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GEOLOGY AND GROUND-WATER HYDROLOGY OF THE ATLANTIC AND GULF COASTAL PLAIN AS RELATED TO DISPOSAL OF RADIOACTIVE WASTES*

By

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GEOLOGY AND GROUND-WATER HYDROLOGY OF THE ATLANTIC AND GULF COASTAL PLAIN AS RELATED TO DISPOSAL OF RADIOACTIVE WASTES*

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ABSTRACT

This report on the Atlantic and Gulf Coastal Plain is a summary of part of the results of a study of hydrologic and geologic aspects of radioactive-waste disposal. The Atlantic and Gulf Coastal Plains form a broad belt which extends from Long Island southward along the Atlantic coast and westward along the Gulf coast to the Rio Grande. It includes the peninsula of Florida, and a broad arm extends up the Mississippi River valley to the southern tip of Illinois. The plain is no more than a few hundred feet above sea level along its inner margin, and it slopes gently to the sea, extending beyond the coastline as the submarine Continental Shelf. Beneath the plain, beds of sand, clay, marl, and limestone of Cretaceous, Tertiary, and Quaternary age dip seaward. Except where they are deeply buried near the coast, the geologic materials commonly are soft and unconsolidated. They lie on a floor of hard consolidated rocks that are similar to those exposed along the inner margin of

the Coastal Plain. The bulk of the sediments accumulated beneath the sea, which invaded the region and retreated many times.

Cretaceous deposits form the basal sedimentary materials beneath most of the Coastal Plain. Although Jurassic rocks form a part of the sedimentary sequence in southern Florida and in parts of the Gulf coast. Cretaceous formations crop out along much of the inland margin of the Coastal Plain, making a broad belt in Texas, Mississippi, Alabama, and southern North Carolina, but they are covered by younger sediments in much of Virginia and Arkansas. Sands and clays form the bulk of the Cretaceous sediments in the outcrop area, the Selma Group of Alabama and Mississippi, and the Austin Chalk of Texas being notable exceptions. The beds dip gently seaward, the average dip being about 40 feet per mile. Where deeply buried, as in peninsular Florida and along the Gulf coast, the sediments have been compacted and reconstituted as shale, sandstone, limestone, and dolomitic rocks.

An immense volume of Tertiary sediments overlies the Cretaceous formations. Beneath parts of the coast of Louisiana and Texas, Tertiary sediments are more than 25,000 feet thick. In southern Florida they are more than 5,500 feet thick. North of Georgia the Tertiary sediments are less than 2,000 feet thick. Clays and fine- to medium-grained sands are characteristic, but thick formations of limestone, chiefly of Eocene age, underlie most of Florida and southern Georgia.

Varieties of sediments of Quaternary age occur in the Coastal Plain, but their total volume is only a fraction of that of Cretaceous or Tertiary sediments. They include limestone in southern Florida, glacial till and outwash on Long Island, river alluvium along stream valleys, deltaic deposits in Louisiana and Texas, and a widespread veneer of coastal sands and clays, which were deposited beneath invading seas during Pleistocene time.

The most striking structural features of the Coastal Plain are (1) the seaward dip of the beds, (2) a coastward increase in thickness of individual beds, and (3) a coastward increase in number of beds. The beds commonly dip only a fraction of one degree--those on the Atlantic coast to the east, and those on the Gulf coast to the south. There are many departures from the gentle homoclinal dip, some beds exhibiting depressed, or negative, features and other beds exhibiting uplifted, or positive, features. Most of the anomalous structures are in the Gulf Coastal Plain. The Mississippi embayment and the Gulf coast geosyncline have the most widespread significance. The Mississippi embayment is a down-warped and down-faulted trough in Paleozoic rocks extending northward along the course of the Mississippi River. Cretaceous and Tertiary seas extended as far north as southern Illinois and received sediments that now dip toward the center of the basin. The Gulf Coast geosyncline is a trough extending along the Gulf coast, in which great thicknesses of Cretaceous and Tertiary sediments accumulated. Subsidence in the basin and accumulation of sediments were attended by gravity strike faults that extend in an arcuate pattern from the panhandle of Florida through southwestern Alabama, southern Arkansas, and a broad belt of Texas. Another complex system of these faults occurs in southern Louisiana. The most prominent positive structural feature is the peninsular uplift of Florida; it is a gentle arch in the sediments, almost paralleling the peninsula. In parts of the Gulf coast salt from deep-lying Jurassic beds has intruded overlying sediments; the salt occurs as plugs and buried domes. More than 200 salt domes are known, some of which reach within a few feet of the land surface, although others reach no closer than a few thousand feet.

Two outstanding earthquakes have been recorded, one in 1811 and 1812 with an epicenter at New Madrid, Mo., and the other in 1886 with an epicenter at Charleston, S. C. Yet, neither the Atlantic nor the Gulf Coastal Plain has a record of being seismically active and neither is earthquake-prone.

The volume of water originally entombed in the sediments of the Coastal Plain was many hundreds of thousands of cubic miles. Most of it was sea water.

The volume of water has decreased and the quality has been altered everywhere. The weight of many hundreds and many thousands of feet of overlying sediments caused water from deep-lying sediments to be squeezed upward as the pore space was reduced. Storage facilities and permeability of deep-lying sediments are now relatively poor.

The Coastal Plain is underlain by an immense artesian system--simple in general terms, but complex in many details. The alternate layers of permeable and relatively impermeable beds and their gentle homoclinal dips are ideally suited to the occurrence of artesian water. Aquifers, which commonly are medium- to coarse-grained sands or limestones, and intervening impermeable beds, which commonly are clays or shales, vary greatly in thickness and areal extent. Some geologic formations contain several aquifers and several impermeable layers, whereas other formations compose only a part of an aquifer. Many aquifers are separated by beds that are lenticular and not altogether impermeable. Thus, there is considerable leakage between many aquifers where there is a difference in artesian head between them.

Beneath all of the Coastal Plain, except a narrow belt along the inner margin, the ground water occurs in three zones in downward succession. They are: (1) the zone of unconfined water at shallow depths, (2) the zone of naturally fresh artesian water, and (3) the zone of salty artesian water. The shallow zone is the water-table aquifer, which extends throughout the Coastal Plain and contains fresh water everywhere except in a few localities near coastal surface waters and in some swampy parts of southern Florida. The zone of fresh artesian water occurs throughout the Coastal Plain except beneath a thin strip along the inner margin and locally along the outer margin of the Coastal Plain; it is commonly thickest in the hinterland, where it ranges in thickness from a few hundred to about 2,000 feet. The salt-water zone includes the basal beds in the outer two-thirds of the region; the zone thickens as a wedge coastward. The salt-water zone occupies much more than half the total aggregate volume of sediments in the Atlantic and Gulf Coastal Plain.

The chemical quality of ground water in the Coastal Plain varies greatly. In most places the water in the shallow water-table aquifers is low in total dissolved mineral matter but is slightly acid. Fresh artesian water in limestone is largely of calcium bicarbonate type, and the hardness commonly ranges between 100 and 300 parts per million. Where the fresh artesian water occurs in sands, the mineral content generally increases gradually with depth in each aquifer, and the water changes from chiefly calcium bicarbonate to chiefly sodium bicarbonate to chiefly sodium chloride.

Water moves into the Coastal Plain aquifers from precipitation, but only a part of the precipitation becomes artesian water. Only in southern Texas is the average annual precipitation less than 38 inches, and only in this region is the capacity of the water-table aquifers greater than the amount of water reaching them. In the rest of the Coastal Plain the potential recharge rate generally exceeds the rate at which the aquifers can accept and transmit water.

The water table is near the ground in many places, and excess water is lost by evapotranspiration or is diverted to surface streams. Some water from the water-table aquifers moves downward to the underlying artesian beds, but generally at a slow rate because of poor properties of water to discharge. Where artesian water occurs at depths of several hundred feet or more, the natural rate of movement may be in feet per year, or even in feet per century. Most rapid ground-water circulation occurs in the water-table aquifers and in the shallow parts of the artesian aquifers. The rate of movement is also quickened around wells that are pumped.

The temperature of water is usually about 2° to 3° F. above the average annual air temperature. The temperature of water increases with depth, averaging about 1° F. for each 60 to 90 feet of increase in depth. The artesian pressures normally increase with depth, but the pressure surface of different aquifers in many cases is only slightly higher than the water table. At depths greater than about 7,000 feet abnormally high fluid pressures have been reported.

INTRODUCTION

This report is part of the results of a study of hydrologic and geologic factors in relation to problems of radioactive-waste disposal. The great breadth and many implications of the waste problem are indicated in the five volumes of the record of "Hearings on Industrial Radioactive Waste Disposal", staged by the Special Subcommittee on Radiation of the Joint Committee on Atomic Energy, Congress of the United States. The records of hearings, which were held on January 28, 29, and 30 and February 2 and 3, 1959, include the findings of many specialists working on the problem from several approaches. The present report, which summarizes the geology, physiography, and hydrology of the Atlantic and Gulf Coastal Plain, is one of a series of four that will cover the Conterminous United States. This work was done by the U. S. Geological Survey on behalf of the Division of Reactor Development, U. S. Atomic Energy Commission.

This report is a general synthesis of the geology of the Coastal Plain, with special attention to factors that should be considered when choosing locations for disposal sites or installations that produce or use radioactive materials. The purpose of the report is not to recommend sites but to present sufficient geologic and hydrologic data to aid the choice or rejection of general areas in which specific sites might be chosen. The last section of the report itemizes several factors that might be noteworthy.

This report was prepared primarily for the use of people who are interested or engaged in radioactive and chemical waste management in the Atlantic and Gulf coastal plains; this includes physicists, chemists, engineers, hydrologists, and production managers. It was prepared also for the use of geologists. The diverse technical training of the audience necessitates a discussion of geologic and hydrologic factors so that a common technical background will be attained by the readers before perusal of report. Because of the wide areal coverage of the report it would be prohibitive to include discussions of all small areas and sites in any region which may be considered suitable for waste management. Therefore, a statement of environmental factors is included so that the readers may interpolate conditions at a particular site.

The Atlantic and Gulf Coastal Plain province is a relatively low region along the eastern and southern margins of the United States. It extends from the sandy islands and capes of Massachusetts and Long Island (fig. 1) to Texas, and includes the Mississippi embayment as far north as Cairo, Ill. It is characterized by relatively flat land and by seaward-dipping strata, which, at shallow depth, are chiefly unconsolidated materials such as sand, clay, and limestone. The strata are almost horizontal, but they tend to thicken and increase in number seaward, in a wedge-like manner. Permeable and relatively impermeable strata are interlayered, and the amount of water held in storage is enormous. The uppermost strata generally contain water that is potable, but the lowermost strata contain salty water. In aggregate, the volume of sediments which contain salty water far exceeds the volume of those which contain fresh water. Much of the ground-water circulation occurs within 200 feet of the land surface, and this circulation is closely related to the flow of water in streams.

In considering the management of radioactive wastes within the Coastal Plain province it is important to distinguish between low-level wastes, which contain relatively small quantities of radioactivity, and high-level wastes, which contain much radioactivity from biologically hazardous long-lived fission productions. Many parts of the Coastal Plain are suitable for the release of some low-level wastes to the ground. Although no high-level wastes have yet been stored in geologic environments, two principal methods of underground containment in geological formations have been considered; these are (1) storage in sedimentary rocks by means of deep wells, and (2) storage in underground openings at comparatively shallow depths, such as in abandoned salt mines (Nace, 1959, p. 2615). Great volumes of sedimentary materials contain unusable salty water and lie at depth beneath the margins of the Coastal Plain; some of these materials are permeable and are sealed beneath tight, impermeable clays and shales. Containment of wastes in parts of deep formations of the Coastal Plain is likely, but problems resulting from the injection of the wastes underground must be removed with certainty if this form of disposal is to be undertaken. A report entitled "Summary of rock salt deposits in the United States as possible disposal sites for radioactive waste" (Pierce and Rich, 1958) includes information on salt domes in the Gulf Coastal Plain.

SCOPE OF WORK AND ACKNOWLEDGMENTS

The information on which this report is based came largely from published reports on the geology and ground-water resources of local areas. Unfortunately, comprehensive and detailed reports cover only parts of the Coastal Plain province. References cited in this report represent only a sample of the published information. The information results chiefly from the search for the two fluids, potable water and oil. Oil geologists have contributed much published geologic information, especially for the Gulf coast. State geological and water-resources surveys and departments also have much information. The U. S. Geological Survey has cooperated with the States in studying the geology and water resources and in publishing the results.

CLIMATE

Ground-water and surface-water hydrology are directly related to climate. Although climate is tremendously important to the purposes of this report, it is treated only briefly because the Coastal Plain contains only two distinctive types of climate.

The Coastal Plain east of the 95th meridian of longitude in eastern Texas receives an average of more than 40 inches of precipitation a year. Near the Mexican border in southern Texas, average precipitation is scarcely 20 inches a year; in that part of Texas, precipitation is about equal to the amount which, over the nation as a whole, is returned to the atmosphere annually by evapotranspiration. Thus, this area has little or no water surplus in any season (Thomas, H. E., 1951, p. 26). All of the Atlantic and most of the Gulf Coastal Plain has a humid climate, receiving between 40 and 60 inches of precipitation a year; there is little or no deficiency of water in any season. The precipitation in the humid part is distributed rather evenly throughout the year, and in only a few months of the year is there less than 2 inches of precipitation. Although snow is not rare in the northern part of the Coastal Plain, almost all precipitation is in the form of rain.

Temperatures vary considerably between the northern and southern extremities of the Coastal Plain. The average annual temperature in Long Island is about 50° F., and in southern Florida about 75° F. The lowest temperature ever recorded ranges from -10° F. in Long Island, to 40° F. in the southern tip of Florida; each locality has recorded at some time a temperature of more than 100° F.

GEOLOGY

Development of the Atlantic and Gulf Coastal Plain

The natural processes of erosion and sedimentation have had obvious effects on the development of all coastal plains. Rocks of the hinterland disintegrate and decay into rock fragments and soils. Rock fragments and soils eventually carry the loosened material toward the sea. This detrital material, as well as precipitated chemical matter and remains of marine organisms, accumulates on the sea floor. Sediments thus accumulated in the sea may reach thicknesses of several hundreds to several thousands of feet without a major interruption.

Another great natural process, differential earth movement, influences the places where sedimentation and erosion occur; the land tends to be elevated in some places and depressed in others, resulting in recession from the land in some places and encroachment on the land in others.

