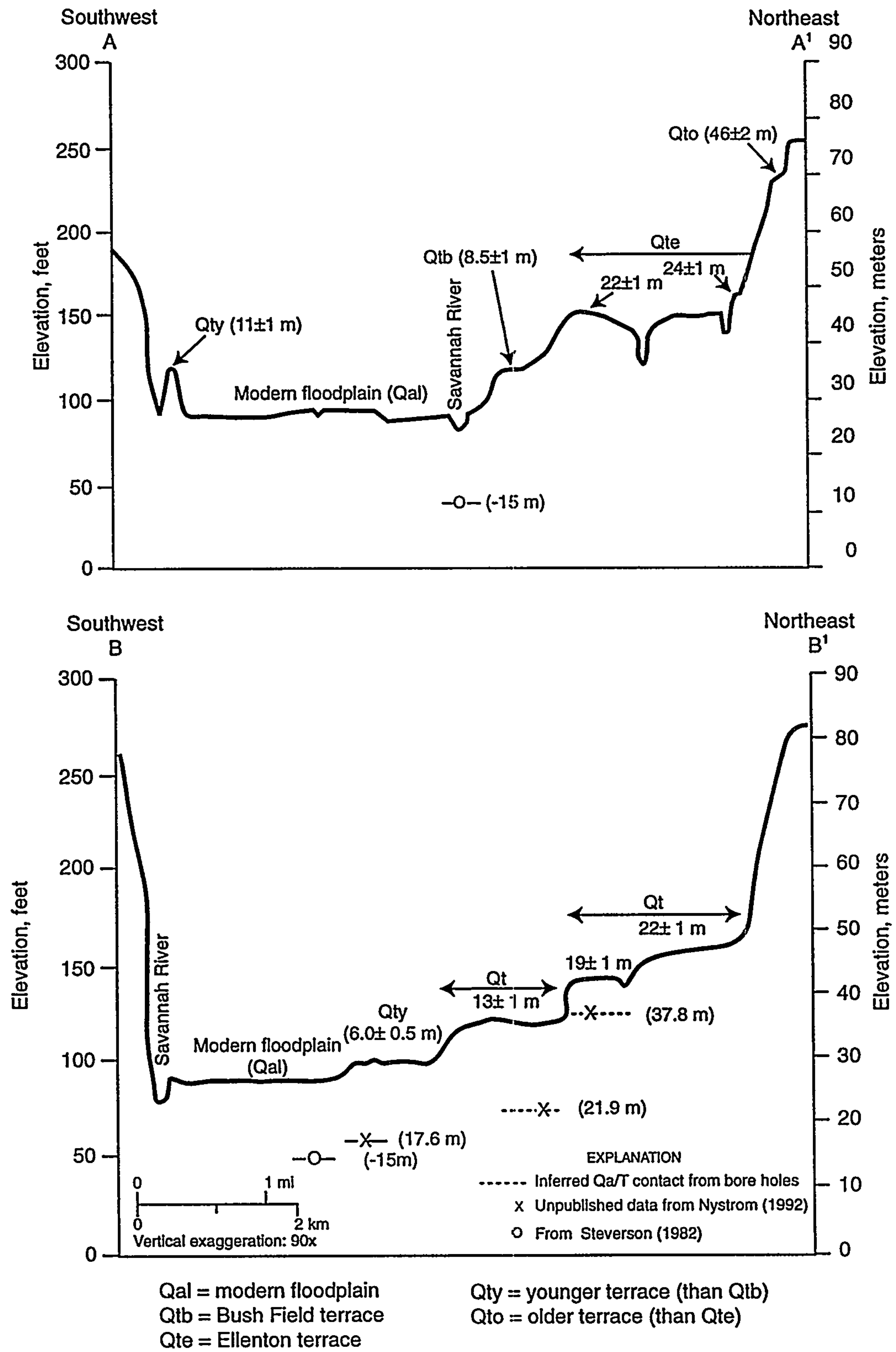

Figure 3-15. Cross-Valley Profile Showing Fluvial Terraces Along the Savannah River Near the Confluence of Upper Three Runs (Profile A-A[1]) and Fourmile Branch (Profile B-B[1]) (Source: Hanson et al. 1993).

Alluvium underlying the Ellenton Terrace surface is well exposed in railroad cuts adjacent to and south of both Fourmile Branch and Upper Three Runs (Geomatrix Consultants 1993). These cuts provide good exposures of the upper 6-7 m (20-23 ft) of the alluvium and soil developed on the terrace deposits. The upper 2-2.5 m (7-8 ft) consists of a massive, loose, light-colored sand to loamy sand (E horizon) that overlies a 2.8-m (9-ft) thick argillaceous horizon developed on poorly sorted, fine- to coarse-grained sand. The approximate upper 0.6 m (2 ft) of the argillic horizon is characterized by increased accumulations of iron and aluminum compounds that form a reticulate mottled plinthite (Btv) horizon.

The base of the alluvium underlying the Ellenton Terrace is not exposed at either the Fourmile Branch or Upper Three Runs railroad cut localities (Geomatrix Consultants 1993). Subsurface data from drill sites near the Fourmile Branch exposures (Figure 3-13) suggest that the strath underlying the alluvium is probably 2-3 m (7-10 ft) below the exposed deposits. The thickness of the Qte alluvium is thus similar to that of the modern floodplain alluvium. Coarser alluvium consisting of interbedded sandy pebble gravel and medium to coarse sand underlies the 17 m (26 ft) Ellenton Terrace at an elevation of approximately 37 m (120 ft) above mean sea level between Pen Branch and Steel Creek near Robbins Station (Figure 3-13) (Geomatrix Consultants 1993).

In railroad cut exposures approximately 0.7 km (0.5 mi) northeast of Robbins Station, alluvium at a comparable elevation exhibits prominent crossbeds and cut-and-fill channels, some filled with fine-grained silty clay. Clasts within these exposures are subrounded to well-rounded resistant quartzite pebbles (generally ≤2 cm [<1 in.]) with a few subrounded clasts of reworked oyster shells or siliceous-calcareous-cemented sand. The alluvium at both exposures is characterized by numerous subvertical, infilled fractures, some lined with rinds of plinthite or ironstone.

Bush Field Terrace Deposits

The Bush Field Terrace (Qtb in Figures 3-13 through 3-15), the lower of the two prominent terraces recognized along the Savannah River, is comparable in width to the modern floodplain and, like the modern floodplain, includes terrace surfaces of slightly differing heights above local base level (Geomatrix Consultants 1993). Surfaces ranging from approximately 8-13 m (26-43 ft) above the Savannah River are included in the Bush Field Terrace (Figures 3-14 and 3-15) (Geomatrix Consultants 1993). Subsurface data for the terrace near Fourmile Branch suggest that some of these surfaces are fill-cut terraces (Geomatrix Consultants 1993).

At SRS, the Bush Field Terrace is preserved primarily on the northeast side of the river (Figures 3-13 through 3-15). Northwest of the site boundary, broad terrace remnants are well preserved on the southwest side of the river, where they are occupied by the Bush Field airport facilities and runways (Geomatrix Consultants 1993). Near the confluence of Lower Three Runs and the Savannah River at the southern margin of the study area, Bush Field Terrace remnants are on both sides of the river (Geomatrix Consultants 1993).

Alluvium thicknesses underlying the Bush Field Terrace surfaces are similar to those of modern floodplain alluvium (Geomatrix Consultants 1993). Based on limited subsurface data from auger holes drilled on the terraces near Fourmile Branch, both the Ellenton Terrace and Bush Field Terrace are fill terraces underlain by alluvium that has a thickness

(9-15 m [29-49 ft]), comparable to that of the modern floodplain near the mouth of Upper Three Runs (Geomatrix Consultants 1993). Like the upper surfaces of the terraces, the erosional unconformity at the base of the alluvium appears to rise in discrete steps away from the river (Figure 3-14). The configurations of the erosional surfaces associated with the series of fluvial terraces as mapped by surface morphology, however, are not well constrained.

The alluvial deposits of the Bush Field Terrace are lithologically similar to the modern floodplain but are slightly more compact and lithified (Prowell 1994b). They also show signs of secondary iron mineralization, oxidation due to weathering, and primitive soil profile development. Prowell (1994b) used these characteristics to distinguish the older sediments of both the Bush Field and Ellenton Terraces from the modern floodplain. Prowell (1994b) grouped the deposits underlying both the Ellenton and Bush Field Terraces based on their indistinguishable lithology.

Geomatrix Consultants (1993) recognized terrace surfaces (Qty in Figures 3-13 through 3-15) slightly higher than the modern floodplain, approximately 5-6 m (16-20 ft) above the present channel. These surfaces of intermediate height are not easily distinguished from the modern floodplain or the next higher terrace, the Bush Field Terrace (Figures 3-14 and 3-15). Subsurface data near Fourmile Branch, however, suggest that the elevation of the erosional unconformity underlying the 6-m (20-ft) terrace surface at this location differs from the underlying strath surfaces associated with the Bush Field Terrace and the modern floodplain (Figure 3-15) (Geomatrix Consultants 1993).

Age of Terrace Deposits

Several approaches were used to estimate the ages of fluvial terraces along the Savannah River. Table 3-1 summarizes these age estimates. As indicated in Table 3-1, relatively consistent correlated-age estimates are obtained for the Bush Field Terrace and Ellenton Terrace along the Savannah River using several approaches. Based on these results, preliminary ages were assigned to the Savannah River terraces as follows: "younger terraces" (29-130 ka), Bush Field Terrace (100-250 ka), and Ellenton Terrace (1 Ma-350 ka) (Geomatrix Consultants 1993). These ages, although in agreement with regional soil chronosequences, are considerably older than ages estimated by Brooks and Sassaman (1990) for portions of the Bush Field and Ellenton terraces near Pen Branch. Brooks and Sassa-

Table 3-1. Summary of Age Estimate for Savannah River Fluvial (Geomatrix Consultants 1993)

Terrace	Regional Correlation[a]	Correlation to Regional Soil Chronostratigraphy[b]	Uplift/Incision Models
Younger Terraces (Qty)	—	—	29 - 130 ka
Bush Field Terrace (Qtb)	90 ka	100 - 200 ka	77 - 345 kg
Ellenton Terrace (Qte)	200 to >760 ka	400 to >1 Ma	360 ka - 1.1 Ma

[a]Correlated ages based on comparison of geomorphic position and morphology of Savannah River terraces to dated fluvial terraces along the Cape Fear and Pee Dee Rivers as described by Soller (1988) and Owens (1989).

[b]Correlated ages based on comparison of soil and weathering characteristics of terrace deposits in the study area to regional data provided in Markewich et al. (1989).

man (1990) concluded, based on geoarchaeological studies, that the terrace surface at approximately 30 m (100 ft) is early to middle Holocene.

Modern Floodplain Deposits

The modern floodplain of the Savannah River is 2-4 km (1.2-2.5 mi) wide at SRS, and generally consists of extensive broad alluvial surfaces at heights ranging from 2-3 m (7-10 ft) above the modern river channel. The relief on these broad surfaces is generally less than 1 m (3 ft) over short distances; over distances that encompass meander scrollwork, meander cut-offs, oxbow lakes, and abandoned meanders, the total relief may be as much as 3 m (10 ft).

Modern floodplain alluvium is typically a fine to very coarse quartz sand in a sparse clay matrix. The sand is generally angular and poorly sorted with small amounts of mica, feldspar, and dark heavy minerals. Intercalated within this unit are well-rounded to subangular gravel strings of milky, yellow, and dark-red quartz. The sandy units generally are overlain by organic-rich clay and silt at the surface (Leeth 1994; Prowell 1994b).

Stevenson (1982) provided more detailed descriptions of numerous cores taken within the modern floodplain, and provided a thorough discussion of the types of fluvial sedimentary environment in which these sediments were deposited. These environments include channel deposits, bank environments, including levee, crevasse channel, and crevasse splay deposits; and floodplain environments such as overbank, abandoned channel, and channel-migration complex depositional systems (Stevenson 1982).

Alluvium in Tributary Stream Valleys

Active deposition has occurred within the principal tributary stream valleys since the late Pleistocene. The deposition of alluvium has created broad floodplains in the valleys consisting of late Pleistocene to recent, poorly sorted sands and organic deposits (Nystrom 1992). The thickness of the alluvium varies from a few feet in the upper reaches of the tributaries to 12 m (40 ft) or more (Nystrom 1992).

In some instances, Quaternary alluvial fan deposits from side tributaries extend into the floodplain covering older terraces and the more recent floodplain deposits. These are especially noticeable on topographic maps along Upper Three Runs. Active deposition in these tributary valleys and aggradation of the valley floors may have preceded active deposition in the Savannah River valley and construction of the modern Savannah River floodplain (Nystrom 1992). Additional remnants of older Quaternary alluvial fill terraces and side valley benches are found along valley margins in most, if not all, of the valleys (Geomatrix Consultants 1993).

Age of Modern Floodplain Deposits

Radiocarbon ages obtained by Geomatrix Consultants (1993) provide age control for young fill terraces along the Savannah River, Upper Three Runs, and Tinker Creek. The radiocarbon age of 130 ± 50 years (sample 91B1-1) for the 2.5-m-high (8-ft-high) terrace along the Savannah River suggests that this is a historic fill terrace. The age of this terrace is consistent with other radiocarbon dates, ranging from 245 ± 85 to 4010 ± 130 14C years before present which were obtained for deposits at depths of 1.43-3.15 m (5-10 ft) within the modern Savannah floodplain (Stevenson 1982). These radiocarbon dates probably represent the age of the upper third of the alluvium underlying the modern floodplain. A Holocene to latest Pleistocene age is inferred for the oldest alluvium associated with the modern floodplain, assuming that aggradation of the modern floodplain is the result of the climatic change from glacial to late Wisconsinian interglacial conditions (Geomatrix Consultants 1993).

Summary

The Savannah River Site (SRS) is located in the Atlantic Coastal Plain physiographic province approximately 40 km (25 mi) southeast of the Piedmont province. The Coastal Plain is underlain by a seaward dipping wedge of unconsolidated and semiconsolidated sediments. This wedge extends from the Fall Line, where the metamorphic and igneous bedrock of the Piedmont province is exposed, to the edge of the continental shelf. Piedmont rocks and Triassic-Jurassic sedimentary rocks form the basement for the Coastal Plain.

Paleozoic and lower Mesozoic rocks at SRS have been eroded and are unconformably overlain by unconsolidated to semiconsolidated Coastal Plain sediments. These sediments are dominated by sands, clays, and mixtures of the two. Calcareous sands and limestones are less abundant, but may be important because of their association with so called "soft zones." These are isolated areas in the subsurface that have little structural integrity during drilling and are probably the result of dissolution of carbonate by relatively acidic groundwaters.

In stream valleys and along river terraces the Tertiary sediments of the Coastal Plain are overlain by Quaternary alluvium. These deposits are typically poorly sorted, fine to very coarse quartz sands with sparse clay matrix (Prowell 1994a). Distinct generations of terraces associated with the Savannah River have been mapped.

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Chapter 4—Structural Geology and Seismology

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Introduction

The SRS is on a portion of the earth's crust that has undergone major deformation during past geologic events. The structures produced by these events are exposed in the Piedmont and the Appalachian Mountains northwest of the site. Sediments deposited during the Cretaceous and Tertiary periods have buried the older, deformed rocks below the site, making study of the older rocks difficult. What is known or inferred about the basement structures has been developed by comparisons to other areas where the rocks and structures are exposed and through reconstruction of the geologic history of the crustal rocks in the regions surrounding the Central Savannah River Area.

Compared to the older events, the deformation of the sedimentary cover has been mild; it primarily involved crustal tilting and minor off set on several faults that have been identified on the site. Seismic events, such as the Charleston earthquake of 1886 and the small earthquakes recorded at the site and surrounding region, demonstrate that adjustment of the crust is an ongoing, albeit subdued process under current tectonic forces.

Regional Setting

The SRS is along the Savannah River in west-central South Carolina. The site is in the Atlantic Coastal Plain geologic province approximately 40 km (25 mi) southwest of the Piedmont province (Figure 4-1). The Fall Line separates the surface exposures of the deformed and metamorphosed Precambrian and Paleozoic rocks in the Piedmont province from the sediments of the Coastal Plain. The Coastal Plain is a surface of low relief that is underlain by a mildly deformed, seaward dipping wedge of Mesozoic and Cenozoic sediments. The sediments are stratified sand, clay, limestone, and gravel that dip gently seaward and range in age from Late Cretaceous to recent. The sedimentary sequence thickens from zero at the Fall Line to more than 1.2 km (0.7 mi) at the coast. At the site, Coastal Plain sediments are about 185-370 m (607-1214 ft) thick.

Two older rock assemblages lie beneath the Coastal Plain sedimentary sequence at SRS. The first is a crystalline terrane of metamorphosed sedimentary and igneous rock that may range in age from Precambrian to late Paleozoic. The second is the lithified terrigenous and lacustrine sediments filling a Triassic rift basin the Dunbarton basin, beneath the southern half of the site (Marine 1974 a and b; Marine and Siple 1974). The crystalline rocks and the Triassic sediments were eroded during the Mesozoic, forming the base surface for deposition of the Coastal Plain sediments. The erosional surface dips approximately 8m/km (42 ft/mi) toward the southeast (Figure 4-2).

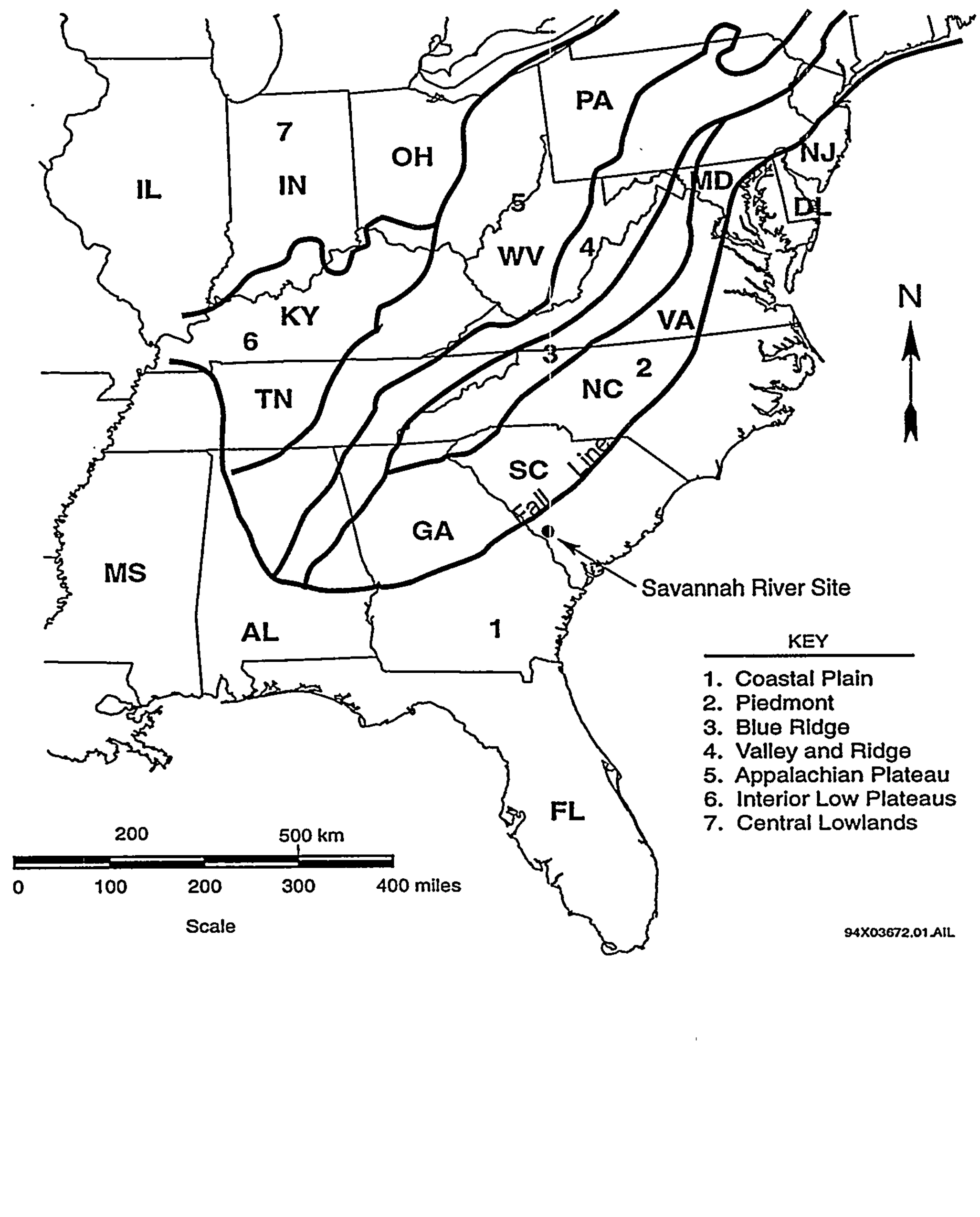

Figure 4-1. Physiographic Provinces of the Southeastern United States (Source: WSRC 1991).

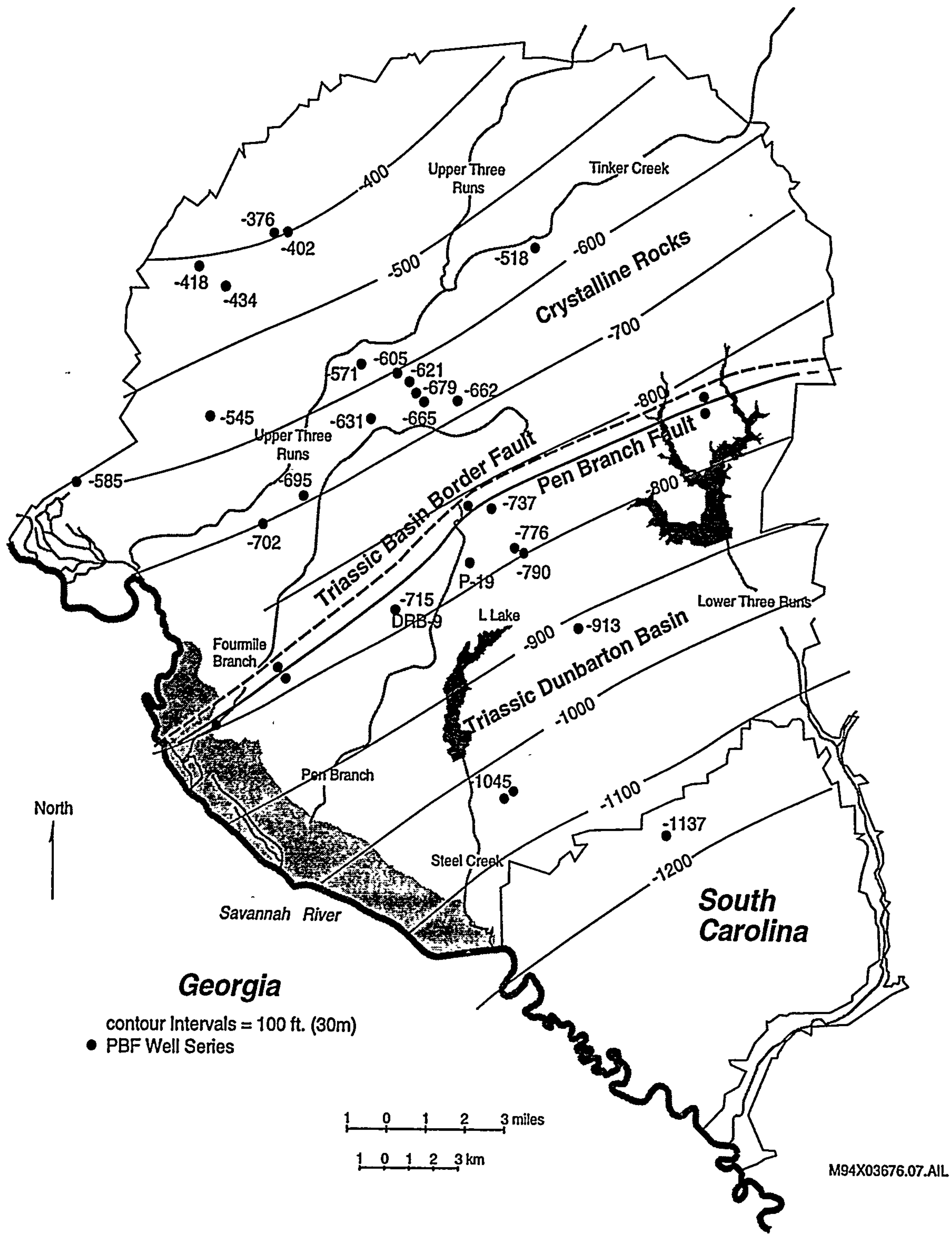

Figure 4-2. Contour Map of the Pre-Cretaceous Basement Surface Near SRS (modified after Marine and Siple 1974).

Regional Structures

Blue Ridge and Piedmont Faults

Deformation associated with the Taconic, Accadian, and Alleghenian orogenies in the southern Appalachians produced several major thrust faults (Figure 4-3). Movement on these faults probably ceased in the Late Paleozoic, as indicated by the age of the youngest sediments and Late Paleozoic granites cut by the faults and by the age of the Mesozoic dikes that cut the faults (Hatcher 1972). Thrusting in the Blue Ridge province was concentrated along the Blue Ridge (Great Smoky) and Hayesville thrust faults (Figure 4-3).

Four major fault zones occur within the Piedmont province: the Brevard fault zone, the Kings Mountain shear zone-Towaliga fault, the Modoc fault zone, and the Augusta fault zone (Figure 4-3). The Brevard fault zone extends from North Carolina to Alabama. It separates the Blue Ridge province from the Piedmont (Clark et al. 1978). The Kings Mountain shear zone-Towaliga fault extends from North Carolina into Georgia. It separates the migmatitic gneissic rocks of the Inner Piedmont from the lower grade metamorphic rocks of the Kings Mountain and Pine Mountain belts (Hatcher 1972). The Modoc fault is in South Carolina and Georgia. It separates the greenschist facies metamorphic rocks of the Carolina Slate belt from the amphibolite facies migmatitic and gneissic rocks of the Kiokee belt (Secor et al. 1986). The Augusta fault zone is near Augusta, Georgia. It separates amphibolite facies Kiokee belt rocks from the greenschist grade rocks of the Belair belt. The Augusta fault and the southeast edge of the Kiokee belt are offset near Augusta by the north-northeast trending Belair fault (Bramlett et al. 1982). The deformed rock and tectonic structures of the Piedmont extend beneath the Atlantic Coastal Plain, but they have been obscured by post-Paleozoic tectonism and deposition of the Coastal Plain sediments.

Rift Basins

The opening of the Atlantic during the early Mesozoic extended and thinned the earlier-formed crust along the current Atlantic coastal margin. Rifting of the crust also formed subsiding crustal blocks bounded by normal faults. The subsiding blocks of crust became the basement rock of the Mesozoic rift basins (Figure 4-4). These basins filled rapidly with terrigenous sediments, keeping pace with the crustal subsidence. Rifting frequently was accompanied by injection of diabase sills and dikes. The Dunbarton Basin, beneath the southeastern part of the SRS, and other Mesozoic rift basins in the southeastern United States have been buried beneath later Mesozoic and Cenozoic sediments. Similar basins, however, are exposed further to the north.

Atlantic Coastal Plain Structures

Postrift tectonism (subsidence and uplift) in the Atlantic Coastal Plain is closely linked to subsidence along the outer continental margin (Gohn 1988). Subsidence of the outer margin resulted from extension and thinning of the crust during early Mesozoic rifting and subsequent postrift thermal contraction of the cooling lithosphere (Gohn 1988). Less altered and thicker continental crust subsided more slowly landward of the oceanic margin. A

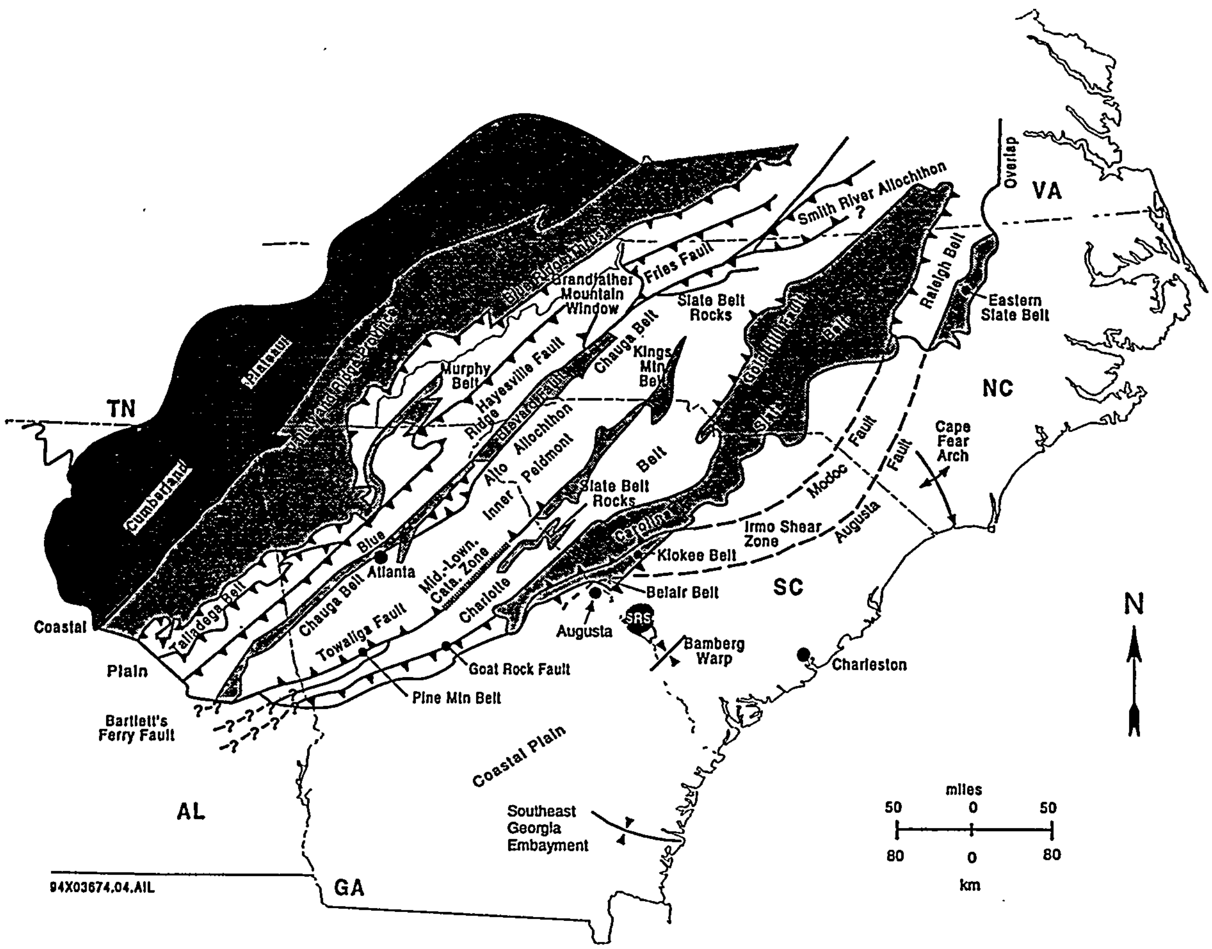

Figure 4-3. Regional Physiographic-Geologic-Tectonic Map of the Southern Appalachians (Source: WSRC 1991, modified after Hatcher 1972).

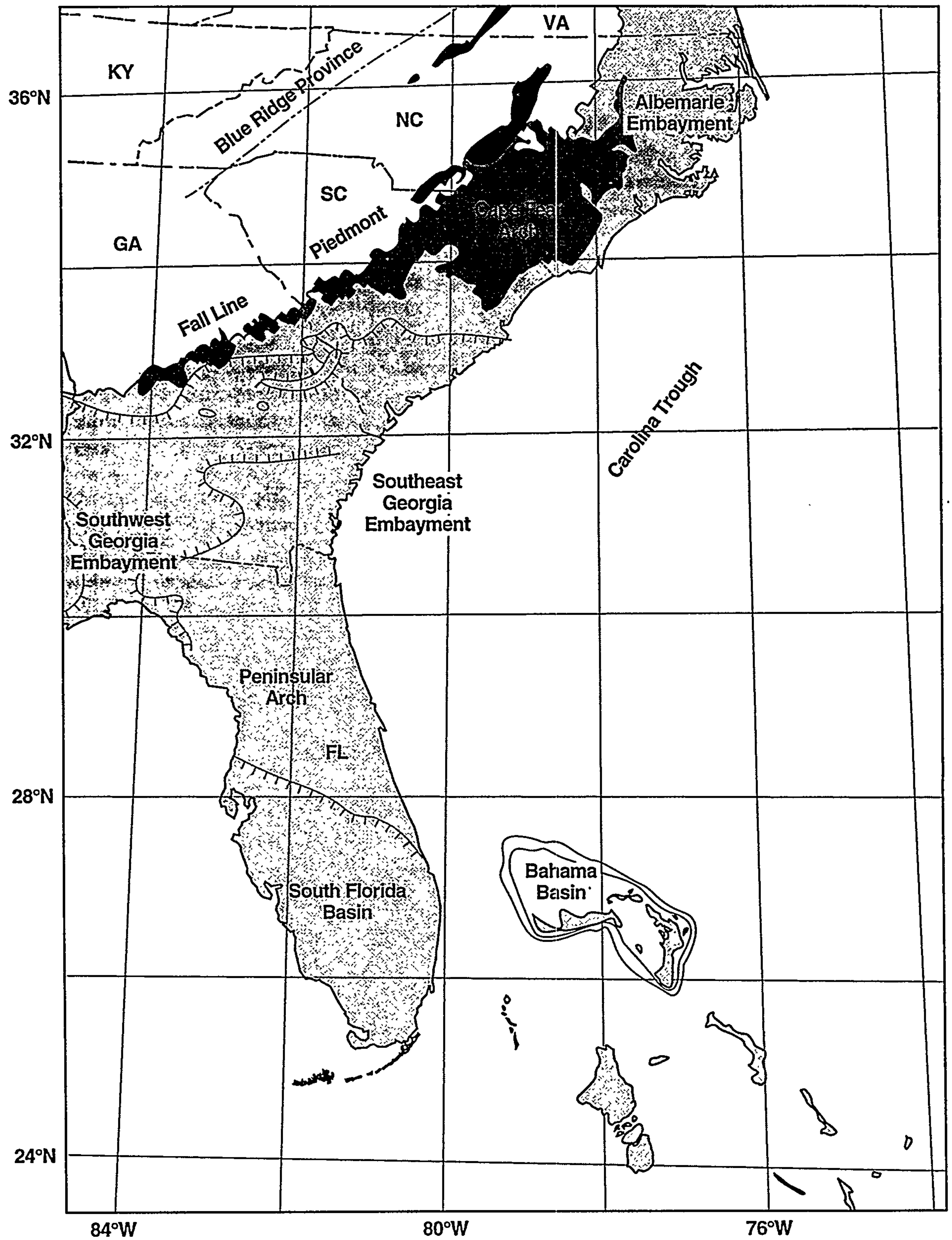

Figure 4-4. Generalized Geologic Map Showing the Location of the Southern Atlantic Coastal Plain and Associated Structures. Cretaceous (dark shading) and Cenozoic (light shading) outcrop belts are indicated, as are exposed early Mesozoic rift basins (black). Boundaries of the subsurface early Mesozoic basins are shown by hatched lines (Source: Gohn 1988).

major sedimentary hinge zone, marking the change from continental to rift-stage crust (Gohn 1988), resulted from this differential subsidence.