During the geologic development of the Atlantic and Gulf Coastal Plain, the sea advanced and retreated many times. The inner margin of the plain, that most remote from the sea, has been submerged during only a fraction of the time that land adjacent to the present coast has been submerged. Therefore, the sediments tend to thicken toward the sea, as a wedge whose thin edge lies along the inner margin of the plain; however, at distances of many tens of miles out to sea the thickness of sediments tends to decrease. Most sediments of the Coastal Plain were deposited in the sea, but some were deposited on land along the lowland margins of the plain. Some of these nonmarine deposits were eroded and redeposited in the sea, although some were preserved by burial under debris from an advancing sea. Whether deposited in the sea or along marginal land areas, the sediments tend to be preserved in nearly flat layers, which dip gently coastward (fig. 2).

General Stratigraphy

The stratigraphy, or the arrangement and position of the individual beds, has been studied with varying intensity

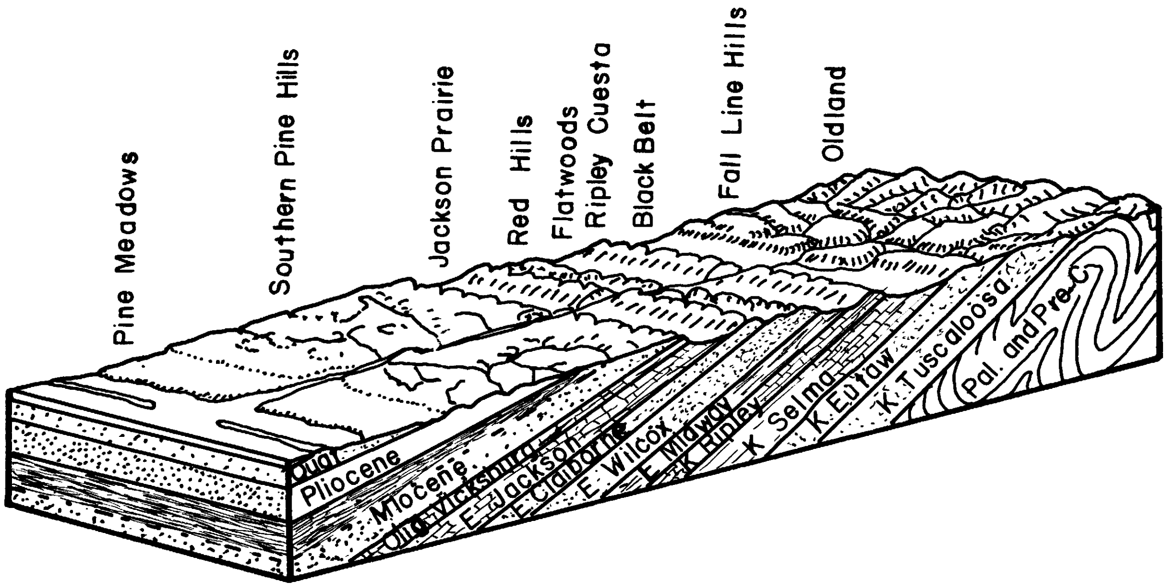


Figure 2. Relation of structure and topography in the East Gulf Coastal Plain. Vertical scale 80 times the horizontal. Physiography of Eastern United States, N. M. Fenneman, 1938, McGraw Hill Book Company.

in different parts of the Atlantic and Gulf Coastal Plain. The character of materials varies with conditions of sedimentation; clay, silt, sand, and calcareous materials such as limestone, marl, and chalk compose the bulk of the sediments.

All rock materials may be classified according to the major unit of time (period) during which they were formed. The Coastal Plain sediments accumulated relatively late in geologic time and are confined to the four more recent periods which, from the youngest to oldest, are: Quaternary, Tertiary, Cretaceous, and (to a lesser extent) Jurassic. The sediments of a period are not the same at all places because conditions of deposition have varied considerably. For example, at a specific time sands and gravels may be deposited near the shore, clays in deeper water, and calcareous oozes (which ultimately form limestone) are deposited in deep water beyond the zone to which land detritus is carried. Figure 3 is a generalized geologic map showing where Quaternary, Tertiary, and Cretaceous sediments occur at the land surface.

Rock materials are conveniently grouped into formations, based on their lithology--that is, the physical character of the constituent materials. To a great extent a formation is local, and is named after a place where its chief character is well exposed. A formation may be only a few feet thick or many hundreds of feet thick, and it may be composed almost entirely of clay, sand, or limestone; most formations contain a variety of individual beds, but one or more dominant features commonly distinguish it from the underlying and overlying formations. As a result of changes in conditions of deposition, all formations show some change in type of mineral constituents. A common change is a gradual transition from a bed composed chiefly of sand to one composed chiefly of clay.

At varying distances from a place where a formation is typically exposed, the character of its material changes to such an extent that its name and its description are no longer appropriate. Thus, different names are applied to rock materials that were deposited at about the same time but at different places. Geologists have spent much time in correlating formations in the Atlantic and Gulf Coastal Plain, in an effort to reconstruct the geologic history. More than 100 formation names are now in use in the region.

A systematic description of all formations is not attempted in this report; rather, salient features of certain formations that are considered especially pertinent are discussed. In this report the geology and ground-water hydrology of each State are discussed in general terms, and tables showing the geologic systems and some of the significant formations are included. References to published reports and maps are made throughout this report, but the reference list is by no means complete.

Summary of Geologic History

The geologic history of the southern and eastern parts of the United States during the many millions of years prior to Jurassic time is less important for the purposes of this report than subsequent history. At the beginning of Jurassic time the land area of the United States extended farther eastward and southward than it does today. The area now occupied by the Coastal Plain province was represented by hard rocks that were being eroded by rain wash and stream action. On the east coast, igneous and metamorphic rocks like those of the Piedmont province of the southern Appalachians were exposed. On the Gulf coast, sedimentary rocks of Paleozoic age, like those of central Tennessee and Kentucky, were exposed.

During the Jurassic time the sea advanced on the land, covering the extreme eastern part of North Carolina, the southern half of Florida, Louisiana, and parts of Texas, Arkansas, and Mississippi. The Cretaceous seas encroached farther, and at one or more times during the Cretaceous Period the sea covered all of the Coastal Plain province. Coarse-grained sediments, including gravels and coarse- to medium-grained sands, are common in basal Cretaceous sediments now exposed along the inner margin of the Coastal Plain. In contrast to these nonmarine and near-shore deposits are the clays and calcareous deposits of deeper water. For example, while sands and clays were deposited near the Cretaceous shoreline in central Georgia, calcareous oozes were accumulating in the deep water of southern Florida. The sea margin oscillated a number of times to different positions during the Cretaceous, and by the end of the Cretaceous a major withdrawal of the sea generally occurred. More than 2,000 feet of Cretaceous sediments accumulated in parts of each Coastal State.

A gradual seaward tilting of the plain caused the Tertiary sea to advance, and sediments to accumulate on the Cretaceous surface. The Tertiary deposits, composed of many formations of clay, sand, marl, and limestone, cover all the Cretaceous deposits except those lying along the inner margin of the Coastal Plain. Because they are widespread and near the land surface, the Tertiary sediments are very important, insofar as water supply and waste disposal are concerned. The seaward or "down dip" change to finer grained material, especially limestone, is as noticeable in the Tertiary as in the Cretaceous deposits. The Tertiary deposits thicken coastward, reaching a thickness ranging from several hundreds to several thousands of feet on the Atlantic Coast. The thickness is greater beneath the Gulf coast, and in southern Louisiana where the factors of subsidence and a good supply of sediments have combined, the aggregate thickness of Tertiary sediments is more than 25,000 feet.

The Quaternary Period is very short in comparison with the Tertiary and Cretaceous. It includes the present (Recent Epoch) and the most recent geologic past (Pleistocene Epoch). The outstanding feature of Pleistocene time was the extensive continental glaciation in the northern hemisphere. Although ice extended southward on the Coastal Plain only as far as Long Island, the effects of the glaciation were felt in all of the Atlantic and Coastal Plain. Worldwide changes of sea level were caused by removal of water from the sea to make the continental glaciers and by return of the water when the glaciers melted (Moore, 1949, p. 430). A rather wide range in climate during the Quaternary affected considerably both erosion and deposition. The sea advanced and retreated several times and left a veneer of deposits consisting chiefly of clay, silt, sand, and gravel. They are confined generally to that part of the plain lying below an elevation of 250 feet. Deposits along the Atlantic coast north of southern Florida are rarely thicker than 75 or 100 feet. Some marine limestone of Quaternary age occurs in southern Florida.

> "Stream deposits form a very important part of the Quaternary formations of the Gulf region, for they comprise not only a great delta and flood plains of the lower Mississippi but alluvial deposits of many other streams." (Moore, 1949, p. 435)

Withdrawal of the sea to its present position has exposed a former sea floor to erosion. In the Recent

Epoch, which occupies only about 2 percent of the Quaternary Period, streams have cut their channels into the relatively soft sediments and erosion is active near most streams. Many of the broad interstream areas remain relatively flat and almost unscathed by erosion.

Structure of the Atlantic and Gulf Coastal Plain

The most striking structural feature of the Coastal Plain is the seaward slope, or dip, of the beds. The beds commonly dip only a fraction of one degree, those on the Atlantic coast to the east and those on the Gulf Coast to the south. The floor of the older rocks on which the sediments lie slope the greatest amount, because most of the formations thicken seaward and "each successively higher sedimentary surface dips somewhat less than the basement floor" (Eardley, 1951, p. 129). There tends to be a coastward increase in thickness of individual beds and in number of beds (fig. 4).

Murray (1957, p. 253) depicts the entire sedimentary sequence as a great coastal geosyncline, or a subsided sedimentary trough, extending approximately from the Upper Cretaceous outcrop belt to the edge of the continental slope, and from the Grand Banks south of Newfoundland to Guatemala. He states (p. 253) that the "Geosyncline is roughly lens-shaped in cross section; approximately equal parts exist, (1) submerged beneath the waters of the Atlantic Ocean and Gulf of Mexico, and (2) emerged adjacent to their shores." On the Atlantic coast subsidence into a geosynclinal basin has been slight, and the sediments appear as though they were deposited on a rather stable, gently sloping platform. On the Gulf coast, however, subsidence of the continental margin is more in evidence. There has been a great accumulation of sediments extending several thousands of feet below the floor of the Gulf of Mexico near the coastal margin (fig. 5). (The Gulf coast geosyncline is a general term commonly used to represent these thick sedimentary deposits.)

There are many departures from the gentle homoclinal, coastward dip; in some areas the formations are depressed and in others they are uplifted. Some of the better known anomalous structures are listed below, and their locations are shown in figure 6. Figure 7 shows the depth to the base of the Coastal Plain sediments (top of basement), and figure 8 shows the thickness of Cenozoic sediments (sediments younger than Cretaceous).

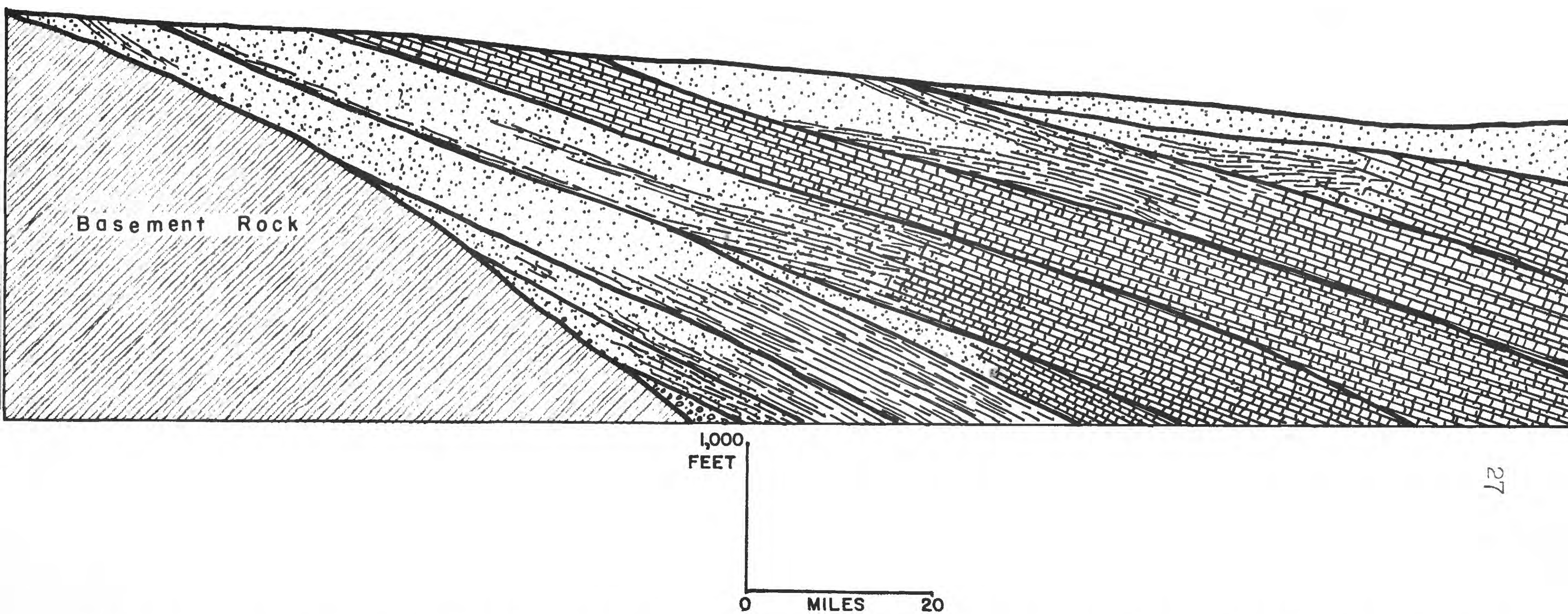


Figure 4. Diagram showing steepening of basement floor and an increase in thickness of individual beds and in number of beds toward the coast.

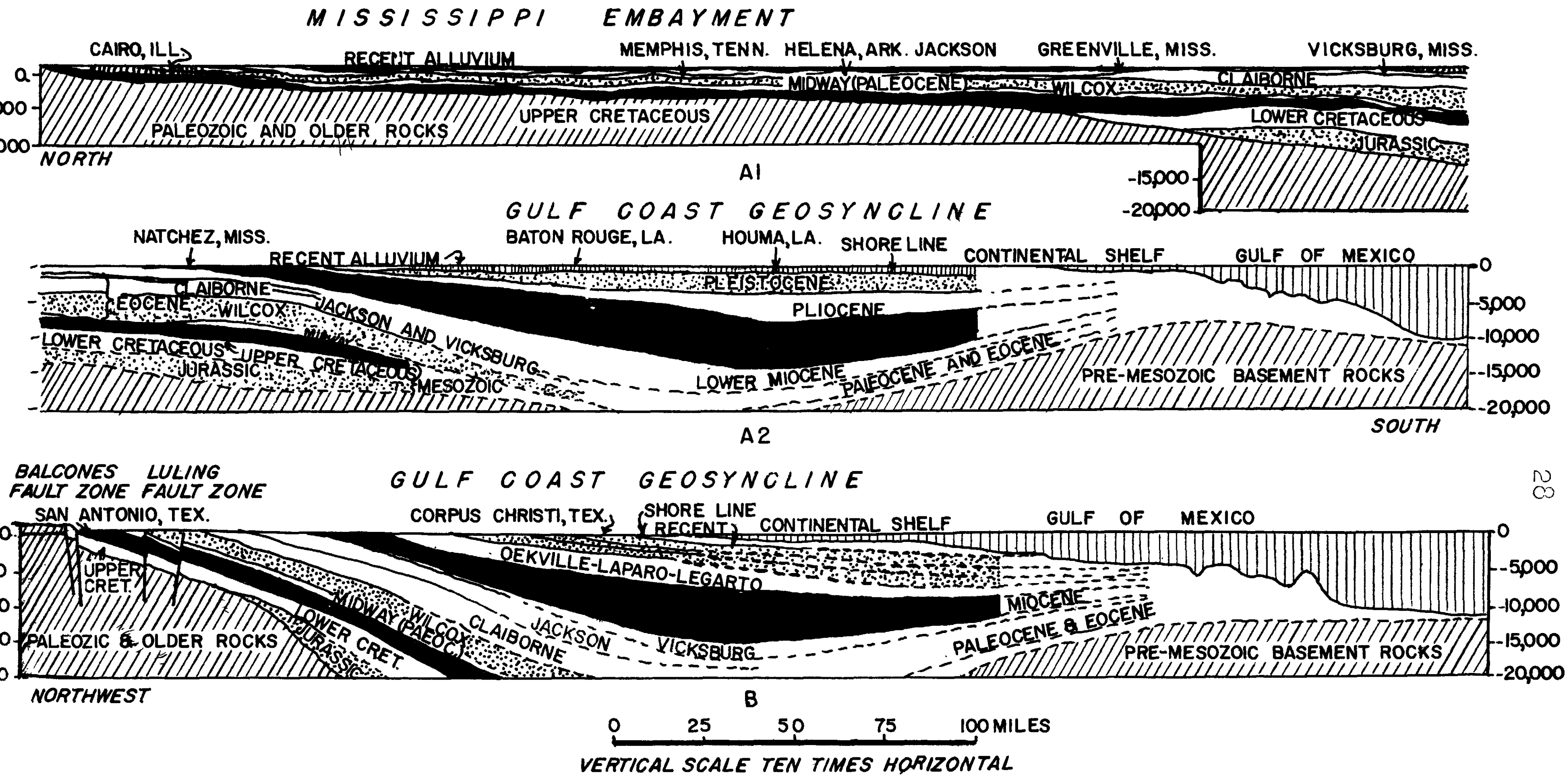


Figure 5. Sections across Gulf Coastal Plain. (A1 and A2) From head of Mississippi Embayment in southern Illinois to edge of Continental shelf off Louisiana coast. B In Texas from San Antonio to edge of Continental shelf. Patterns shown are arbitrary, and no attempt has been made to indicate the complex variations in lithology of the sediments. (Figure and caption from King, 1959, who adapted figure from Fisk, 1944, Storm, 1945, and others).

Negative, or depressed, structural features

1. Chesapeake-Delaware basin, or Salisbury embayment - a broad but very gentle trough in the basement rocks extending westward from the coast of Delaware and northern Virginia. Trough was filled and concealed by Eocene sediments (Spangler and Peterson, 1950, fig. 17).

2. Southeast Georgia, or Savannah basin - a slightly embayed basin between the Cape Fear arch and the Ocala-Peninsula uplift.

3. South Florida basin - a southward-dipping shelf in southern Florida, on which several thousands of feet of Cretaceous and Tertiary chemical precipitates accumulated.

4. Southwest Georgia basin - a slightly embayed basin west of the peninsula of Florida.

5. Mississippi embayment - a downwarped, downfaulted trough in Paleozoic rocks in which Cretaceous and Tertiary seas reached as far north as the southern tip of Illinois. Sediments dip toward center of basin (fig. 9).

   "The boundary between the Paleozoic rocks and the relatively unconsolidated materials filling the embayment can be traced through Alabama, Mississippi, Tennessee, western Kentucky, the southern tip of Illinois, southwest Missouri, and Arkansas. Several thousand feet of sand, gravel, clay, lignite, chalk, and limestone have been deposited in the embayment during its complicated history of advances and regressions of the sea." (Schneider, 1947, p. 629)

   The axis of the trough roughly follows the Mississippi River but is somewhat obscure in southern Louisiana because of the great coastward thickening of sediments in this region.

6. North Louisiana syncline - a basin or gentle trough extending southeastward between two relatively stable positive areas - the Sabine and Monroe uplifts.

7. East Texas embayment - a syncline, or basin, that includes a large region of the Coastal Plain of northeast Texas.

> "Underlying much of the basin are salt deposits from which numerous salt domes have been formed, constituting the inner salt dome province of the Texas Coastal Plain." (Sellards and Baker, 1934, p. 42)

The basin, or structural trough, extends northwestward in an area surrounding Grayson and Fannin Counties, and is conspicuous as a Cretaceous re-entrant into older rocks. The basin forks around the Sabine uplift (fig. 6), one arm extending eastward near southern Arkansas and the other extending southward. The East Texas embayment, which has a complex history, persisted until near the close of Eocene time (Sellards and Baker, 1934, p. 42).

8. Rio Grande embayment - lying partly in Texas and partly in Mexico, this basin received great thicknesses of Cretaceous and Tertiary sediments. It is a gentle downwarped area in the Rio Grande valley. Minor structural features occur within this large embayment (Sellards and Baker, 1934, p. 40).

9. Downfaulting zones - associated with the downwarping of the southern margins of the continent are major systems of gravity faults, or of pronounced downflexing (Murray, 1957, p. 254). This down-to-the-coast system of faults has an arcuate pattern extending from the panhandle of Florida, through southwestern Alabama, southern Mississippi, southern Arkansas, and through a broad belt of Texas. Southern Louisiana also has several complex systems of these faults. A great thickening of sediments on the gulfward side of the fault zones is characteristic.

Positive, or uplifted structural features

1. Cape Fear arch, or Carolina ridge - a southeast-trending ridge in basement rocks near the North and South Carolina border. Coastal Plain sediments, almost all of which are Upper Cretaceous,

are less than 1,700 feet thick beneath the mouth of the Cape Fear River. The surface of the arch was emerged during most of Tertiary time, and only a thin veneer of upper Tertiary sediments is present.

2. Peninsular arch, or Ocala Peninsular uplift - a gentle arch whose crest extends from about Cape Canaveral on the east coast of Florida northwestward to central Georgia. According to Applin (1951, p. 3-5), the Peninsular arch and Ocala uplift are two separate but parallel structures. They are responsible for the peninsula or platform that has characterized Florida since Early Cretaceous time. Although now emerged, the peninsula has a long history of submersion. The uplift brings to the surface Eocene formations that are flanked by younger sediments.

3. Hatchetigbee anticline - an uplift extending northwestward in southern Alabama. The anticline brings to the surface some Eocene beds that are buried updip and to the north.

4. Wiggins anticline - an east-west trending arch through Stone and George Counties, Miss. Uppermost Cretaceous sediments show effects of uplift.

5. Jackson dome - a roughly circular arch near Jackson, Miss., in which the uppermost Cretaceous beds are about 3,000 feet nearer the surface than normally would be expected. Some uplifting continued to the Miocene (Thomas, E. P., 1950, p. 1505).

6. Monroe uplift - a broad gentle dome centering in the northern part of Ouachita Parish, La., and having a diameter of approximately 75 miles. Sediments older than Oligocene appear to have been arched upward in the area. This structural dome constitutes the reservoir of the Monroe gas field, which is the largest field, in areal extent, in Louisiana.

7. Sabine uplift - a broad, relatively flat-topped dome in De Soto and Caddo Parishes. Although irregular in form, its dimensions are about 80 miles in length and 65 miles in width, its long

axis trending northward. The uplifted area is separated from the Monroe uplift by a small syncline. On the highest part of the structure the Porters Creek Clay of Midway Group is exposed at the surface. Oil and gas are produced from structures within the uplifted area.

8. San Marcos arch - a broad, gentle southeast-trending arch inferred to be a buried continuation of pre-Cretaceous movements from the Llano region (Sellards and Baker, 1934, p. 44). Some Upper Cretaceous formations are thin on the arch.

9. Salt domes - Salt from deep-lying beds has intruded overlying sediments in the form of domes and plugs (fig. 10). The salt domes range in diameter from less than a mile to more than 4 miles. Some of the domes are within a few feet of the land surface, but others are many thousands of feet below. There are more than 200 salt domes in the Gulf coast area (fig. 11). They are important structural features because their upward intrusion resulted in an arching and pinching out of beds; local complex faults also are common. The anomalous structural conditions surrounding salt domes are ideal for the accumulation of oil. Pierce and Rich (1958) discuss the subject of salt domes in relation to disposal sites for radioactive wastes and present a bibliography of more detailed studies of salt deposits.

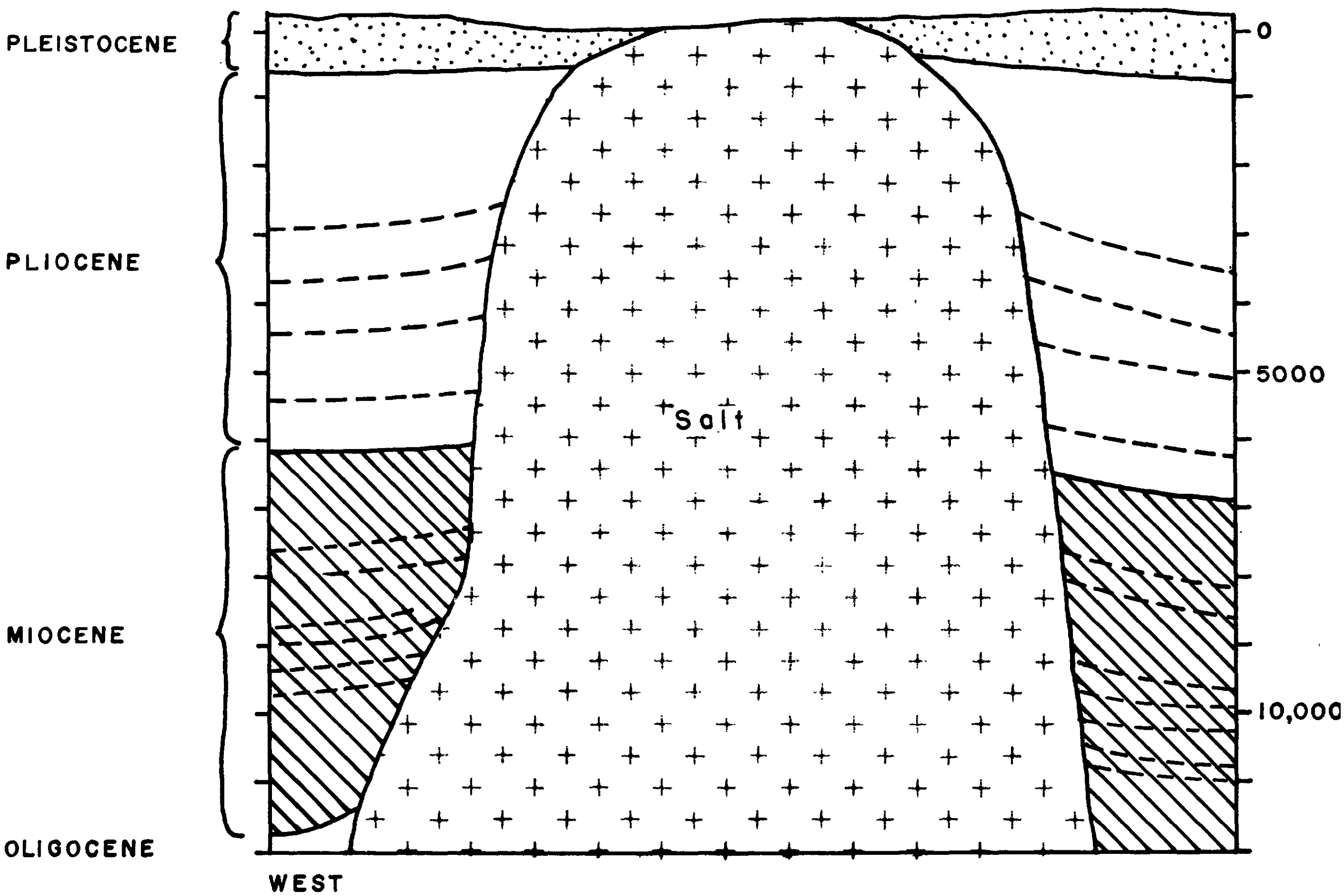


Figure 10. Cross-section of a typical salt dome, Avery Island, south-central Louisiana. Horizontal scale same as vertical (after Carsey, 1950).

Soils of the Coastal Plain

A great variety of soils occurs in the Coastal Plain province, but they cannot be systematically treated in this brief discussion. Their character and composition result from the geologic conditions during the deposition of the surficial geological formations and from the nature and intensity of weathering and erosion on these formations. Of general and widespread occurrence are sandy surface soils underlain by a subsoil zone of clay, sandy clay, or clayey sand. Beneath the subsoil are the flat-lying beds that have been relatively undisturbed by soil-forming processes. Where topographic relief is appreciable and where the water table is rather deep, there is a tendency for dissolved and suspended matter to move downward from the surface soil and to be deposited in the subsoil zone. For example, the rolling Sand Hills region, along the inner margin of the Coastal Plain in South Carolina and Georgia, has a well-developed sandy surface soil that is distinctly separate from the clayey subsoil. On the other hand, where the land is flat and poorly drained, there is a tendency for the soil profile to be poorly developed.

Soils with poor internal drainage generally contain considerable carbonaceous material. Upland soils are composed almost exclusively of mineral matter.