Differential subsidence is not the sole cause of tectonism recorded in the Atlantic Coastal Plain sediments. The presence of Late Cretaceous and Cenozoic compression faults and differences in the thickness of Upper Cretaceous and Cenozoic stratigraphic units suggest that intraplate stress fields and resulting fault systems have played a role in Coastal Plain tectonism (Gohn 1988).

The Albemarle embayment, Cape Fear arch, and Southeast Georgia embayment are the major postrift structures associated with the southeastern Coastal Plain in the three-state region of North Carolina, South Carolina, and Georgia (Figure 4-3 and 4-4). Gohn (1988) suggested that the Albemarle embayment resulted primarily from the progradation of the modern North Carolina coastline nearly to the edge of the continental shelf, and that, were it not for this fact, the Albemarle area would not otherwise be considered an embayment. Structures associated with the Coastal Plain in Florida include the Peninsular arch, the South Florida basin, and the southwest Georgia embayment (Figure 4-4). These postrift structures control the sedimentary wedge thickness along the southeastern coast (Gohn 1988). The thickness of the sedimentary wedge is greatest in the embayments or basins, while thinning occurs over the arches (Figure 4-5). SRS is on the southwest flank of the Cape Fear arch in a broad area of gently seaward dipping sedimentary units. The region has been referred to as the "Carolina Platform" by some authors (Gohn 1988).

Structural Geology Of The Savannah River Site

Crystalline Basement

Basement crystalline rocks within the site are similar to those found in the Piedmont Province immediately northwest of the Fall Line, 20–25 km (12.4-15.5 mi) northwest of SRS. Preliminary work on drill core lithology suggests that both Savannah River and Augusta terrane rocks are present in cores taken at SRS (Maher et al. 1994). The Augusta terrane rocks are greenschist facies, and the Savannah River terrane rocks are generally amphibolite facies. A large granitic pluton, the Graniteville pluton, crops out to the north and northwest of SRS. The ages of both the Savannah River terrane and the Augusta terrane are uncertain but are assumed to be Late Precambrian to Paleozoic. Both are intruded by Paleozoic age plutons (Maher et al. 1994). A Cambrian trilobite was found in the Augusta terrane (Maher et al. 1994). Some of the younger Paleozoic plutons do not show evidence of pervasive regional deformation (Maher et al. 1994).

Metavolcanic rocks of greenschist facies commonly are represented by chlorite schist and finely layered, quartzofeldspathic biotite fine-grained gneiss. Gneiss from wells drilled during the Pen Branch fault investigation are usually coarse-grained and have both amphibole and quartzofeldspathic layers or segregations. The metamorphism in these rocks records regional penetrative strain from the Paleozoic and more localized deformation in the Mesozoic and Cenozoic (Maher et al. 1994).

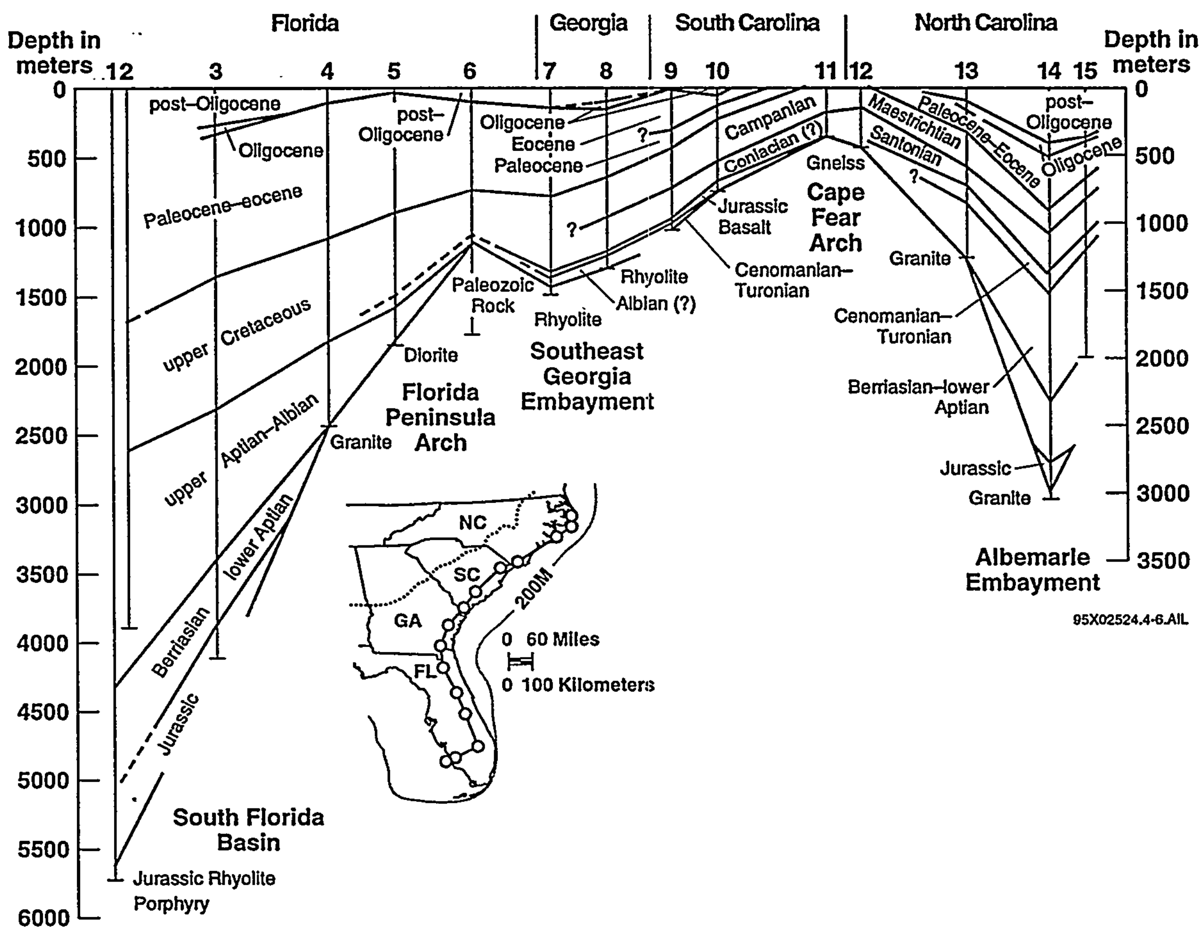

Figure 4-5. Generalized Stratigraphic Cross-Section Along the Modern Coastline from Florida to North Carolina (Source: Gohn 1988).

Dunbarton Basin

Investigations 1967–1974

The Dunbarton basin has been investigated since Siple (1967) identified the basin from aeromagnetic and well data (Figure 4-6). Marine (1974a and b) and Marine and Siple (1974) described subsequent seismic reflection surveys and additional well data. The structure was interpreted as an asymmetric graben approximately 50 km (31 mi) long and 10–15 km (6.2-9.3 mi) wide, bounded by normal faults to the northwest and southeast (Figures 4-6 and 4-7). The axis of the basin strikes N 63° E, parallel to the regional strike of crystalline basement (Marine and Siple 1974). The consolidated sediments that fill the basin are generally a distinctive brownish-red to maroon. There are no surface exposures of the rocks of the Dunbarton basin, but other Triassic basins are exposed elsewhere in the Piedmont (Figure 4-4). These other basins display characteristics similar to the inferred characteristics of the Dunbarton basin, including basin-bounding faults, similar sediments, and minor mafic intrusions (Marine and Siple 1974).

Nine wells drilled in the southeastern half of SRS penetrated sedimentary rocks of the Dunbarton basin. Recovered core is primarily clastic sedimentary rock (Marine and Siple 1974). Conglomerate, fanglomerate, sandstone, siltstone, and mudstone are the dominant lithologies. These rocks are similar to the conglomerate and fanglomerate facies in other Newark Supergroup basins (Steele and Colquhoun 1985). The lithology and stratigraphy identified in these cores indicate that the northwest side of the basin is the proximal side with a larger component of coarse-grained rock types present than on the southeast side of the basin. Marine and Siple (1974) also suggested the basin is asymmetric, with greater paleorelief along the northern boundary.

The thickness of the basin fill is not well known. The DRB-9 core entered crystalline rock beneath Triassic sedimentary rock at -711 m (-2333 ft) mean sea level. Lewis (1974) postulated 1.52 km (0.94 mi) of displacement on the northwest border fault and recent seismic reflection data indicate the northwest side of the basin to be about 2.5 km (1.5 mi) deep (Stephenson and Stieve 1992).

Investigations 1985–1991

Additional investigations, including standard seismic reflection, potential field surveys, in situ stress measurements, and high-resolution shallow seismic reflection surveys, were conducted at SRS from 1985 to 1991. These studies were conducted to determine the cause of two small earthquakes that occurred at the site in 1985 (local magnitude: 2.6; Stephenson and Acree 1992) and in 1988 (local magnitude 2.0; Stephenson 1988) and to better understand the deformational history of Coastal Plain sediments.

The northern boundary of the Dunbarton basin is where the Pen Branch fault cuts Coastal Plain strata. The rift-related strata beneath the Coastal Plain, proximal to the Pen Branch fault, dip southeast. On the southeastern side of the basin, vibroseis data (Chapman and Di Stefano 1989) suggest that strata in the basin dip northwest. Bright reflectors are interpreted as mafic sills that intruded parallel to bedding of older strata in the rift basin (Domoracki et al. 1992). These bright reflectors may indicate the southern border of the Dunbarton basin.

The geometry and structure of the basin's southern margin have not been well documented. Faye and Prowell (1982) proposed the existence of the Millet fault (Figure 4-8), based on

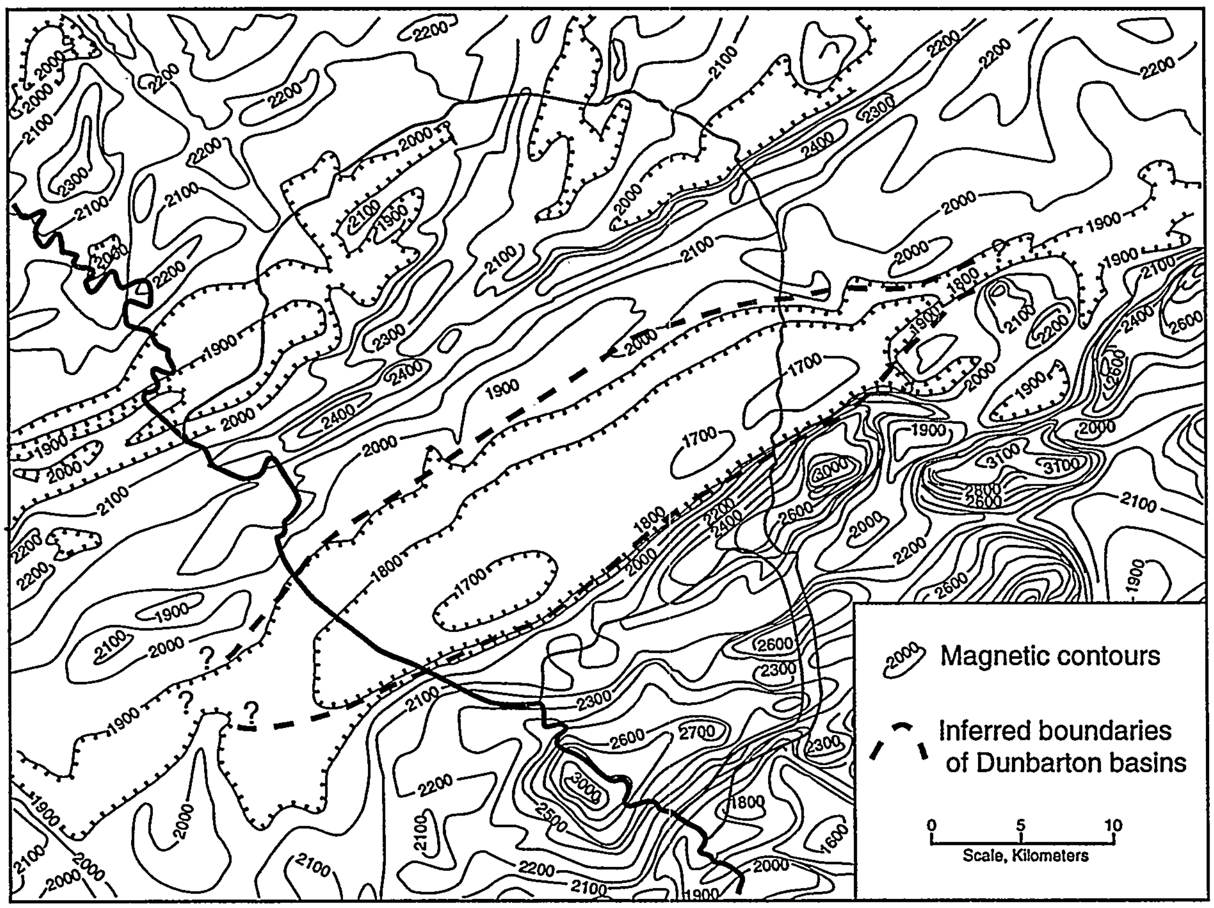

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Figure 4-6. Aeromagnetic Map Showing the Outline of the Dunabarton Basin Underlying the Savannah River Site (Source: Marine and Siple 1974).

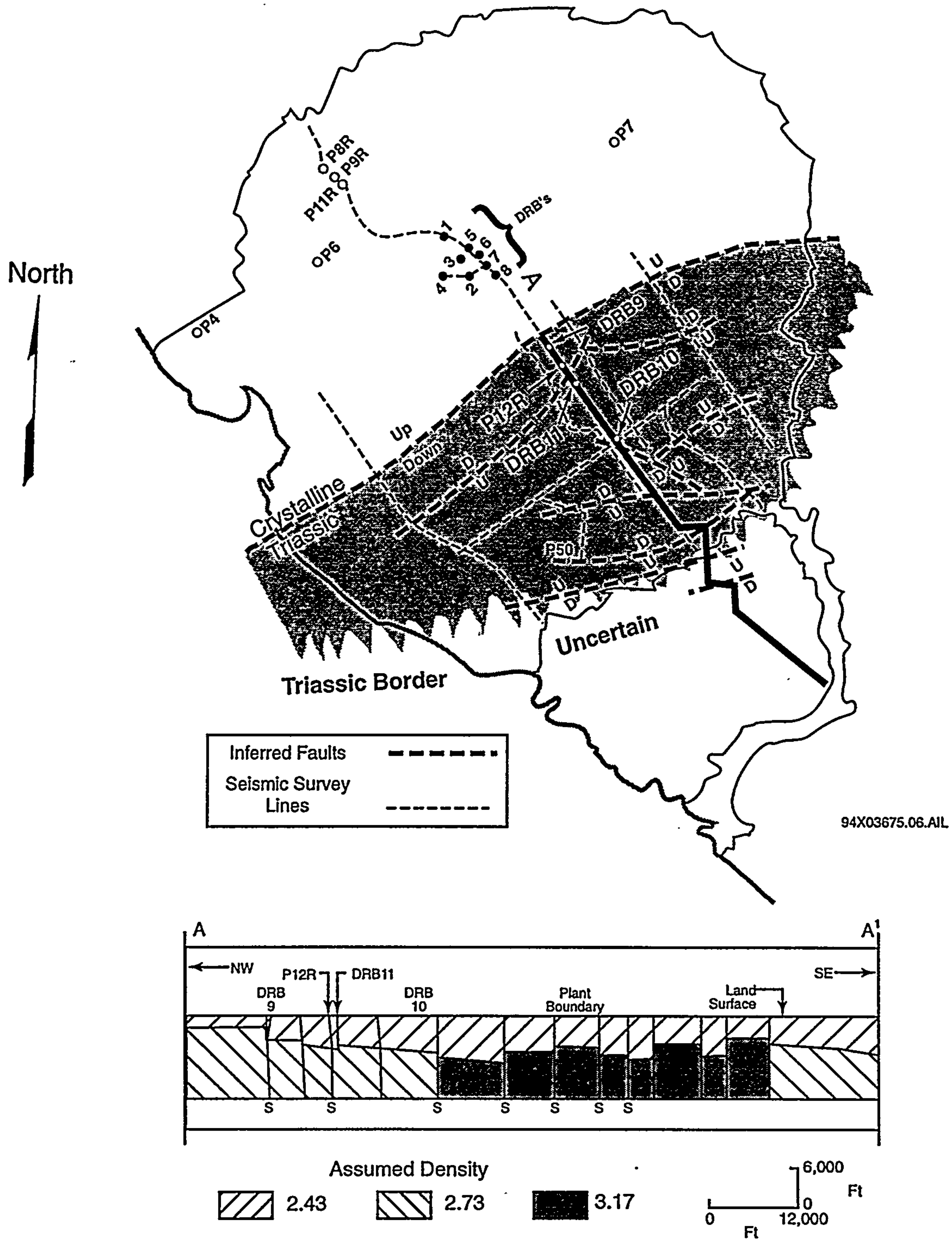

Figure 4-7. Structure Within Dunbarton Basin Based on Seismic Reflection and Gravity Survey at the Savannah River Site (modified after Marine 1974b).

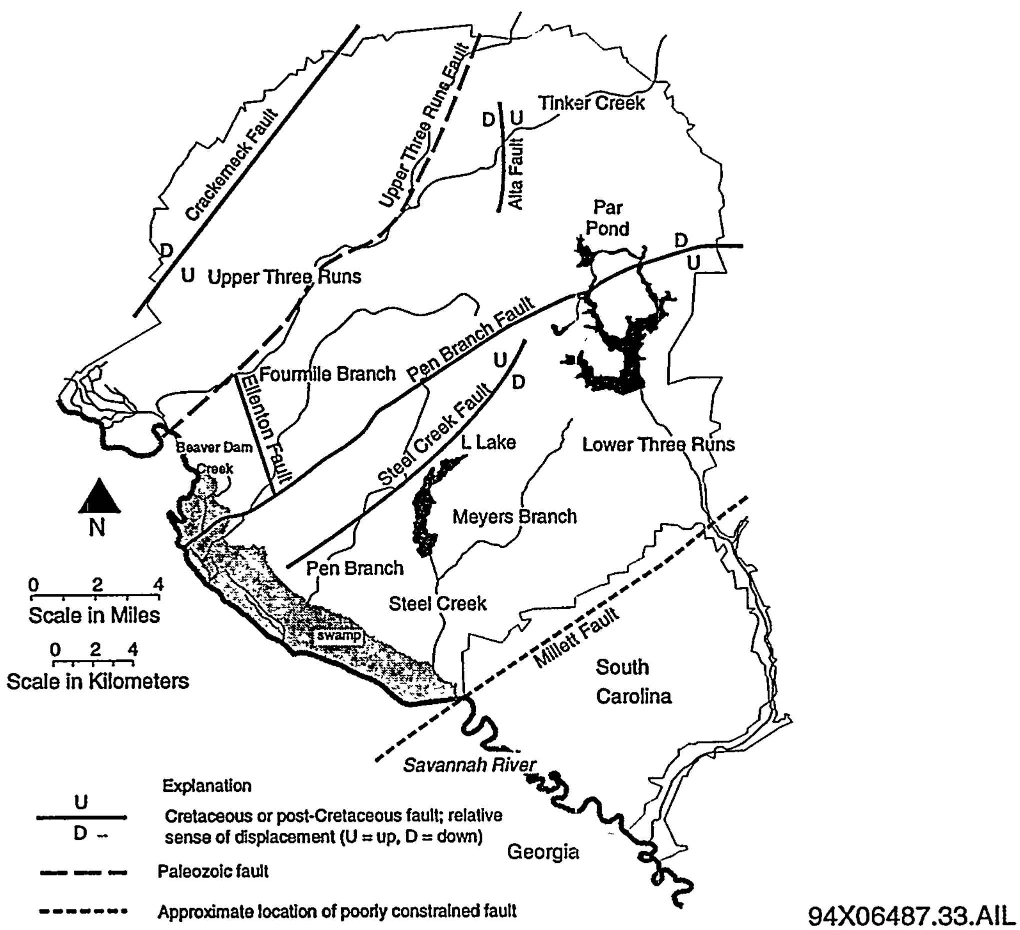

Figure 4-8. Map Showing Locations of Faults Identified in the Savannah River Site Subsurface (Source: Stephenson and Stieve 1992).

hydrogeologic information and data from bore holes just beyond the southern boundary of the site. While the existence of this fault is dubious, potential field data (Figure 4-6) suggest that the southern margin of the basin is in the approximate location of the proposed fault. Aeromagnetic and gravity data provide evidence that the basement rock is influenced by mafic intrusions south of the basin. In effect, these mafic intrusions define the southern margin of the Dunbarton Basin (Stephenson and Stieve 1992).

The magnetic data contain numerous high-frequency, closed-contour features indicative of shallow structures and lower frequency features indicative of deeper-seated features. The host rock is perhaps crystalline metamorphosed rock similar to what is found further to the northwest beneath SRS. In addition, Madabhushi et al. (1992) suggest this is a terrane separating the Appalachian from crust of different affinity farther to the southeast.

Post-Triassic Features

Cenozoic structural features include gentle folding, uplift of the crust following or during deposition of the Coastal Plain sediments, and faulting in these sediments.

Geophysical data have been used extensively on the site to identify subsurface faults. Stephenson and Stieve (1992) compiled the available geophysical data and corroborated or identifed several faults. They reported that the faults can be grouped according to which of two major trends they follow. The first trend is to the northeast, with strikes ranging from approximately N 60° E to N 80° E. The second trend is to the northwest, with strikes ranging from approximately N 10° W to N 30° W. The northeast-trending faults generally are traceable over greater distances.

Northeast-Trending Faults

Pen Branch Fault

The Pen Branch fault (Figure 4-8) initially was identified in the subsurface at SRS in 1989 based upon interpretation of earlier seismic reflection surveys and other geologic investigations (Marine and Siple 1974; Chapman and Di Stefano 1989; Snipes et al. 1989; Stieve et al. 1991). This fault may be coplanar with the northern boundary fault of the Triassic Dunbarton basin. The Pen Branch fault strikes northeast across the middle of SRS, parallel to the boundary of the Dunbarton basin. Relative movement on the fault during the Cretaceous and Tertiary was down to the northwest, raising Triassic rock higher than the crystalline basement (Stephenson and Chapman 1988; Snipes et al. 1989; Stieve et al. 1991). There also could be a component of strike-slip movement on the fault based on earthquake focal plane solutions (Stephenson et al. 1985).

The fault dips southeast at approximately 50° in Coastal Plain section and shallows to approximately 40° in basement (Sen and Coruh 1992). The surface of the basement rock at about 300 m (1000 ft) below land surface is clearly offset, and shallower layers appear folded over the fault. The confirmatory drilling program is an ongoing effort to resolve the shallowest extent of this fault and confirm the seismic reflection interpretation.

Steel Creek Fault

Steel Creek fault is southeast of the Pen Branch fault within the area of the Dunbarton basin (Figure 4-8). This fault trends roughly parallel to the Pen Branch fault; the sense of motion on the fault is down to the southeast. Seismic data suggest a horst block formed between the Steel Creek and Pen Branch faults (Sen and Coruh 1992). Above the Triassic strata, the fault offsets Cretaceous horizons, but the shallowest extent of the fault is not well known.

Crackerneck Fault

The Crackerneck fault is in the northwestern part of SRS (Figure 4-8). The fault strikes north-northeast, and its sense of motion is down to the northwest. The fault was recognized on two seismic lines, but the lateral extent was not determined from the seismic reflection data. The data indicate the basement reflector is clearly offset, and there may be some deformation in the shallow section. However, there are essentially no marker reflector horizons in this area to indicate the shallowest extent of the fault.

Upper Three Runs Fault

Upper Three Runs fault (Cumbest and Price 1989) is in the northwest quadrant of the site and underlies the current Upper Three Runs drainage (Figure 4-8). The fault cuts the crystalline basement rock, but offset of the Mesozoic erosion surface has not been seen in the seismic data. It dips shallowly to the southeast, and may merge with the Augusta fault beneath the Dunbarton basin. Because of the geometric relationship, a coeval relationship is implied (Stieve and Stephenson, 1995).

Northwest-Trending Faults

Atta Fault

The Atta fault is in the northeast quadrant of SRS and has a northerly strike (Figure 4-8). The dip of the fault appears to be near vertical. Marker horizons indicate relative movement down to the west. Seismic data suggest offset reflectors in the deeper section of the Coastal Plain and draping reflectors in the shallower section. The upward penetration of the Atta fault is uncertain in the data because reflectors are ambiguous in the shallowest part of the section (Stephenson and Stieve 1992). The Atta fault has not been seen in seismic lines in the area of its projected southerly extension. No subsurface data are available from the northerly projection of the Atta fault.

Ellenton Fault

The Ellenton fault, in the west-central area of SRS, strikes north-northwest and is thought to be near vertical (Figure 4-8). The sense of motion of the fault is down to the east. The relationship of the Ellenton fault with the Pen Branch fault is not well known, but the orientation of both faults is compatible with a single fault system (Stephenson and Stieve 1992).

Seismology

Regional Seismicity

Earthquake activity in the eastern United States (Figure 4-9) is widespread, but concentrated in two broad, subparallel bands trending approximately northeast to southwest (Bollinger 1992). The more distant band, the New Madrid seismic zone, is 750 km (460 mi) northwest of the site and includes the epicenters of the 1811-1812 New Madrid earthquakes that shifted the course of the Mississippi River and were felt throughout the central and eastern United States. The closer band of epicenters parallel the Appalachians through the Valley and Ridge and Blue Ridge provinces about 300 km (180 mi) distant from the Savannah River Site (Figure 4-9). Seismic activity in this zone is concentrated in eastern Tennessee.

A historical seismicity map of the southeastern United States (Figure 4-10) shows the seismic activity trend in the Valley and Ridge and Blue Ridge provinces. Figure 4-10 also shows a cluster of magnitude 3 and greater earthquakes in central Virginia and more widely distributed earthquake epicenters in the Piedmont and Coastal Plain in Georgia and the Carolinas. The area of eastern North Carolina and the area from southern Georgia into Florida are marked by low levels of seismic activity.

The orientation of the stress regime throughout the southeastern United States appears to be fairly uniform with and on an approximately northeast to east-northeast horizontal compressive axis (Zoback and Zoback 1981). Zoback et al. (1986) concluded that this orientation of the regional stress regime is consistent with plate-tectonic ridge-push forces for the North American Plate. This implies that the probable cause of much of the observed seismicity in the region is due to the action of tectonic stress on local zones of weakness. Bollinger et al. (1987) described the available focal mechanism data for the region. Most of the data indicate thrust or strike-slip faulting.

Bollinger et al. (1987) pointed out that the major difference between seismic activity along the Appalachian trend and the activity in the Piedmont and Coastal Plain is the focal depth of the earthquakes. In the Appalachians west of the Piedmont, the maximum concentration of foci occurs at depths of 9.5-11 km (6-7 mi). In contrast, the corresponding focal depths for Piedmont and Coastal Plain earthquakes are much shallower, ranging from 6.5-8 km (4-5 mi). Bollinger et al. (1987) suggest that these differences indicate contrasts in the thickness of the seismogenic crust.

Savannah River Site Subregional Seismicity

Several clusters of seismic activity have been identified within a 350-km (200-mi) radius of the Savannah River Site (Bollinger 1992). These areas include the Charleston, South Carolina seismic zone on the coastline of South Carolina (Figure 4-11), and the Bowman, South Carolina seismic zone east of the Savannah River Site (Figure 4-11).

Charleston, South Carolina Seismic Zone

The Charleston, South Carolina, seismic zone covers the approximate area of the most intense effects of the August 31, 1886, Charleston earthquake (Figures 4-12 and 4-13). The

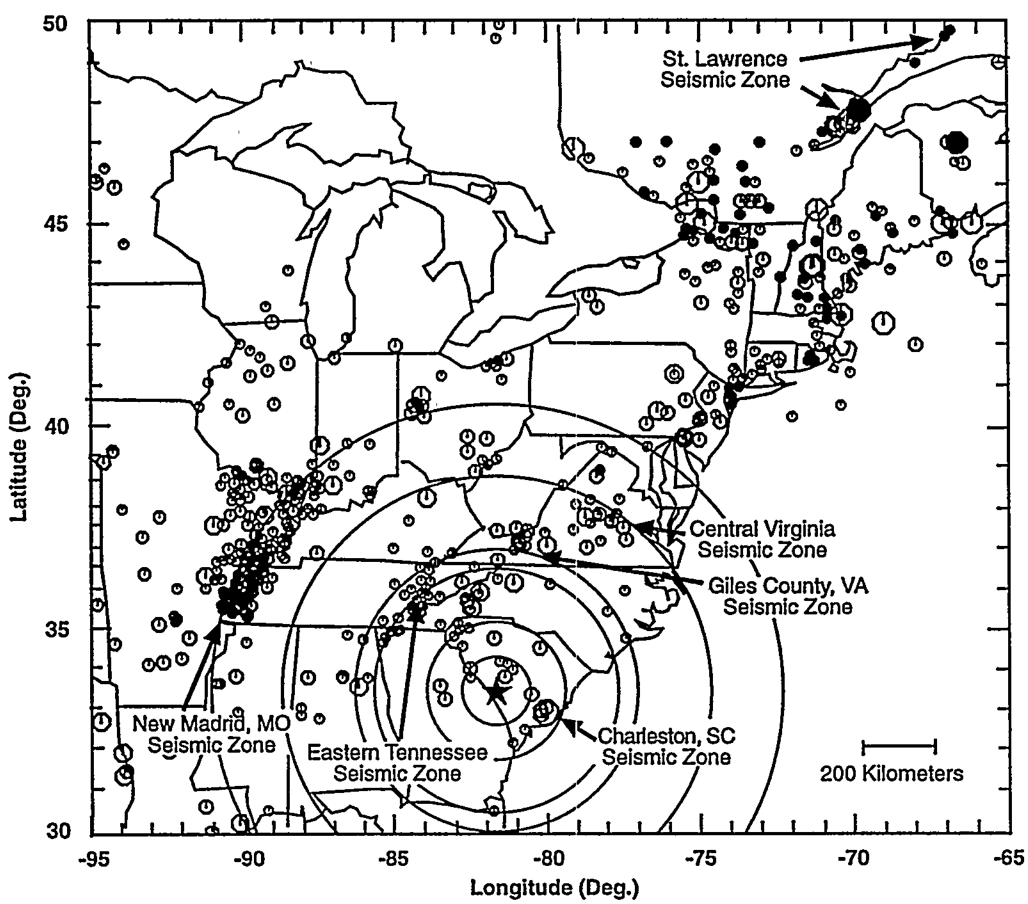

Figure 4-9. Seismicity Map for Central and Eastern North America, 1568-1987. Epicenters, scaled to magnitude, shown by octagon symbols (from Bollinger 1992).

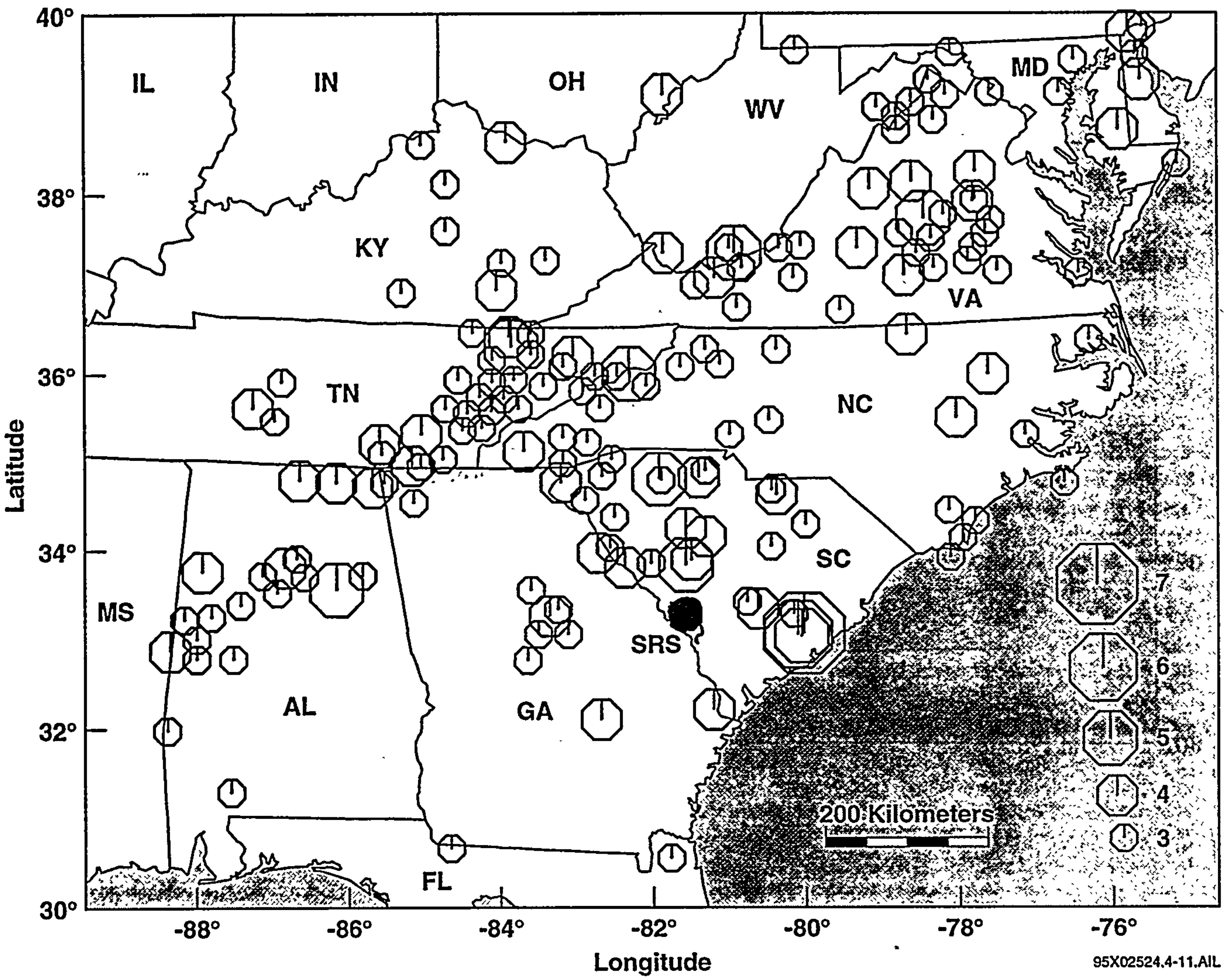

Figure 4-10. Historical Seismicity in the Southeastern United States, Magnitude 3 or Greater, 1698-1977 (after Stephenson and Acree 1992).