> "Oxygen forms the framework for soil minerals and it, hydrogen, silicon, aluminum and iron are the most abundant elements in mineral soils. Except for calcareous soils, which may contain as much as 75 percent calcium carbonate, and some latosols high in TiO_2, oxides of silicon, aluminum and iron make up at least 90 percent of the mineral portion. Silicon, aluminum and iron exist in soils in primary, clay and oxide minerals." (Thomas and Coleman, 1959, p. 1865)

Quartz is the predominant mineral in the sands and silts of the humid parts of the Coastal Plain, but in the subhumid part (southern Texas) the proportion of other minerals in sand-size fractions is larger. Clay minerals are present almost everywhere, both in the soils and in the underlying geologic formations. The clay minerals are very important for their capacity to be chemically bound to dissolved radioactive nuclides. Thomas and Coleman (1959, p. 1861-1912) have discussed the interaction of radioactive nuclides and soils.

GROUND-WATER HYDROLOGY

Summary of the Hydrologic Cycle

Upon reaching the land surface as precipitation, water takes diversified courses; however, most of it ultimately goes back to the ocean, which may be considered the primary reservoir. Much of the precipitation filters into sandy surface soils, although some finds its way into rivers, creeks, and ditches immediately after each rain. Some water evaporates immediately at the land surface, and some of that which seeps into the soil is evaporated or transpired by vegetation. If the rain is prolonged, some water passes below the root zone; a part is impeded in its downward movement by clay beds and is shunted laterally, even above the water table, to a steep slope, where it is evaporated; some of the water moves downward to the water table, which is the top of the zone in which the openings in the rock materials are saturated with water. Upon reaching the water table, it becomes ground water. This does not make way for a final resting place, because ground water moves by gravity to some low place where it discharges from the earth materials. The movement may be extremely slow if impediments are in its path or if avenues for escape are poor. Ground water discharges naturally, (1) as evapo-transpiration in low areas, (2) as seepage and springs, which tend to sustain the flow of streams in long periods of fair weather, and (3) as leakage into marginal seas.

Zone of Saturation and the Water Table

All the open spaces below the surface of the Coastal Plain are filled with air, water, or oil or gas. Oil and gas occur only in selected, rather deep parts of the Coastal Plain, and they occupy only a small fraction of the total pore spaces. Air, being lighter than water, is confined almost exclusively to the zone of pore spaces above the water table. Since the water table lies normally no deeper than a few feet or a few tens of feet below the land surface, the volume of water-saturated materials, and also the volume of water held in the sediments, is enormous.

The depth to the water table depends on the frequency and intensity of precipitation, on the ability of earth materials to transmit water, and on topography. Where a humid climate prevails, as in all of the Coastal Plain except the southern part of Texas, the frequency of periods of precipitation causes the water table to be near the land surface, especially in the low, flat areas (fig. 12). In the humid part of the Coastal Plain the water table has a higher elevation beneath the upland, or interstream, areas than in the stream valleys; as a result, ground water moves toward the valleys and discharges into the streams. In the arid part of the Coastal Plain the water table has a higher elevation beneath the upland, or interstream, areas than in the stream valleys; as a result, ground water moves toward the valleys and discharges into the streams. In the arid part of the Coastal Plain the scarcity of recharge keeps the water table at a relatively low stage; water from streams seeps downward, adding water to the zone of saturation and building up the water table beneath the streams. The relation of the water table to streams is shown in figure 13. Where both poorly permeable materials, such as clay, sandy clay, or fine sand, and relatively flat topography exist, the water table is within a few feet of the land surface in the humid part of the Coastal Plain; this is a common condition. Where permeable materials, such as coarse sand or limestone, underlie hilly topography the water table may lie 40 feet, or more, below the ground.

In most parts of the Coastal Plain there is only one water table. However, a local zone of saturation may occur above the main zone of saturation, its water surface being known as a "perched" water table. A perched water table is likely to occur only, (1) where streams have cut deeply into permeable beds, resulting in a greater than normal depth to the main water table, and (2) where an impermeable zone lies in the permeable materials above the main water table. Perched water tables commonly are confined to a fringing zone near escarpments that border some streams. The perched zones of saturation are relatively unimportant as a source of water supply, but their possible existence needs to be considered in evaluating the management of radioactive wastes, because the direction and rate of movement of water from these zones cannot be easily predetermined. For example, a perched water table occurs in the area of the Savannah River Plant (Horton and Patterson, 1959, p. 1214).

The Artesian System

The geologic structure of the Atlantic and Gulf Coastal plain is ideally suited for the occurrence of artesian water

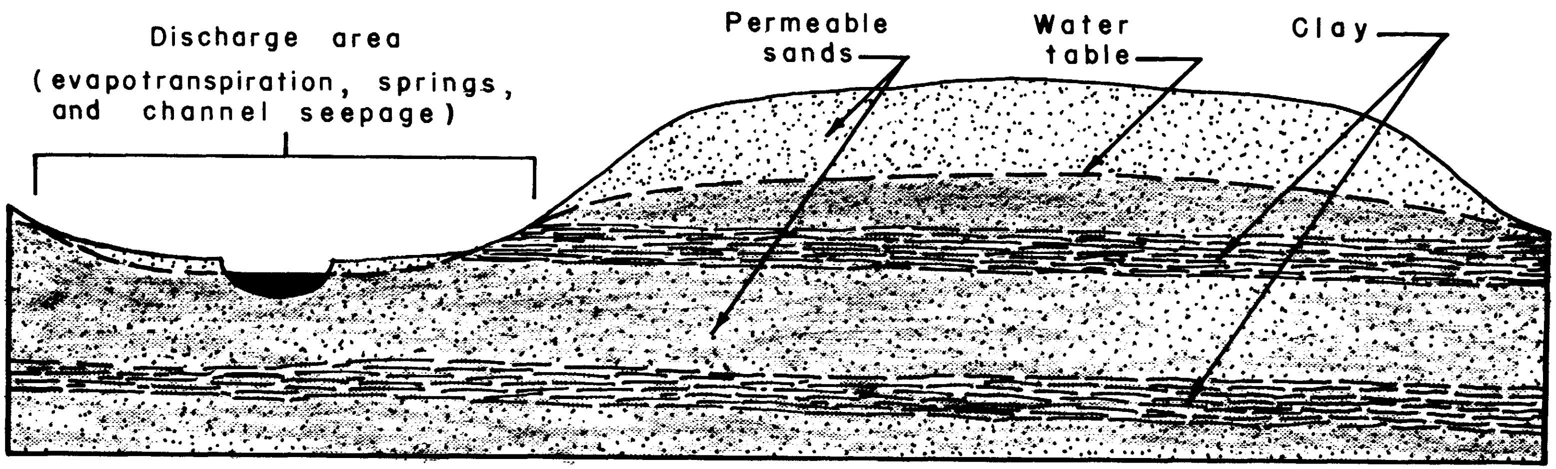


Figure 12. Diagram showing the results of the lowering of a stream valley through a water-table aquifer and into an artesian aquifer. Ground-water discharge from both aquifers occurs in the valley as evapotranspiration, as spring flow, and as seepage into the stream.

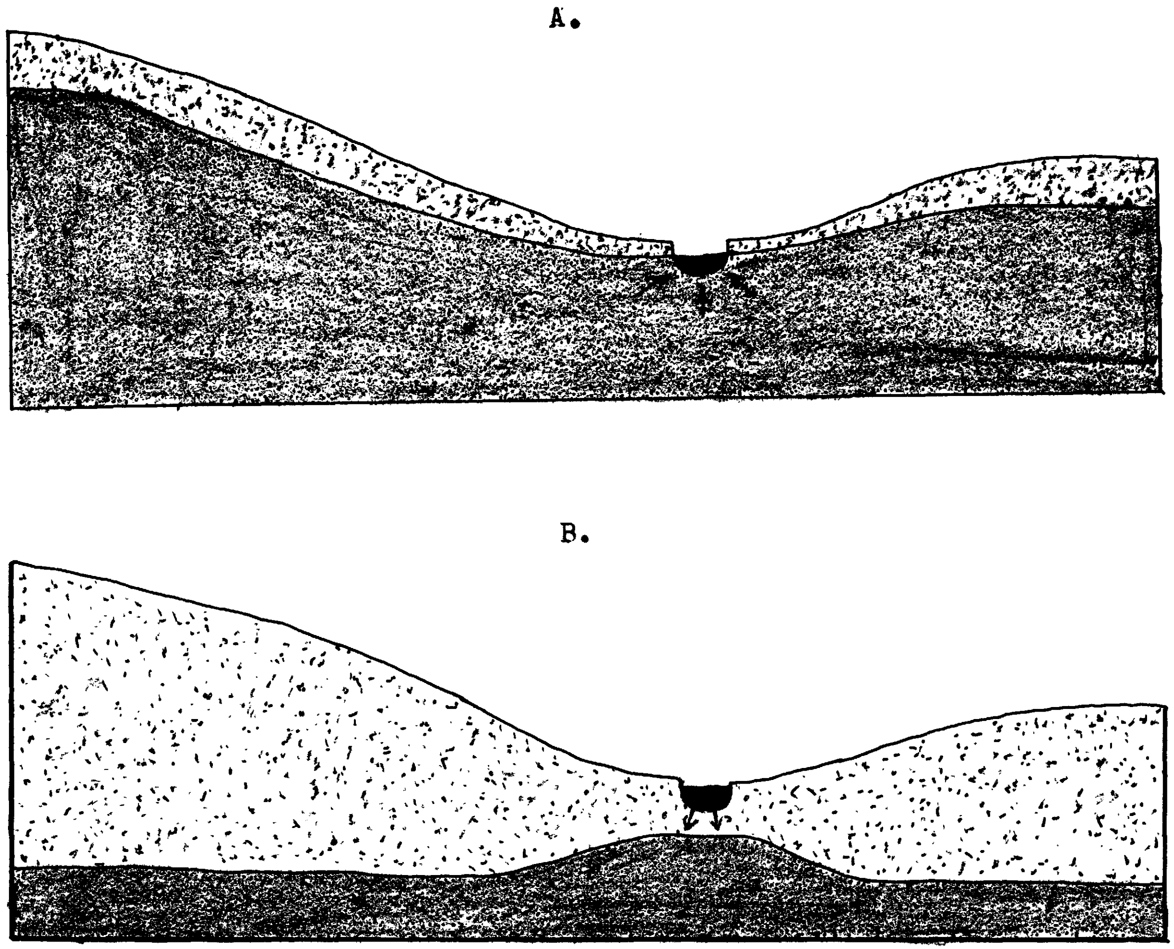


Figure 13. Diagram showing the relation of the water table to streams in humid areas A, and in subhumid or arid areas B.

(fig. 14). The idea that artesian water is deep water is not altogether accurate, and a better distinction between water-table and artesian conditions is necessary. The water table is the top of the zone of saturation, and it separates air-filled pore space above from water-filled pore space below. At some place below the water table a relatively impermeable bed occurs, which retards the further downward movement of water. This impermeable bed, commonly of clay in this region, acts to confine water under pressure that lies beneath it. The water enters the ground, reaches the water table, and flows . . . "down with the slope of

> the water table to a point where the zone of saturation is interrupted by an impermeable bed. Part of the water may pass above the bed and continue to flow under water-table conditions, and part of it flows beneath the bed. Now it is confined, pressing upward against the impermeable bed with a head equivalent to the difference in elevation between that point and the elevation of the water table in the area of recharge, less the loss of head resulting from friction in movement. This is confined, or artesian, water; it will rise in a tightly cased well to a height above the bottom of the confining bed equivalent to the pressure head at that point. If the head happens to be above the land surface, as it commonly is in the valleys or along the coast . . . . the well will flow." (McGuinness, 1951, p. 12-13)

The Coastal Plain is composed of many different beds, some of which allow water to pass through them readily, while others prevent or retard the movement of water. The more permeable ones, commonly medium to coarse sand or limestone, are referred to as aquifers. The poorly permeable or impermeable beds, commonly clay or shale, are called aquicludes. The interlayered sands, clays, and limestone form a composite artesian system composed of a number of separate artesian aquifers and aquicludes. Since most geologic formations contain more than one type of material, they rarely coincide precisely with either aquifers or aquicludes. For example, the Magothy Formation of New Jersey, Delaware, and Maryland, and the Black Creek Formation of the Carolinas contain at least two sand aquifers and two clay aquicludes. The tendency for most of the beds to have a coastward homoclinal slope slightly greater than that of the land surface results in an increase in depth to a specific artesian bed toward the coast; the number of artesian zones below a specific place also increases toward the coast.

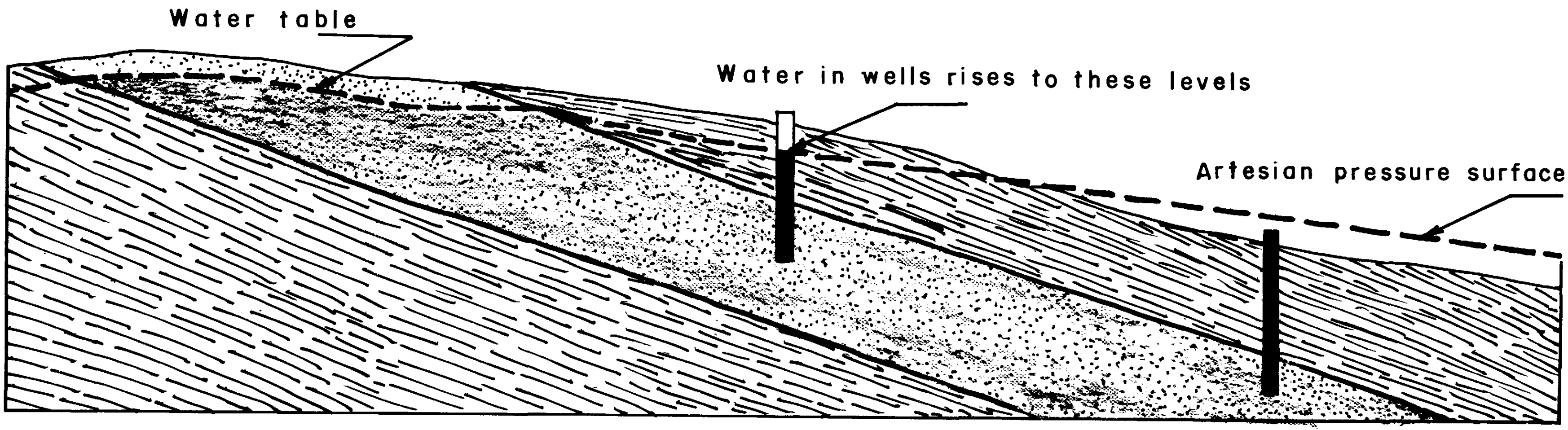


Figure 14. An example of an artesian aquifer of the Coastal Plain. The permeable sand bed lies between impermeable beds of clay. Water enters the aquifer (where it is exposed at the land surface) with greater ease than it can escape from it. Thus, there is sufficient head to force water above the top of the aquifer and even above the land surface at some low elevations.

Storage Characteristics and Permeability of the Coastal Plain Sediments

Water in the Coastal Plain deposits may be considered as occurring in an immense underground reservoir. The water in storage is actually in transit from places of recharge, where water enters the ground, to places of discharge, where water moves out of the underground reservoir. Thus, we might look on the earth materials both as a reservoir and as a system of conduits, receiving water at the upper end of the system and discharging it at the lower end.

The total amount of water held in storage in the Coastal Plain materials is enormous, but not all of this water would drain out, even if conditions were favorable for it. Some would be held by capillary attraction and would resist the pull of gravity. Clay, which has small openings but a high proportion of total pore space, tends to retain more water than sand, which has larger but less numerous pore spaces.

Whether we are concerned with withdrawing water or injecting fluids underground, it is important to distinguish between the storage capacities of water-table and artesian aquifers. Water taken from a water-table aquifer comes from storage as water drains by gravity from pore spaces, and the water table is depressed within the aquifer. The pressure surface of an artesian aquifer lies above the top of the aquifer. Withdrawal of artesian water depresses the pressure surface, but it does not unwater the aquifer or replace water with air unless the cone of depression lowers into the aquifer. Rather, the water is derived from storage because relief of pressure allows compaction of the aquifer and slight expansion of the water.

The "coefficient of storage" is a mathematical expression of the storage capacity of rock materials. By definition, the coefficient of storage of a water-table aquifer is the fraction of a cubic foot of water that will drain out by gravity from a cubic foot of saturated rock; the coefficient of storage for water-table conditions ranges from about 0.02 to more than 0.40, and commonly is 0.10 to 0.25. The coefficient of storage of an artesian aquifer is the fraction of a cubic foot of water that is released from storage in a vertical column of the aquifer 1 foot square when the head is lowered 1 foot; values range from 0.00001 to about 0.005. Where the pressure head stays above the top of the aquifer (artesian), the storage capacity is much less than when the head lies within the aquifer (water table).

The geologic materials in the Coastal Plain range widely in their capacity to transmit water. Aquifers are composed of permeable materials; aquicludes (confining beds) are composed of impermeable, or relatively impermeable, materials, and they prevent or greatly retard vertical movement of water. Most of the impermeable beds consist of clays and shales. Most of the aquifers consist of sand, gravel, and, less commonly, limestone. The description of each State on subsequent pages in this report includes notes on salient features of the geologic formations which contain extensive or important aquifers or aquicludes.

Two important geologic features of the Atlantic and Gulf Coastal Plain should be considered in relation to permeability and storage capacity of the deposits. One feature is the tendency of individual formations to become finer grained and less permeable toward the coast; this applies especially to Cretaceous and Tertiary deposits and not necessarily to the relatively thin surficial Quaternary deposits. In general, coarse materials, such as sands and gravels, were deposited near shore as the shoreline oscillated across the area that is now the inland half of the present Coastal Plain. Clays and calcareous materials tended to be deposited in deeper water. Therefore, most beds of sand become finer grained and grade into clay or silt down the dip, or seaward.

The second important geologic feature is the tendency of the permeability and storage capacity of the sediments to decrease with increased depth. The weight of overlying materials compacts sediments and squeezes some water out and forces it upward. Pore space decreases and some sediments may become reconstituted into relatively dense rock. Most sands and clays of the Coastal Plain are unconsolidated to depths greater than 1,500 feet. Below 2,000 feet clays tend to become shaly. Some calcareous deposits become consolidated into limestones at relatively shallow depths; where water has been able to move through the limestone to dissolve the rock and enlarge some pore spaces, the beds may be very permeable. However, most sediments at depths greater than about 3,000 feet have been largely consolidated, and their permeabilities are much less than those of unconsolidated shallower sediments.

Operation of Ground-Water Reservoirs

Some general aspects of the hydrologic cycle and some characteristics of the underground reservoir and its water have been considered. In order to evaluate correctly the possibilities for waste management, at least in gross terms, the circulatory system of ground water must be understood. Factors for consideration include the presence of, (1) water-table aquifers, (2) aquicludes, and (3) artesian aquifers. Every area contains either a water-table aquifer or an aquiclude, and, except for a narrow zone along the inner margin of the Coastal Plain, an alternating sequence of aquicludes and artesian aquifers underlie the water-table aquifer. Water moves, (a) into each, (b) through each, and (c) out of each aquifer. Distinctive though these considerations seem to be, they must be synthesized, for they have interdependent tendencies.

Water which enters an artesian aquifer generally passes first through a water-table aquifer or through an infiltration zone, which regulates recharge by accepting or rejecting water according to certain conditions. Recharge to a water-table aquifer results from infiltration of precipitation and percolation of water through the soil to the water table; also, in parts of south Texas, where the precipitation is slight, some recharge occurs by seepage downward from some streams. Liquid outflow and evapotranspiration are natural processes of ground-water discharge. Under natural conditions, at places beyond the influence of pumped wells, aquifers are in a state of approximate dynamic equilibrium. The average rates of discharge from aquifers during a long term of years equals the rates of recharge. The height of a water table depends on the amount of water stored in the aquifer. But during a complete season or climatic fluctuation, virtual balance exists between discharge and recharge by natural processes. For example, in the humid part of the Coastal Plain the streams flow perennially because the ground water discharges continually by seepage into stream valleys. Continuous outflow of ground water causes the water table to decline except during and immediately after periods of prolonged precipitation when recharge from precipitation exceeds discharge.

The humid and semiarid parts of the Coastal Plain differ in their facilities for recharge. In the humid region, water-table aquifers receive recharge during most of the year, though it is most abundant during wet seasons, and the water table remains high in interstream areas.

The aquifers become full and reject some recharge. The excess water leaks out into the valleys as seeps and springs, or builds up the zone of saturation to a level near the land surface, where water is lost to evaporation and transpiration. In the less humid part of the Coastal Plain, as in south Texas, the water table normally is low--even below the bottoms of many stream channels. There, the aquifers accept most water that filters through surface materials because the aquifers can accept and carry away more water that is available from recharge.

Figure 15 shows the relation of rainfall to streamflow and to water levels in water-table wells in the humid part of the Coastal Plain--in Bundick Creek drainage basin, Beauregard Parish, La. Jones and others (1956, p. 225) explained that in that basin, "Peak streamflow, as in

> November and December 1948, results principally from surface runoff (overland flow). Low flow, however, such as that between the middle of March and the middle of November in 1948, is derived almost exclusively from ground-water seepage. The amount of streamflow derived from ground water is shown approximately by the dashed line ---------."

That a part of recharge to the water-table aquifer is lost to a stream in the humid part of the Coastal Plain is indicated by the sustained dry-weather flow of the perennial streams. To some extent each artesian aquifer of the Coastal Plain acts as a pipe or conduit, transmitting water from a place of recharge at a higher elevation to a place of discharge at a lower elevation. The analogy soon breaks down, because most aquifers in their downdip and coastward direction are less permeable, are filled with dense, highly mineralized water, and, in general, have extremely poor facilities for discharging water at great depths. There is a tendency for water to move upward, even through relatively impermeable aquifers with less hydrostatic pressure. Some water discharges into the sea and some moves upward through aquicludes and aquifers to reach a stream, or the water-table aquifer. In places, streams cut into artesian aquifers and bleed water from them; even where relatively impermeable beds separate the uppermost artesian aquifer from a stream, upward leakage to the stream valley may be considerable (fig. 16). Recharge from the water-table aquifer to the uppermost artesian aquifer occurs when and where the water table is higher than the pressure surface of the artesian aquifer. In many parts of the Atlantic and Gulf Coastal

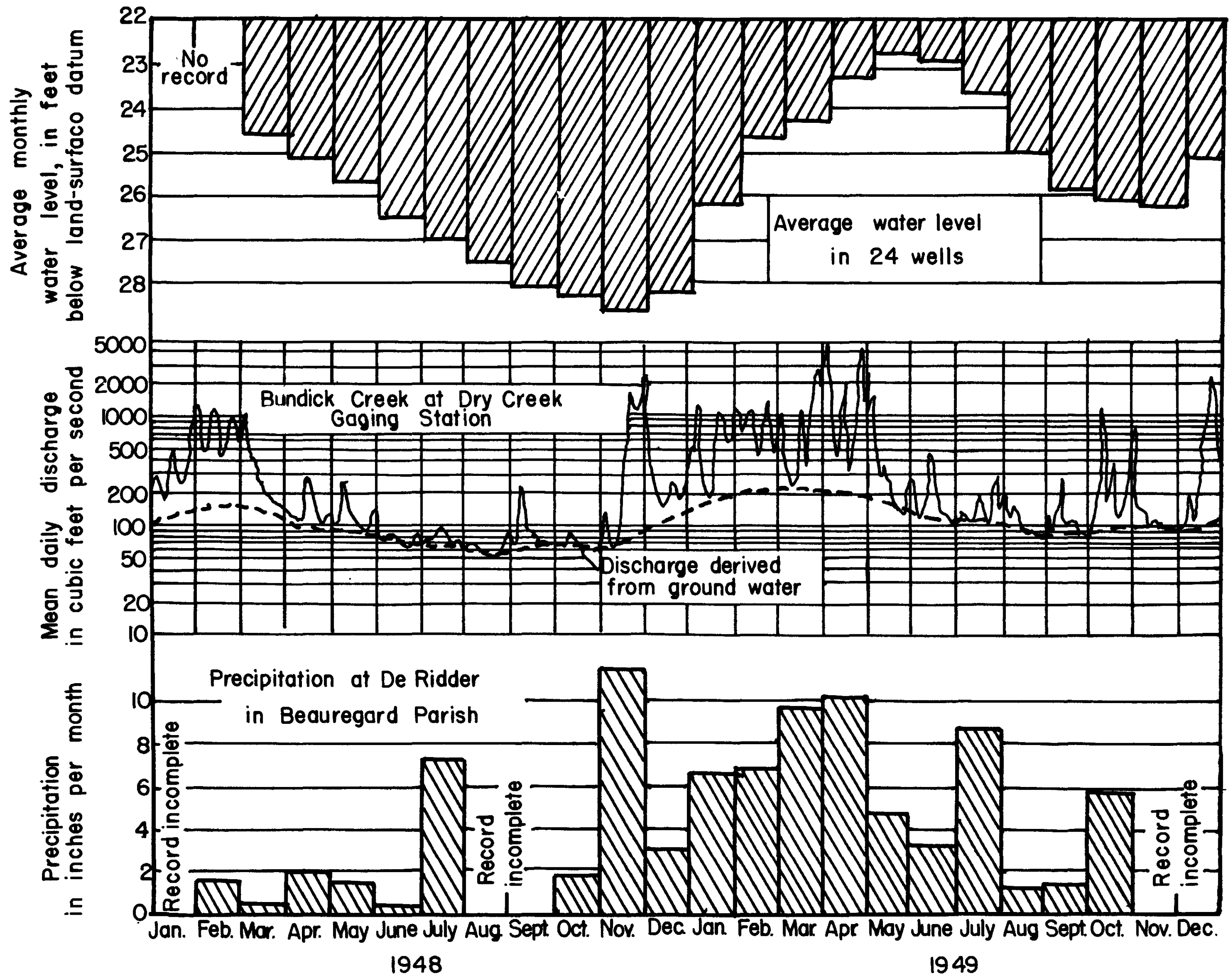


Figure 15. Hydrographs showing the relation of ground-water levels to stream flow and precipitation in Beauregard Parish, Louisiana (Jones and others, 1956).

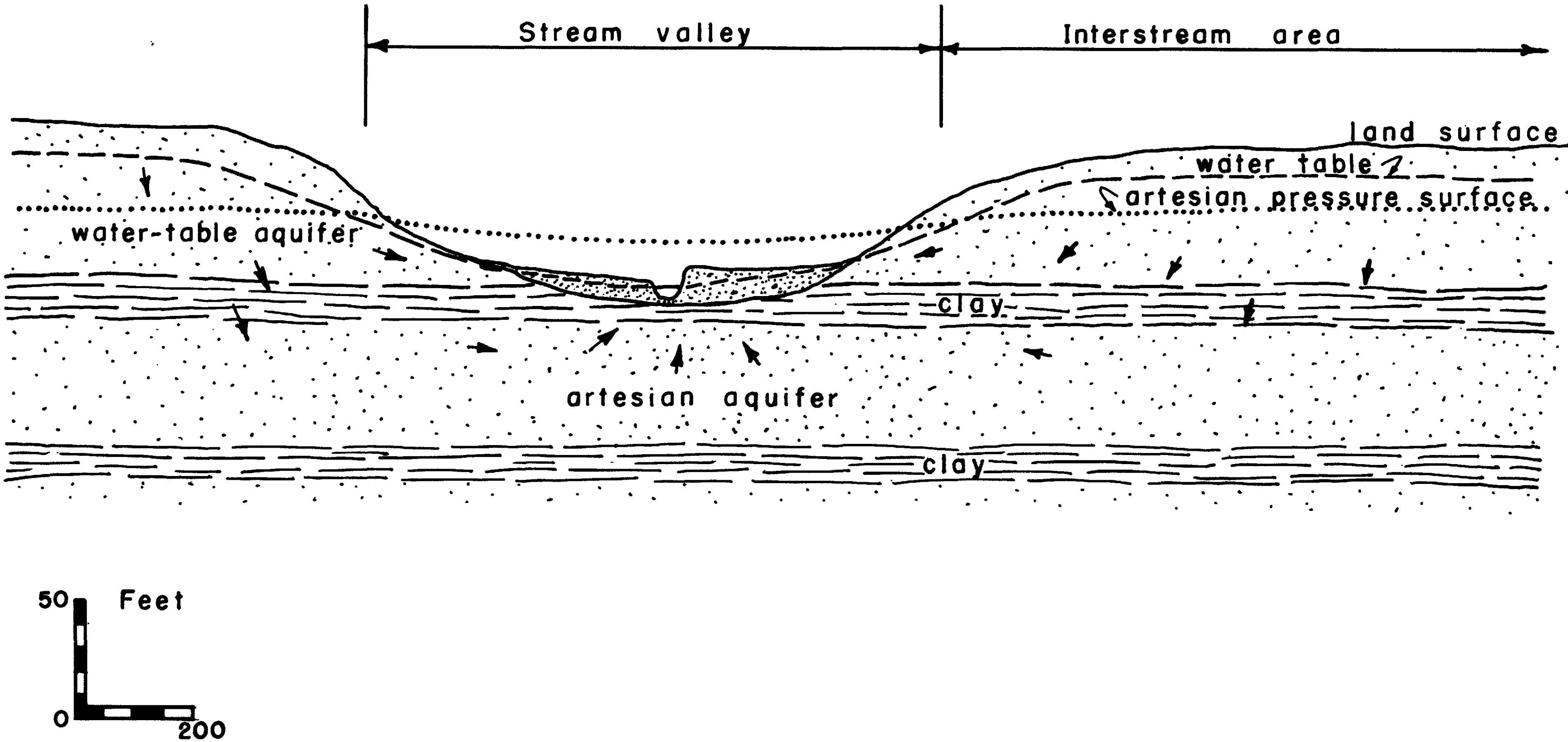


Figure 16. Diagrammatic cross section through a stream valley showing (1) difference in head between water-table and artesian aquifer in stream valley and beneath interstream areas and (2) the movement of water into and from both types of aquifers.