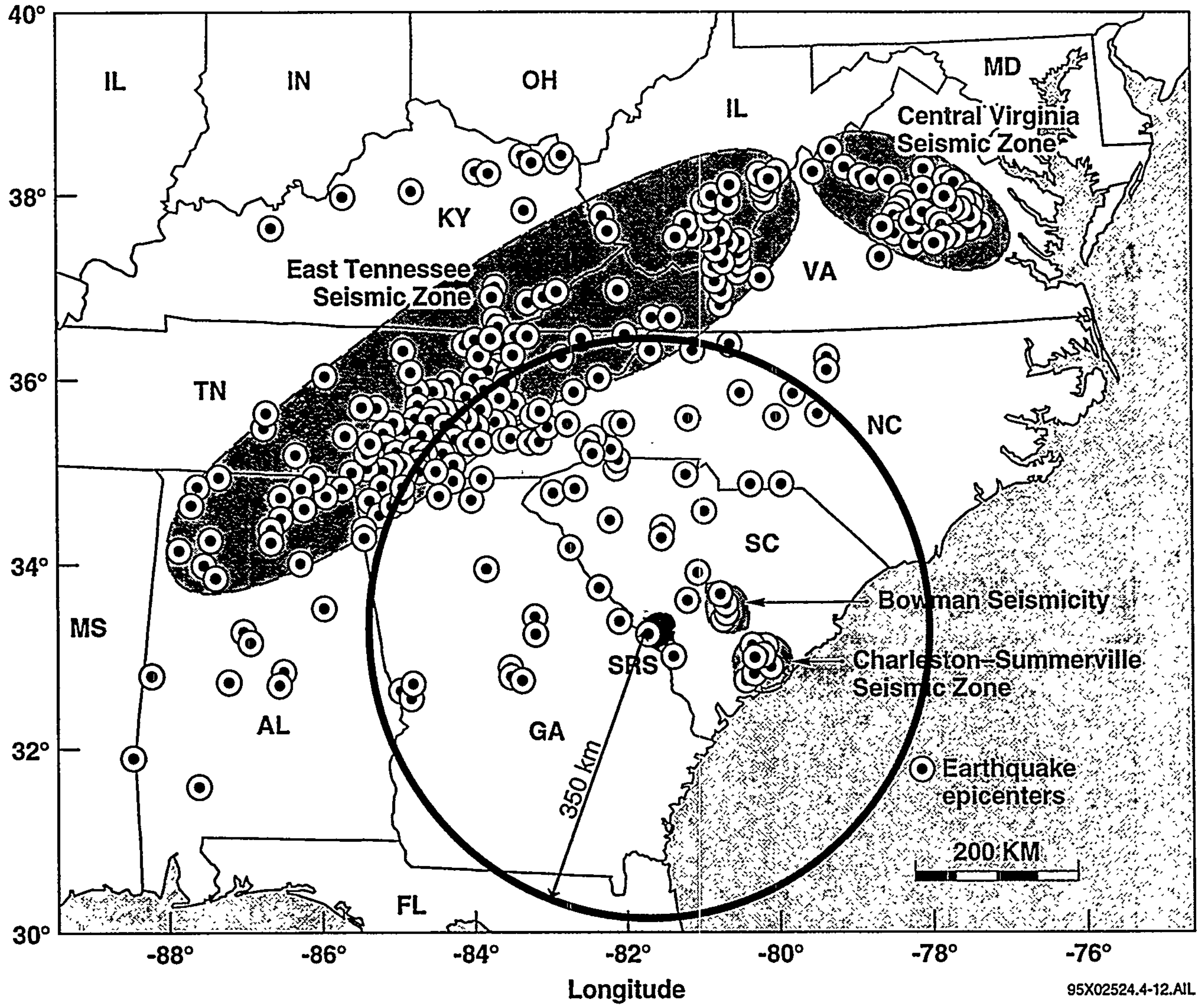

Figure 4-11. Instrumental Seismicity in the Southeastern United States, Including the Savannah River Site Local Region, July 1977 to June 1987 (Source: Bollinger et al. 1987).

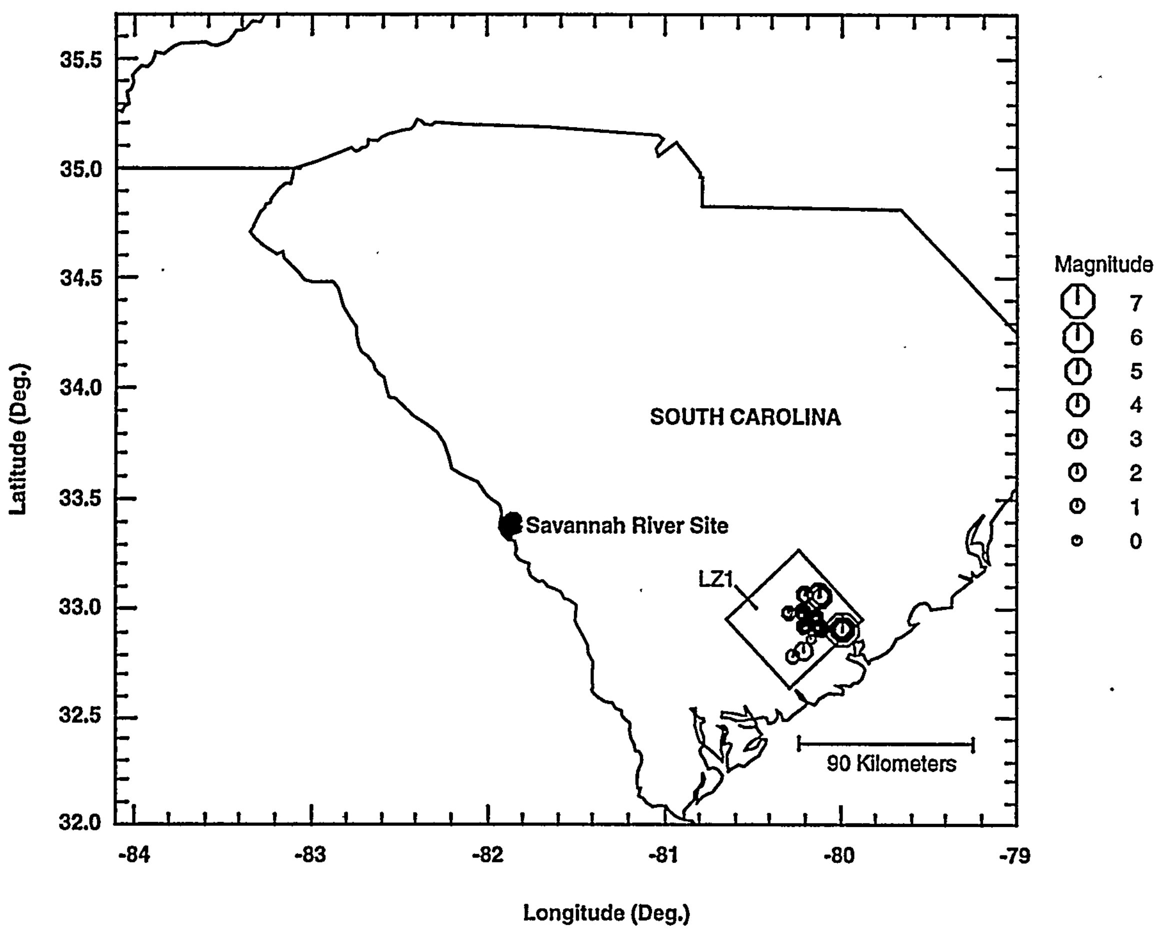

Figure 4-12. Seismicity Map for the Charleston, South Carolina Seismic Zone for 1974-1991. Epicenters, scaled to magnitude, are shown by octagon symbols. Number of epicenters plotted = 98 (Source: Bollinger 1992).

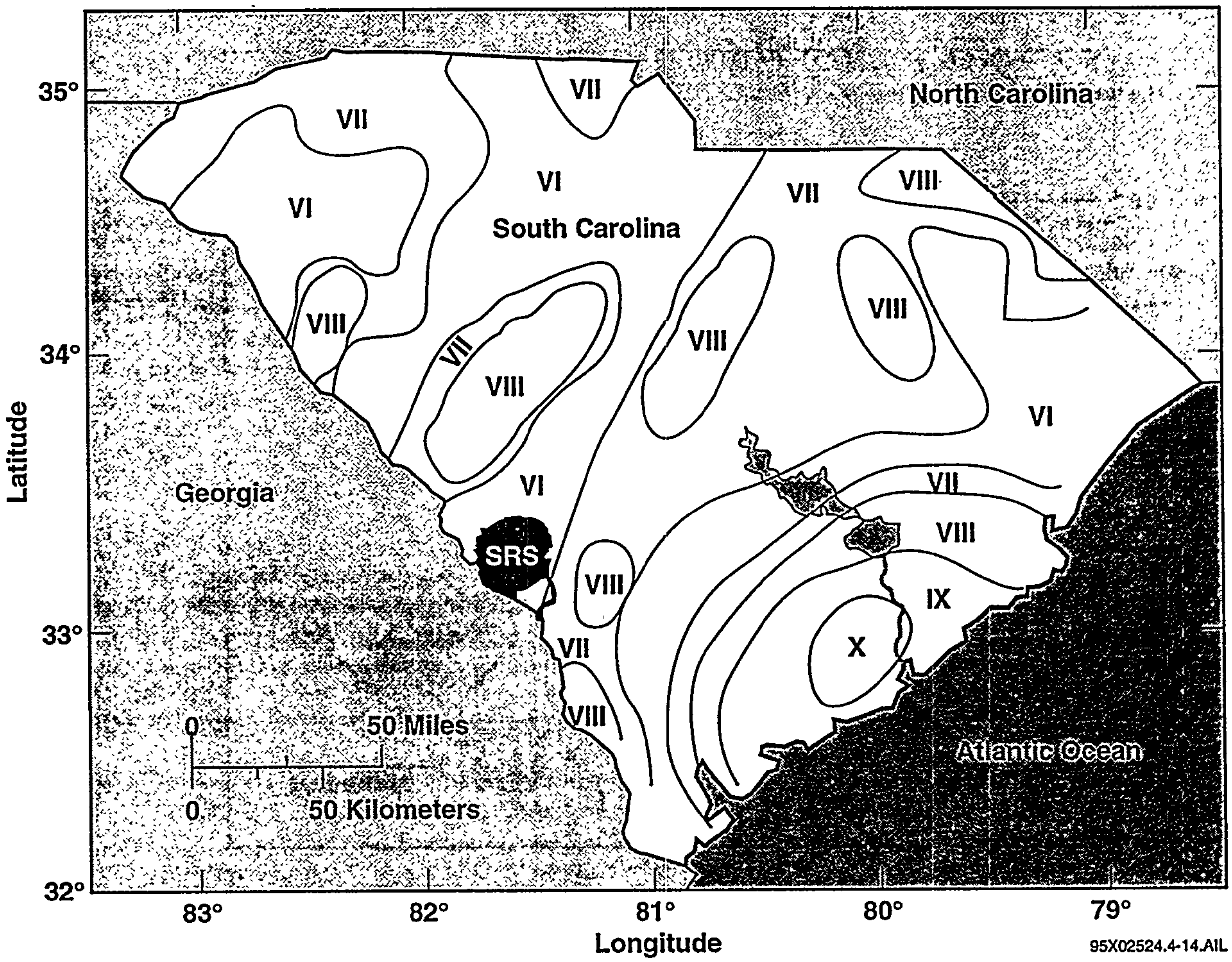

Figure 4-13. Isoseismal Map Showing Effects of Charleston Earthquake on South Carolina. Contours correspond to modified Mercalli intensities (from Bollinger 1977).

1886 Charleston earthquake is the largest earthquake in the historical record to occur in the Southeast. The Charleston, South Carolina seismic zone is the only zone near SRS capable of such intense shocks (Bollinger 1992).

The extent of damage from the 1886 earthquake in Charleston was such that the intensity was classified as X on the modified Mercalli Scale of 1931 (correlated by Bollinger (1983) to a surface wave magnitude of 7.0 ± 0.5). Twenty-seven deaths were attributed to the earthquake, in addition to considerable structural damage. Effects in the area that is now SRS were significant (Visvanathan 1980).

Newspaper reports indicate that in Ellenton the earthquake "shook houses at a terrible rate;" in Aiken, "church bells rang... window weights rattled... plaster cracked;" in Bath, "houses swayed, walls cracked, chimneys broke, clocks stopped;" in Langley, "a dam broke, destroying 1000 feet of railroad track;" and in Beech Island, there was "alarm among men and animals" (Visvanathan 1980). Bollinger (1977) assigned Modified Mercalli Intensities of V-VIII to the areas around the present location of SRS. Figure 4-13 shows an isoseismal map of the effects of the Charleston earthquake throughout South Carolina. The map shows that intensity was not a simple function of distance from the earthquake.

The search for geologic structures to account for the Charleston earthquake has been extensive, but no structures can be definitively linked to the earthquake at present (Bollinger 1992). The intensity X isoseismal from the August 31, 1886, event forms an ellipse that trends to the northeast, parallel to the coastline (Figure 4-13). Bollinger (1983) concluded that the strike of the causal fault should be northeast, parallel to the trend of the intensity X isoseismal. Several reverse faults with strikes to the northeast occur in the Charleston area (Wentworth and Mergner-Keefer 1983; Hamilton et al. 1983). In addition, Behrendt et al. (1983) found evidence for subhorizontal faulting. From studies of earthquakes recorded by seismic instruments, Talwani (1982) proposed alternatively that two intersecting buried faults occur near the Charleston, South Carolina seismic zone, with the primary movement related to a northwest trending fault system.

Several mechanisms have been proposed to explain the cause of the Charleston earthquake based on the effects of the 1886 event, recent seismic activity, and various studies of subsurface structure. Behrendt et al. (1983) suggested that older reverse faults, reactivated in the Cenozoic and related to a detachment zone, or décollement, may explain the seismicity. Seeber and Armbruster (1981, 1987) argued that back-slip along a detachment fault could have caused the Charleston earthquake. Talwani (1982) said the shock was the result of movement along the two intersecting faults inferred from recent seismic records. Bollinger (1983) also proposed that movement along two intersecting structures could be responsible for the seismicity in the Charleston, South Carolina hypothesis seismic zone. Bollinger (1992) however, supports Phillips' (1988) hypothesis that the two intersecting structures are a meteorite impact structure and a Triassic basin border fault. Though several hypotheses have been proposed, none is backed with sufficient evidence to achieve the general acceptance of the seismological community (Bollinger 1992).

Bowman, South Carolina Seismic Zone

A cluster of low-level seismic epicenters (magnitude [M]<4) exists near Bowman, South Carolina (Figures 4-11 and 4-14). This cluster became active in the 1970s, ceased activity in the early 1980s, then became active again at a low level in the late 1980s. This seismic

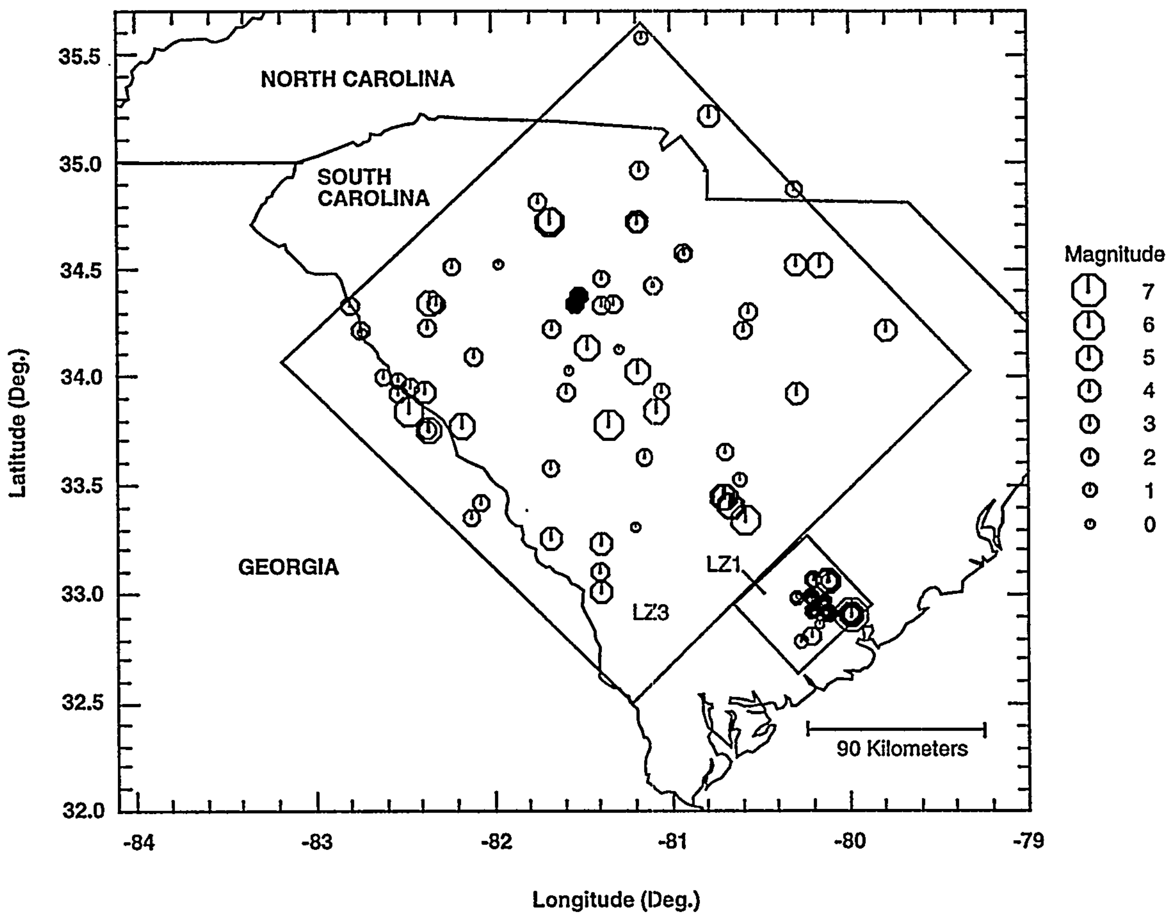

Figure 4-14. Instrumental Seismicity Map for the South Carolina Piedmont and Coastal Plain Seismic Zone Including the SRS Local Zone. Epicenters, scaled to magnitude, are shown by octagon symbols. Number of epicenters plotted = 99 (Source: Bollinger 1992).

zone can be interpreted to be on a northwest trend from the Charleston-Summerville zone (Bollinger 1973). Talwani and Colquhoun (1986) and Talwani et al. (1987) have emphasized this aspect in attempts to link the two seismic zones. The spatial clustering habit is the same as that observed in the Charleston area. There is no evidence to date that major earthquakes or long-term seismic activity is associated with the Bowman seismic zone (Bollinger 1992). The total strain energy release to date has been small.

Local Seismic Activity

Known seismic activity within 50 km (30 mi) of the SRS is primarily in the areas to its east and southeast (Figure 4-14). This seismic activity consists of several earthquakes felt in 1897 (their magnitudes and intensities are unknown) and eight or so earthquakes recorded since the 1970s. The 1970s mark the beginning of intensive seismic study of the region, primarily for safety analysis of nuclear facilities. The majority of the earthquakes recorded since operations began at SRS has been low magnitude ($M<3$) isolated events, with no dependent foreshocks or aftershocks detected (Bollinger 1992).

Two of the smaller earthquakes had epicenters on the site: a magnitude 2.6 in June 1985 (Stephenson et al. 1985) and a 2.0 magnitude event in 1988. Talwani et al. (1985) determined a focal mechanism for the 1985 event, but it was not well constrained. The mechanism yielded a north-northeast P-axis orientation; whereas a northeast-east northeast orientation is expected from the regional stress regime. One nodal plane (strike N 23°E and dip 46° SE) is subparallel to the Dunbarton basin margin and was the preferred fault plane interpretation of Talwani et al. (1985). They also interpreted a northwest-trending feature from potential-field data and ascribed the 1985 shock to its intersection with the Dunbarton basin border fault.

Three earthquakes with magnitudes greater than M3 have been felt in the region since the 1970s: August 14, 1972; October 10, 1974; and most recently, August 8, 1993.

The August 8, 1993, earthquake ($M=3.2$) had an epicenter about 40 km (25 mi) northeast of the center of the site and about 12 km (7.4 mi) northeast of Aiken, South Carolina. The event was most strongly felt near Couchton, South Carolina. The focal mechanism determined from seismic records of the SRS Seismic Network and the South Carolina Seismic Network, shows left-lateral strike slip on a steeply dipping, northwest striking, fault plane (Talwani and Stevenson 1993). It was not associated with any identified seismic source zones, but rather seemed to be characteristic of widely spread events throughout the central Piedmont and Upper Coastal Plain of the state.

Most of the seismicity in the Piedmont area north of the site has been associated with reservoirs (Stephenson 1992). Reservoir-induced seismicity has been monitored at Lakes Jocassee, Keowee, and Clarks Hill Reservoir in northwestern South Carolina and Monticello Reservoir in central South Carolina.

Summary

The geology of the Savannah River Site (SRS) and surrounding area has been shaped by a variety of forces. The Taconic, Acadian, and Alleghenian orogenies produced metamorphism and faulting in the southern Appalachians down through the Piedmont. Early Mesozoic rifting opened rift basins such as the Dunbarton Basin located beneath SRS. Post-rift tectonism (subsidence and uplift) and intra-plate stress fields have resulted in other structures that are recognized at the surface and within the subsurface of the SRS area.

The Dunbarton Basin, a major structure beneath the SRS, is an asymmetric graben approximately 50 km (31 mi) long and 10-15 km (6.2-9.4 mi) wide. It is bounded to the northwest and southeast by normal faults. The sediments filling the basin are similar to those found in other Triassic rift basins and are dominated by conglomerate, fanglomerate, sandstone, siltstone, and mudstone.

Cenozoic faulting is recognizable in the sediments of the Coastal Plain. At the SRS two groups of faults occur; one trends to the northeast and the other trends to the northwest. The northeast trending faults are generally traceable over a greater distance and include the Pen Branch, Steel Creek, Crackerneck, and Upper Three Runs faults. The northwest trending faults include the Atta and the Ellenton.

Seismic activity in the vicinity of the SRS has been studied extensively because of the safety issues associated with nuclear facilities. Historical seismicity maps show three areas responsible for most earthquake activity. The largest area with the highest density of earthquakes is along the Appalachian Mountains. Two smaller areas that are important to the SRS are the Charleston seismic zone and the Bowman seismic zone. Seismic activity in the Charleston zone includes the Charleston earthquake of 1886 that caused extensive structural damage and 27 deaths. Seismic activity within 50 km (31 mi) of the SRS has been rare (eight earthquakes recorded since the 1970s) and of low intensity. An extensive seismic monitoring system records earthquake activity on the SRS.

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Chapter 5—Hydrogeology

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Introduction

During the past two decades, and particularly since the end of the Cold War, much of the geologic work being conducted on the Savannah River Site has been focused on groundwater issues. Past operations on the site have impacted shallow groundwater, and some areas contain contaminants at levels that require remediation and cleanup. On a larger scale, the groundwater on the site is part of the regional ground-water resource that provides water for drinking, irrigation, and industrial uses. Groundwater on the site discharges directly to the Savannah River, its tributaries, and to the Salkehatchie River, having a direct impact on the aquatic environments of the region.

There have been numerous studies in recent years to assess the ground-water resources in order to ensure their proper protection, development, and management. In addition to the U.S. Department of Energy, various federal and state agencies, including the South Carolina Water Resources Commission, the Georgia Department of Natural Resources, and the U.S. Geological Survey (USGS), have participated in these studies. Because of the impact the site has had on the regional ground-water resources, more is known about the hydrogeology of the site than of the surrounding areas. This is reflected in this chapter by the emphasis on the hydrogeology of the site and its immediate environs. Studies are underway to integrate the hydrogeology of the site into regional ground-water models of the Central Savannah River Area (Clarke 1995).

Hydrostratigraphic Nomenclature

Because of the complexity of the region, the fact that aquifers do not naturally conform to political boundaries, and that the site adjoins the South Carolina-Georgia stateline, nomenclature has presented a problem for investigators for the various state and federal agencies. The hydrostratigraphic nomenclature presented in this chapter is based on the recommended guidelines for the classification of hydrostratigraphic units developed by the South Carolina Hydrostratigraphic Nomenclature Subcommittee, and follows, in large part, the work of Aadland et al. (1995). The subcommittee consists of members from industry, federal, and state agencies who are involved with ground-water investigations throughout South Carolina and Georgia.

The draft classification scheme (Table 5-1) developed by the subcommittee follows guidelines published by Laney and Davidson (1986) for naming hydrogeologic units in USGS reports. The hydrostratigraphic classification uses a hierarchy of aquifer and confining units ranked at four levels. The terms that have been adopted as formal hydrostratigraphic names at SRS are all based on geographic locations or names, such as the "Steed Pond aquifer."

Hydrogeologic province is level 1, the highest level of the classification. This is equivalent to the term "system" used by Miller and Renken (1988) to designate major regional rock or

Table 5-1. Proposed South Carolina Hydrostratigraphic Unit Nomenclature (Lewis and Aadland 1994) (Levels 2 to 4 correspond to the terminology of Laney and Davidson [1986])

Level	Hydrostratigraphic Units
1	Hydrogeologic Province
2	Aquifer System/Confining System
3	Aquifer Unit/Confining Unit
4	Aquifer/Confining Zone (informal)

sediment assemblages that behave as a single, unified hydrologic unit. Level 2 is the aquifer system or confining system. Clarke et al. (1985) defines an aquifer system as a body of material of varying hydraulic conductivity that acts as a water-yielding hydrologic unit of regional extent. Although the aquifer systems are of regional extent, they may contain discontinuous confining layers that separate them locally into two or more aquifers (Laney and Davidson 1986). By analogy, confining systems are also of regional extent and separate aquifer systems.

Aquifer units and confining units, level 3, are the fundamental units of hydrostratigraphic classification. The terms "aquifer" and "confining unit" or "aquitard" are defined in terms of their relative capacity to transmit water. As used by the South Carolina Hydrostratigraphic Nomenclature Subcommittee and defined by Bates and Jackson (1987), an aquifer is a mappable body of rock or sediment that is sufficiently permeable to conduct groundwater and to yield significant quantities of water to wells and springs. A confining unit, in contrast, is a geologic unit or system of units that is resistant to groundwater flow because of its lower permeability. In coastal plain sediments, units that consist predominantly of sand and gravel are capable of transmitting large quantities of water, and therefore are generally considered to be aquifers. Units that consist predominantly of silt and clay are generally confining units, i.e., aquitards. Horizontal flow in the confining units usually is not addressed because few hydraulic head measurements are available from these units. To a good approximation, flow in confining units is predominantly limited to vertical flow between aquifer units in response to differences in the hydraulic head across the aquitard.

Aquifers and confining units may be informally subdivided locally into zones, level 4, characterized by properties that are significantly different from the associated unit, such as hydraulic conductivity, water chemistry, or lithology. In addition, informal names based on lithology occasionally are used in discussions and site reports. For example, the "green clay zone" serves as a useful, informal marker for both lithostratigraphers and hydrostratigraphers.

Regional Setting

Two hydrogeologic provinces are recognized in the Central Savannah River Area (Figure 5-1). The first is the Piedmont Hydrogeologic Province. As defined by Aadland and Bledsoe (1990a,b), this province includes two distinct lithologic and hydrologic regions (Siple 1967, Marine 1975, Marine 1979a, b): the crystalline rock of the Piedmont and the lithified sedimentary rocks, including mudstone, sandstone, and conglomerate, contained within the Dunbarton Basin. The crystalline rock is exposed northwest of the site and extends below the site under the cover of the Atlantic Coastal Plain sediments (Figure 5-2). The lithified sediments of the Dunbarton basin are found only in the southern half of site and are buried beneath coastal plain sediments. The second province, the Southeastern Coastal Plain Hydrogeologic Province, derives its name and description from the USGS's Regional Aquifer-System Analysis (or RASA) program (Johnson 1991).

The Southeastern Coastal Plain Hydrogeologic Province covers a region of approximately 307,000 km^2 (120,000 mi^2) of the Coastal Plain of South Carolina, Georgia, Alabama, Mississippi and Florida, and a small contiguous area of southeastern North Carolina (Figure 5-1). It extends from the Mississippi embayment in central Mississippi to the southwestern flank of the Cape Fear arch in North Carolina.

The Southeastern Coastal Plain Hydrogeologic Province grades laterally to the northeast into the Northern Atlantic Coastal Plain aquifer system (Meisler 1980), and to the west into the Mississippi embayment and Coastal Lowlands aquifer systems (Grubb 1986). The northwestern limit of the province is the updip limit of Coastal Plain sediments at their contact with crystalline rocks at the Fall Line. The topography of the region ranges from extensive, flat, coastal swamps and marshes 1-2 m (3-6 ft) above sea level to rolling uplands, 100-250 m (330-820 ft) above sea level, along the inner margin of the region (Aller et al. 1987).

Piedmont Hydrogeologic Province

Overview

The Piedmont Hydrogeologic Province consists of the crystalline, Pre-Cretaceous rocks of the Piedmont basement complex and the consolidated sediments filling the Dunbarton Basin. Neither of the rock types provide sufficient water to wells to be used for industrial or municipal water supplies. To the south of the Fall Line, where the sediments of the Coastal Plain are thin, wells drilled into the crystalline rock provide water for domestic use. Groundwater flow in this province was studied at SRS in the mid-1960s and early 1970s to assess the safety and feasibility of storing radioactive waste in these rocks (Marine 1967a and b, 1966, 1974; Webster et al. 1970).

Crystalline Basement

The crystalline rock of the Piedmont Hydrogeologic Province is predominantly hornblende gneiss and chlorite-hornblende schist typical of rocks associated with the Carolina Slate belt (Marine 1979b) (Chapter 3 - Regional Geology and Stratigraphy). These rocks generally have low porosity and permeability, and groundwater flow is primarily along fractures in the rock.

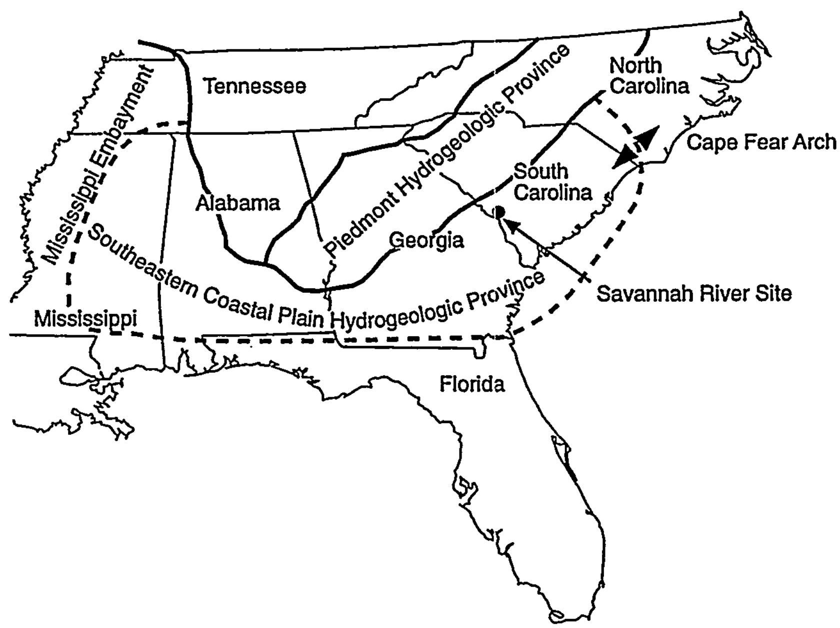

Figure 5-1. Regional Surface Exposures of the Piedmont and Coastal Plain Hydrogeologic Provinces (after Grubb 1986).

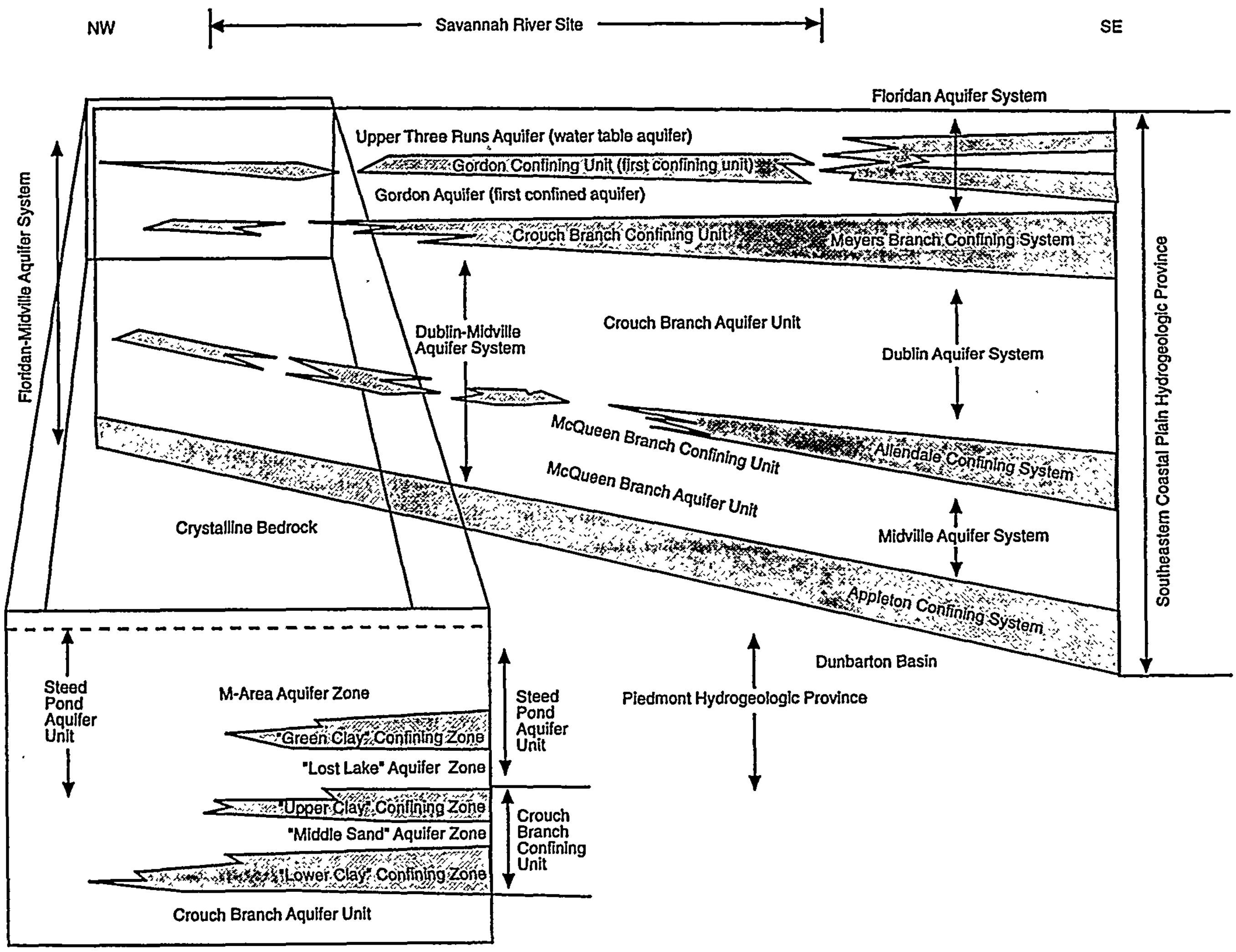

Figure 5-2. Generalized Hydrostratigraphic Cross-section of the SRS Region (after Aadland et al. 1992).

Water injection and withdrawal tests were conducted on the crystalline basement rocks that underlie SRS. Marine (1966 and 1979b) found that two types of fractures exist in the crystalline bedrock: minute fractures that pervade the entire rock mass but transmit water slowly (rocks containing only this type of fracture are virtually impermeable) and fractures with larger openings that transmit water more readily and are vertically restricted but can be traced laterally.

Logan and Euler (1989) took hydraulic head measurements in the deep-rock borings that penetrated the basement rocks and in wells completed in the overlying sediments. A head difference averaging about 4.3 m (14 ft) exists between the crystalline rock of the Piedmont Hydrogeologic Province and the overlying sediments of the Southeastern Coastal Plain Hydrogeologic Province, with the crystalline rock having the greater head. This difference is largely caused by the continuous pumping of process-water supply wells in the area, which reduce the head in the overlying aquifers. The head in the crystalline rock was estimated to have been about 0.6 m (2 ft) higher than the head in the overlying aquifers before site operations began (Logan and Euler 1989).

Marine (1979a) compiled a potentiometric map for groundwater in the crystalline rock of the Piedmont Hydrogeologic Province (Figure 5-3). Heads range from more than 70 m (230 ft) mean sea level (msl) along the Fall Line in northern Aiken County, to 59 m (195 ft) msl near the center of SRS, to 33.5 m (110 ft) msl along the Savannah River, where the river crosses the Fall Line. These potentials define an arcuate path of water first flowing south from the recharge area along the Fall Line, then swinging to the west beneath SRS, and then moving north to the discharge area near the intersection of the Savannah River with the Fall Line. Marine (1979a) estimated the mean groundwater velocity at about 6.3 cm/yr (2.5 in./yr). Because the data are sparse, Logan and Euler (1989) suggested that it is unclear whether this indicates a regional direction of flow or simply an alteration of the flow path because of the local orientation of the fracture zones.