Plain the water table and the pressure surface of the uppermost artesian aquifer have about the same elevation on the upland, or interstream, areas; as the water-table aquifer is recharged, the difference in head between the aquifers is increased, and water moves slowly downward through relatively impermeable materials to the artesian aquifer (fig. 16).

In the Atlantic and Gulf Coastal Plain the rate of flow is directly proportional to the hydraulic gradient, which is the difference in head in feet between two points, divided by the distance between them, also in feet. The hydraulic gradient tends to steepen around areas of discharge, and consequently the rate of flow tends to increase. Thus, the rate of flow in water-table and uppermost artesian aquifers tends to increase in the vicinity of stream valleys. The rate of flow also quickens around wells that yield water. Movement depends also on the character and structure of the rocks. Ground water flows through permeable materials and between or around impermeable ones, following the path of least resistance like surface water (McGuinness, 1951, p. 25). In vertical sections throughout the Coastal Plain three general zones are distinguished in which water moves at differing rates. In zone 1 of figure 17 streams intersect the water-table and uppermost artesian aquifers, which discharge water relatively rapidly to the streams. The zone extends about 100 to 200 feet below the base of the streams, and the rate of ground-water movement is on the order of feet per day or feet per year. The base of zone 2 is arbitrary also and may be considered as extending to a depth of several hundred feet, or perhaps to a depth at which the water is salty; the water in zone 2 has no good discharge facilities and its rate of movement generally is on the order of feet per year. Zone 3 contains only salty water, and has extremely poor facilities for discharging water; the rate of movement may be considered in terms of feet per century. Withdrawal of water from wells or introduction of fluids through wells would steepen the hydraulic gradient in an aquifer, and quicken the flow in any of the zones.

Chemical Character of Water

The chemical character of water in the Coastal Plain ranges from some low-mineralized, shallow water containing less than 25 ppm (parts per million) of total dissolved

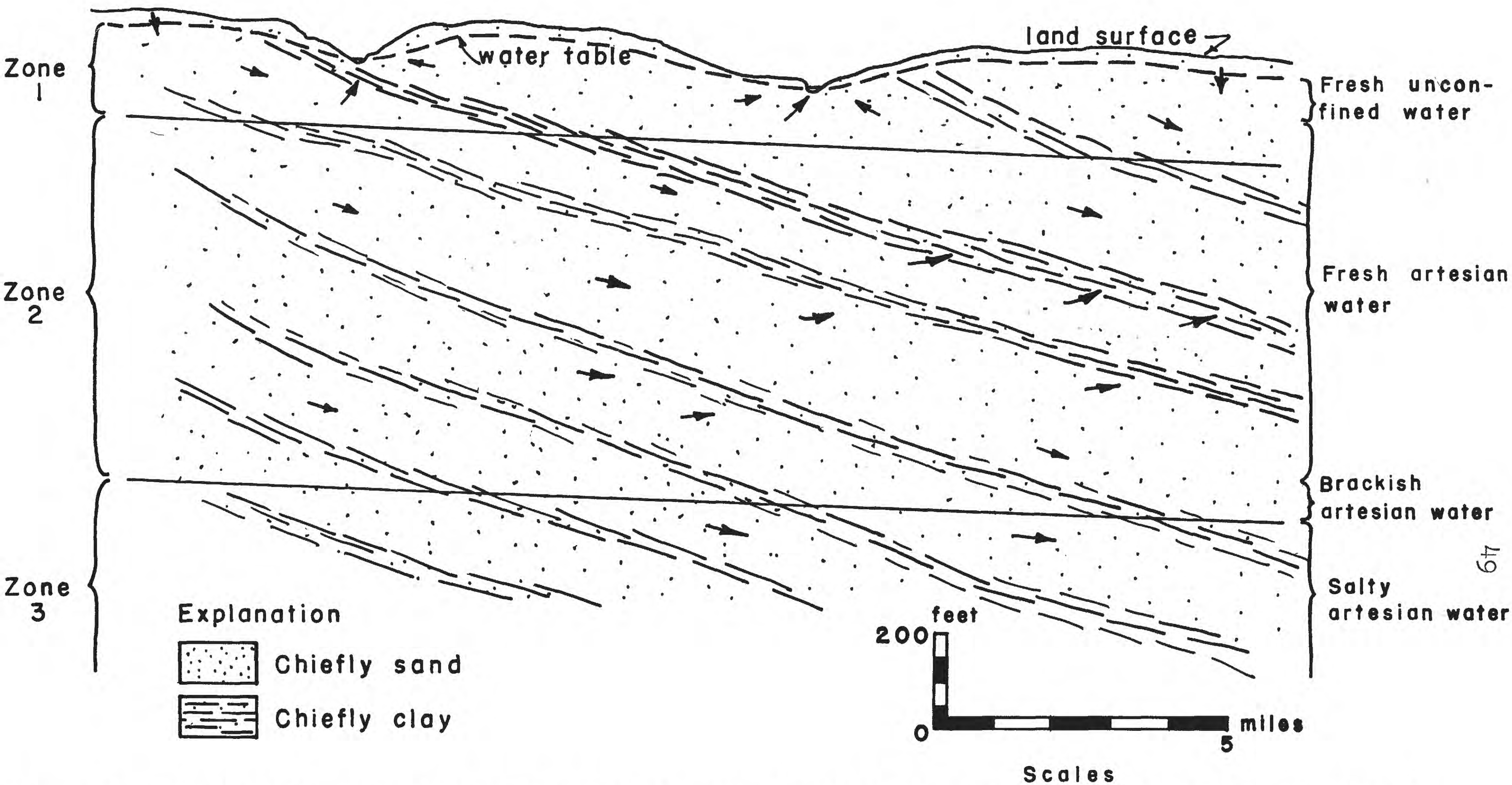


Figure 17. Hypothetical section showing three vertical zones through which water moves at different rates. Zone 1 includes the water-table aquifer and to some extent the uppermost artesian aquifer; discharge of water is considerable, and movement may be considered in terms of feet per day. Zone 2 includes most of the fresh artesian water and perhaps some salty artesian water, several aquifers generally being involved; water moves slowly, to some extent downdip and coastward and to some extent upward through relatively impermeable layers, but facilities for discharge are poor. Zone 3 contains salty water at considerable depth; water is so confined that movement may be considered in terms of feet per century. The thickness of each zone may vary considerably from place to place.

solids to deeply buried brines whose total dissolved-mineral content is several times that of sea water (table 1, no. 14). Sea water contains about 35,000 ppm of total dissolved solids, of which slightly more than 19,000 ppm are chloride ions and more than 10,000 are sodium ions.

Almost all of the sediments either were deposited in sea water or had sea water introduced into them at some time in their history. Yet, almost nowhere do the sediments now contain water identical to that of the sea. Movement has been the keynote to changes in the character of the water, for all the water has moved some distance and, in doing so, has been influenced by the character of sediments and by the character of contiguous water in its path. Water from precipitation has flushed out the former salt water in most of the beds along the inner margin of the Coastal Plain and in the uppermost beds in most of the coastal areas. Thus, we must make a distinction between the water that is fresh and potable and water that is salty. The Public Health Service recommends that dissolved solids should not exceed 500 ppm and that chloride should not exceed 250 ppm for a water to be of good chemical quality for domestic use. Most of the saltiness is due to sodium and chloride ions. Two exceptions include some deeply buried brines that have more calcium than sodium and some water of intermediate depth in south Texas that is relatively low in chloride but high in calcium and magnesium sulfate. However, for the purposes of this report, water containing less than 500 ppm of chloride is considered fresh.

As water moves through the Coastal Plain sediments toward places of discharge its chemical character changes in most cases becoming more mineralized with distance and time of travel. Some of the changes are evolutionary and may be traced in a general way. Table 1 lists several analyses of water from wells, each of which may be typical of certain areas or zones. In all the Coastal Plain except southern Texas almost all of the water upon reaching the water table has passed downward through rather insoluble and leached sands and clays. The water-table aquifers generally are composed of sands containing very little soluble material. Thus, much shallow ground water is characterized by low total-dissolved solids, considerable free carbon dioxide, and a pH value ranging from 5.0 to 7.0. Where the water-table aquifer is limestone, as in the northwestern part of the peninsula of Florida, the water quickly dissolves the limestone and increases in calcium bicarbonate content. Foster (1942, p. 838) and Cederstrom

(1945c, p. 99) have shown that some waters increase in calcium bicarbonate as they move certain distances through sandy artesian aquifers; however, because of the ion-exchange capacities of some clays and glauconite, further downdip and coastward movement tends to soften the water as calcium from the water is exchanged for sodium of the earth materials. Belts of soft sodium bicarbonate water from artesian sand aquifers occur especially in Virginia, North and South Carolina, Alabama, and Mississippi. Hard calcium bicarbonate water is characteristic of limestone aquifers; all of the fresh artesian water in peninsular Florida is of this type. In south Texas the fresh ground water is mineralized somewhat more than in other parts of the Coastal Plain province; in this area many of the public and private supplies deliver water containing 1,000 ppm of dissolved solids (Broadhurst and others, 1950, p. 2).

The zone of fresh water overlies the zone of salt water throughout the Coastal Plain province, but in a few places lenses of fresh water may be found below lenses of salty water. Generally the depth to salty water is greater beneath high inland places than beneath low coastal places (fig. 18). Along the inner margin of the Coastal Plain all the beds may contain fresh water, whereas along the coast only the uppermost beds contain fresh water. South Carolina appears to be the only coastal State which contains a greater percentage of fresh water than salty water; Delaware contains nearly as much fresh as salty water. Florida and Louisiana contain large volumes of fresh water, but since sediments in these States are extremely thick and extend far below sea level, the volume of fresh water is much less than that of salty water. The surface of the salt-water body is very irregular, and information is not yet adequate in most States to map it with reasonable accuracy.

Table 2 lists a few chemical analyses of water from some selected streams. The drainage basins of these streams are large and the water is a mixture of both overland flow and ground-water discharge from diverse rock materials; therefore, relating the geology to the chemical character of water from these streams, as well as other large streams, is difficult.

Temperatures and Artesian Pressures

The temperature of water in the water-table aquifers usually is about 2° to 3° F. above the average annual

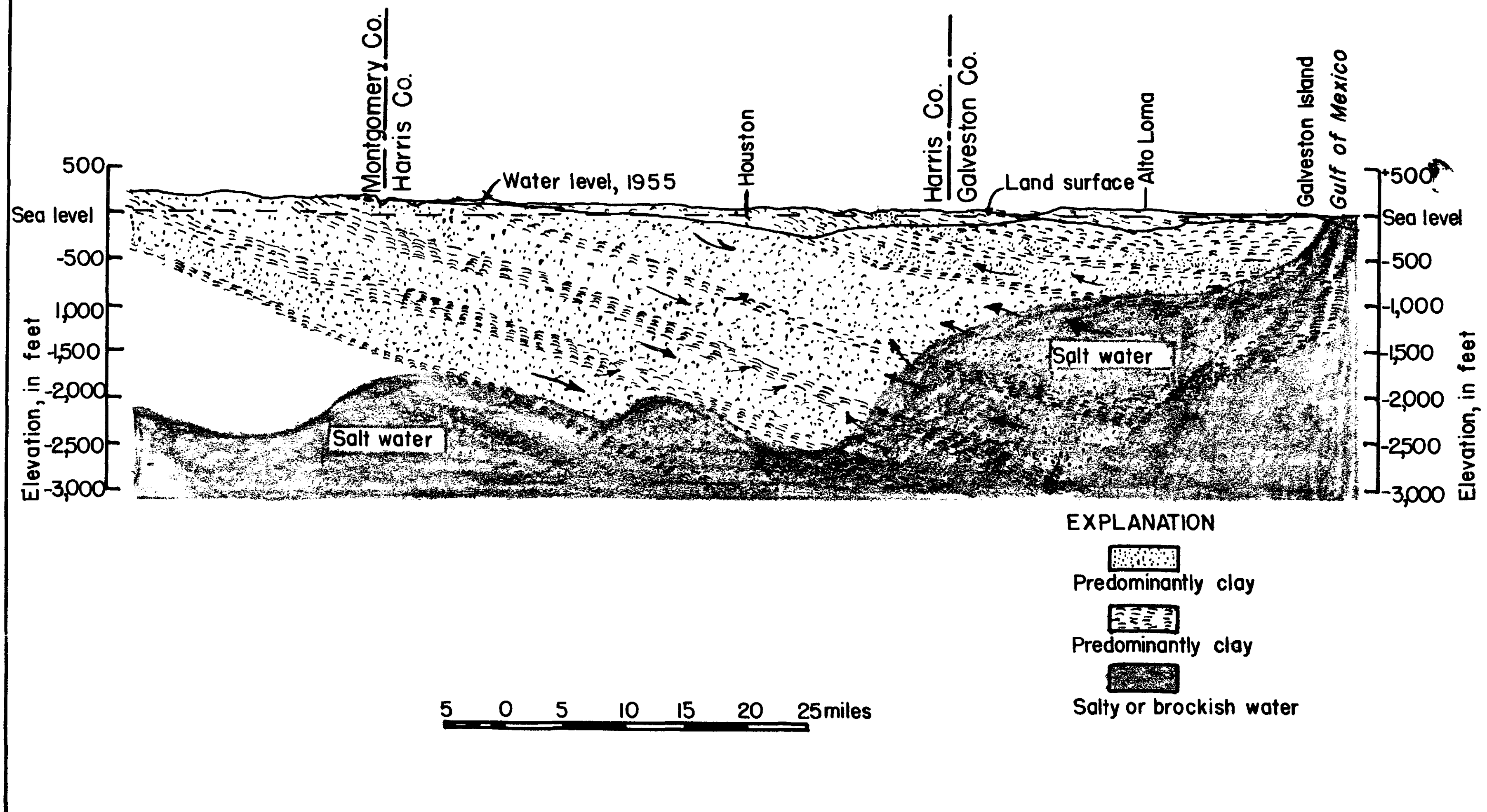


Figure 18. Generalized cross section in the Houston area, Texas showing relation of fresh and salty water near the coast and the movement of water toward the area of ground-water withdrawal (Wood, 1956).

temperature. The shallow ground water ranges in temperature from about 55° F. in Long Island to more than 70° F. in parts of the Gulf Coastal Plain. The temperature of water increases with depth. Bennett and Meyer (1952, p. 173) report an increase of about 1° F. for each 60 feet of depth in Maryland, whereas an increase of about 1° F. for each 90 feet of increase in depth is noted in Louisiana (Jones and others, 1956, p. 431).