Dunbarton Basin

Aadland and Bledsoe (1990) also consider the red consolidated sediments of the Dunbarton Basin part of the Piedmont Hydrogeologic Province in the SRS area. The hydraulic conductivity of these rocks is extremely low, ranging from approximately 3×10^{-9} to 1×10^{-6} m/day (1×10^{-7} to 4×10^{-5} in/day) (Marine 1974). Dissolved solids in the basin waters are nearly twice as high as in the surrounding crystalline rock, approaching the levels of sea water (Marine 1974; Marine and Siple 1974). Groundwater in the basin also is characterized by hydraulic head values that are significantly higher than those in the overlying Coastal Plain aquifers. Three of the wells, DRB 9, DRB 10, and DRB 11 (Figure 5-4), have heads over 61 m (200 ft) higher than those in the overlying aquifer (Marine 1974; Marine and Fritz 1981).

Marine (1974) evaluated several possible explanations for these high-head conditions. Three potential explanations remained plausible after that analysis: osmotic-membrane phenomena, current tectonic compression, and warming due to post-Pleistocene climatic changes. Of these explanations, the osmotic-membrane mechanism is the most plausible (Marine 1974; Marine and Fritz 1981). Figure 5-5 shows pressure recovery data following the drilling of two wells, DRB 10 and DRB 11 (Figure 5-4), into the Dunbarton sedimentary rocks. Both wells exhibit pressure recovery curves that exceed the calculated osmotic equilibrium pressure. Marine and Fritz (1981) explain this discrepancy by suggesting that the

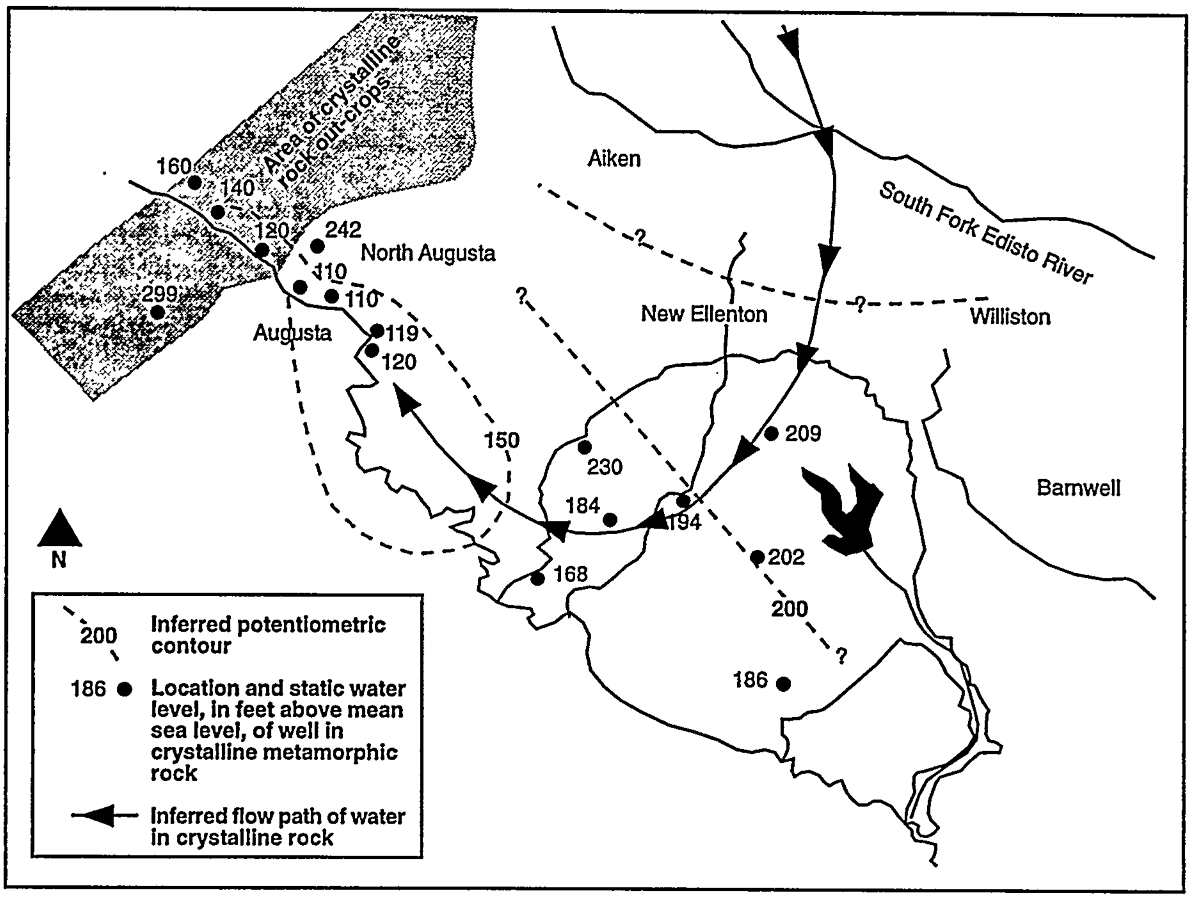

Figure 5-3. Potentiometric Map for the Crystalline Bedrock (modified after Marine 1979b).

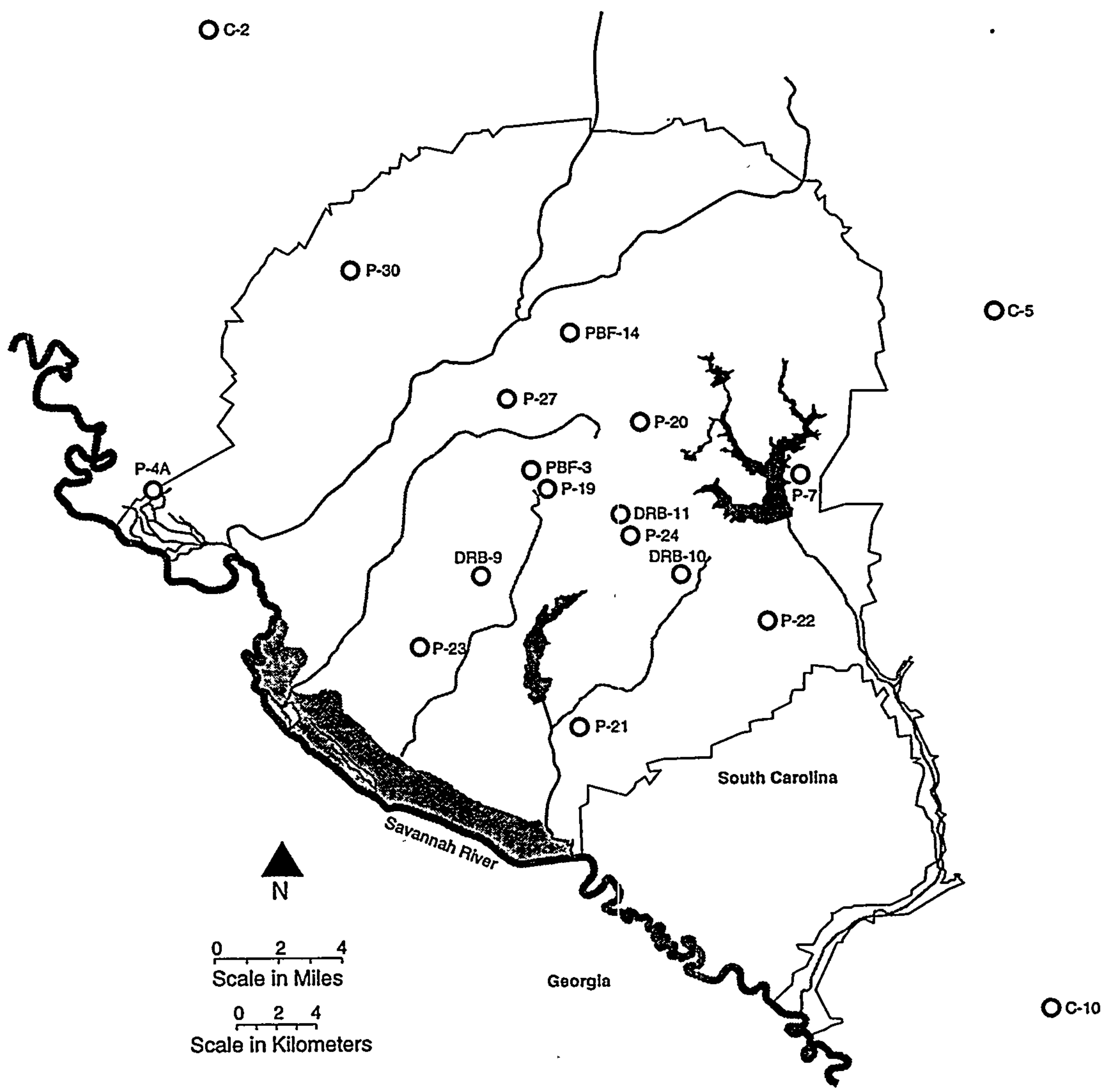

Figure 5-4. Well Location Map for the Savannah River Site and Surrounding Areas (modified after Strom and Kaback 1992).

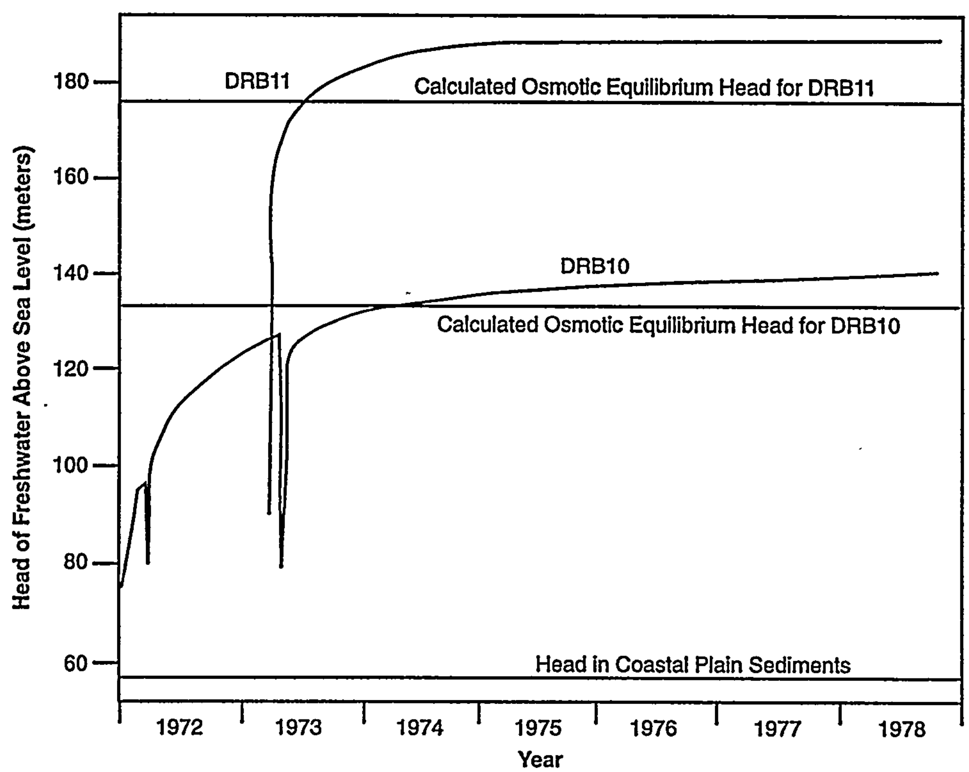

Figure 5-5. Pressure Recovery Curves from Two Wells Drilled into the Dunbarton Basin (after Marine and Fritz 1981).

water analyses used to calculate the theoretical osmotic pressure represent a composite sample that does not necessarily reflect the zone of highest pressure. Higher osmotic pressures would be expected since waters of higher dissolved concentrations are at shallower depths in the basin (Marine and Fritz 1981).

Southeastern Coastal Plain Hydrogeologic Province

Overview

The aquifers of the Southeastern Coastal Plain Hydrogeologic Province are the principal source of drinking water for the region and are used widely in agricultural and industrial processes including extensive use at the SRS. Because of the dependence on this resource, a considerable amount of attention has been given in recent years in South Carolina and Georgia to investigating the origin, flow, and chemistry of the aquifer systems. Major studies sponsored by the U.S. Department of Energy have recently been completed by the Westinghouse Savannah River Company, the South Carolina Water Resources Commission, the Georgia Department of Natural Resources, the USGS and the South Carolina Department of Natural Resources. A significant milestone was reached with the publication by the Water Resources Division of the State of South Carolina of the "Hydrogeologic Framework of West-Central South Carolina" by Aadland et al. (1995). The hydrogeologic nomenclature used in this Environmental Information Document is taken from that publication, and those interested in detailed descriptions and properties of the hydrogeologic units should consult that reference.

The Southeastern Coastal Plain Hydrogeologic Province comprises a multi-layered assemblage of clay and marl beds that retard water flow interspersed with beds of sand and limestone that transmit water more readily. Ground-water flow paths and flow velocity for each of these units are governed by the hydraulic properties, the geometry of the particular unit, and the distribution of recharge and discharge areas. Hydraulic conductivity in the aquifer units of the Coastal Plain ranges from 3 to 100 m/day (10 to 400 ft/day) (Aller et al. 1987). Regional recharge rates range from 50 to 500 mm/year (2 to 20 in/year) (Aller et al. 1987).

The sediments that make up the Southeastern Coastal Plain Hydrogeologic Province in west-central South Carolina and east-central Georgia have been grouped into three aquifer systems divided by two confining systems, all of which are underlain by the Appleton Confining System (Figures 5-2 and 5-6). The Appleton Confining System separates the Southeastern Coastal Plain Hydrogeologic Province from the underlying Piedmont Hydrogeologic Province (Figure 5-2). The areal extent of the aquifer systems is controlled by the limits of effective confining systems (Figure 5-7). Individual aquifer and confining units are delineated within each of the aquifer systems (Figures 5-2 and 5-6). These units may be further subdivided into local aquifer and confining zones.

Aquifer and confining systems on the site include the Floridan aquifer system, the Meyers Branch confining system, the Dublin aquifer system, the Allendale confining system, the Midville aquifer system, and the Appleton confining system. Clarke et al. (1985) named the Dublin and Midville aquifer systems from locations in Georgia. The aquifer units that make up two these systems are hydraulically connected under the Savannah River to aquifers in South Carolina (Siple 1967). The system nomenclature used by Clarke et al. (1985) in

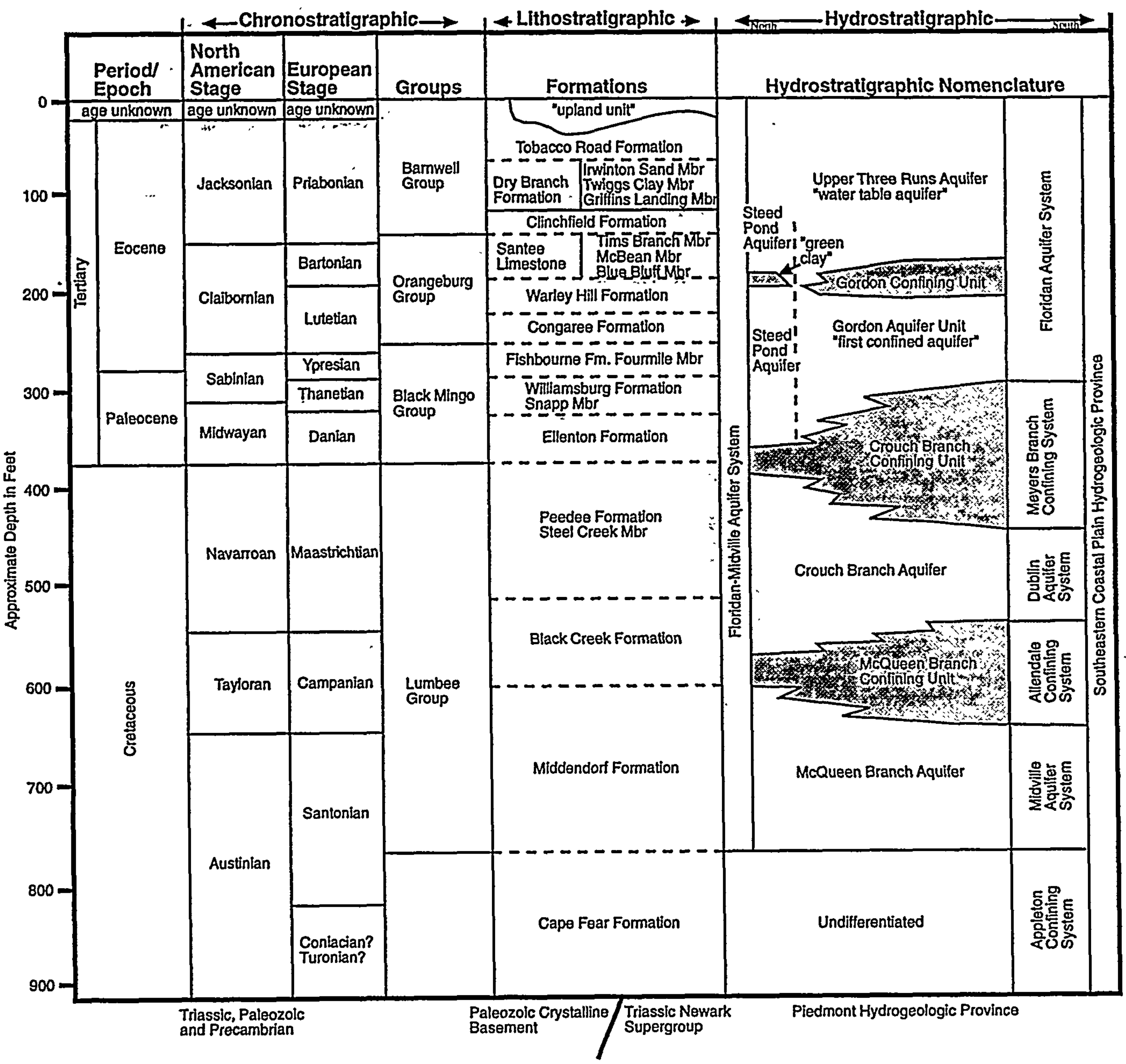

Figure 5-6. Correlation between Chronostratigraphic, Lithostratigraphic, and Hydrostratigraphic Units in the SRS Region (modified after Aadland et al. 1995).

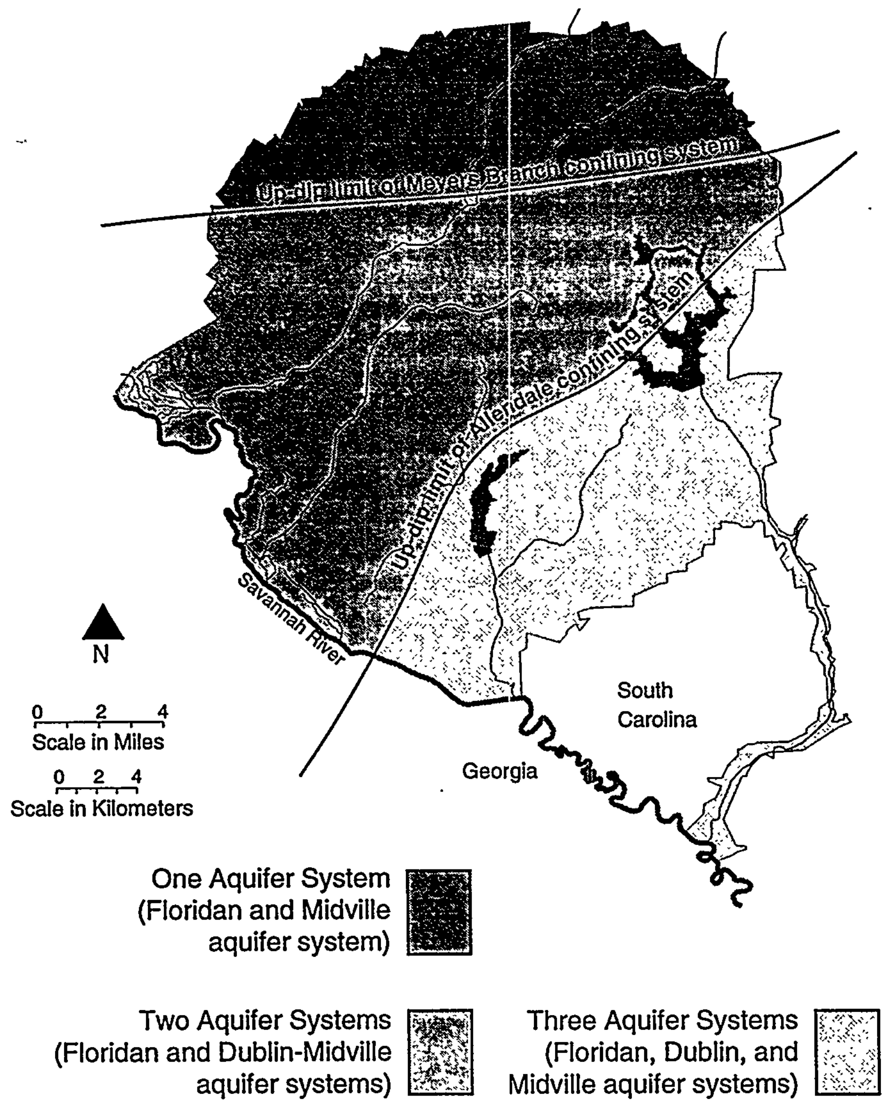

Figure 5-7. Extent of Confining Systems in the SRS Region (modified after Aadland et al. 1995).

Georgia has been extended into South Carolina at the SRS to emphasize and correlate the regional distribution of these units.

Figure 5-6 shows the correlation between the lithostratigraphic nomenclature used for the Atlantic Coastal Plain sedimentary units and hydrostratigraphy used for the Southeastern Hydrogeologic Province. The principal aquifers underlying the SRS area are described below in descending order.

Floridan Aquifer System

The Floridan aquifer system at SRS consists of a thick sequence of Paleocene to upper Eocene sands with minor amounts of gravel, and clay, and a few limestones. This sequence was deposited under mostly marine conditions. In the southern part of the area, the clastic sediments grade into the platform limestones that form the carbonate phase of the Floridan aquifer system. The boundary between the clastic and the carbonate phases of the aquifer system is a lithologic transition, and the two phases are connected hydraulically (Aadland et al. 1995).

The transition zone is the approximate northern extent of the thick carbonate platform that extended from the Florida peninsula through the coastal area of Georgia to southwestern South Carolina during the early Tertiary period (Figure 5-8). Miller (1986) did not consider the up-dip clastic facies that are equivalents of the Floridan carbonate rocks to be part of the Floridan aquifer system. They are, however, hydraulically connected with it and are thus part of its regional flow system. The up-dip clastic phase of the Floridan aquifer system, as defined by Aadland et al. (1995) and the carbonate phase of the Floridan aquifer system, as defined by Miller (1986), are treated as a single hydrologic system. Aucott and Speiran (1985a), for instance, found that there are no regionally significant water-level differences between them, and there is little evidence of an intervening confining unit.

Aucott and Speiran (1985a, b) also referred to the clastic phase of the Floridan aquifer system as the "Tertiary sand aquifer." They combined all of the Eocene sandy units in the Barnwell and Orangeburg Groups into the Tertiary sand aquifer because "they act hydraulically as a single aquifer in most of the State." In the SRS area, however, confining beds in these formations support a substantial head difference between overlying and underlying units.

For the southern portion of the SRS area, Aadland et al. (1995) divided the Floridan aquifer system into the Upper Three Runs aquifer, the Gordon confining unit, and the Gordon aquifer, (Figure 5-6). They further divide the Upper Three Runs aquifer into two aquifer zones over large parts of SRS: a lower aquifer zone and an upper aquifer zone separated by the "tan clay" confining zone. The tan clay confining zone is considered "leaky" over much of the site and may be thin or absent in places.

For the northern portion of the SRS area, Aadland et al. (1995) interpret the Gordon confining unit to pinch out and the Gordon and Upper Three Runs aquifers to colaesce to form the Steed Pond aquifer (Figure 5-2). The northern part of SRS is generally regarded to be that part north of Upper Three Runs. The Steed Pond aquifer is divided into two zones where a significant hydraulic head difference between the upper and lower portions is present. These zones, the M-Area aquifer zone and the Lost Lake aquifer zone, are the lateral equivalents of the lower aquifer zone of the Upper Three Runs aquifer and the Gordon aquifer, which are identified south of Upper Three Runs. At some locations north of

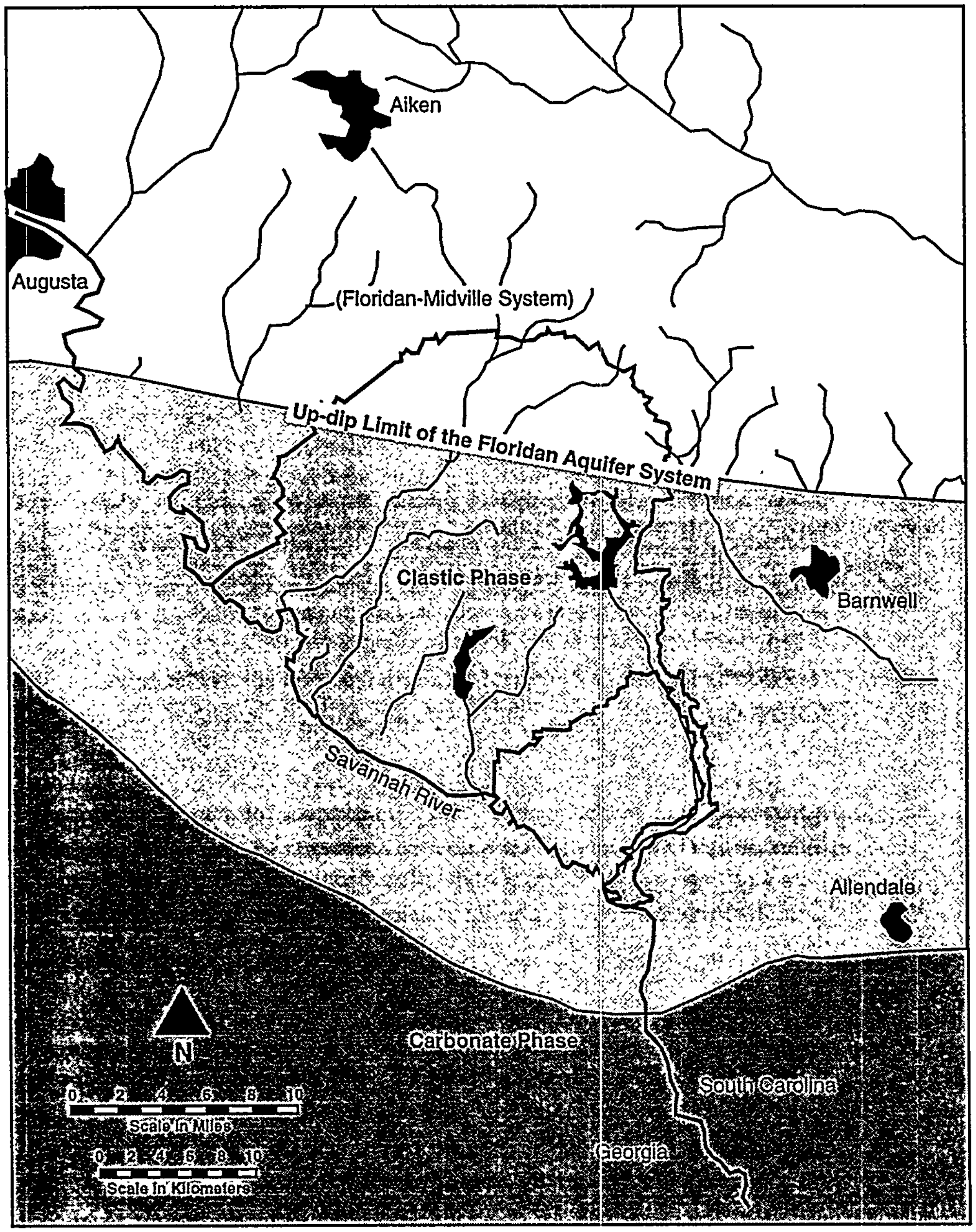

Figure 5-8. Position of the Clastic and Carbonate Phases of the Floridan Aquifer System near the Savannah River Site (modified after Miller 1986, and Aadland et al. 1995).

Upper Three Runs, the Lost Lake aquifer zone is divided into upper and lower sub-zones where a low permeability formation exists that supports a substantial hydraulic head difference between the upper and lower sub-zones. Generally, this low permeability layer is present in the Lost Lake aquifer zone in the northern and western portions of A/M Area, but not in the southern and eastern portions. A summary of measured hydraulic properties for aquifers and aquifer zones of the Floridan aquifer system are presented in Table 5-2. Additional information is contained in Appendix IV, Hydrogeologic Properties of SRS Hydologic Units.

The groundwater table, or water table, is the interface between the sub-surface zone of saturation and the vadose zone. At this surface, groundwater is unconfined and under pressure equal to that of the atmosphere. This interface can occur within different hydrostratigraphic units at different locations. At SRS the water table occurs in the M-Area aquifer zone beneath the A/M Area but declines in elevation in the vicinity of Upper Three Runs and occurs in the Gordon aquifer close to that stream. In the General Separations Area (F, H, S, and Z Areas) the water table occurs in the upper aquifer zone of the Upper Three Runs aquifer and subsequently into the Gordon aquifer as it approaches Upper Three Runs. A generalized term, the "water table aquifer," is used in this report to describe the uppermost unconfined aquifer at any particular location within SRS. Likewise, a generalized term, the "first confined aquifer," is used to refer to the uppermost confined aquifer beneath the water table aquifer. Use of the latter term can help to avoid confusion that may result from the current SRS convention of using different aquifer names for equivalent aquifers in the northern and southern portions of SRS, for example the use of "Lost Lake aquifer zone" and "Gordon aquifer" on the opposite sides of Upper Three Runs.

Water Table Aquifer

The water table aquifer includes all the geologic formations above the Warley Hill Formation (Figure 5-6), which include the sandy and locally calcareous sediments of the Santee Limestone and all the heterogeneous sediments in the overlying Barnwell Group from the water table down to the first confining unit. Porosity and hydraulic conductivity of the aquifer are generally high, although interbedded clay layers frequently function as local aquitards. In the central portion of SRS, clay layers within the Dry Branch Formation (tan clay confining zone of Aadland et al. 1995) are effective enough to merit subdividing the aquifer, the Upper Three Runs aquifer unit in this region, into an upper aquifer zone and a lower aquifer zone separated by the tan clay confining zone.

Figure 5-9 shows a potentiometric surface map for the water table aquifer. Horizontal groundwater flow is generally towards the nearest surface water feature that is in communication with the water table. In the northwestern corner of the site, where aquitards are generally less competent, vertical flow into underlying aquifer zones is more pronounced. This is partially the result of tan clay supporting a large hydraulic head difference, resulting in pronounced downward gradients locally. The low hydraulic conductivity of the aquitard retards the vertical flow of groundwater despite the high gradient.

Although the water table aquifer is not used on site as a source of drinking or process water, it has been investigated in detail at waste sites due to its importance in contaminant trans-

Table 5-2. Representative Hydraulic Properties of Aquifers at the Savannah River Site Based on Pumping Tests Results

Unit	Number of Tests	Mean Transmissivity (m^2/day)	Mean Hydraulic Conductivity (m/day)	Mean Storage Coefficient	References
Water table aquifer					
M-Area Aquifer - A/M Area	1	8.29×10^1	1.62×10^1	5.45×10^4	9
"upper aquifer zone" - H-Area	1	3.9×10^1	3.96×10^0	1.2×10^{-4} to 9.3×10^{-3}	1
"lower aquifer zone" - GSA[a]*	4	6.1×10^0	3.2×10^{-1}		1
"lower aquifer zone" - FASB[b]	1	6.2×10^1	3.1×10^0	1.6×10^{-4}	2
First confined aquifer					
Lost Lake aquifer zone	10	2.51×10^2	1.43×10^1	2.1×10^{-3}	3, 6, 9
upper Lost Lake aquifer zone	4	1.15×10^2	1.91×10^1	2.3×10^{-4}	8, 9, 10
lower Lost Lake aquifer zone	6	2.7×10^2	3.51×10^1	1.12×10^{-4}	7, 8, 9, 10
Gordon aquifer - HSAB[c]	2	1.98×10^2	9.9×10^0	2.6×10^4	5
Gordon aquifer - GSA	1	1.99×10^2	1.16×10^1	5.6×10^{-4}	4
Crouch Branch aquifer					
A/M-Area*	1	8.53×10^0	8.53×10^0		11
south of Upper Three Runs	9	2.36×10^1	2.36×10^1	4×10^{-4}	11
McQueen Branch aquifer					
A/M Area	1	1.83×10^3	3.32×10^1	3×10^{-4}	11
GSA	8	2.73×10^3	3.64×10^1	7.5×10^{-4}	11

1. D'Appolonia (1981) cited in Aadland et al. (1995)
2. FASB - F-Area Seepage Basins.; Chas. T. Main, Inc. (1990) cited in Aadland et al. (1995).
3. Geraghty and Miller (1986) cited in Aadland (1995).
4. HSAB - H-Area Seepage Basins; CH_2M-Hill (1989) cited in Aadland et al. (1995).
5. Albenesius et al. (1990).
6. Hiergesell (1993).
7. Hiergesell (1994).
8. Hiergesell et al. (1994).
9. Hiergesell and Pemberton (1995).
10. Hiergesell et al. (1996).
11. Siple (1967).

*Single-well test.
[a]GSA = General Separations Area.
[b]FASB = F-Area Seepage Basins.
[c]HASB = H-Area Seepage Basins.

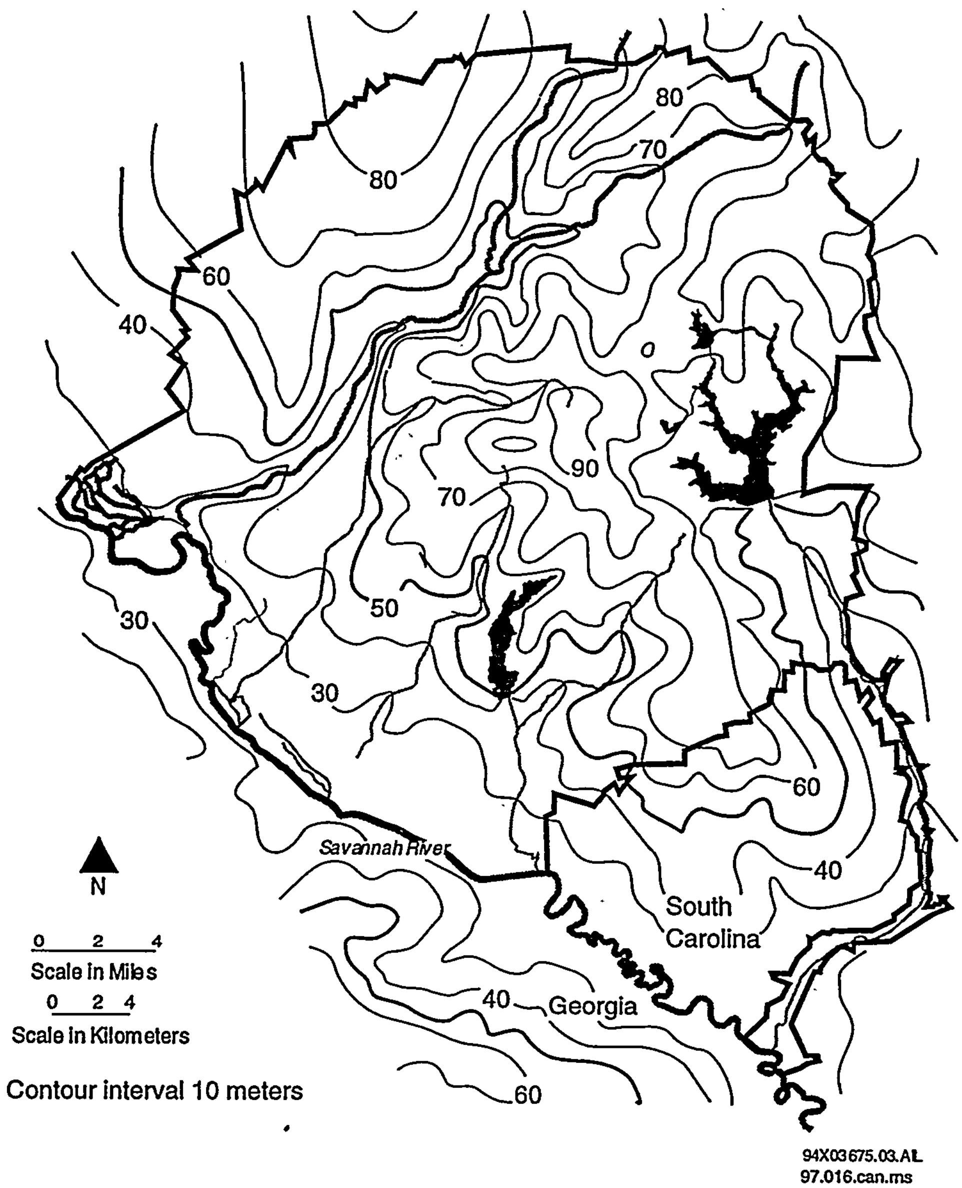

Figure 5-9. Water Table Aquifer for the Savannah River Site and Vicinity (modified after Hiergesell 1995).

port. The best data on the water-table aquifer south of Upper Three Runs are available in reports on these waste sites (Dunaway et al. 1987a, b; Huber and Bledsoe 1987; Jaegge et al. 1987; Killian et al. 1987; and Pekkala et al. 1987). For areas north of Upper Three Runs, data are available in Hiergesell (1995) and Lewis and Aadland (1992).

Gordon Confining Unit and Green Clay Interval

The first major laterally persistent aquitard encountered on the site is a distinctive Tertiary clay and sand interval that is informally referred to as the "green clay interval." Its lithostratigraphic position has been debated. Aadland et al. (1995), for example, consider the unit to be part of the Warley Hill Formation; whereas Fallaw and Price (1995) assign this interval to their "Tinker Formation," a siliciclastic, up-dip equivalent of the Santee Limestone (cf. Tims Branch Member).

The interval making up this aquitard can be traced over much of the site by its lithologies and characteristic signature on electric logs. The interval is characterized by variable facies ranging from clay-rich, calcareous sediment in the southern third of SRS; to silty, clayey sands in the middle third; to relatively clean quartz sands to the north (Aadland et al. 1995). As such, porosity and hydraulic conductivity of the confining unit vary widely, and the confining characteristics decrease to only localized influence in the northern part of SRS. In some areas, and especially in the central and southern part of SRS, the unit supports a hydraulic head differential exceeding 30 m (98 ft) between the water table and first confined aquifer.

Aadland and Bledsoe (1990) and Aadland et al. (1995) chose to divide the aquifers and aquitards of the Floridan aquifer system into separate units north and south of Upper Three Runs because of these lateral changes in lithologies and the interruption in the lateral continuity of the units. In particular, the aquitard has been breached by incision of the Savannah River and Upper Three Runs (Figure 5-10). Formally, the green clay interval is the "Gordon confining unit" south of Upper Three Runs and the "green clay confining zone of the Steed Pond aquifer" north of Upper Three Runs. Aadland et al. (1995) defined their Gordon confining unit on the basis of the sediments that were penetrated in well P-27 near the center of SRS (Figure 5-4), where the unit consists of a single sandy clay bed 2.1 m (7 ft) thick.

Gordon Aquifer and Equivalents

At SRS, the aquifer lying between the green clay interval and the Crouch Branch confining unit consists of fine-to coarse-grained, unconsolidated quartz sands with pebble zones; it commonly has clay beds and stringers. The sediments making up the aquifer generally are assigned to the lower Orangeburg Group and upper portions of the Black Mingo Group (Figure 5-6). There is significant lateral variation in lithology going downdip in the section. The quartzose sediments grade into fossiliferous, glauconitic limestones and into the platform limestones of the carbonate phase of the Floridan aquifer system.

As with the overlying confining zone, formal nomenclature changes near Upper Three Runs. North of Upper Three Runs, where the green clay interval is discontinuous, the section is part of the Steed Pond aquifer. At A/M Area, where the green clay interval locally provides an effective aquitard, the interval is the "Lost Lake aquifer zone" of the Steed Pond aquifer unit. South of Upper Three Runs, the interval has been assigned to the Gordon

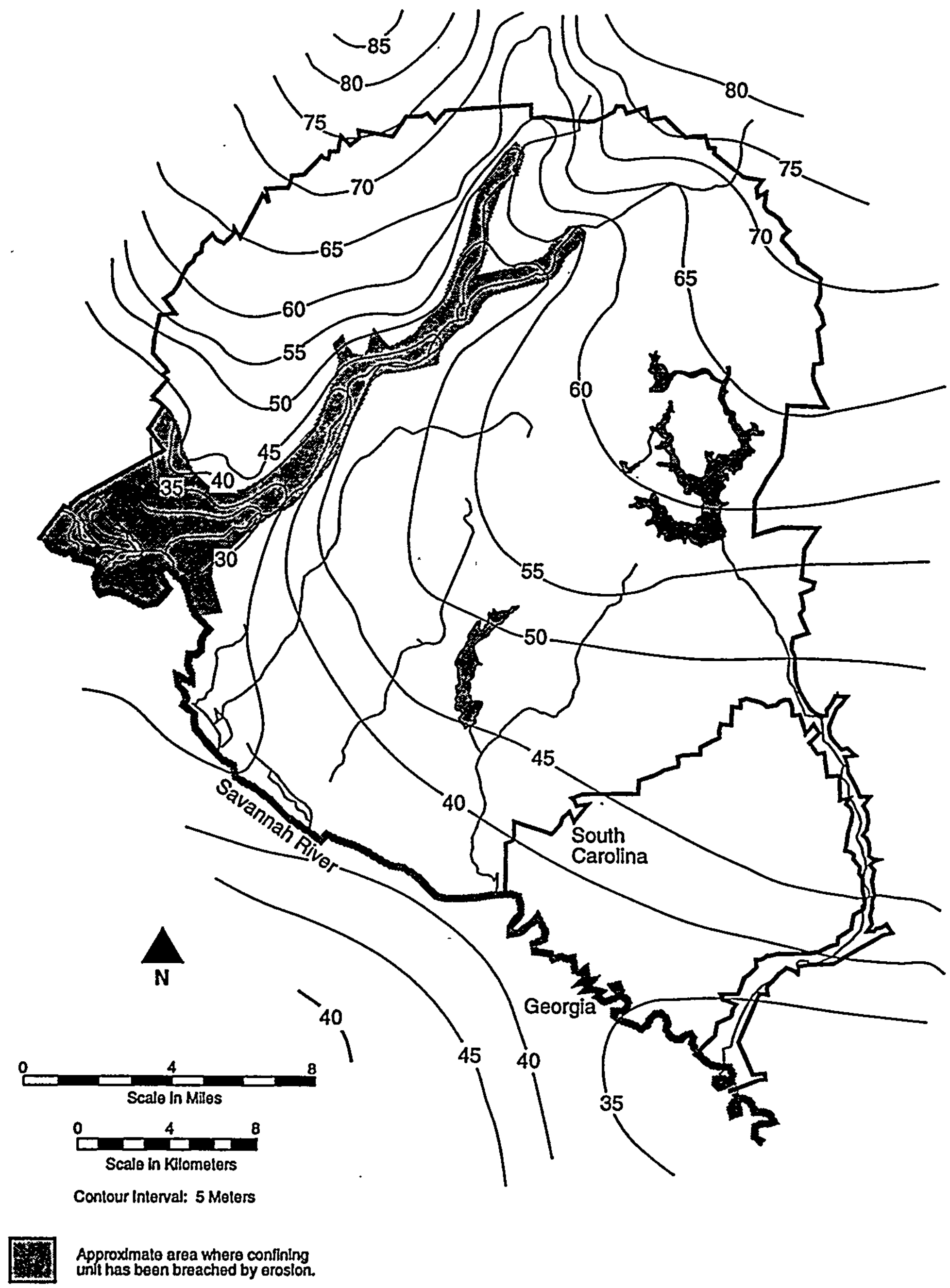

Figure 5-10. Potentiometric Map of the Gordon Confining Unit and Up-dip Equivalent Aquifer Zones.

aquifer. It is equivalent there to the Gordon aquifer system described by Brooks et al. (1985) and named for the City of Gordon in Wilkinson County, Georgia.

According to Aadland et al. (1995), most of the Gordon aquifer at SRS is under confined conditions except along the fringes of Upper Three Runs and the Savannah River. A potentiometric map of the aquifer and its up-dip equivalents (Figure 5-10) show the natural discharge areas of the aquifer along the wetlands fringing Upper Three Runs and the Savannah River. Incision of these streams has dissected the Floridan aquifer system and resulted in unconfined conditions along these waterways for the Gordon aquifer.

The thickness of the first confined aquifer varies from about 14 m (45 ft) to more than 24 m (80 ft), generally thickening to the east and southeast (Aadland et al. 1995). Thickness variations in the vicinity of the Pen Branch fault suggest depositional effects due to movements on the fault in early Eocene time.

The Gordon aquifer is a municipal water supply source for the town of Barnwell, South Carolina, southeast of the site (Newcome 1990) and provides limited drinking water to SRS and to the surrounding rural population both in South Carolina (Aadland et al. 1995) and Georgia (Summerour et al. 1993). The aquifer is capable of large yields at SRS, tens to hundreds of liters per minute (Table 5-2). Nearby, at Barnwell municipal wells, some wells yield 1500 liters per minute (400 gpm). The number of users of this aquifer probably will increase as the region develops, but most users who require very large quantities of water will develop wells in deeper aquifers.

Meyers Branch Confining System

The Meyers Branch confining system separates the Floridan aquifer system from the underlying Dublin and the Dublin-Midville aquifer systems (Figures 5-2 and 5-6) (Aadland et al.1995). At the South Carolina coastline, the confining system is composed primarily of the Paleocene evaporites (the Cedar Key Formation) that underlie the carbonate platform deposits of the Floridan aquifer system. Updip, the lithology of the system changes to the siliciclastic clays and sands of the upper clays of the Peedee Formation, the Ellenton Formation, and the Snapp member of the Williamsburg Formation. The system in the up-dip area is laterally equivalent to the Baker Hill-Nanafalia [confining] unit described by Clarke et al. (1985) in Georgia. At the SRS, the system pinches out and ceases to function as a regional confining system (Figure 5-7). It is composed on site of only the Crouch Branch confining unit.

Crouch Branch Confining Unit

The Crouch Branch confining unit separates the first confined aquifer from the underlying Crouch Branch aquifer (Figure 5-2) on the site. The unit varies in thickness from 0 m north of A/M Area to more than 30 m (100 ft) to the south. Aadland et al. (1995) subdivided their Crouch Branch confining unit into the following three hydrogeologic zones: the "upper clay" confining zone, the "middle sand" aquifer zone, and the "lower clay" confining zone.

The upper clay confining zone consists of the gray, tan, yellow, green, orange, brown, and purple silty clays that have been mapped as the Fishburne Formation by Fallaw (1991) but are considered Ellenton by Aadland et al. (1995). In parts of the northwestern portion of the site, the upper clay confining zone is thin or absent. At these locations, only the basal clay (lower clay confining zone of the Crouch Branch confining unit) that directly overlies the uppermost Peedee sand is effective as a confining unit between the first confined aquifer and the underlying Crouch Branch aquifer. The sands in the middle sand zone of the Crouch Branch confining unit are thus often connected hydraulically to the what Aadland et al. (1995) call the Lost Lake aquifer zone and are considered by those authors to be part of the overlying Steed Pond aquifer (Figure 5-2).

The lower clay confining zone consists of the varigated red, purple, yellow, and orange and, in places, dark to light gray massive clay bed that caps the Peedee Formation. This zone has been referred to as the lower Ellenton clay, the Ellenton clay, the Peedee clay, and the Ellenton/Peedee clay in previous SRS reports. The lower clay confining zone of the Crouch Branch confining unit is missing, and the underlying Crouch Branch aquifer is in direct hydraulic communication with the Steed Pond aquifer (Aadland et al. 1995).

Dublin Aquifer System

Clarke et al. (1985) originally named and described the Dublin aquifer system for a hydrogeologic section in a well at Dublin, Georgia, about 128.7 km (80 mi) southwest of the site. The system includes the transmissive units of the upper Cretaceous and lower Tertiary sands underlying the Kaber Hill-Nanafalia unit (i.e. the Meyers Branch confining system). Throughout most of east central Georgia, the system consists of a single hydrogeologic unit. In places, however, thick clay beds divide the system into two or more discrete aquifer units (Clarke et al. 1985).

The system extends beneath the Savannah River into western central South Carolina and is recognized on the site by a single aquifer unit, the Crouch Branch aquifer. The Crouch Branch aquifer is present across SRS and crops out parallel to the Fall Line north of the site. However, few data are available for the aquifer outside of SRS. Transmissivity in the Crouch Branch aquifer at SRS is relatively high (Table 5-2) because of its coarse sand and low clay content. Additional information on hydraulic properties of the Crouch Branch aquifer is contained in Appendix IV, "Hydrogeologic Properties of SRS Hydrologic Units."

In the southern part of the SRS area and farther south and east, the Dublin aquifer system makes a transition from lower delta plain to prodelta deposition as indicated by a decrease in grain size and an increase in clay content (Aadland et al. 1995). This results in much lower values for the hydraulic conductivity and transmissivity in the Dublin aquifer system in these areas. At the up-dip limit of the Allendale confining system, the Dublin aquifer system merges with the underlying Midville system to form the Dublin-Midville aquifer system and, eventually, the Floridan-Midville system at the extreme northern edge of the site (Figure 5-7).

Crouch Branch Aquifer Unit

Aadland et al. (1995) defined the Crouch Branch aquifer based on the sediments that were penetrated in well P-27 (Figure 5-4). The aquifer is overlain by the Crouch Branch confining unit and is underlain by the McQueen Branch confining unit. In previous SRS reports, the Crouch Branch aquifer also has been called the Black Creek, the Tuscaloosa, the Upper Cretaceous aquifer, and Aquifer IB. The aquifer persists throughout the SRS; however, north of A/M Area, the Crouch Branch confining unit becomes sandier, eventually becoming ineffectual. Aadland et al. (1995) interpret the Crouch Branch aquifer to coalesce with the Steed Pond aquifer at that point.

The Crouch Branch aquifer is 75.3 m (247 ft) thick in well P-27 (Figure 5-4) (Aadland et al.1995). This includes the sands in the upper third of the Black Creek Formation and the Steel Creek member of the Peedee Formation. The sands consist of quartz with a 5-20% clay matrix and trace amounts of plagioclase and potassium-feldspar. Kaolinite is the major clay mineral; minor to trace amounts of illite, smectite, and pyrite exist (Strom and Kaback 1992). The aquifer varies from about 30 m (100 ft) to more than 107 m (350 ft) thick. The thickness of the aquifer is quite variable near the Pen Branch fault where sedimentation apparently was affected by movement on the fault during Paleocene time (Aadland and Bledsoe 1990). Aadland et al. (1995) also have defined a high permeability zone in the aquifer which runs northeast to southwest through the center of the site and parallel to the Pen Branch fault (Figure 5-11). They inferred that this high permeability zone is a result of the deposition of coarse-grained, clean sands as shoaling that occurred in response to uplift along the fault.

Figure 5-11 shows the potentiometric-surface for the Crouch Branch aquifer beneath SRS. Horizontal flow in the Crouch Branch aquifer is predominantly from the recharge area north of the site toward the Savannah River, the regional drain for the Central Savannah River Area (CSRA). Upward flow also occurs in the vicinity of the Upper Three Runs tributary of the Savannah River. The head difference map across the Crouch Branch confining unit (Figure 5-12) shows areas of upward gradient. The direction of the hydraulic gradient between the Crouch Branch and the overlying aquifer changes from upward to downward away from the influence of Upper Three Runs and the Savannah River.

The Crouch Branch aquifer is a water source in several production areas of the site; however, new or replacement production wells, by agreement with the State of South Carolina, will not be completed in this aquifer in order to maintain its high potentiometric head and reduce the risk of contaminants moving into the deeper aquifers on the site.

Allendale Confining System

The Allendale confining system is in the southeastern half of the site and separates the Midville aquifer system from the overlying Dublin aquifer system (Figures 5-2 and 5-6). Figure 5-7 illustrates the up-dip limit of the system, as defined by Aadland et al. (1995). North of the up-dip limit, the thinner, intermittent clay beds of the McQueen Branch confining unit separate the McQueen Branch and Crouch Branch aquifer units of the Dublin-Midville aquifer system (Figure 5-2). The confining system thickens uniformly from about 15 m (50 ft) at the up-dip limit to more than 61 m (200 ft) near the southeastern boundary of the site.

Aadland et al. (1995) defined the Allendale confining system based on the sediments penetrated by the C-10 well near the town of Allendale, Allendale County, South Carolina (Figure 5-4). The system is 49.4 m (162 ft) thick at that location and consists primarily of clay and sandy clay with minor interbedded sand and clayey sand. The total clay thickness is 48.2 m (158 ft) (90% clay and sandy clay). Overall, the system consists of beds of slightly lignitic, glauconite-bearing, very micaceous clay, with intermittent silty, sandy clay beds (Aadland et al. 1995). X-ray diffraction analyses of two Allendale mudstone samples indicate that the mudstone consists of clay minerals with subordinate quartz and trace amounts of pyrite and muscovite. Kaolinite is the dominant clay mineral with trace amounts of illite (Strom and Kaback 1992).

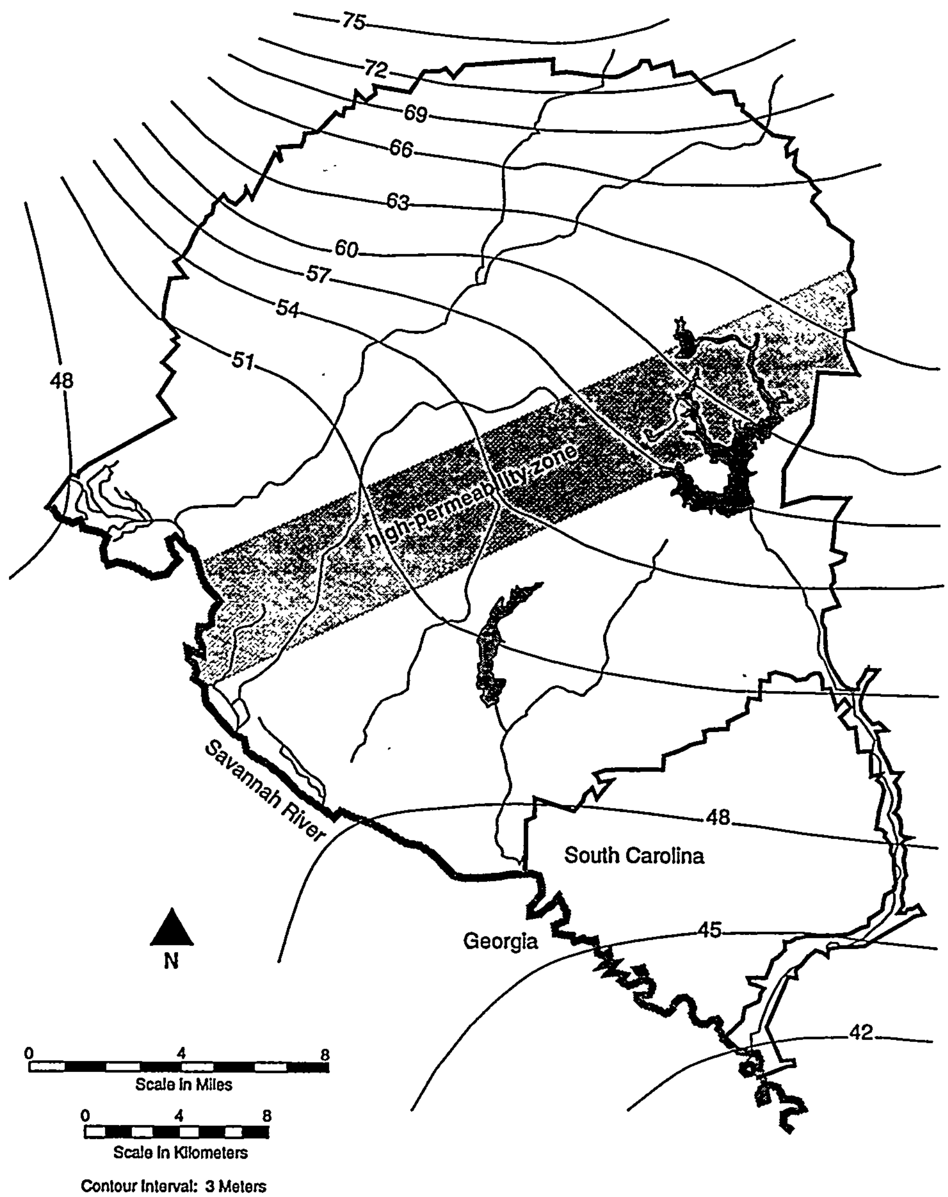

Figure 5-11. Potentiometric Map for the Crouch Branch Aquifer Beneath the SRS (modified after Aadland et al. 1995).

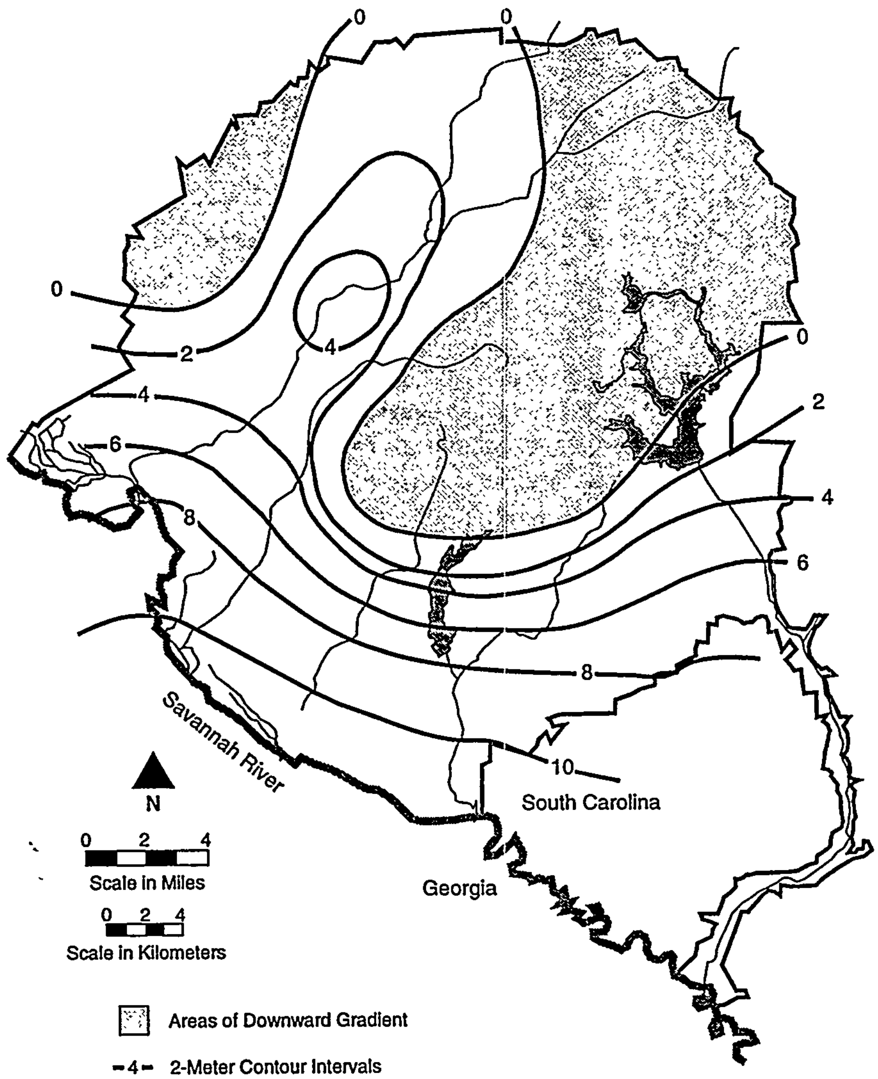

Figure 5-12. Hydraulic Head Difference Between the Crouch Branch Aquifer and the First Confined Aquifer (difference in meters; positive values indicate areas of upward flow from the Crouch Branch into the overlaying aquifers).

McQueen Branch Confining Unit

On SRS, a single aquitard is recognized in the Allendale confining system. The McQueen Branch confining unit separates the McQueen Branch aquifer from the overlying Crouch Branch aquifer (Aadland et al. 1995). The clayey silty sand and clay beds of the McQueen Branch confining unit cap the lower of the two upward-fining sequences that characterize the Black Creek Formation. In the northern part of SRS, the fine-grained sediments in the interval suggest lower delta plain environments of deposition. To the south, the sediments are generally finer-grained and consist of clayey silt and fine- to medium-grained, moderately to well-sorted, micaceous, carbonaceous, and locally glauconitic sand. The abundance of macrofauna and microfauna fossils (Prowell et al. 1985) suggest delta front or shallow-shelf environments. The approximate northern limit of the shallow shelf or delta front deposits generally corresponds to the northern limit of the Allendale confining system (Figure 5-7).

The McQueen Branch confining unit is 16.8 m (55 ft) thick in the P-27 well (Figure 5-4) and consists of the sandy clay confining beds in the middle third of the Black Creek Formation (Aadland et al. 1995). The clay beds indicate deposition in lower delta plain environments, such as an interdistributary bay or back-barrier bay, where clay thicknesses can vary greatly over relatively short distances. The thickness of the unit is variable and ranges from 0 to 22.9 m (0 to 75 ft) near the P-26 well in the southwestern part of SRS. The unit thins and pinches out between wells P-27 and P-19 (Figure 5-4), leaving the McQueen Branch and Crouch Branch aquifers in hydraulic communication. Farther south, between wells P-19 and P-24 (Figure 5-4), the confining unit is re-established and persists throughout the remainder of the region. The silty clays of the McQueen Branch confining unit become thicker and more continuous in the southern part of the site, and grade laterally into other units, making up the Allendale confining system (Figure 5-2).

Representative hydraulic properties of the McQueen Branch confining unit are compiled in Table 5-2. A listing of hydraulic property estimates made using several different techniques is in Appendix VI.

Midville Aquifer System

The Midville aquifer system is in the southern two-thirds of the SRS, overlies the Appleton confining system, and is separated from the overlying Dublin aquifer system by the Allendale confining system (Figures 5-2 and 5-6). Figure 5-7 illustrates the up-dip limit of the Allendale confining system, as defined by Aadland et al. (1995).

Clarke et al. (1985) defined the Midville aquifer system and named it for the sediments that were penetrated in a well near the town of Midville in Burke County, Georgia. Hydrostratigraphic units correlative with the Midville aquifer system in Georgia are beneath the SRS, and the name now is used for these units in South Carolina and at SRS.

Sediments that were penetrated in reference well P-21 (Figure 5-4) are typical of the Midville aquifer system in the SRS subsurface (Aadland et al. 1995). The well is in the southeastern corner of SRS near Steel Creek. The Midville is 70.7 m (232 ft) thick in P-21 with a total sand thickness of 59.7 m (196 ft) contained in five beds. Here, the Midville consists of the medium- to coarse-grained sands of the Middendorf Formation, and the better sorted, typically fine-grained sands of the lower third of the Black Creek Formation (Figure 5-6).

North of the up-dip limit of the Allendale confining system, the regional separation between the Dublin and the Midville aquifer systems disappear; the combined units are referred to collectively as the Dublin-Midville aquifer system. A similar coalescing occurs north of the up-dip limit of the Meyers Branch confining system; the combined aquifers are collectively referred to as the Floridan-Midville aquifer system.

McQueen Branch Aquifer

The McQueen Branch aquifer, a single aquifer of the Midville system, is recognized at the SRS and was named for the McQueen Branch tributary of Upper Three Runs. It is the lowermost aquifer recognized at the site and has, at various times, been referred to as the Middendorf, the lower Cretaceous, the lower Tuscaloosa, and Aquifer IA. Aadland et al. (1992) used the name "McQueen Branch aquifer" for this lowermost aquifer, which is both a lithostratigraphic and hydrostratigraphic equivalent to the Midville aquifer system of Clarke et al. (1985) in Georgia.

At the type well (P-27TA) for the McQueen Branch aquifer that Aadland et al. (1995) described, the McQueen Branch aquifer includes the Middendorf Formation and the lower third of the Black Creek Formation. These units thicken toward the southeast and change in lithology. At the type well, the total aquifer thickness is about 58 m (203 ft), including several clay beds that cap the Middendorf Formation and this location. The transmissive sand units are typically medium- to very coarse-grained sand in the Middendorf Formation and fine- to medium-grained sand of the lower third of the Black Creek Formation. Down dip, the sands become more fine-grained as the depositional environments changed from upper delta plain to lower delta plain-shallow marine settings.

The clay layers near the top of the Middendorf Formation function as confining zones in the northern part of the site. Upper and lower aquifer zones can be distinguished in the McQueen Branch aquifer (Bledsoe et al. 1990; Aadland and Bledsoe 1990), especially near A/M-Area. Near the Pen Branch fault, the separation of zones diminishes as the clay and sandy clay layers in the top of the Middendorf Formation thin or pinch out, possibly as a result of shoaling due to uplift along the Pen Branch fault. To the south, clayey zones are ineffective in segregating the McQueen Branch aquifer into zones (Bledsoe et al. 1990).

Figure 5-13 shows a potentiometric surface map for the McQueen Branch aquifer beneath SRS. In general, horizontal flow in this aquifer is towards the Savannah River. Based on the low conductivity of the sediments making up the Appleton confining system beneath this aquifer and the weak vertical gradients with the overlying Crouch Branch aquifer over most of the site, the flow in this aquifer is essentially horizontal over most of SRS. However, there is a strong upward hydraulic gradient near the Savannah River, which is believed to be the discharge point for this aquifer. Regional hydraulic heads in Georgia and South Carolina also indicate that the Savannah River is the ultimate discharge for this aquifer in the vicinity of SRS (Aadland et al. 1992). Recharge of this aquifer likely occurs near SRS, where the sediments of the Middendorf Formation are exposed near the Fall Line.

The McQueen Branch aquifer is highly transmissive (Table 5-2 and Appendix IV). It, therefore, serves as the major production aquifer for much of SRS. In the past, groundwater production wells at SRS were screened in both the McQueen Branch and Crouch Branch aquifers. In 1985, the site committed to the State of South Carolina to complete production wells only in the McQueen Branch Aquifer in order to minimize the potential for contamination reaching production wells and spreading to the deeper aquifers.

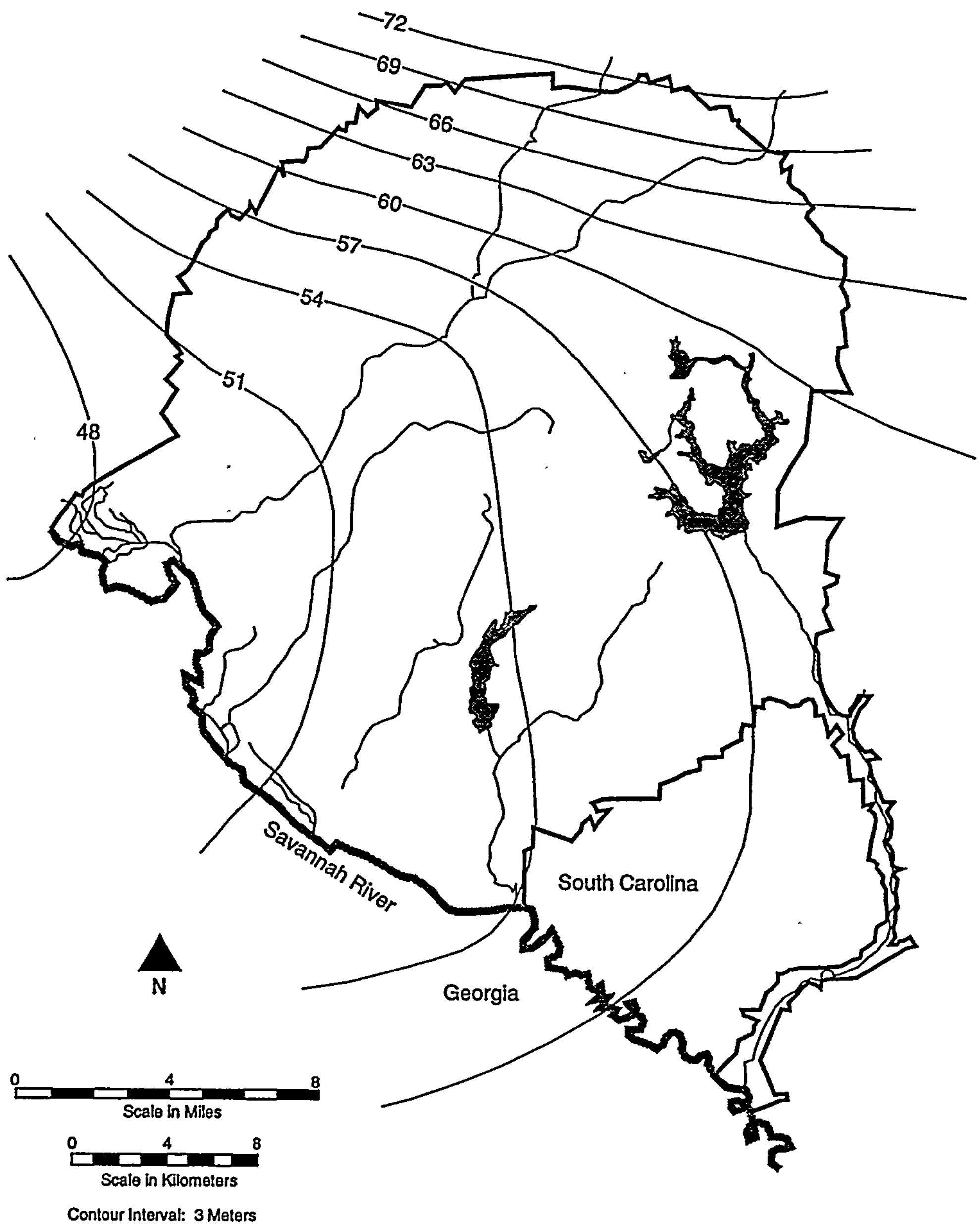

Figure 5-13. Potentiometric Map of the McQueen Branch Aquifer Beneath the Savannah River Site (Elevations are in meters above mean sea level) (modified after Aadland et al. 1995).