There is a continuous movement of water between aquifers, the direction of movement being toward the aquifers with the least fluid pressure. Of the aquifers that have surface intake areas, the deeper ones tend to crop out or have their intake areas at higher elevations than the shallower ones. Thus, the deeper the aquifer the greater is the tendency for it to have more pressure than the overlying aquifer, but this tendency is subdued by leakage from the higher- to the lower-pressure aquifer. In the lowland parts of the Coastal Plain flowing artesian wells yielding fresh water are common, and deeper wells yielding salty water would flow even higher above the land surface than the water table. Rubey and Hubbert (1959, p. 169) state that "for most water wells, and for most oil wells within

> a range of about 0 to 7,000 feet, the height above the stratum to which the water will rise is equal approximately to the depth of the stratum below the surface of the ground or, perhaps more accurately, below the water table."

The theme of their paper deals with abnormally high fluid pressures, such as those found at depths of 8,000 feet or more in the Gulf coast region of Louisiana and Texas.

Flow of Water in Streams

Many streams of the Atlantic and Gulf Coastal Plain vary considerably in their flows from day to day, season to season, and year to year. The rate of flow is a function of the geology and is dependent on rainfall, topography, ground-water geology, vegetation, size of drainage area, and other factors. To a great extent the factors are so intricately related that they cannot be considered logically in this brief discussion. However, one aspect of rainfall may be mentioned. In all the Coastal Plain, except southern Texas near the Mexican border, the rainfall exceeds 40 inches a year; precipitation in this amount allows appreciable recharge on the interstream areas, resulting in a high water table beneath the interstream areas (fig. 12). This condition causes (1) a continuous discharge of ground water into stream valleys, (2) a close network of perennial streams, and (3) a tendency for streams to increase in flow coastward. In contrast is the sub-humid part of southern Texas, where precipitation is slight, and the water table receives so little of the precipitation that it is often depressed even below stream level; instead of gaining, the streams lose water by downward percolation to the water table and, therefore, streams are sparse and may not increase in flow coastward.

Information on the flow of streams is collected by the U. S. Geological Survey. Continuous records of the flow at gaging stations are kept, and are published in annual water-supply papers of the Survey. Selected summary-type data on some of the major streams are given in table 3.

LONG ISLAND

Topography

Long Island represents the northernmost part of the emerged section of the Atlantic Coastal Plain. Separated from the mainland by Long Island Sound, the island is based on a crystalline-rock surface which slopes gently to the southeast. Most of the island is underlain by sands, gravels, and clays of Cretaceous age, although more than three-fourths of the volume of sediments above sea level are glacial deposits of Pleistocene age.

The land surface is a slightly dissected plain, ranging in altitude from sea level to more than 200 feet. The northern shore, in its western half, is deeply notched by steep-sided bays which are related to valleys carved in the scarp of a former upland (Fenneman, 1937, p. 18). The southern border of the plain has tidal mud flats and shallow bays that are separated from the ocean by sandy barrier beaches (Perlmutter and others, 1959, p. 417). The surface drainage is represented mainly by small, shallow streams fed chiefly by ground-water discharge.

From outcrops near Long Island City, Queens County, the bedrock surface becomes more deeply buried toward the south-central part of Suffolk County, where it is estimated to be about 2,200 feet below sea level. The bedrock materials are metamorphic and igneous rocks.

Cretaceous System

The Cretaceous deposits of Long Island consist of the Raritan and Magothy Formations, both of which contain sand, clay, and gravel. The Raritan is divided into two members, the Lloyd Sand Member below (resting on bedrock) and an overlying unnamed clay member.

The Lloyd Sand Member ranges in thickness from about 20 feet in northwestern Queens County to about 350 feet or more in southeastern Suffolk County. It consists of gray sand and gravel and lenses of clay and sandy clay. Two or three water-bearing zones separated by layers of clay or other poorly permeable materials have been recognized in the Lloyd Sand Member. The less permeable zones normally are very extensive. The Lloyd Sand Member has long been used as a source of water supply on the North Shore from Flushing to the vicinity of Huntington and on the South Shore along the beaches. Little is known about the Lloyd Sand Member in eastern Suffolk County. The clay member of the Raritan overlies the Lloyd Sand Member and forms a relatively impermeable seal for the underlying water, although, in some places, later erosion has removed the clay and allowed overlying Pleistocene sand and gravel to be in contact with the Lloyd Sand Member. The clay generally consists of 50 to 300 feet of laminated silty beds and solid clay beds with subordinate sandy layers.

Cretaceous deposits above the clay member of the Raritan have been considered equivalent, at least in part, to the Magothy Formation of New Jersey. The Magothy Formation consists of a wide variety of sands and clays of different colors. The formation is absent in northwestern Kings County but reaches a thickness of about 1,000 feet in southern Suffolk County. The sands are used widely as an aquifer throughout most of Long Island except in Kings County.

Quaternary System

Deposits of Tertiary age are absent on Long Island, indicating that a long period of erosion passed before the Pleistocene glaciation. The Jameco Gravel is a body of glacial outwash, composed chiefly of brown sand and gravel deposited on the Magothy Formation (Perlmutter and others, 1959, p. 422). In Kings County the deposits range from 50 to 150 feet in thickness, and the top of the gravel lies from 100 to 200 feet below sea level. In Queens County the Jameco Gravel ranges from 30 to 150 feet in thickness, and the top of the formation occurs from 80 to 250 feet below sea level. In Nassau County the Jameco deposits have been identified only in a narrow fringe area along the South Shore. Water in the gravel is confined.

Overlying the Jameco Gravel is an interglacial formation known as the Gardiners Clay. It consists chiefly of dark-gray or greenish-gray silty clay. In Kings County the Gardiners Clay is 50 to 180 feet below sea level, and is normally about 50 feet thick, except in the northern part where it thins to about 10 feet. In Queens County it ranges from 50 to 200 feet below sea level, and in thickness from 10 to 150 feet. In Nassau County the Gardiners Clay is 20 to 60 feet thick and occurs 40 to 100 feet below sea level.

Other glacial deposits not readily differentiated occur at or near the land surface. They are as much as 200 feet thick in parts of Kings and Queens Counties and possibly thicker in parts of Suffolk County.

General Statement

Geology

A wedge of unconsolidated sediments which thicken to the southeast characterizes the Coastal Plain deposits of Long Island. The sediments below sea level are of Cretaceous age, except for scattered deposits of Pleistocene materials which fill numerous depressions. The surface and near-surface deposits are chiefly the results of Pleistocene glaciation. Beds of relatively pure sand and relatively pure clay are common, but so are heterogeneous bodies of sands, clays, and gravels. The bedrock surface slopes southeastward at a rate of more than 50 feet per mile, and the thickest section of sediments is slightly more than 2,000 feet. The homoclinal dip is the prevailing structural feature, and no noteworthy folding or faulting has been recognized.

Hydrogeology

Several features of the hydrology of Long Island are not typical of other parts of the Atlantic and Gulf Coastal

Plain. No major river system dissects the unconfined aquifer, although ground water does exude from surface sands along the coasts, in the small short streams, and in low swampy ground. The ground-water bodies beneath the island are, in a general sense, hydrologically connected to form a single, large, fresh, ground-water reservoir; on the other hand, the lowermost aquifer, the Lloyd sand, to a great extent is separated from overlying permeable sands and gravels by relatively impermeable clays. Heavy withdrawal of water from wells in parts of the island has caused water to move vertically through clay beds to the sand bed from which water is pumped. Thus, much of the fresh water beneath the island, as well as some fringing brackish water, is being diverted from its natural course.

The salt-water situation on Long Island has been summarized by Lusczynski and Geraghty (1956, p. 5), who report that salty water occurs: (1) near the mouths of the many fresh-water streams, (2) at shallow depths in the shore areas and along the barrier beaches, (3) at moderate depths below fresh water in the North and South Forks of Suffolk County, (4) offshore, generally under natural conditions, in the intermediate and deeper formations around the perimeter of the island, and (5) in certain inland areas in the shallow and intermediate formations where sea-water encroachment has resulted from heavy, continued overpumping. Considered in a general way, salty ground water circumscribes the fresh ground water around the island. Only in a few places is a point in the salty ground water more than 3 miles laterally and 500 feet vertically from fresh ground water.

NEW JERSEY

Topography

The Coastal Plain province in New Jersey is formed by beds of clay, sand, gravel, and other loosely cemented rocks of Cretaceous, Tertiary, and Quaternary age. These strata cover about three-fifths of the State, lying southeast of a line that could be drawn from Trenton to the Raritan Bay. The area is described (Kummel, 1940) as a gentle, dissected plain that rises gradually from sea level at the coast to about 400 feet above sea level in the central part of the State.

More than half of New Jersey's Coastal Plain lies below an elevation of 100 feet. The numerous estuaries and marshes bordering the streams are conspicuous evidence of submerged valleys which had their origins at a time when the entire area stood at an elevation considerably higher above sea level than it does today.

In addition to that portion of the Coastal Plain that is above sea level in New Jersey, the submerged portion of the plain, or the Continental Shelf, extends eastward for about 100 miles. This submerged portion of the Coastal Plain has an average surface gradient of about 6 feet per mile to a depth of about 600 feet.

Cretaceous System

Cretaceous formations crop out along a belt 12 to 15 miles wide, which extends from the Raritan Bay southwestward to the Delaware River where it skirts along the east side of the river into Salem County and then passes southward into Delaware. These deposits are described by Kummel (1940, p. 114) as unconsolidated sand, clay, and greensand marl that dip 25 to 60 feet per mile to the southeast and have a total aggregate thickness of 500 to 1,000 feet in their outcrop areas.

The deposits thicken to the southeast, and at Atlantic City the aggregate thickness of Cretaceous sediments is more than 2,500 feet.

The Raritan Formation, which lies on the basement rocks in the western part of the Coastal Plain, and the overlying Magothy Formation are considered here as a unit because they are composed of lenticular beds of sands and clays. Lignite and carbonized material give the clay a blue to dark-gray color. Some of the sand beds are very permeable, and the sand aquifers are very important to the water supply of New Jersey. Barksdale and others (1958, p. 96-135) discuss in considerable detail the permeabilities of the aquifers, the direction of movement of the water, and features of its chemical character.

Overlying the Raritan-Magothy unit are several younger Cretaceous formations that will not be discussed separately here. Each is relatively thin and each, in its own outcrop area, has its own distinctive characteristics apparent when studied carefully; however, downdip under cover of younger sediments these formations are not readily separable except by a study of their fossils. In aggregate, they are glauconitic sands and clays, light and dark clays, and interbedded quartz and glauconitic sands. Two sand aquifers of moderate importance occur in this group of formations. They are the Englishtown Formation and the Wenonah Formation and Mount Laurel Sand considered together. They are separated from each other and from the sands of the Raritan-Magothy unit by clayey formations. In the fresh-water parts of all the Cretaceous aquifers the water commonly is soft, and contains less than 150 parts per million of dissolved solids; in some areas it contains less than 50 ppm.

Tertiary System

The lower part of the Tertiary sediments in New Jersey is represented by three formations of Paleocene and Eocene age. These are the Hornerstown Sand and the Vincentown Formation of Paleocene age and the Manasquan Formation of Eocene age. The outcrop belt of these sediments extends northeastward across the State, and lies southeast of the outcrop belt of Cretaceous sediments. The Hornerstown is a bed of glauconitic sand, with some quartz and clay (Kummel, 1940, p. 127). The Vincentown also contains some glauconite-quartz sands, but, in addition, has some calcareous materials in the form of broken shells. The Manasquan consists of glauconitic sand and a capping bed of greenish-white clay and fine sand. These formations in aggregate do not greatly exceed 100 feet in thickness where they crop out, but toward the southeast they thicken appreciably. Only the Vincentown is an aquifer of importance, and its importance is due more to its great areal extent than to its permeability; it furnishes as much as 300 gallons a minute to wells near Salem (Barksdale and others, 1958, p. 148), but elsewhere it commonly yields lesser amounts.

The Kirkwood Formation, of Miocene age, underlies the southern part of the State and thickens toward the southeast, reaching a thickness of 1,000 feet in Atlantic and Cape May Counties (Barksdale and others, 1958, p. 150). In outcrop it is composed chiefly of fine-grained sands with subordinate amounts of clay; farther downdip, clay layers account for most of the formation. In spite of an increase in clay content, the water-bearing characteristics of the Kirkwood improve (the sands become coarser) with distance from the intake area. The Cohansey Sand, of Miocene age, overlies the Kirkwood. It is composed chiefly of light-colored, medium-to coarse-grained sand, with some clay and gravel beds.

> "The Cohansey sand is potentially by far the most productive aquifer in the New Jersey Coastal Plain. It is here considered as a single hydrologic unit, even though in some places it contains more than one distinct water-bearing bed. It is composed predominantly of highly permeable and generally well sorted sands and gravels and is thus able to store and transmit large quantities of water. It crops out either at the surface or beneath a veneer of permeable Pleistocene deposits over an area of 2,350 square miles, more than the outcrop area of all other aquifers in the Coastal Plain of the State. It is thus exposed to and able to absorb vast quantities of recharge from precipitation" (Barksdale and others, 1958, p. 155).