Appleton Confining System

Aadland et al. (1995) defines the Appleton confining system by the sediments the C-10 well penetrates near the town of Allendale, in Allendale County, South Carolina. The unit is 73 m (240 ft) thick in the C-10 well and consists of saprolite derived from basement rocks, and the interbedded sands, clayey sands, and clays of the Cape Fear Formation. The Cape Fear Formation consists of arkosic to subarkosic sands of varying color with textures ranging from very fine to very coarse. Coarse pebble zones are present. Updip, the Appleton confining system is typified by sediments that were penetrated in SRS well PBF-3 (Figure 5-4). The Appleton confining system rests directly on crystalline basement rocks and the sedimentary rocks of the Dunbarton Basin that constitute the Piedmont hydrogeologic province (Figures 5-1 and 5-2) (Aadland et al. 1995).

Groundwater Usage

The site operates more than 100 production wells to provide water for processing nuclear materials, and for domestic water, and fire protection. (Hubbard et al. 1988). Because of the generally high water quality and transmissivity of the McQueen Branch and Crouch Branch aquifers, most of the production wells are developed in these units. Only occasionally have lower capacity production wells been developed in the Gordon or Upper Three Runs aquifer units. Groundwater withdrawals have averaged approximately 8.2 million gallons per day (mgpd) over the past three decades, with peak average withdrawal rates, up to 11 mgpd, during the mid 1980s (Figure 5-14).

Approximately half the groundwater is used at the F and H Area separation facilities near the center of the site; another 25% is used at the A/M Area near the northern site boundary (Hubbard et al. 1988). The withdrawal rates are similar to those of nearby municipalities such as Barnwell and Aiken (Arnett et al. 1995). The major impact of these withdrawals has been the lowering of the potentiometric head of the pumping aquifers in the vicinity of F and H Areas and the A/M Area, the increase in the downward leakage of groundwater from overlying aquifers (Siple 1967), and the interception of the flow of groundwater from recharge areas north of the site toward the Savannah River (Hubbard et al. 1988).

Summary

Because of its location near the up-dip edge of the Atlantic Coastal Plain, the hydrogeology of the region surrounding SRS is complex. Confining units, or aquitards, tend to thin out or be intermittent in effectiveness. Likewise, transmissive units change in thickness, composition, and hydraulic conductivity from one edge of the site to the other.

Over the past decade, studies to characterize the hydrogeology of the site and to develop a consistent hydrostratigraphic nomenclature have made significant progress. The on-site hydrostratigraphy has been clarified by the identification of individual aquifer and confining units. Regional correlations have been made by the development of system nomenclature with the assistance of the South Carolina Hydrostratigraphic Nomenclature Subcommittee.

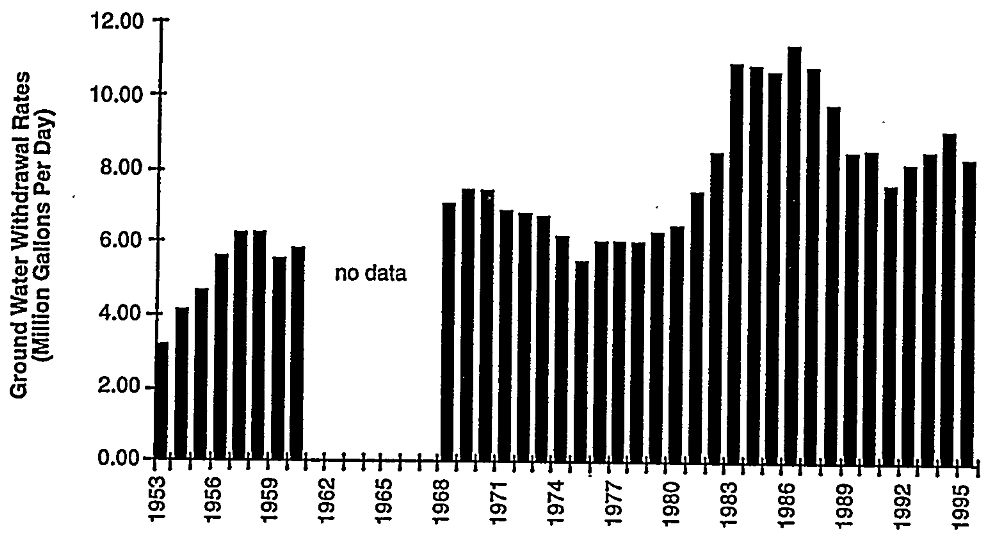

Figure 5-14. Changes in Groundwater Withdrawal Rates over Time.

A South Carolina Department of Natural Resources publication (Aadland et al. 1995) documents in detail both the regional hydrostratigraphic correlations and site-specific description of the principal aquifer and confining units on SRS.

In general, the deeper aquifers are the more transmissive units, and most ground-water production wells are developed in these aquifers. Recharge to the deep aquifers is largely from north of the site where the geologic formations making up the aquifers are exposed at the land's surface. Vertical recharge from overlying aquifers contribute to the flow. Discharge of the deep aquifers is primarily to the Savannah River by upward migration through overlying aquifers in the Savannah River stream valley.

Shallow aquifers have not been important as a water source at the site, but are used extensively off site in rural areas as sources of domestic water. Recharge to shallow aquifers is primarily local, and discharge is primarily to major tributaries of the Savannah River such as Upper Three Runs, Lower Three Runs, Fourmile Branch, and Steel Creek. The water table aquifer has been studied in detail on SRS to insure proper remediation of contaminated groundwater and to manage and protect the aquatic environment.

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Chapter 6—Groundwater Quality

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Introduction

This chapter summarizes general ground-water quality, microbiology of aquifers, and issues related to contaminant transport in groundwater at SRS. Understanding the chemistry and the processes that govern the chemistry of uncontaminated groundwater is important to any assessment of groundwater contamination. This chapter begins with a discussion of the chemistry of local groundwater and the geochemical processes that control this chemistry. Microbiological processes also influence the chemistry of local groundwater; therefore, some of the important microbiological processes evident in SRS groundwater are discussed in the second section. The final section summarizes the important properties of SRS aquifers that influence the nature of contaminant-aquifer interactions and, thus, the transport of contaminants in groundwater.

Water Quality

The quality of the groundwater in the Coastal Plain sediments at SRS and the surrounding areas is generally suitable for most domestic and industrial use. The waters are dilute with total dissolved solids ranging from less than 10 mg/l to about 150-200 mg/l. The pH values range from as low as 4.9 to a maximum value of 7.7. Where the groundwater is in contact with limestone, the average pH value is around 6.0. Many SRS groundwaters are corrosive to metal surfaces because of the chemical characteristics of the waters and the frequently low pH values. High dissolved iron concentrations in some units also may be of concern. The site uses a degassification/filtration process to raise the pH and remove iron in domestic water supplies when necessary.

Most of the shallow groundwater is derived from local recent precipitation. Groundwater samples collected from depths less than about 60 m (197 ft) contain tritium in concentrations indicative of post-1950s precipitation in the SRS region (Strom and Kaback 1992). In addition, Strom and Kaback (1992) found that the sodium:chloride ratio in shallow groundwater is similar to that of seawater, but the relative amounts of calcium and sulfate in shallow groundwater are greater than in seawater.

Hydrochemical Facies

The groundwater within the Coastal Plain sediments, though dilute, shows significant changes in the level of dissolved oxygen, the redox potential of the water, dissolved trace constituents, and major cations and anions. These changes in the diagnostic chemical characteristics of the ground-water solutions represent the cumulative effects of reactions between the influent waters and the materials that make up the sediments along groundwater flow paths. The most notable changes in the chemical characteristics of the groundwater are those in the major cation and anion compositions. These changes are illustrated on trilinear, or "Piper," diagrams (Figures 6-1 to 6-5). On the diagrams, the major cation composition is plotted on the lower left trilinear diagram and the major anion composition on the lower right trilinear diagram. By extending lines from the composition points on the

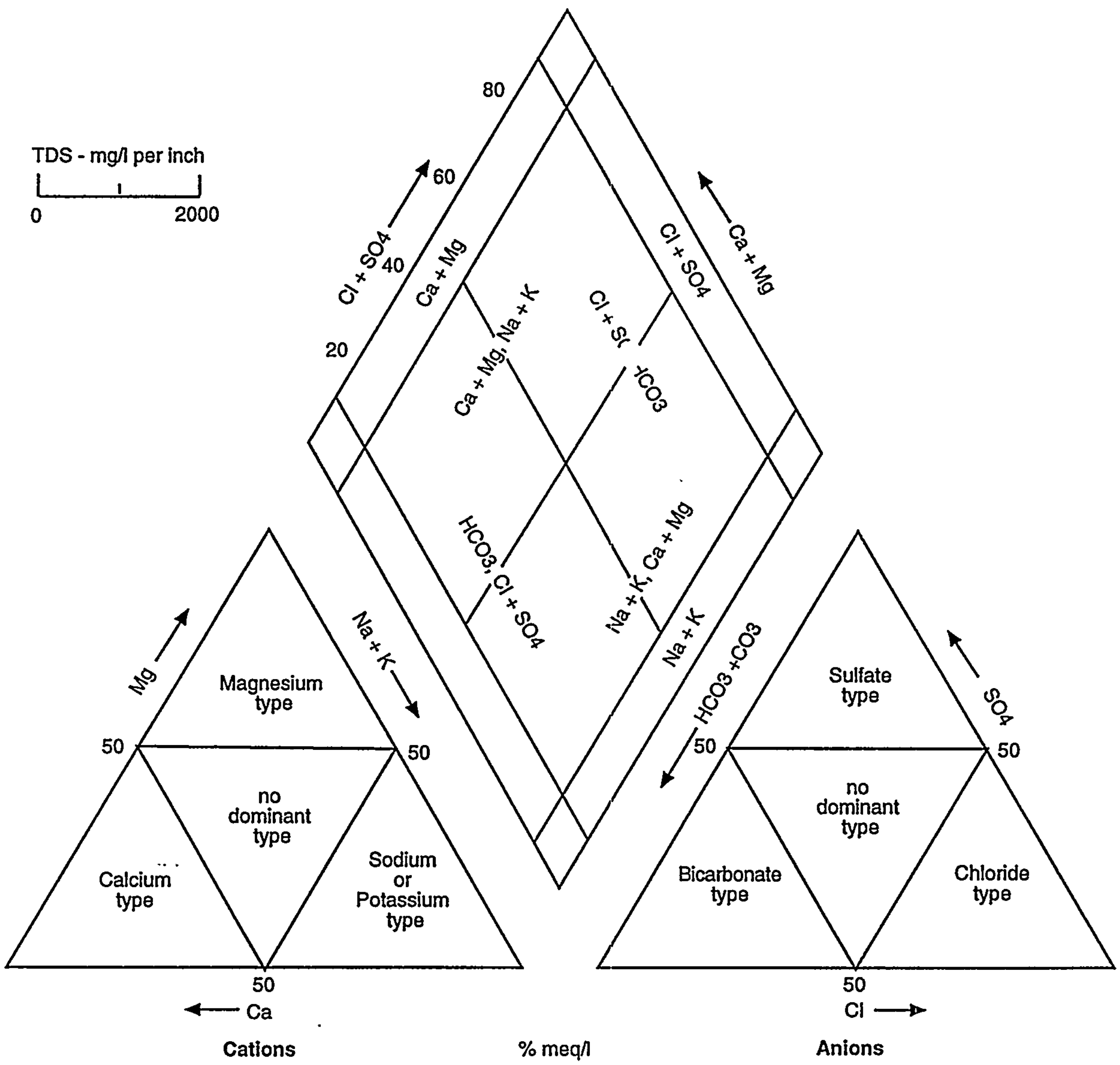

Figure 6-1. Piper Diagram Illustrating Hydrochemical Facies (after Back 1966).

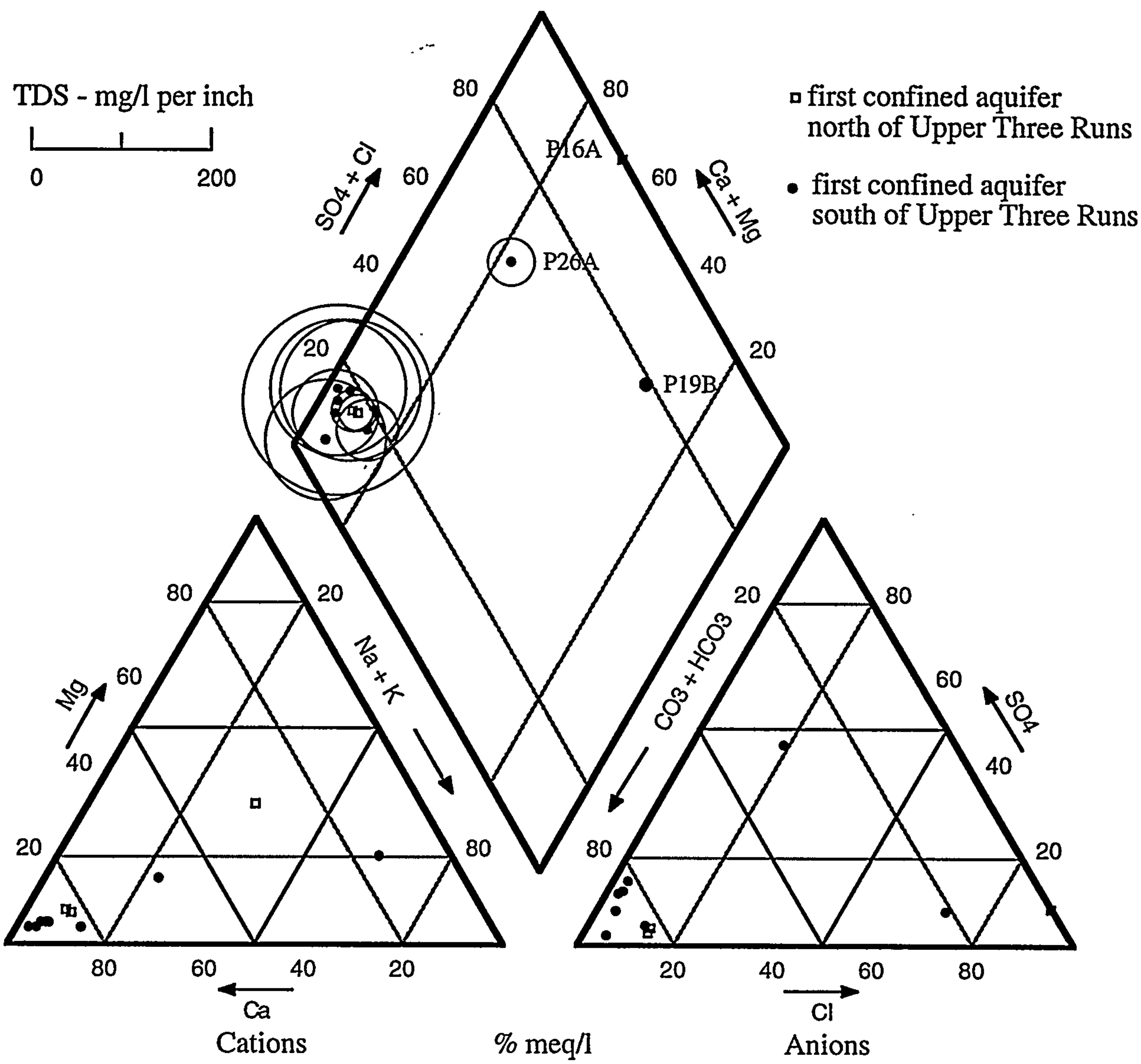

Figure 6-2. Piper Diagram for Water Table Aquifer Water Samples from the SRS and Surrounding Region. (IDB-IC is part of the P14 well-cluster. FC2E is part of the P28 well-cluster) (Source: Strom and Kaback 1992).

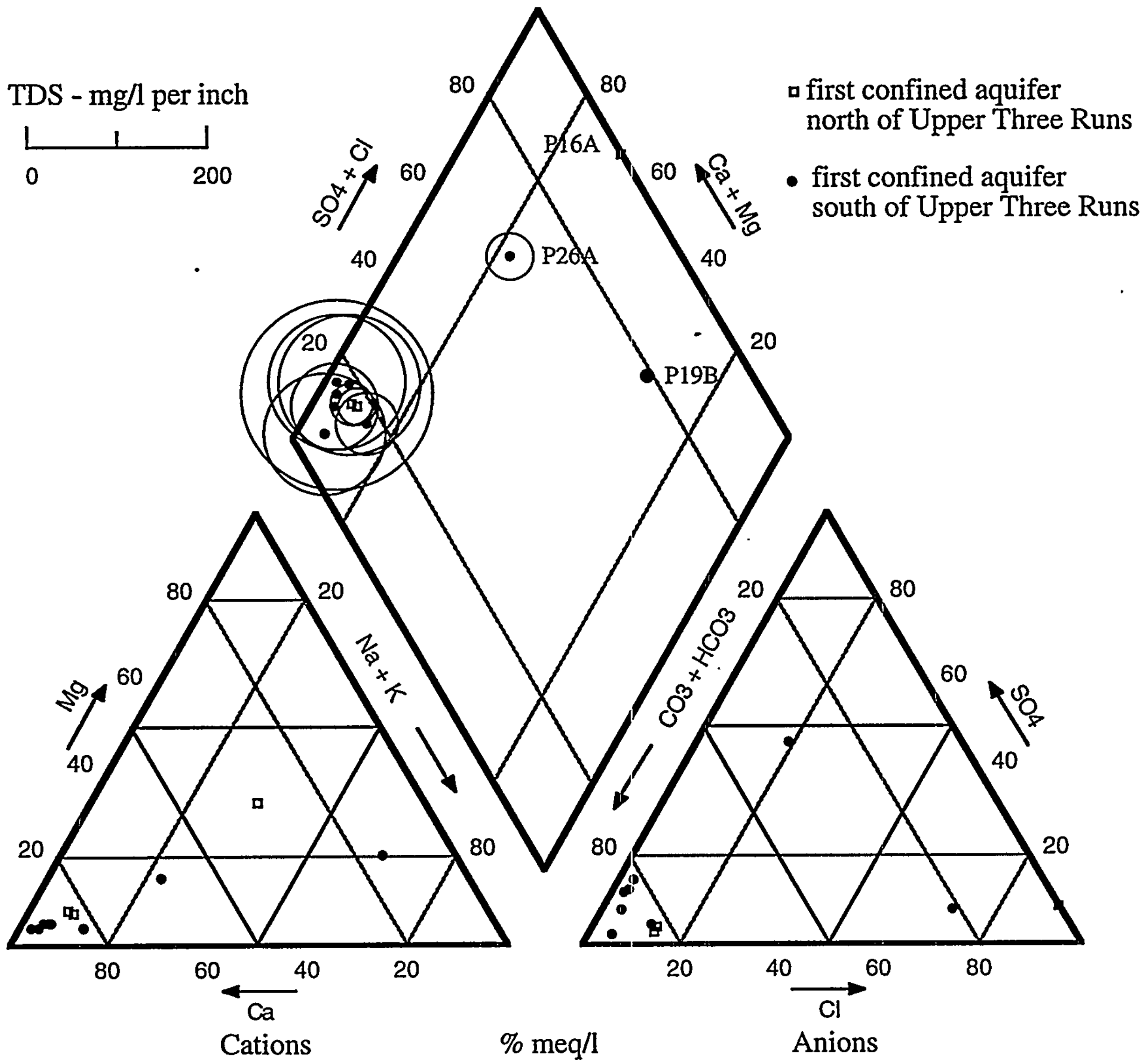

Figure 6-3. Piper Diagram for First Confined Aquifer Water Samples from the SRS and Surrounding Region (Source: Strom and Kaback 1992).

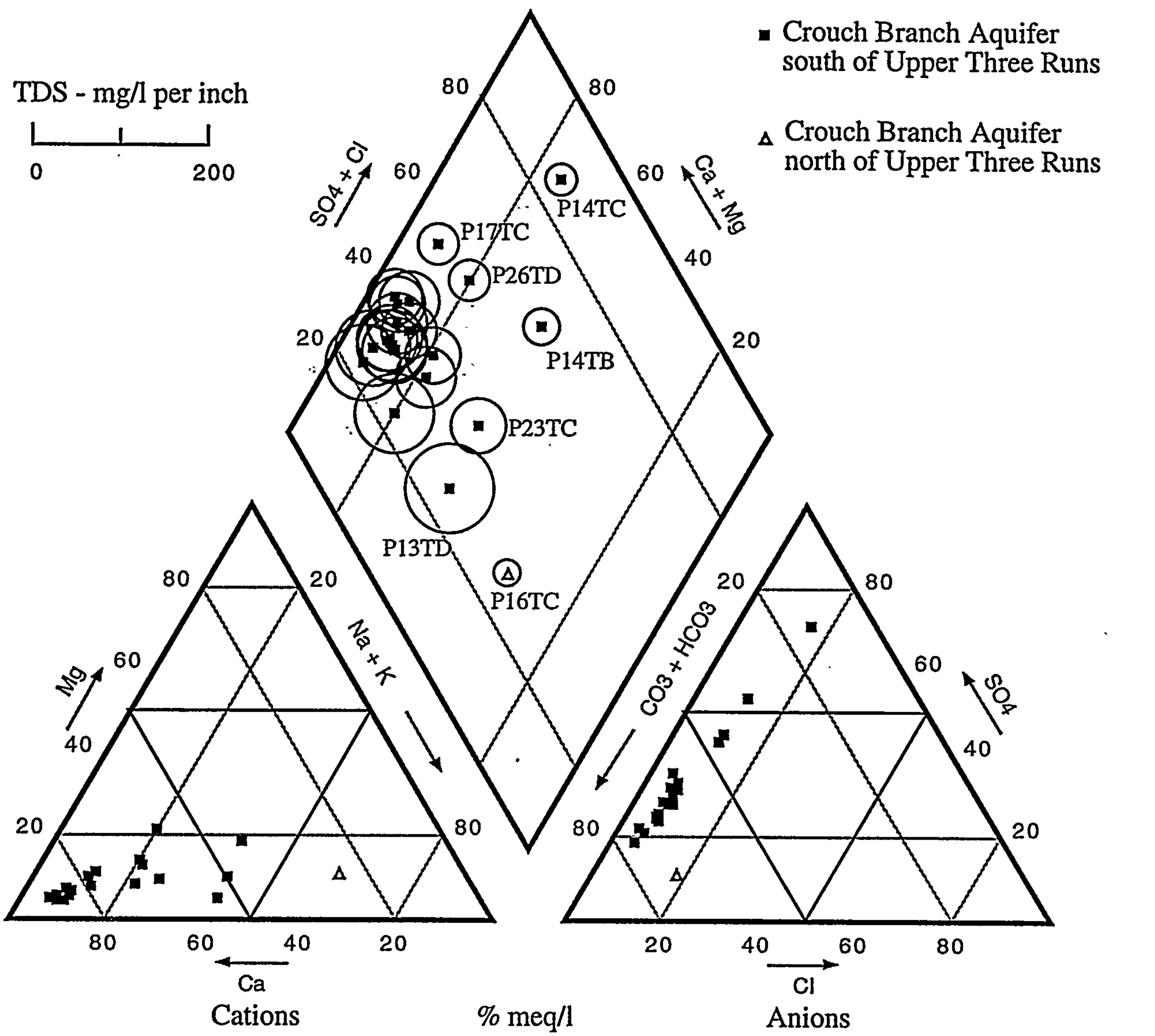

Figure 6-4. Piper Diagram for Crouch Branch Aquifer Water Samples from the SRS and Surrounding Region (Source: Strom and Kaback 1992).

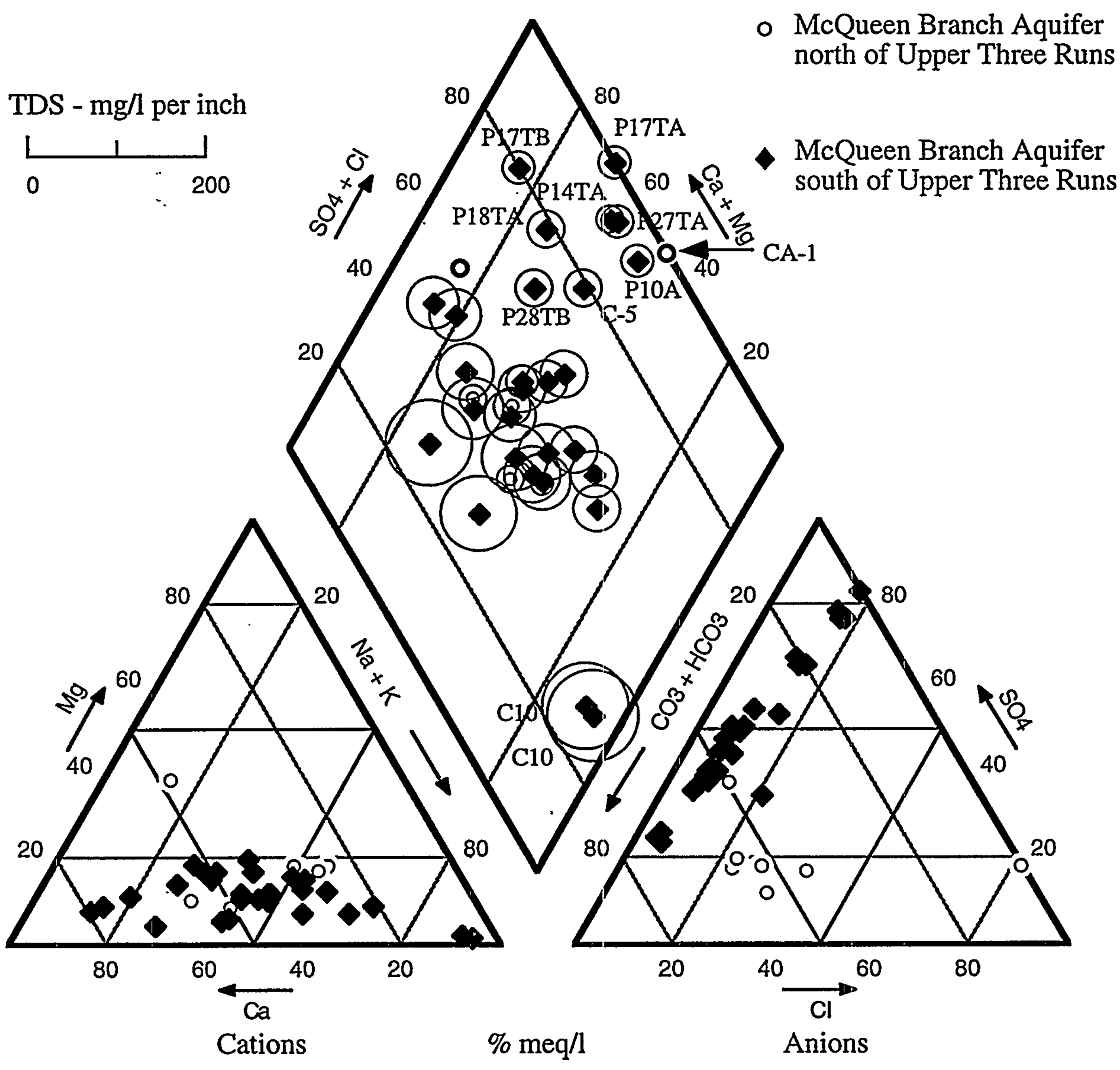

Figure 6-5. Piper Diagram for McQueen Branch Aquifer Water Samples from the SRS and Surrounding Region (P10A is part of the P19 well-cluster. CA-1 is near Aiken, north of this map coverage.) (Source: Strom and Kaback 1992).

trilinear diagrams parallel to the external edges, a common intersection is found and plotted as a circle on the diamond-shaped grid. The diameter of the circle is proportional to the concentration of total dissolved solids in the water samples. Piper diagrams use major element chemistry to classify groundwater into water types (Figure 6-1). They are useful in identifying major trends in groundwater chemistry that reflect reactions between the water and aquifer materials.

Strom and Kaback (1992) showed that groundwater chemistry and water type vary with aquifer and that there are distinct chemical trends sitewide. The groundwater at the northern edge of the site, where only one aquifer system is present, is relatively acidic and is not dominated by any particular chemical type (Figure 6-2). To the south, where more than one aquifer system exists, the groundwaters of the different aquifers are more distinct. The Tertiary aquifers are dominated by calcium-bicarbonate groundwater, which probably reflects reaction with calcareous sediments (Figures 6-2 and 6-3). The Cretaceous aquifers show evolutionary trends from sulfate-rich groundwaters to bicarbonate-rich groundwaters (Figures 6-4 and 6-5). The carbon isotopic signatures of these groundwaters suggest that the bicarbonate is primarily from the microbial oxidation of organic material in the aquifers, rather than the dissolution of carbonate minerals (Murphy et al. 1992).

In addition to these trends, Strom and Kaback (1992) found that the Cretaceous aquifers were mostly anaerobic south of Upper Three Runs. The iron concentrations in the anaerobic zones are high, typically between 1 and 5 mg/l. This indicates that the aquifers are reducing, but that bacterially mediated sulfate reduction is not significant. These patterns are consistent with the findings of Chapelle and Lovely (1992). They proposed that a high iron zone that parallels that Fall Line in South and North Carolina results from iron-reducing bacteria inhibiting the growth of sulfate-reducing bacteria. The use of iron in oxyhydroxide minerals by iron-reducing bacteria suppresses the concentrations of substrates required by the sulfate-reducing bacteria.

Microbiology

DOE initiated a program in 1986 to investigate the microbiology of the deep subsurface sediments at SRS (Ghiorse and Wobber 1989). Three deep boreholes were drilled: P24, P28, and P29 (Figure 6-6). Four core-recovery techniques for aseptically sampling the subsurface sediments were applied and tested for their ability to provide samples uncontaminated with drilling mud or other sources for surface contamination (Phelps et al. 1989a). Different core-recovery tools were found to be appropriate for different geological conditions. They found no physical evidence of drilling fluid or other surface sources for microbial contamination. In contrast, Sinclair and Ghiorse (1989) reported the presence of phototrophs in many of the samples, some from as deep as 213 m (699 ft) below the surface.

Sinclair and Ghiorse (1989) interpreted the presence of light-requiring phototrophs as an indication of some connection between the aquifer and the surface, through which these organisms could pass with relative ease. They argued against contamination during sampling and suggested that phototrophs occur in upgradient wells that are close to recharge zones and stream cuts. In addition, Sinclair and Ghiorse (1989) suggested that the presence of previously installed monitoring wells may be a pathway for phototrophs to reach deep aquifers.

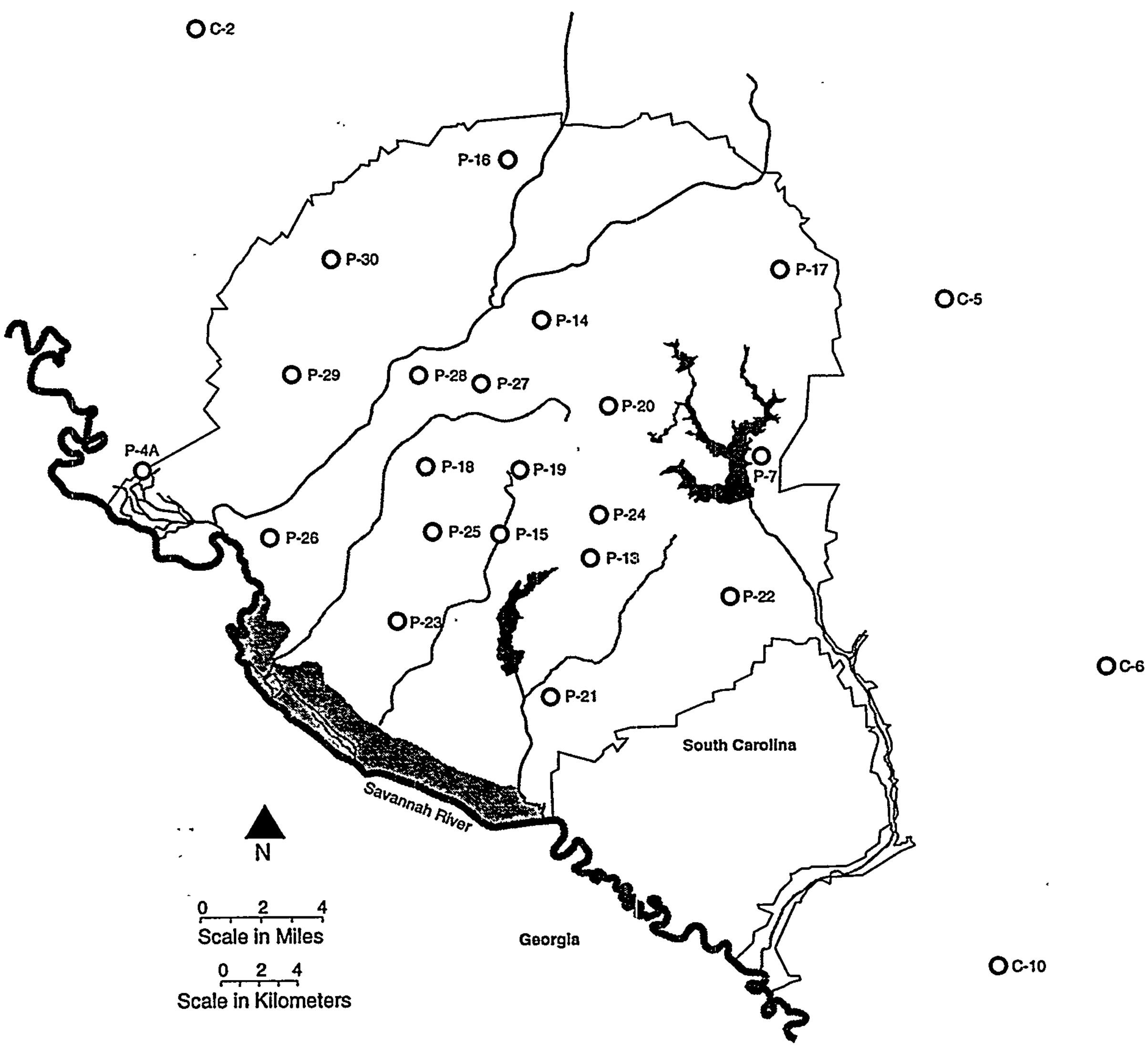

Figure 6-6. Well Location Map for SRS and Surrounding Region (modified after Strom and Kaback 1992).

Several investigators found a diverse and abundant suite of microorganisms in the SRS sediments (Balkwill 1989; Fliermans and Balkwill 1989; Fredrickson et al. 1991 and 1989; Hicks and Fredrickson 1989; Sinclair and Ghiorse 1989). Differences were noted in the microbial populations based on lithologic characteristics (Balkwill 1989; Fredrickson et al. 1989; Phelps et al. 1989b; Sinclair and Ghiorse 1989) and depth of the samples (Fredrickson et al. 1988; Sinclair and Ghiorse 1989). The results of these studies suggest that subsurface microbial populations play a significant role in diagenesis and subsurface geochemistry at SRS.

Microbial Diversity

Fredrickson et al. (1989) quantified autotrophic and heterotrophic bacterial populations in SRS subsurface sediments from the P24, P28 and P29 boreholes (Figure 6-6). Autotrophic bacteria populations were generally less dense than 103 per gram of dry sediment, with sulfur-oxidizing bacteria being the most frequently encountered group. Nitrifying bacteria were detected mainly in sediments from borehole P28, and their presence was correlated with pore-water ammonium concentrations. Heterotrophic bacteria greatly exceeded autotrophic with population densities greater than 10^6 per gram of dry sediment in about 60% of the samples. Microaerophilic N_2-fixing bacteria were cultured from more than 50% of the samples, and bacteria capable of growth on H_2 were cultured from 35% of the subsurface sediments examined.

Sinclair and Ghiorse (1989) examined the distribution and populations of bacteria, protozoa, algae, and fungi in the sediments of boreholes P24, P28, and P29. They found a surprisingly diverse suite of microorganisms (Table 6-1). Bacteria were found to be widely distributed in the subsurface. Bacterial population densities were occasionally as great at depth as in surface sediments, and the populations exhibited significant diversity with respect to the types of bacteria present. Eukaryotic microorganisms were also widely distributed, with the exception of algae, which were not present in any of the P24 sediment samples. An assortment of phototrophs (unicellular and filamentous green algae, diatoms, phytoflagellates, and a few cyanobacteria) were in more than half of the P28 and P29 sediment samples. Fungi were widespread at low population densities in all three subsurface profiles, with all but 5 of 47 samples containing fungi.

Sinclair and Ghiorse (1989) attributed the presence of phototrophs in samples from wells P28 and P29 to the wells' proximity to recharge zones, stream cuts, and previously installed monitoring wells. Thus, they concluded that samples from well P24 are probably most representative of deep subsurface environments.

Sinclair and Ghiorse (1989) found that subsurface samples generally exhibited a much higher viable (colony-forming units) to total bacteria ratio (as determined by the acridine orange direct count method). Values of this ratio ranged from 20 to 100% in the subsurface, compared with 0.4 to 1.7% in the surface sediments. Population densities of eukaryotic microorganisms were generally several orders of magnitude lower than bacterial populations.

Balkwill (1989) studied the diversity and morphological characteristics of aerobic bacteria in surface sediments and subsurface sediment samples from the vadose zone, aquifers, and confining units in boreholes P24, P28 and P29. Viable counts (colony-forming units) varied widely between geologic formations, ranging from 0 (no growth) to 1.2×10^8 cells per gram

Table 6-1. Number of Different Types of Microorganisms in SRS Subsurface Sediments (Source: Sinclair and Ghiorse 1989)

Type of Organisms	P24	P28	P29
Bacterial colonies	0 - 22	0 - 26	0 - 27
Fungal colonies	0 - 3	0 - 4	0 - 4
Actinomycete colonies		0 - 1	
Amoebae	0 - 4	0 - 4	0 - 4
Flagellates	0 - 3	0 - 6	0 - 4
Unicellular green algae		0 - 3	0 - 2
Filamentous green algae		0 - 1	0 - 1
Filamentous cyanobacteria		0 - 1	0 - 1
Diatoms			0 - 1

of dry sediment. The greatest growth was observed under low-nutrient conditions, but many also were capable of growth on nutritionally-rich media. Bacterial growth occurred on single carbon-source media, but the viable population counts were generally substantially lower than those obtained on complex media. Balkwill (1989) also examined temperature effects on growth. Greatest growth was observed at moderate temperatures characteristic of the ambient environment from which the samples were taken. Substantial growth occurred in surface sediment samples at elevated temperatures, but little or no growth occurred at elevated temperatures in samples from the subsurface. Analysis of colony types revealed a diverse bacterial microflora, with 172 distinct colony types found in the P24 samples, 236 in the P28 samples, and 168 in the P29 samples. More than 3500 microbial strains were isolated from these colony types.

DNA testing of the subsurface bacterial isolates revealed an even greater diversity than did standard bacterial identification methods (Jiménez 1990). Jiménez (1990) tested 18 bacterial isolates from the P24, P28, and P29 sediment samples, which had been identically classified as Pseudomonas luteola, using conventional methods. The greatest similarity among the isolates was 57%, suggesting that they were all different species. Similar results were obtained for eight isolates, which had been identified as Pseudomonas aeruginosa. Jiménez (1990) also found that bacterial isolates from the same depositional environment were, in general, more closely related than bacteria from formations having their origin in different depositional environments.

Lithologic Influences on Microbial Populations

Several investigators found inverse relationships between clay content and microbial populations and activity. Fredrickson et al. (1989) found that sediment texture, primarily clay content, was the best predictor of bacterial populations, showing an inverse relationship. The bacterial populations decreased as clay content increased. Sinclair and Ghiorse (1989) also found an inverse relationship between clay content and microbial populations.

Balkwill (1989) showed that the density of viable microflora varied significantly more between geologic formations (vertically) than within a given stratigraphic layer (horizontally). Vadose zone sediments and samples with clay content above 40% yielded the lowest viable bacterial populations. There was no general decrease in population density with depth. The specific composition of the heterotrophic subsurface microflora, however, varied considerably between geologic formations.

Two investigations (Balkwill 1989; Sinclair and Ghiorse 1989) suggested fundamental distinctions between bacterial populations might arise from lithology and environmental conditions in which the bacteria were growing. The distinctions were identified by the bacteria's gram reactions, which are based on their cell-wall structure and are a fundamental way of dividing bacteria (Clifton 1958; Doetsch and Cook 1973).

Of the more than 3500 microbial strains isolated by Balkwill (1989), 1200 were isolated on PTYG agar. These strains isolated on PTYG agar were examined using light microscopy and by gram reaction testing. A greater percentage of gram-positive strains were found in vadose zone sediments (27%) and high clay content samples (45-63%) than from transmissive aquifer sediments (8-17%). Relatively few microbial cells were detected under light microscopic examination of high clay content samples. The majority of these (95%) were small, nondividing cocci or coccoid rods that occurred individually. Some filamentous forms also were observed. Aquifer samples contained large numbers of microbial cells, approximately 65% of which were small cocci or coccoid rods that occurred individually. The aquifer microflora was more diverse morphologically than the microflora in confining units. Cells undergoing division and microcolonies (5-40 cells) were seen frequently, and large colonies (greater than 100 cells) also were observed.

Sinclair and Ghiorse (1989) tested 240 bacterial isolates from the deep subsurface for their gram reaction. Most were gram-negative (73%). Again, there was a strong association between gram-positive bacteria and clay content. In samples with greater than 50% clay, 100% of the isolates were gram-positive; in samples with 30%-50% clay, 83% were gram-positive; while in samples less than 30% clay, 21% were gram-positive. They also showed a strong association between gram-negative bacterial isolates and high sand content samples; however, gram-positive bacteria never were excluded.

Sinclair and Ghiorse (1989) also tested 89 isolates for their ability to deposit lipophilic storage material after growth on carbon-enriched agar. Most (74%) were capable of depositing lipophilic storage material. Most of those originated from high sand samples, and most (84%) were gram-negative.

Metabolic Flexibility

Hazen et al. (1991) compared the microbiology of the subsurface sediments from boreholes P24, P28, and P29 to the microbiology of the groundwater samples obtained from the same formations as the sediment samples. The bacterial populations in the groundwater were generally 2-3 orders of magnitude lower than in the adjacent sediments. The viable microbial counts for groundwater were generally 3-5 orders of magnitude lower than the sediment counts. These results indicated that the majority of the microbial community in the deep subsurface is attached to the sediments. The bacterial communities associated with the sediments were also generally more metabolically flexible than the groundwater bacterial communities. A larger proportion of the total sediment bacterial populations were capable of metabolizing a broad variety substrates than the groundwater population.

Fredrickson et al. (1988) found that plasmid occurrence in bacteria tended to increase with subsurface depth. The higher metabolic cost for maintaining the additional DNA is apparently offset by the fact that the bacteria can metabolize a greater number of compounds. This capability appears to convey a significant advantage in the deep subsurface because the number of available carbon sources is limited. This interpretation is consistent with the results of Sinclair and Ghiorse (1989), who found that subsurface samples generally exhibited a much higher viable (colony-forming units) to total bacteria ratio (as determined by the acridine orange direct count method). Values of this ratio ranged from 20 to 100% in the subsurface, compared with 0.4 to 1.7% in the surface sediments.

Microbial Colonization

Sargent and Fliermans (1989) discuss three hypotheses regarding how microorganisms got into the subsurface sediments. Two hypotheses involve transport through the sediments. The first involves predominantly vertical transport from the surface sediments by displacement during weathering, followed by continued downward migration in the groundwater. The second hypothesis involves predominantly horizontal transport with groundwater flow carrying the microbes from their source areas to their present locations. This would require transport of 60-80 km (37-50 mi) in the deeper aquifers. The third hypothesis is that microbial populations were introduced or were part of the original sedimentary deposition and have simply continued to survive and evolve. Preferential attachment of the microbial populations to the sediments (Hazen et al. 1991) and the DNA comparison test results of Jiménez (1990) support the indigenous population theory, although influence by the other two processes can not be ruled out.

Microbial Influences on Subsurface Geochemistry

Madsen and Bollag (1989) measured microbial activity using carbon dioxide ($^{14}CO_2$) evolution from glucose and indole, methane production, and sulfate ($^{35}SO_4^{-2}$) reduction in sediment samples from boreholes P24, P28, P29, and MCB-5 over periods of 1-5 days. The short times were employed to minimize laboratory-induced artifacts. No methane production was observed in any of the sediment samples. Sulfate reduction was observed in only 2 of 16 samples from borehole P28 and was totally absent in borehole MCB-5 (P24 and P29 were not tested). Sulfate reduction was carbon-limited in two additional samples from P28 and was both carbon- and electron-donor-limited in two other samples. Rates of aerobic microbial CO2 production from glucose in the subsurface samples were lower than in the surface soils, but were comparable to surface soils for metabolism of indole. Anaerobic activity was observed in many samples. Injecting sterile air following initial anaerobic tests generally produced large increases in microbial activity, suggesting the presence of facultative aerobic microorganisms or a predominance of aerobic microorganisms. The lack of methanogenesis and the infrequent zones of sulfate reduction suggests that aerobic metabolism is pervasive in the SRS sediments (Madsen and Bollag 1989).

McMahon and Chapelle (1991) provided strong evidence that microbial fermentation in aquitard sediments can provide the source of carbon substrates that support the large, respiring microbe populations in subsurface aquifers. They examined sediments from a borehole near Lake City, South Carolina, for simple volatile fatty acids and found alternating bands of low and high formate and acetate concentrations with depth; higher concentrations were associated with aquitards and the lower concentrations with aquifers. The magnitudes of formate and acetate they found were consistent with the range of background dissolved organic carbon measurements found in North American groundwaters (Leenheer et al. 1974). McMahon and Chapelle (1991) estimated carbon dioxide (CO_2) production in the aquifer sediments based on acetate and formate diffusion from the aquitards into the aquifers followed by organic anion conversion to CO_2 during microbial respiration. The estimated rate of CO_2 production compared favorably with an independent estimate based on a mass balance calculation of dissolved inorganic constituents along an aquifer flow path. Additional laboratory incubation tests provided further evidence supporting their hypothesis. Fermentation exceeded respiration in the aquitard sediments, leading to accumulation of the simple organic acids. In aquifer sediments; however, respiration greatly exceeded fermentation, yielding a net consumption of simple organic acids.

Murphy et al. (1992) tried to extend the work of McMahon and Chapelle (1991) by suggesting that microbial degradation of lignite acts as microsites to supply carbon sources to respiring bacteria. They combined geochemical modeling with groundwater chemistry and isotope analyses to assess the role of microorganisms on the chemical evolution of groundwater along three distinct flow paths in the Middendorf Formation (McQueen Branch Aquifer) in the SRS region. The terminal points of the flow paths were wells P28 and P29 for the first, P24 for the second, and C10 for the third. The groundwaters were generally of low pH (4.5 to 6.9), had low electrical conductivity, and had an ionic composition dominated by sodium, calcium, sulfate and bicarbonate concentration. Several ions, including sulfate, potassium, and sodium, increased in concentration by more than an order of magnitude along the longest flow paths (those terminating in P24 and C10). Other changes along the flow paths included increases in pH, conductivity, and bicarbonate concentration. Isotope data are provided for ^{13}C and ^{14}C of the dissolved inorganic carbon and for tritium, but the interpreted support for their hypothesis is weak. The range of observed changes in the $\delta^{13}C$ values was 0.9-1.3 per milliliter. This range is likely within the background variability in the groundwaters.

Murphy et al. (1992) also estimated *in situ* respiration rates in the Middendorf Formation (McQueen Branch Aquifer) as CO_2 production using two independent methods. The two methods generally yielded comparable results, differing by less than a factor of five for three of the four wells, and by approximately an order of magnitude in the fourth well. The rates ranged from 3.5×10^{-6} to 4.3×10^{-4} mmol CO_2/l/yr. McMahon et al. (1990) measured CO_2 production rates in incubated sediment samples. Their results can be converted to the same units by assuming values for the bulk density of the sediment (1.6 g/cm^3) and for porosity (0.25). Two samples from the Middendorf Formation (McQueen Branch Aquifer) in a borehole near Aiken yielded CO_2 production rates of 9.5×10^{-5} and 6.4×10^{-4} mmol CO_2/l/yr using these assumptions. These values are approximately two orders of magnitude lower than CO_2 production rates estimated for the shallower aquifers near Hilton Head, South Carolina (Chapelle et al. 1988), but are in the same range as other determinations made on sediment samples from South Carolina Coastal Plain sediments (McMahon et al. 1990).

The results cited above suggest that microbial influences on subsurface geochemistry at SRS may be significant. CO_2 and carbonate equilibria play an important role in the alkalinity of natural waters (Drever 1988). Production of CO_2 will therefore influence the aquifer alkalinity and pH. This influence can be seen in the evolution of Cretaceous aquifer groundwater from sulfate-rich to bicarbonate-rich (Murphy et al. 1992).

Contaminant Transport

General Factors

The transport of contaminants by groundwater is controlled by several chemical processes and the physical process of groundwater flow. These processes include precipitation-dissolution, acid-base reactions, oxidation-reduction, adsorption, and biodegradation. These reactions are influenced by the chemistry of the groundwater and physical properties of the aquifer such as mineralogy and grain size. In addition, some contaminants can be transported associated with colloidal material or as nonaqueous phase liquids (NAPLs). Because transport of contaminants can involve all of these reactions and many are interrelated, modeling of contaminant migration in groundwater is quite complex. All reactions, kinetics of the reactions, and heterogeneities in the physical properties of the aquifer must be considered. To date, there are no models that successfully incorporate all of these considerations to accurately predict the behavior of contaminants in real systems.

The most widely used method of estimating contaminant behavior is to use empirical observations of contaminant retardation during groundwater flow. Retardation is defined as the ratio of the contaminant average linear velocity to groundwater average linear velocity. When the simplifying assumption is made that all reactions involving a contaminant are reversible and rapid relative to groundwater flow (i.e., equilibrium is achieved), it has been shown that:

$$R = 1 + \frac{\rho_b K_d}{n}$$

where ρ_b is the bulk density of the sediment, n is the effective porosity of the sediment, and K_d is the distribution coefficient that describes the partitioning of a contaminant between the solid and aqueous phases. The simplifying assumption neglects many precipitation-dissolution and acid-base reactions, most oxidation-reduction reactions, and all biodegradation reactions. However, for contaminants in some systems, this retardation equation provides a reasonable estimate. It can also often be used effectively to estimate a minimum retardation. This is valuable for studies such as risk assessments, where travel times of contaminants to exposure points may affect risk calculations.

Bulk densities (ρ_b) vary among SRS sediments. Bulk density is a function of the total porosity and mineralogy of the sediment. For a sediment with a given mineralogy, the bulk density is inversely proportional to total porosity. Bulk density depends on mineralogy because the densities of the major minerals in SRS sediments vary from about 2.5 to 4.3 g/cm^3. Thus, the proportion of various minerals in the sediment affects the bulk density. Table 6-2, showing bulk densities of various geologic units on the SRS, is reproduced from Looney et al. (1987). They recommend using a bulk density of 1.6 g/cm^3 for general transport and assessment calculations.

Effective porosity (n) is defined as the fraction of the total volume of sediment that is pore space available for groundwater flow and transport. Effective porosity is different from total porosity because total porosity includes all pore spaces, even those unavailable to

Table 6-2. Parameters for General Inorganic and Organic Contaminant Transport Estimations (Looney et al. 1987)

Parameter	Recommended Value
Bulk Density (*ρb*)	1.6 g/cm^3
Effective Porosity (*n*)	0.2 (dimensionless)
Fraction of organic carbon (*foc*)	0.01 (dimensionless)
Coefficients for Karickhoff type equation	
A	0.79
B	-1.71

groundwater flow. Looney et al. (1987) recommended using an effective porosity value of 0.2 for general transport and assessment calculations involving SRS sediments.

The distribution coefficient (K_d) is defined by Fetter (1988) as:

$$K_d = \frac{dC^*}{dC}$$

where C^* is the mass sorbed per unit bulk dry mass of soil and C is mass concentration in solution. In practice, K_d values generally are measured in the laboratory with single contaminants sorbed to soils or specific minerals pertinent to soils.

The distribution coefficient (K_d) for a contaminant is dependent on several aquifer properties and chemical properties of the contaminant. Contaminants are retarded in their migration through an aquifer by incorporation into solid phases during precipitation reactions, ion exchange, and sorption to the surfaces of aquifer materials. These reactions depend, in part, on the mineralogy and the available surface area of the aquifer materials.

Inorganic Contaminant Transport

One measure of the ability of a sediment to sorb cations is the cation exchange capacity (CEC). The CEC is controlled by the mineralogy of the sediments with clay-rich sediments having higher CECs than sandy sediments. Siple (1967) reported CEC values that range from less than 1 milliequivalent per 100 grams (meq/100g) to greater than 15 meq/100g. The higher values are generally from the McBean Formation where smectites are relatively abundant. Figure 6-7 is a histogram illustrating the CEC values obtained from different geologic units (Siple 1967). The data are arranged from youngest to oldest going from top to bottom in the chart. Units dominated by kaolinite clay generally have lower CECs while the smectite-rich McBean and Warley Hill units typically have CECs at the higher end of the range.

Though the anion exchange capacity is rarely measured, the process of anion exchange is pertinent to SRS sediments. The acidic nature of SRS soils, particularly when combined with acidic contaminant plumes can result in sorption of anions by the sediments. Korom (1993) documented this process in SRS soils.

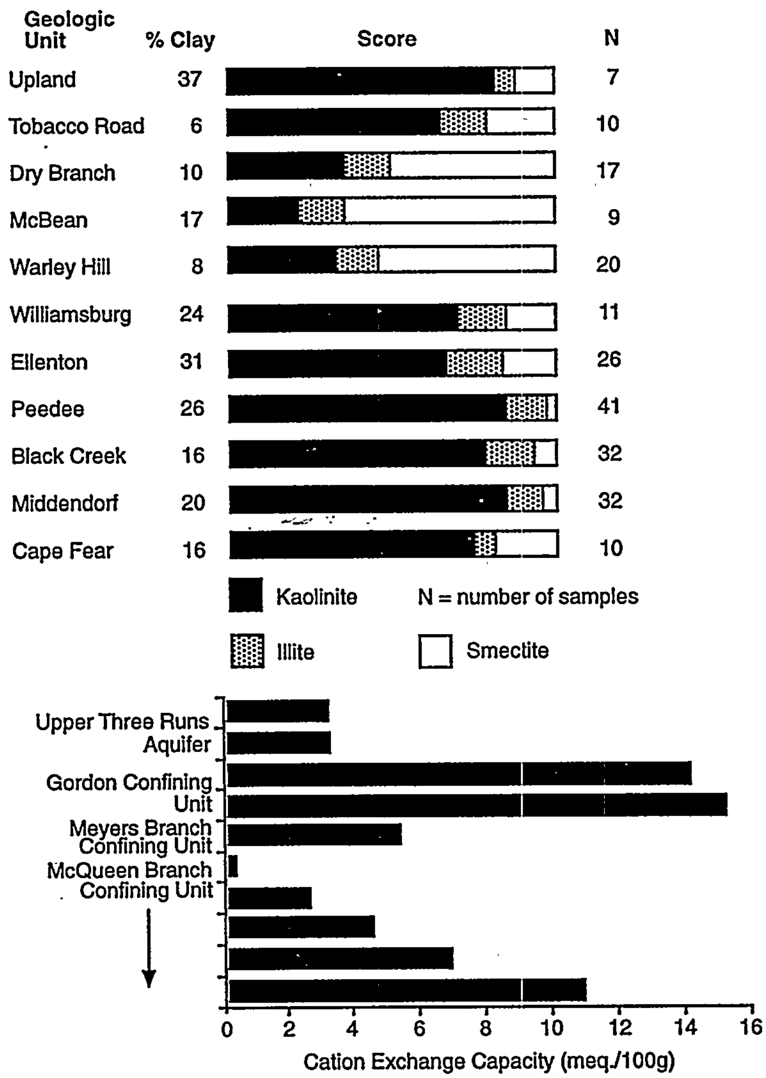

Figure 6-7. Graphs Ilustrating the Clay Mineralogy (top) and Cation Exchange Capacity (bottom) of Samples from Various Geologic Units at SRS (after Siple 1967; Strom and Kaback 1992).

Minerals react with a contaminant plume in different ways. The concentration of adsorption sites and the strength with which these sites bind various contaminants varies among minerals. Likewise, some minerals are open to ion exchange reactions; others are not. Dissolution of some minerals may result in precipitation of related phases that may incorporate contaminants as co-precipitates. In addition, dissolution of minerals may indirectly affect the mobility of contaminants by changing the pH of the groundwater or increasing the concentration of complexing ligands in the groundwater. Because soils are mechanical mixtures of minerals that may exhibit this wide array of behaviors, the mineralogic composition of a soil is important to the transport behavior of contaminants.

In general, quartz is the dominant mineral in the siliciclastic aquifers at the SRS. Because quartz is relatively nonreactive and often is coated by other phases, its influence on water quality is negligible. The more reactive silicate components of the Coastal Plain sediments include feldspars and a variety of phyllosilicates, including mica and clay minerals. Glauconite and zeolites occasionally are encountered in Eocene sediments, especially in the more marine-influenced sections.

The clay minerals in SRS sediments exert a strong influence on the transport of many contaminants because of the clays' larger surface area and higher surface charge. Strom and Kaback (1992) surveyed the clay mineralogy of different geologic units at SRS. They found that kaolinite is the predominant clay mineral in most SRS sediments, especially in the older Cretaceous sediments and the youngest sediments, the upland unit. Smectites (montmorillonite or other expandable-layer clays) are found in all of the geologic units but seem to be most abundant in the Dry Branch, McBean, and Congaree Formations. Other clay minerals identified by Strom and Kaback (1992) include minor amounts of illite and a mixed layered clay tentatively identified as an illite or vermiculite. Looney et al. (1990) found that kaolinite was dominant in their samples of background surface soils. Vermiculite was found to be less abundant than kaolinite, but more abundant than the minor amounts of illite identified in the surface soils.

Nonsilicate minerals are not adundant in the aquifers underlying SRS, but they are widespread and have a marked effect on groundwater chemistry. Those nonsilicate minerals that have been identified by X-ray diffraction in core samples include calcite, pyrite, marcasite, gypsum, barite, goethite, and hematite. Calcite is a major component in Eocene sediments in the southern half of the site. Groundwater that has been in contact with the Eocene sediments approaches equilibrium with calcite and is generally higher in calcium and bicarbonate ions and in total dissolved solids than water that has only been in contact with siliciclastic aquifers. Pyrite and marcasite are sulfide minerals that are typically the product of the early diagenesis of sediments deposited under reducing conditions. Their oxidation in the subsurface can help to maintain reducing conditions and increase the acidity and sulfate concentration of the groundwater. Dissolution of gypsum and barite also elevates the sulfate concentration of groundwater.

Iron oxides and oxyhydroxides, such as hematite and goethite, are generally the most abundant of the nonsilicate minerals and can have a major effect on groundwater chemistry and contaminant transport. These minerals generally occur as fine-grained pore-filling and grain-coating phases. Thus, for much of the sediment at SRS, it is the surfaces of these minerals that have the most contact with passing groundwater. The surface properties of these iron minerals are conducive to the adsorption of many metals and radionuclides.

Phosphate minerals such as apatite, monazite, and crandallite commonly occur in SRS sediments. Though their relative abundance is low, these minerals may have an influence on the transport behavior of many contaminants. Phosphate phases of contaminants such as uranium, plutonium, and lead are relatively insoluble and may precipitate if phosphate is available. The dissolution of naturally occurring phosphate minerals under mildly acidic conditions can provide the necessary phosphate for precipitation of contaminant phosphate phases. In addition, the naturally occurring phosphate minerals generally contain concentrations of uranium, thorium, and their progeny that are considerably elevated above the background soil levels. They may also contain elevated concentrations of a variety of other elements including arsenic and the lanthanide elements. Thus, at more acidic conditions, where the phosphate phases of these constituents are unstable, the naturally occurring constituents may be released into the groundwater. This can obscure the true nature and extent of a contaminant plume.

Migration of contaminants rarely occurs strictly according to the concepts of retardation as governed by Kd values. Complexing by inorganic and organic ligands, and sorption to colloidal particles can enhance the mobility of contaminants. However, Kd values typically are measured in simple systems where these processes are insignificant. For realistic risk assessment and other groundwater modeling, these effects must be considered.

The ambient groundwater at SRS contains inorganic ligands that can significantly enhance the mobility of certain contaminants. For example, at typical chloride concentrations and $pH<5.5$, mercury may exist predominantly in a neutrally charged chloride complex that is not readily adsorbed by sediments. The dominance of this complex may explain the relatively rapid migration of mercury in the contamination plume from the H-Area Seepage Basins. Iodide, which occurs in SRS groundwater in concentrations up to 500 mg/l (Stone et al. 1984), forms even stronger complexes with mercury and may also enhance the mobility of cadmium. Another example of constituents in ambient groundwater affecting the mobility of contaminants is the carbonate complexing of uranium and plutonium. At $pH>6$, these carbonate complexes can dominate the transport behavior of uranium and plutonium and such behavior should be considered for contaminant plumes that migrate through calcareous sediments.

Colloids suspended in groundwater also can enhance the mobility of contaminants if the contaminants are adsorbed by or coprecipitated with the colloidal particles. Kaplan (1993) studied colloidal migration of radionuclides in the plume that originated from the F-Area Seepage Basins. This study suggested that the mobility of a very small fraction of the plutonium released was enhanced by colloidal migration. The migration of other radionulcides was less affected. Though a small fraction of plutonium associated with colloidal material may have migrated, there is no evidence that this mechanism plays a major role in contaminant transport in SRS aquifers.

Organic Contaminant Transport

The retardation of nonionic organic contaminants is related to the fraction of organic carbon in the sediments of an aquifer. Karickhoff et al. (1979) presented the following relationships to describe the K_d value for an organic constituent in terms of the fraction of organic carbon (*foc*), the distribution coefficient normalized to particulate organic carbon (K_{oc}), and the octanol-water partition coefficient (K_{ow}):

$$K_{oc} = \frac{K_d}{foc}$$

$$\log K_{oc} = A \log K_{ow} + B$$

The *foc* is measured in aquifer sediments, the K_{ow} is related solely to the chemistry of the contaminant and is available in many compilation tables, and the coefficients *A* and *B* are empirical fitting parameters. Looney et al. (1987) present a discussion of these relationships and the coefficients A=0.79 and B=-1.71, which are consistent with K_d values measured at SRS. Looney et al. (1987) recommend the use of 0.01 as the fraction of organic carbon (*foc*) in SRS aquifers when no site specific data are available.

Table 6-2 summarizes parameters recommended by Looney et al. (1987) for use in general contaminant transport estimates at the SRS. Site-specific data should be used whenever possible and considerations discussed in this chapter (mineralogy, complexing, etc.) should be addressed when contaminant transport calculations are made.

Summary

Three factors are recognized as having major impact on the quality of groundwater in the SRS region: the composition of rainfall, microbiological activity in the subsurface, and chemical reactions with the sediments in the Coastal Plain. The principal chemical components of rainwater in the region reflect a sea water composition plus calcium and sulfate, likely derived from the burning of fossil fuel. Microbiological activity increases the bicarbonate content of the water and leads to suboxic conditions in many of the deeper aquifer units. Chemical constituents are added to groundwater by weathering of silicate minerals and, more important, dissolution of limestone and oxidation of sulfide minerals. In the southern areas of the region, natural water softening by cation exchange processes has lead to the formation of high sodium and low calcium water types in several of the aquifers.

Diverse microfaunal communities that include both autotrophic and heterotrophic populations have been identified in the subsurface. Both groups play significant roles in diagenesis of sediments and subsurface geochemistry of both natural and contaminated areas.

Many of the current studies of groundwater quality on the site focus on the role of inorganic and microbiological processes on migration, retention, and break-down of contaminants in the subsurface. These studies are particularly important in developing models of contaminant transport, interpretation of ground-water monitoring data, and development of remediation strategies for contaminated sites. Due to the complexity of the subsurface environment, its general inaccessibility, and the reactions taking place, many simplifying assumptions normally are made in the models. To date, there are no models that successfully incorporate all of the geochemical, biochemical, and physical transport processes, and current estimates rely heavily on empirical observations and analysis.

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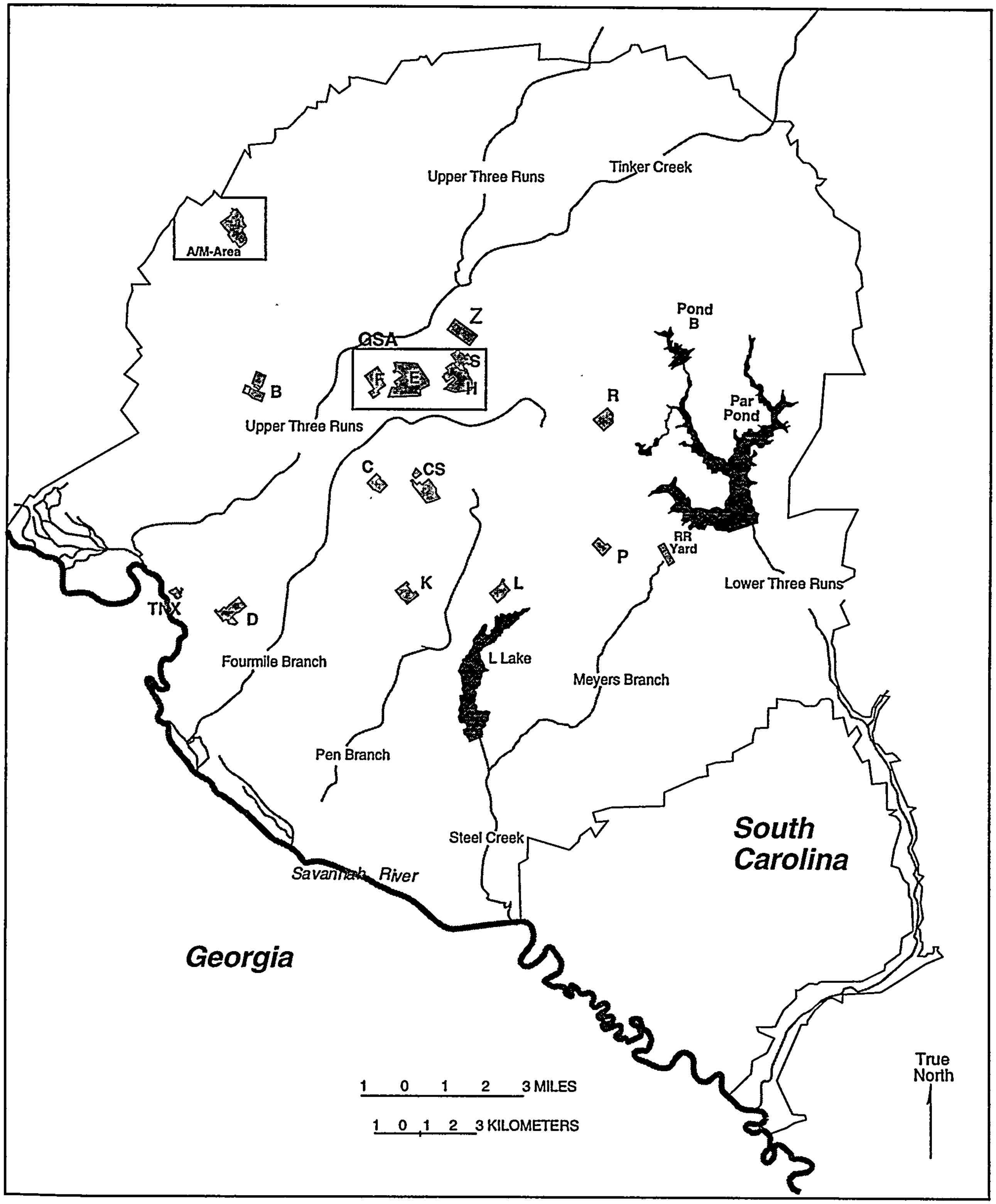
Upper Three Runs
Tinker Creek
A/M-Area
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Pond
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Upper Three Runs
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Par
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CS
RR
Yard
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Lower Three Runs
K
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TNX
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L Lake
Fourmile Branch
Meyers Branch
Pen Branch
Steel Creek
South
Carolina
Savannah River
Georgia
1 0 1 2 3 MILES
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True
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Geologic Time Scale

Major Geochronologic/Chronostratigraphic Units

Eon	Era	Period/System	Epoch/Series	Approximate age million years before present
Phanerozoic	Cenozoic	Quaternary	Holocene	.010
			Pleistocene	2
		Tertiary	Pliocene	5
			Miocene	24
			Oligocene	38
			Eocene	55
			Paleocene	63
	Mesozoic	Cretaceous		138
		Jurassic		205
		Triassic		~240
	Paleozoic	Permian		290
		Pennsylvanian		~330
		Mississippian		360
		Devonian		410
		Silurian		435
		Ordovician		500
		Cambrian		~570
Proterozoic		(pre-Cambrian)		2,500
Archean				

After Dutro, J.T., jr., R.V. Dietric, and R.M. Foose, 1989, AGI Data Sheets, 3rd ed., American Geologican Institute, Alexandria, VA, 22303.

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Glossary of Terms

acidogenic - A material or system that can produce an acid or hydrogen ion by chemical reaction.

adsorption - Adherence of gas molecules, or of ions or molecules in solutions, to the surfaces of solids with which they are in contact.

aeromagnetic survey - A magnetic survey made with an airborne magnetometer.

allochthon [sed] - A mass of redeposited sedimentary materials originating from distant sources.

allochthon [tect] - A mass of rock that has been moved from its place of origin by tectonic process, as in a thrust sheet or nappe.

alluvial - Pertaining to material deposited by streams or running water or descriptive of materials composed of alluvium.

alluvium - Materials such as clay, silt, sand, or gravel that are transported and deposited by running water such as a stream, river, or flood.

amphibolite - A metamorphic rock consisting mainly of amphibole and plagioclase with little or no quartz. As the content of quartz increases, the rock grades into hornblende plagioclase gneiss.

anaerobic - Describes an organism that can live in the absence of free oxygen; also describes its activities.

andesite - A dark-colored, fine-grained extrusive rock.

anelastic - Pertaining to the inelastic relaxation of small deformations, especially absorption of vibrations or seismic energy.

antiform - A fold whose limbs close upward in strata for which the stratgraphic sequence is not known.

aquifer - A body of rock or sediment that contains sufficient saturated, permeable material to conduct groundwater.

aquitard - A confining bed that retards, but does not prevent, the flow of water to or from an adjacent aquifer; a leaky confining bed.

argillaceous - Composed of clay-size particles or clay minerals.

argillic - Pertaining to clay or clay minerals; e.g. "argillic alteration" in which certain minerals of a rock are converted to clays.

arkose - A feldspar-rich, typically coarse-grained sandstone, commonly pink or reddish to pale gray or buff, composed of angular to subangular grains that may be either poorly or moderately well sorted, usually derived from the rapid disintegration of granite or granitic rocks, and often closely resembling granite.

aseptic - Pristine, clean, no bacteria.

augen - In foliated metamorphic rocks, such as schists and gneisses; large, lenticular mineral grains or mineral aggregates having the shape of an eye in cross section, in contrast to the shapes of other minerals in the rock.

autotrophic - Making its own food by photosynthesis, as a green plant, or by chemosythesis, as any of a certain bacteria.

authigenic - Describes rock constituents and minerals that have not been transported or that crystallized locally at the spot where they are now found.

basalt - A dark-colored mafic igneous rock, commonly extrusive but locally intrusive, composed mainly of calcic plagioclase and pyroxene. The extrusive equivalent of gabbro.

basement - The crust of the earth below the sedimentary deposits.

bimodal - Having two modes. Bimodal distribution: Two modes having a higher frequency of occurrence than other adjacent individuals or classes.

bioclastic - A single fossil fragment. Material derived from the supporting or protective structures of animals or plants.

biomoldic - Porosity created by the dissolution of skeletal tests.

biosphere - All the volume occupied or favorable for occupation by living organisms. All living organisms of the earth and its atmosphere.

bryozoans - Any invertebrate belonging to the phylum Bryozoa and characterized chiefly by colonial growth; a calcareous skeleton, or, less commonly, a chitinous membrane; and a U-shaped alimentary canal with mouth and anus.

calcarenite - A limestone consisting of more than 50% detrital calcite particles of sand size; a consolidated calcareous sand.

calcareous - Describes a substance that contains calcium carbonate. When applied to a rock name, it implies that as much as 50% of the rock is calcium carbonate.

calcilutite - A limestone consisting of more than 50% detrital particles of silt or clay size or both; a consolidated calcareous mud.

caliche - A reddish-brown to buff or white calcareous material of secondary accumulation, composed largely of calcium salts.

Cambrian - The earliest period of the Paleozoic era, from between 570 and 500 million years ago (Appendix II).

carbonaceous - Describes a rock or sediment that is rich in carbon; coaly.

carbonate - A sediment formed by the organic or inorganic precipitation from an aqueous solution of carbonates of calcium, magnesium, or iron.

Carolina bay - Any of various shallow, commonly oval or elliptical, generally marshy, closed depressions in the Atlantic Coastal Plain (from southern New Jersey to northeast Florida, especially developed in the Carolinas), ranging from about 100 m (328 ft) to many kilometers long, rich in humus, and containing tree and shrub vegetation different from that of surrounding areas.

Cenozoic - An era of geologic time, from 63 million years ago to present (Appendix II).

chalcedony - A cryptocrystalline variety of quartz. It is commonly microscopically fibrous.

chlorite - A group of platy, monoclinic, usually greenish minerals associated with and resembling the micas.

chlorite schist - A schist in which the main constituent is chlorite.

chlorite-hornblende schist - A schist in which chlorite and hornblende are the main constituents with little or no quartz.

chronostratigraphic -A time stratigraphic unit.

clast - An individual constituent, grain or fragment of a sediment or rock, produced by the mechanical weathering (disintegration) of a larger rock mass; e.g. a phenoclast.

clastic - Pertaining to or being a rock or sediment texture composed principally of broken fragments that are derived from pre-existing rocks or minerals and that have been transported individually from their places of origin.

clinoptilolite - A potassium-rich zeolite mineral.

cocci - A spherical cell.

colloidal - Describing particle-size of less than 0.00024 mm, i.e. smaller than clay size.

collophane - Any of the massive cryptocrystalline varieties of apatite, often opaline, horny, dull, colorless, or snow-white in appearance, that constitute the bulk of phosphate rock and fossil bone and that are used as a source of phosphate for fertilizers; especially carbonate-apatite or a hydrox-apatite containing carbonate, and sometimes francolite.

confining unit - A body of impermeable or distinctly less permeable material stratigraphically adjacent to one or more aquifers.

conglomerate - A coarse-grained, clastic sedimentary rock composed of rounded (to subangular) fragments larger than 2 mm in diameter (granules, pebbles, cobbles, boulders), set in a fine-grained matrix of sand, silt or any of the common natural cementing materials (such as calcium carbonate, iron oxide, silica, or hardened clay); the consolidated equivalent of gravel both in size range and in the essential roundness and sorting of its constituent particles.

Cretaceous - The final period of the Mesozoic era covering between 138 and 63 million years ago (Appendix II).

cristobalite - A mineral: SiO_2. It is a high temperature polymorph of quartz and tridymite.

Darcy (measurement) - A standard unit of permeability, equivalent to the passage of one cubic centimeter of fluid of one centipoise viscosity flowing in one second under a pressure differential of one atmosphere through a porous medium having an area of cross-section of one square centimeter and a length of one centimeter.

delta plain - The level or nearly level surface composing the landward part of a large delta; an alluvial plain characterized by repeated channel bifurcation and divergence, and multiple interdistributary flood basins.

dendritic drainage - A tree-like drainage pattern in which the streams branch randomly in all directions and at almost any angle.

depositional environment - An environment suitable for the accumulation of earth materials such as a river delta, shallow seas, or lakes.

detachment fault - Detachment structure of strata due to deformation, resulting in independent styles of deformation in the rocks above and below.

dextral - Pertaining, inclined, or spiraled to the right.

diabase - An intrusive rock composed mainly of labradorite and pyroxene and characterized by an ophitic texture.

diagenesis - All processes that occur in sediment after it is deposited and buried, and before the onset of metamorphism. Compaction, cementation, authigenic mineral formation, etc., are all part of this process.

dike - A tabular igneous intrusion that cuts across the bedding or foliation of the country rock.

dike swarm - A group of dikes, either radial from a single source or in parallel, linear arrangement.

dinoflagellate - A one-celled, microscopic, chiefly marine, usually solitary flagellate organism with resemblances to both animal (motility, ingestion of food) and plant (photosynthesis) kingdoms, characterized by one transverse flagellum encircling the body and usually lodged in a longitudinal groove and one posterior flagellum extending out from a similar median groove.

dip - The angle that a surface makes with the horizontal, measured perpendicular to the strike of the surface and in the vertical plane.

embayment - The formation of a bay, such as by the sea overflowing a depression of the land near the mouth of a river.

Eocene - The Eocene epoch occured during the early Tertiary period from 55 million to 38 million years ago (Appendix II).

eolian - Related to wind. Includes deposits as loess and dune sand; sedimentary structures such as wind-formed ripple marks; or erosion and deposition accomplished by the wind.

epicenter - That point on the earth's surface that is directly above the focus of an earthquake.

ERZ - vertical error estimate for the focal depth of an earthquake.

evapotranspiration - The sum of evaporation and transpiration.

extensional basin - A basin formed by crustal extension or pulling-apart of the crust. Extensional basins usually are bounded on one or both sides by normal faults.

facies - Rock (or sediment) type that grades laterally into another, indicating a change in depositional environment.

fall line - An imaginary line or narrow zone connecting waterfalls and rapids on several adjacent near-parallel rivers, marking the points where these rivers make a sudden decent from an upland to a lowland, as at the edge of a plateau.

fanglomerate - A sedimentary rock consisting of slightly waterworn, heterogeneous fragments of all sizes, originally deposited in an alluvial fan and subsequently cemented into a firm rock characterized by a considerable persistence parallel to the depositional strike and by a rapid downdip thinning.

fault - A surface or zone of rock fracture along which there has been displacement, from a few centimeters to a few kilometers in scale.

feldspathic - Describes a rock or other mineral aggregate containing feldspar.

felsic - Applied to an igneous rock, having light-colored minerals in its mode; also, applied to those light-colored minerals as a group.

fill-cut terraces - A terrace formed by deposition of sediments in a stream valley, usually from a change in the climate or by raising the local base level of the stream or valley.

fluvial - Pertaining to a river or rivers.

focal depth - The distance from the focus of an earthquake to the epicenter.

foraminiferan - Any protozoan belonging to the order Foraminifera, characterized by the presence of a test composed of agglutinated particles or of secreted calcite (and related to silica or aragonite) and commonly found in marine to brackish environments from the Cambrian to the present.

fugacity - A thermodynamic function expressed in units of pressure and used in calculations of chemical equilibrium.

fuller's earth - A very fine-grained, naturally occurring earthy substance (such as a clay or clay-like material) possessing a high adsorptive capacity, consisting largely of hydrated aluminum silicates (chiefly the clay minerals montmorillonite and palygorskite).

geomorphology - The branch of geoscience that treats the general configuration of the earth's surface. The study of the classification, description, nature, origin, and development of present landforms and their relationships to underlying structures, and of the history of geologic changes as recorded by these surface features.

geophysics - Application of physics to the earth.

glauconite - A dull-green, amorphous, and earthly or granular mineral of the mica group: $(KNa)\ (AlFe+^3Mg)_2\ (AlSi)_4O_{10}(OH)_2$.

glauconitic - Describes a mineral aggregate that contains glauconite, resulting in the characteristic green.

gneiss - A foliated rock formed by regional metamorphism in which bands or lenticles of granular minerals alternate with bands and lenticles in which minerals having flaky or elongate prismatic habits predominate.

Goethite - A yellowish, reddish, or brownish-black mineral. Goethite is the commonest constituent of many forms of natural rust or of limonite, and it occurs as a weathering product in the gossans of sulfide-bearing ore desposit.

graben - An elongate, relatively depressed crustal unit or block that is bounded by opposing normal faults on its long sides.

gradient (stream) - A rate of descent, the elevational loss of a stream over a given distance.

granitoid - A granitic rock.

greenschist - A schistose metamorphic rock whose green color is due to the abundance of chlorite, epidote, or actinolite.

head - See hydraulic head.

hematite - A common iron mineral that occurs as rhombohedral crystals, in masses or fabrous aggregates. Hematite can occur in different earthy colors, often as a red-brown and gray-black.

heterogeneous - Composed of unrelated or unlike parts.

heterotropic - Obtaining food from organic material only; unable to use inorganic matter to form proteins and carbohydrates.

hornblende gneiss - A gneissic metamorphic rock consisting of hornblende.

horst block - An elongated, relatively uplifted crustal unit or block that is bounded by faults on its long sides.

hydraulic conductivity - The rate of flow of water in meters per day through a cross section of one square foot under a unit hydraulic gradient, at the prevailing temperature (field permeability coefficient) or adjusted for a temperature of 60°F.

hydraulic gradient - In an aquifer, the rate of change of total head per unit of distance of flow at a given point and in a given direction.

hydraulic head - The height of the free surface of ground water.

hydrophobicity - Not capable of uniting with or absorbing water.

hydrosphere - All waters of the earth, such as the groundwater, oceans, rivers, and water in the atmosphere.

hypocenter - The point within the earth that is the center of an earthquake and the origin of the elastic waves that are produced by an earthquake.

igneous rock - A rock or mineral that solidified from magma or partly molten material.

illite - A general name for a group of three-layered, mica-like clay minerals that are widely distributed in argillaceous sediments.

intercalate - Describes layered material that exists or is introduced between layers of different character; especially said of relatively thin strata of one kind of material that alternate with thicker strata of some other kind of material, such as lava flows, beds of shale, or intrusive sills that are "intercalated" in a large body of sandstone.

interdistributary bay - A pronounced indentation of the delta front between advancing stream distributaries, occupied by shallow water, and either open to the sea or partly enclosed by minor distributaries.

interfluvial - Lying between streams; a divide.

intrusive rock - Both the process and the rock so formed, such as an igneous intrusion. A rock that crystallized below the surface of the earth.

isoclinal - A fold in which the limbs are parallel.

isopach - A line drawn on a map through points of equal thickness of a stratigraphic unit or group of stratigraphic units.

isopotentiometric map - A map delineating equal groundwater levels.

isoseismal - A line connecting points on the earth's surface of equal earthquake intensity.

Jurassic - The period of the Mesozoic era from 205 to 138 million years ago (Appendix II).

kaolin - A group of clay minerals characterized by a two-layered structure in which each silicon-oxygen sheet is alternately linked with one aluminum-hydroxyl sheet and having the approximate composition of $Al_2Si_2O_5(OH)_4$.

kaolinite - A common clay mineral of the kaolin group: $Al_2Si_2O_2$.

kinematic - The branch of mechanics that deals with motion.

labradorite (mineral) - A dark mineral of the plagioclase feldspar group.

lacustrine - Formed in a lake or lakes; e.g. "lacustrine sands" deposited on the bottom of a lake, or a "lacustine terrace" formed along the margin of a lake.

lepisphere - A micro-sized spheroidal diagenetic body, usually composed of silica, with radial crystal orientation and scaly crystal terminations on the outer surface.

ligand - An element or ion that forms a coordination complex with a central, usually metallic, atom.

lignite - A brownish-black coal.

limy clay - A clay consisting of large amounts of lime.

lipophilic - Having a strong attraction for fats.

liquefaction - The transformation of loosely packed sediment into a fluid mass preliminary to movement of a turbidity current by subaqueous slumping or sliding; often occurs during earthquakes.

lithified - Changed to stone; consolidated from a loose sediment to a solid rock.

lithologic - The description of a rock type.

lithosphere - The solid portion of the earth, as compared to the atmosphere and the hydrosphere.

lithotectonic - A unit of rocks that is unified by structural or deformational features, mutual relations, origin, or historical evolution.

lysimeter - An instrument used to measure quantities of water used by plants, evaporated from soil, and lost by deep percolation.

macrofauna - Living or fossil animals large enough to be seen with the naked eye.

mafic - A magnesium- and iron-rich igneous rock composed of one or more ferromagnesian, dark-colored minerals such as pyroxene or olivine.

mafic volcanic rock - A volcanic rock composed of one or more ferromagnesian, dark-colored minerals in its mode.

marcasite - A common light yellow or grayish mineral. It is dimorphous with pyrite and resembles it in appearance.

marl - A soft, grayish to white, earthy or powdery, usually impure calcium carbonate precipitated on the bottom of fresh water lakes and ponds.

meander - One of a series of regular, sharp, freely developing, and sinuous curves, bends, loops, turns, or windings in the course of a stream.

meander cut-offs - A shortened channel segment where a stream cuts through a meander neck.

meander scroll - One of a series of long, parallel, closely fitting, arcuate ridges and troughs formed along the inner bank of a stream meander as the stream migrates laterally down-valley and toward the outer bank.

Mesozoic - An era of geologic time from 63 to 240 million years ago (Appendix II).

metagraywacke - A metamorphosed sedimentary rock unit called a graywhacke, which is a coarse, angular grained sandstone.

metamorphic rock - A rock derived from preexisting rocks by mineralogical, chemical, and textural changes, in the solid state, in response to marked changes in temperature, pressure, shearing stress, and chemical environment at depth in the earth's crust, below the zones of weathering and diagenesis.

metasediment - A sediment that has been metamorphosed.

metavolcanic - Volcanic rocks that have been metamorphosed.

micaceous - Consisting of, containing, or protaining to mica.

micritic limestone - A limestone consisting of more than 90% micrite.

microaerophilic - Any organism that grows optimally in a microaerobic environment.

microfauna - Living or fossil animals too small to be seen with the naked eye.

migmatitic - A composite rock composed of igneous or igneous-looking or metamorphic materials that are generally distinguishable megascopically.

miogeosyncline - A geosyncline in which volcanism is not associated with sedimentation.

modified Mercalli scale - An earthquake intensity scale, having 12 divisions expressed as I to XII.

morphogenetic - Pertaining to the origin of morphological features.

mudstone - An indurated mud having the texture and composition of slate, but lacking its fine lamination or fissility.

muscovite - A mineral of the mica group, which is colorless to yellowish or pale brown, and is a common mineral in gneisses and schists.

mylonite - Strongly foliated fault rock that exhibits characteristics of high ductile (mostly simple shear) strain. Decrease of grain size from the original rock is characteristic of mylonite, along with ribbon quartz and rotated porphyroclasts. S-C fabrics are commonly present. Microfabric is commonly only partially recovered or recrystallized but may be totally recrystallized if deformation ceased during or before a thermal event.

nappe - A sheetlike, allochthonous rock unit, which has moved on a predominantly horizontal surface. The mechanism may be thrust-faulting, recumbent-folding, or both.

normal fault - A fault in which the hanging wall has moved down relative to the footwall.

ophiomorpha - A pseudogenus that includes the noded burrows of shrimp and crabs found in sediments.

orogeny - The process of mountain building, accompanied by metamorphism, plutonism, and associated deformation, resulting from subduction, terrane accretion, or continent collision.

osmotic equilibrium pressure - The pressure exerted by a solvent passing through a semipermeable membrane in osmosis, equal to the pressure that must be applied to the solution in order to prevent passage of the solvent into it.

oxbow lake - The crescent-shaped, often ephemeral body of standing water situated by the side of a stream in the abandoned meander after the stream formed a neck cutoff.

Paleozoic - An era of geologic time, from 240 to 570 million years ago (Appendix II).

palynology - The study of pollen of seed plants and spores.

palynomorph - A microscopic, resistant-walled organic body found in palynologic maceration residues; a palynologic study object.

paragneiss - A gneiss formed by metamorphism of a sedimentary rock.

pelecypod - A benthic aquatic mollusk belonging to the class Pelecypoda, characterized by a bilaterally symmetrical bivalve shell, a hatchet-shaped foot, and sheet-like gills.

percentile - Any of the values in a series dividing the distribution of the individuals in the series into 100 groups of equal frequency.

permeability - The property or capacity of a porous rock, sediment, or soil for transmitting a fluid.

petrography - The description and systematic classification of rocks.

phototroph - An organism that obtains energy from light.

phyllosilicate - A group of minerals with a flat structure, such as the micas.

piezometer - A pipe or well casing installed into an aquifer to measure the water level.

plagioclase - A group of triclinic feldspars of general formula: $(NaCa)Al(SiAl)Si_2O_8$.

plasmid - A small, DNA-containing, self-reproducing cytoplasmic element that exist outside the chromosome, as in some bacteria.

plinthite - A soil consisting of a mixture of clay with quartz with other diluents, that is rich in sesquioxides, poor in humus, and highly weathered.

pluton - An igneous intrusion.

polycrystalline - Describing an assemblage of crystals.

porosity - The percentage of the bulk volume of a rock or soil that is occupied by space.

postkinematic - Describes a geologic process or event occurring after any kind of tectonic activity, or said of a rock or feature so formed.

potassium - A soft, silver white, waxlike metallic chemical element that oxidizes rapidly when exposed to air.

potassium feldspar - An alkali feldspar containing the Or molecule ($KAlSi_3O_8$); e.g. Orthoclase, microcline.

potentiometric map - A map showing the elevation of a potentiometric surface of an aquifer by means of contour lines or other symbols.

Precambrian - All geologic time and its corresponding rocks, before the beginning of the Paleozoic; it is equivalent to about 90% of geologic time (Appendix II).

progradation - The building forward or outward toward the sea of a shoreline or coastline by nearshore deposits of river-borne sediments or by continuous accumulation of beach material thrown up by waves or moved by longshore drifting.

protolith - The unmetamorphosed rock from which a metamorphic rock formed.

pyrite - A common, pale-bronze or brass-yellow, isometric mineral: FeS_2.

pyroxene - A group of dark rock-forming silicate minerals.

quartz - Crystalline silica, an important rock-forming mineral: SiO_2.

quartzarenite - A sandstone that consists primarily of quartz.

quartzite - A granoblastic metamorphic rock consisting mainly of quartz and formed by recrystallization of sandstone or chert.

raypath - The imaginary line along which a wave or ray travels; the course of travel between two points of a disturbance in an elastic medium.

recumbent - An overturned fold with a horizontal axial surface.

redox - The oxidation reduction state of a system.

regime - A regular or systematic pattern of occurrence or action, or a condition or style having widespread influence, as a sedimentary regime.

regolith - The entire layer or mantle of fragmental and loose, incoherent, or unconsolidated rock material or soil, of whatever origin (residual or transported) that forms the surface of the land and overlies or covers the more coherent bedrock.

regression - The retreat or withdrawal of the sea from land areas.

reticulate - A rock in which crystals are partially altered to a secondary mineral, forming a network that encloses the remnants of the original mineral.

retrograde metamorphism - A type of polymetamorphism by which metamorphic minerals of a lower grade are formed at the expense of a higher grade mineral.

saprolite - A soft, earthy, clay-rich, thoroughly decomposed rock formed in place by chemical weathering; preserves structures from the original rocks.

scarps - A relatively straight, clifflike face or slope breaking the general continuity of the land by separating surfaces lying at different levels, such as along the margin of a plateau or mesa.

schist - A strongly foliated crystalline rock formed by dynamic metamorphism that can be readily split into thin flakes or slabs due to the well developed parallelism of more than 50% of the minerals present, particularly those of lamellar or elongate prismatic habit, e.g. mica, hornblende.

seismic reflection - The return of a wave incident upon a surface to its original medium. Also, in seismic prospecting, the indication on a record of such reflected energy.

seismic refraction - The deflection of a seismic wave due to its passage from one to another medium of differing density.

shear zone - A tabular zone of rock that has been crushed or bracciated by many parallel fractures due to shear strain. Such an area often is mineralized by ore-forming solutions.

siliciclastic - Pertaining to clastic noncarbonate rocks that are dominated by quartz and other silicates.

sill - A tabular igneous intrusion that parallels the layered structure of the surrounding rock.

slug test - An *in situ* method of determining hydraulic conductivity of rock or sediment into which a well or piezometer is installed. The water level is raised a known volume by adding a slug of water or by lowering a solid cylinder of known volume into the well or piezometer and measuring the rate at which the level returns to the ambient hydraulic head.

slumping - A landslide characterized by a shearing and rotary movement of a generally independent mass of rock or earth along a curved slip surface and about an axis parallel to the slump from which it descends.

smectite - The name for the group of clay minerals that includes montmorillonite, saponite, hectorite, beidellite, and nontronite. Members of this group all have a high layer charge and swell in the presence of water.

sorting - The dynamic process by which sedimentary particles having some particular characteristic (such as similarity of size, shape, or specific gravity) are naturally selected and separated from associated but dissimilar particles by the agents of transportation; usually refers to sorting by grain size.

speciation - In geochemistry, the distribution of components among the various chemical species in a system. In paleontology, the production of new species of organisms from pre-existing ones during evolution.

stock - An igneous intrusion that is less than 40 mi^2 in surface exposure, is usually, but not always, discordant, and resembles a batholith except in size.

storage coefficient - For surface waters such as a reservoir, a coefficient expressing the relationships of the surface area to the mean annual flow that supplies it. In hydrology, it is "storativity."

storativity - The volume of water that an aquifer releases from storage per unit surface area of aquifer per unit decline in the component of hydraulic head normal to that surface, or the specific storage times the aquifer thickness.

strain - Permanent deformation in the form of distortion, translation, and rotation.

strata - The plural of stratum.

strath - An elongate, broad, and steep-sided depression on the continental shelf, usually glacial in origin.

stratum - A tabular or sheetlike body or layer of sedimentary rock, visibly separable from other layers above and below; a sedimentary bed.

stress - In a solid, the force per unit area.

strike - The compass direction or azimuth of a horizontal line lying on an inclined surface.

strike-slip movement - In a fault, the component of movement or slip that is parallel to the strike of the fault.

structural geology - The branch of geology that deals with the form, arrangement, and internal structure of rocks, and especiallyecially with the description, representation, and analysis of structures, chiefly on any small scale.

subaerial - Erosional conditions and processes, such as eolian deposits, that exist or operate in the open air or immediately adjacent to the land surface.

subarkose - A sandstone that does not have enough feldspar to be classified as an arkose.

synkinematic - A geologic movement occurring during a tectonic event.

tectonic - Describing or pertaining to the forces involved in, or the resulting structures or features of, tectonics.

tectonics - A branch of geology dealing with the broad architecture of the earth, that is, the regional assembling of structural or deformational features, a study of their mutual relations, origins, and historical evolution.

tectonism - A general term for all movement of the crust produced by tectonic processes, including the formation of ocean basins, continents, plateaus, and mountain ranges.

terranes - A term applied to a rock or group of rocks and to the area in which it outcrops.

terrigenous - Derived from the land or continent.

Tertiary - The oldest period of the Cenozoic era (after the Cretaceous of the Mesozoic era and before the Quaternary), between 63 and 2 million years ago (Appendix II).

texturally immature - A description of sand or sandstone that indicates poor size sorting and relative angularity of the individual grains.

thrust sheet - The mass of rock comprising the hanging wall above a thrust fault.

transgression - The spread or extension of the sea over land areas, and the consequent evidence of the advance (such as strata deposited unconformably on older rocks, especially where the new marine deposits are spread far and wide over the former land surface).

transgressive - An event whereby the sea covers part of a land mass.

transmissivity - In an aquifer, the velocity at which water of the prevailing kinematic viscosity is transmitted through a unit width under a unit hydraulic gradient.

transpiration - The process by which water is absorbed by plants, usually through the roots, and is evaporated into the atmosphere from the plant surface.

Triassic - The oldest period of the Mesozoic era between 240 and 205 million years ago (Appendix II).

trilobite - Any marine arthropod belonging to the class Trilobita, characterized by a three-lobed, ovoid to subelliptical exoskeleton divisible longitudinally into axial and side regions and transversely into anterior, middle, and posterior regions.

ultisol - A soil order characterized by the presence of an argillic horizon.

unconformity - A break in the stratigraphic sequence where some portion of geologic history is missing. Produced by nondeposition, erosion, or both, resulting in a loss of strata for part of the geologic record.

vadose zone - The zone of unsaturated groundwater flow. This zone is limited above by the land surface and below by the zone of total saturation.

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Table IV-1. Compilation of Hydraulic Properties of the Water Table Aquifer North of Upper Three Runs

Source	Porosity	Hydraulic Conductivity (m/day)	Transmissivity (m^2/day)	Storativity	Leakage/day
1		range: 9.75-19.2	range: 235-470	range: 6.0×10^{-4} - 5.0×10^{-5}	range: 3.6×10^{-4} - 1.3×10^{-3}
		mean: 13.1	mean: 320	mean: 6.6×10^{-4}	mean: 6.8×10^{-4}
		s: 4.3	s: 105	s: 1.7×10^{-4}	s: 4.2×10^{-4}
		geometric mean: 12.8	geometric mean: 309		geometric mean: 6.0×10^{-4}
		n: 4			
2			92.3	9.9×10^{-3}	
3	range: 0.35 - 0.40				

1. Geraghty and Miller (1986), cited in Aadland et al. (1995).
2. Hiergesell and Pemberton (1995).
3. Eddy-Dilek et al. (1993).

Table IV-2. Compilation of Hydraulic Properties of the Water Table Aquifer South of Upper Three Runs

Source	Porosity	Hydraulic Conductivity (m/day)	Transmissivity (m^2/day)	Storativity
1		range: 0.090 - 01.10		
		mean: 0.20		
		median: 0.19		
		n: 38		
2		range: 0.055 - 12.3		
		mean: 1.55		
		median: 0.372		
3 upper zone	range: 0.20 - 0.25	mean: 3.96	mean: 39.0	1.2×10^{-4} - 9.3×10^{-3}
3 lower zone	range: 0.20 - 0.25	(3 H Area tests) mean: 0.268	(3 H Area tests) mean: 5.76	
		NE of H Area: 0.488	NE of H Area: 8.18	
4 lower zone		5.79	89.2	
5 lower zone		mean: 3.05	range: 52.0 - 64.6	range: 1.1×10^{-4} - 2.6×10^{-4}
			mean: 62.2	

1. Parizek and Root (1986).
2. Evans and Parizek (1991).
3. D'Appolonia (1981), cited in Aadland et al. (1995).
4. Christensen and Gordon (1983).
5. Chas. T. Main, Inc. (1990), cited in Aadland et al. (1995).

Table IV-3. Compilation of Hydraulic Properties of the First Confining Unit North of Upper Three Runs

Source		Area	Vertical Hydraulic Conductivity (m/day)	r/B	Leakage/day
1	measured in core	A/M-Area	range: $9.1 \times 10^{-6} - 9.1 \times 10^{-3}$		
2	multiple well pumping tests	A/M-Area			range: $6.0 \times 10^{-5} - 1.0 \times 10^{-2}$ mean: 2.06×10^{-3} s: 3.40×10^{-3} geometric mean: 7.02×10^{-4} n: 8
3	pump tests	A/M-Area	range: $4.85 \times 10^{-4} - 2.76 \times 10^{-3}$ mean: 1.60×10^{-3} s: 1.14×10^{-3} geometric mean: 1.28×10^{-3} n: 3	range: $4.6 \times 10^{-2} - 8.2 \times 10^{-2}$	range: $2.7 \times 10^{-4} - 1.8 \times 10^{-3}$
4	pump tests in 2-inch wells	A/M-Area		range: $2.6 \times 10^{-2} - 1.3 \times 10^{-1}$ mean: $7.7 \times 10^{-2} - 5.6 \times 10^{-2}$ geometric mean: 6.0×10^{-2}	

1. Eddy et al. (1991).
2. Geraghty and Miller (1986), cited in Aadland et al. (1995).
3. Hiergesell (1993).
4. Hiergesell and Pemberton (1995).

Table IV-4: Compilation of Hydraulic Properties of the First Confining Unit South of Upper Three Runs

Source	Technique	Porosity	Vertical Hydraulic Conductivity (m/day)	Leakage/day
1	measured in core	mean: 0.48 s: 0.12	mean: 8.32×10^{-3} s: 1.97×10^{-2} geometric mean: 5.06×10^{-4} n: 6	
2, 3, 4, and 5	measured in core		range: 3.35×10^{-7} - 8.23×10^{-4} n: 22	
6	measured in core		range: 3.72×10^{-5} - 5.94×10^{-5} n: 3	
7	7-day pump			range: 2.94×10^{-5} - 5.72×10^{-5} average: 4.33×10^{-5}

1. Bledsoe et al. (1990).
2. WSRC (1992), WSRC-RP-92-837, cited in Aadland et al. (1995).
3. Sirrine (1991a), cited in Aadland et al. (1995).
4. Sirrine (1991b), cited in Aadland et al. (1995).
5. WEGS (1991), cited in Aadland et al. (1995).
6. Aadland et al. (1995).
7. CH_2M Hill (1989), cited in Aadland et al. (1995).

Table IV-5. Compilation of Hydraulic Properties of the First Confined Aquifer North of Upper Three Runs

Source	Porosity	Hydraulic Conductivity (m/day)	Transmissivity (m^2/day)	Storativity	r/B
1			13.7		
2		range: 6.71 - 44.2 mean: 18.0 s: 12.8 geometric mean: 14.6 n: 8	range: 906 - 6,030 mean: 2,440 s: 1,750 geometric mean: 2,000 n: 8	range: 2.3×10^{-4} - 1.8×10^{-2} mean: 2.9×10^{-3} s: 6.1×10^{-3} goemetric mean: 8.0×10^{-4} n: 8	
3			mean: 390 s: 61.3 geometric mean: 108 n: 4	mean: 2.2×10^{-3} s: 4.3×10^{-3} geometric mean: 3.7×10^{-4}	mean: 7.7×10^{-2} s: 5.6×10^{-2} geometric mean: 6.0×10^{-2} n: 4
4	range: 0.354 - 0.415	range: 9.77 - 15.9	range: 29.8 - 48.4	range: 3.73×10^{-3} - 4.49×10^{-3}	range: 0.73 - 1.45

1. Christensen and Gordon (1983).
2. Geraghty and Miller (1986), cited in Aadland et al. (1995).
3. Hiergesell and Pemberton (1995).
4. Eddy-Dilek et al. (1993).

Table IV-6. Compilation of Hydraulic Properties of the First Confined Aquifer South of Upper Three Runs

Source	Area	Hydraulic Conductivity (m/day)	Transmissivity (m^2/day)	Storativity
1	General Separations Area	range: 7.32 - 12.5 mean: 10.0 s: 1.98 n: 6	range: 120 - 238 mean: 185 s: 41.8 s: 10	range: 2.0×10^{-4} - 2.9×10^{-4} mean: 2.7×10^{-4}
2		11.6	range: 186 - 213 mean: 199 n: 2	range: 2.3×10^{-4} - 8.8×10^{-4} mean: 5.6×10^{-4}
3			196	2.8×10^{-4}
4	C Area		734	
	P Area		1,245	

1. Albenesius et al. (1990).
2. CH_2M Hill (1989), cited in Aadland et al. (1995).
3. Sirrine (1991c), cited in Aadland et al. (1995).
4. Parizek and Root (1986).

Table IV-7. Compilation of Hydraulic Properties of the Crouch Branch Confining Unit

Source	Technique	Area	Porosity	Vertical Hydraulic Conductivity (m/day)	Leakage/day
1	measured in core samples	sitewide	mean: 0.41 s: 0.09 n: 30	mean: 6.86×10^{-3} s: 2.02×10^{-2} geometric mean: 1.06×10^{-4} n: 30	
2	measured in core samples			range: 3.0×10^{-6} - 3.0×10^{-4}	
3	measured in core samples			8.62×10^{-5}	
4	pumping tests	A/M Area			range: 1.5×10^{-4} - 4.3×10^{-4} mean: 2.4×10^{-4}

1. Bledsoe et al. 1990.
2. Geo Trans (1988), cited in Aadland et al. (1995).
3. Sirrine (1991a), cited in Aadland et al. (1995).
4. Geraghty and Miller (1983), cited in Aadland et al. (1995).

Table IV-8. Compilation of Hydraulic Properties of the Crouch Branch Aquifer

Source	Technique	Area	Hydraulic Conductivity (m/day)	Transmissivity (m^2/day)	Storativity
1	pumping tests	C Area	range: 36.0 - 64.3	range: 1,020 - 1,770	
		D Area	range: 41.1 - 69.2	range: 1,480 - 2,510	
		F/H Area	range: 17.4 - 26.2	range: 929 - 1,390	
		K Area	range: 9.14 - 25.3	range: 279 - 622	
		L Area	range: 27.7 - 38.4	range: 845 - 1,210	
2	pumping tests	P Area	range: 11.9 - 23.5	range 650 - 883	4.0×10^{-4}
		R Area	35.7	1,110	4.0×10^{-4}
		K Area	29.0	1,360	
		C Area	42.1	range: 1,108 - 1,740	
		M Area	8.53	418	
3	pumping tests	A/M Area	11.3	975	4.2×10^{-4}
4	single-well pump test	Williston & Martin, SC	range: 13.1 - 14.9	range: 622 - 1,370	

1. GeoTrans (1988), cited in Aadland et al. (1995).
2. Siple (1967).
3. Geraghty and Miller (1983), cited in Aadland et al. (1995).
4. Newcome (1993).

Table IV-9. Compilation of Hydraulic Properties of the McQueen Branch Confining Unit

Source	Technique	Porosity	Vertical Hydraulic Conductivity (m/day)	Leakage/day
1	measured in core	mean: 0.41 s: 0.11 geometric mean: 0.40 n: 10	mean: 2.11×10^{-3} s: 4.30×10^{-3} geometric mean: 1.84×10^{-4} n: 10	
2	calculated from weighted unit thickness and sitewide geometric mean K_v for clay units			mean: 1.2×10^{-5} s: 1.4×10^{-5} geometric mean: 7.0×10^{-6} n: 34

1. Bledsoe et al. (1990).
2. Aadland et al. (1995).

Table IV-10. Compilation of Hydraulic Properties from Pumping Tests in the McQueen Branch Aquifer

Source	Area	Hydraulic Conductivity (m/day)	Transmissivity (m^2/day)	Storativity
1	P Area	30.0	1,080	1.5×10^{-4}
2	F Area	12.5 - 88.4		
	L Area	28.4		
3	F Area	16.2 - 43.3		
	H Area	29.3 - 64.0		
	M Area	33.2		
4	Allied General Nuclear Services	14.9	mean: 1,740 n: 3	

1. Bledsoe et al. (1990).
2. GeoTrans (1988), cited in Aadland et al. (1995).
3. Siple (1967).
4. Newcome (1993).

Table IV-11. Compilation of Hydraulic Properties of the Appleton Confining Unit

Source	Technique	Area	Porosity	Vertical Hydraulic Conductivity (m/day)
1	laboratory measurement	well C-10	range: 0.26 - 0.31 mean: 0.28 n: 3	range: 1.16×10^{-3} - 4.88×10^{-3} mean: 3.35×10^{-3} n: 3
2	pump test	saprolite		range: 2.65×10^{-4} - 1.46×10^{-3} n: 2
2	pump test	Cape Fear Formation	average: 0.30	average: 3.96×10^{-5}

1. Core Laboratories (1992), cited in Aadland et al. (1995).
2. Marine (1975).

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