Quaternary System

Relatively thin discontinuous patches and sheets of surface materials cover much of the outcrop area of the Cretaceous and Quaternary sediments. The surface materials are a wide assortment of sands, clays, and gravels, which commonly are less than 20 feet thick, but which reach a thickness of 40 feet or more in the southern extremity of the State. These surface sediments are not major aquifers, but they do form an important part of the hydrologic regimen; they collect, store, and transmit water to underlying formations and to surface streams. The water table generally lies in the surface deposits.

General Statement

Geology

Anderson (1951, p. 281) estimates that there are about 3,200 cubic miles of Coastal Plain sediments in New Jersey. Approximately 5,000 square miles of the State are underlain by Coastal Plain sediments. About 3,800 square miles of this area are underlain by sedimentary rocks more than 1,000 feet thick.

Wherever the Cretaceous, Tertiary, and Quaternary deposits are exposed in pits or other excavations in New Jersey, they appear to be horizontal, but from subsurface information it is known that the deposits dip toward the coast at from 10 to more than 50 feet per mile. The lowermost strata have the greatest dip. The basement rocks underlying the New Jersey Coastal Plain are believed to be chiefly igneous and metamorphic rocks (Ewing and others, 1940, p. 1839).

The simple homoclinal structure so often referred to in this report is typified in the Coastal Plain of New Jersey. The sediments as a whole dip and thicken to the southeast. Logs prepared by Richards (1948, p. 42-49) and structure maps prepared by Spangler and Peterson (1950, figs. 12-24) emphasize the simple structure. At Atlantic City the sediments are more than 4,500 feet thick, the lowermost 2,500 feet being of Cretaceous age. No major faults have been noted in sediments.

The sediments are almost all unconsolidated or loosely consolidated. Locally, some calcareous beds of the Tertiary System show a tendency toward induration, but looseness characterizes the sediments that lie above a depth of 2,000 feet, and perhaps to a greater depth.

Hydrogeology

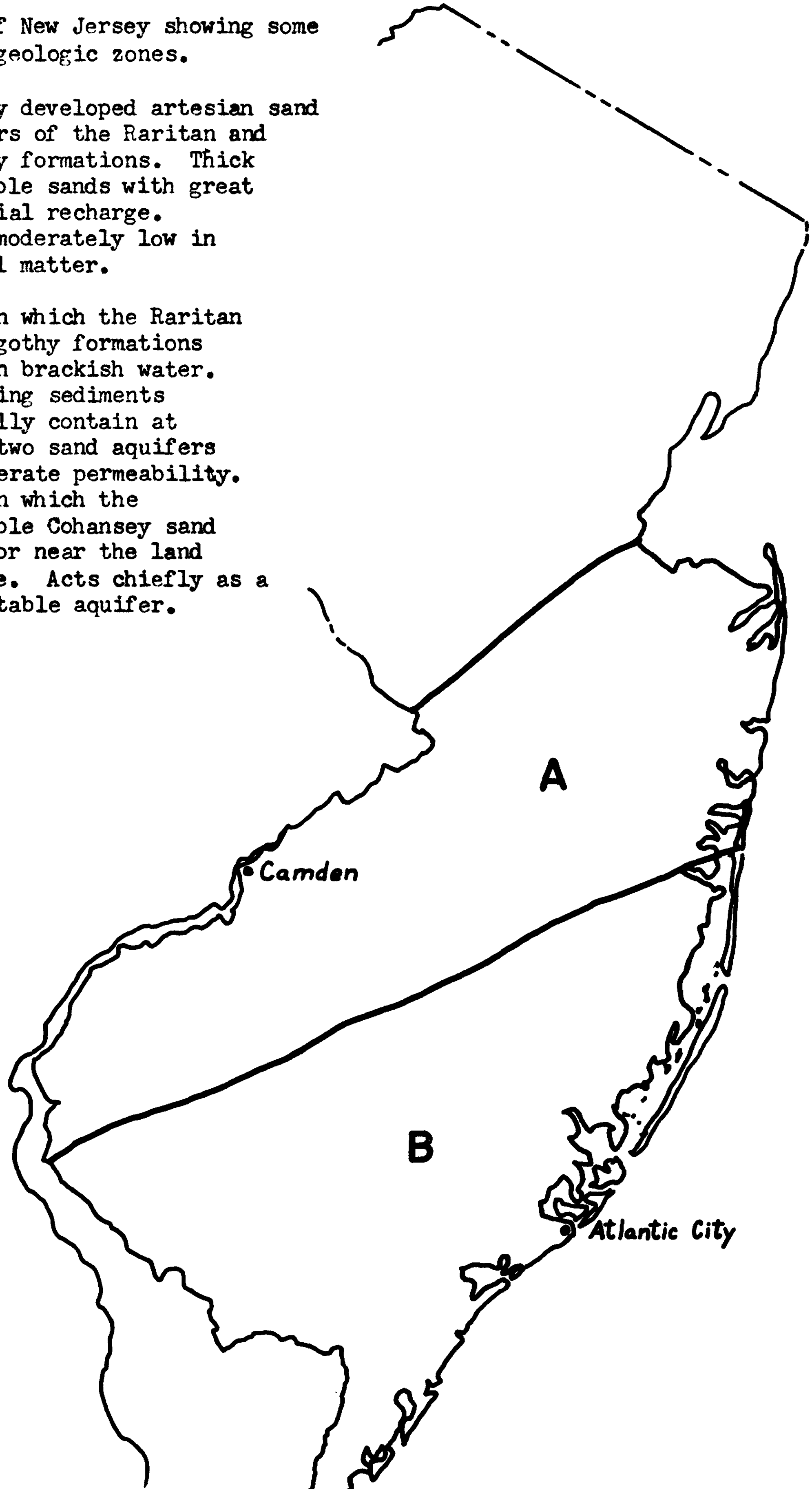
Where the topography is relatively flat the water table lies within a few feet of the land surface. When the water table rises after periods of precipitation more water is lost to evapotranspiration and more leaks out into streams. The water-table aquifer is in the surface or near-surface sand and varies greatly in permeability. It is used widely for rural domestic supplies, but up to the present time has had only a limited use for industry.

A series of sand aquifers and clay aquicludes compose the over-all artesian system of the Coastal Plain of New Jersey. The basal sand aquifer, consisting of permeable zones in the Raritan and Magothy Formations, yields large quantities of water, although in parts of southern New Jersey it contains brackish water (fig. 19). As a general rule, the sediments to a depth of 500 feet contain fresh water, whereas those deeper than 1,000 feet contain water too brackish for use. The saltiness tends to increase with depth, but there is no indication that the chloride content is greater than that of sea water, not even at

Figure 19. Map of New Jersey showing some hydrogeologic zones.

A. Heavily developed artesian sand aquifers of the Raritan and Magothy formations. Thick permeable sands with great potential recharge. Water moderately low in mineral matter.

B. Area in which the Raritan and Magothy formations contain brackish water. Overlying sediments generally contain at least two sand aquifers of moderate permeability. Area in which the permeable Cohansey sand is at or near the land surface. Acts chiefly as a water-table aquifer.



the base of the sediments near Cape May at the southern tip of the State.

Within the limitations of the data, Barksdale and others (1958) have made an excellent analytical study of the recharge, movement, and discharge of artesian water in New Jersey. They point out that although the homoclinal dip does control to a great extent the movement of water, a predominant downdip movement should not be presumed. Rather, major areas of discharge are in some cases the permeable parts of the outcrop zone where stream channels and low, swampy areas provide nearby discharge; much recharge moves only a short distance through the aquifer before it is discharged. Figure 18 of the Barksdale report indicates the general nature of water movement in the Raritan and Magothy Formations.

MARYLAND AND DELAWARE

Topography

The Coastal Plain in Maryland underlies about 7,688 square miles of the State's total area. About 3,300 square miles of this area are covered by large bays and drowned rivers. There are about 6,500 square miles below which sediments are more than 1,000 feet thick. In Delaware more than 94 percent of the total area is underlain by Coastal Plain sediments, and more than 2,000 square miles are underlain by more than 1,000 feet of sediments.

The Chesapeake Bay trends diagonally across the Coastal Plain and separates two topographic divisions, the Western Shore and Eastern Shore (includes Delaware in this report). The Eastern Shore is a flat, almost featureless plain, similar to the coastal areas of the South Atlantic States; the Western Shore, however, is a rolling upland, the topography of which is only slightly less subdued than that of the Piedmont province on the west.

Most of the surface drainage basins of the Maryland Coastal Plain are tributary to the Chesapeake Bay. Parts of Prince Georges, Charles, and St. Marys Counties include the Potomac River drainage, and a small part of Worcester County lies within the Atlantic Ocean drainage, but the remainder of the area lies within the Chesapeake Bay drainage.

In Delaware most streams discharge into either the Delaware Bay or the Atlantic Ocean. A small portion of Kent County and about half of Sussex County are drained by the Choptank, Nanticoke, Wicomico, and Pocomoke Rivers, all of which discharge into Chesapeake Bay.

Streams in the Coastal Plain province, because of low surface gradients, flow sluggishly in winding courses toward the bays or into tidal estuaries. The broad tidal flats or swamps along the shore of the bays contain salty water.

The dense crystalline rocks of the basement on which the sediments lie have a surface slope southeastward of about 45 feet per mile; however, this rate of dip increases near the Atlantic Coast to more than 100 feet per mile.

Cretaceous System

The Patuxent Formation, of Early Cretaceous age, which lies on basement rocks, forms an outcrop belt that ranges from 2 to 7 miles wide along the inner margin of the Coastal Plain. In its area of outcrop it reaches a maximum thickness of about 100 feet, but coastward it becomes much thicker and reaches a thickness of 1,500 feet near the southeastern tip of Delaware. The formation consists chiefly of clay and sandy clay with varying amounts of angular, coarse- to medium-grained gray or white sand. The clay is generally white to gray, although, locally, dark lignitic clays occur.

The percent of different types of sediments in the Patuxent Formation has been calculated by different investigators, working in different parts of the Maryland Coastal Plain. Otton (1955, p. 22) reported that the Patuxent Formation in parts of Prince Georges County consists of 55 percent sand and gravel; four wells within the District of Columbia showed that 37 percent of the formation consisted of sand and gravel, whereas four wells farther south at Indian Head showed that sand and gravel comprised about 23 percent of the formation. Northeast of these areas, however, Bennett and Meyer (1952, table 4) reported the Patuxent Formation in Baltimore consisted of 61 percent sand and gravel.

Wells drawing water from the Patuxent Formation range in specific capacity from 0.3 to 10.2 gallons per minute per foot of drawdown. To the east of the area in which it is a prominent aquifer, the sands become finer and the percentage of clay increases. The total dissolved solids in water from the Patuxent, as reported by Otton (1955, p. 161), ranged from 18 to 227 and averaged 91 parts per million. The pH of the water from 33 different sources ranged from 4.7 to 8.2 and averaged 6.1.

The Arundel Clay of the Potomac Group overlies the Patuxent Formation. It crops out in a belt 1 to 4 miles wide east of the outcrop of the Patuxent and reaches a thickness of 200 feet east of Baltimore (Bennett and Meyer, 1952, p. 59). The Arundel is composed chiefly of gray and red clay with moderate amounts of sand.

The Patapsco and Raritan Formations may be considered together as a unit. They consist chiefly of red, gray, and brown clay and interbedded sand and sandy gravel (Otton, 1955, p. 39). Carbonaceous material and pyrite are dispersed through some of the sand and clay layers. The formations reach a total thickness of more than 700 feet at Annapolis, where the best water-bearing sand section is 60 to 75 feet thick (Otton, 1955, p. 56).

Tertiary System

The wedge of sediments composing the Tertiary System thickens to the southeast, though not at a uniform rate. The sediments may be placed in two groups according to their proportion of permeable sands. The lower group includes the Brightseat Formation, of Paleocene age, and the Aquia and Piney Point Formations, of Eocene age, which in aggregate contain a moderate to large proportion of quartz and glauconitic sand. The upper group consists chiefly of thick beds of Miocene clay, with several subordinate beds of moderately permeable sands; these include the Calvert, Choptank, and St. Marys Formation of the Chesapeake Group. The sand aquifers yield substantial amounts of water to wells in southeastern Maryland and southeastern Delaware. Along the upper reaches of Chesapeake Bay the Tertiary sediments thin and pinch out where the Cretaceous deposits are exposed.

Quaternary System

Surface deposits of sand, clay, and gravel, which may be of Pleistocene age in some places and of Pleistocene and Recent ages in other places, are grouped as a part of the Quaternary System in this report. They have been described in Maryland by Hack (1955), Otton (1955, p. 99-106), and Rasmussen and Slaughter (1955, p. 103-120). In Delaware they have been described by Rasmussen (1955, p. 61). Bennett and Meyer (1952, p. 68) have grouped the sediments into two main units, upland and lowland. The upland deposits are arbitrarily considered to be of Pliocene and/or Pleistocene age, lying higher than 40 feet above sea level; commonly, they are thin, discontinuous, and erratic deposits of sand, gravel, and clay. The lowland deposits consist chiefly of Pleistocene and Recent age, lying below an elevation of 40 feet, and extending to depths as great as 200 feet below sea level. The surface deposits tend to thicken to the southeast and reach their maximum thickness near the southern boundary of Delaware.

The surface deposits have a relatively high proportion of permeable sand. They represent the material in which the water table occurs in the southeastern halves of both Maryland and Delaware. In Sussex County, Delaware, and in Wicomico, Somerset, and Worcester Counties, Maryland, these deposits are the principal aquifer.

General Statement

Geology

The sedimentary rocks of the Coastal Plain of Maryland and Delaware are sand, gravel, clay, shell beds, and marl, which range in age from Early Cretaceous to Recent. They are underlain by igneous and metamorphic rocks and in some places by consolidated sedimentary rocks of Triassic age. Sands and clays, occurring both as distinctive and rather pure beds and as mixed deposits, compose the bulk of the sediments. Gravels are almost restricted to shallow surface deposits and to basal deposits that lie on the basement rocks; even in these deposits they occur in minor quantities. Calcareous materials commonly occur as shell beds and marls in Tertiary deposits, but consolidated limestone beds are virtually absent. Clays of the Cretaceous, lying deeper than 3,000 feet near the coast, tend to be compacted into shales.

The structure of the Coastal Plain of Maryland and Delaware is a homocline, sloping in a southeast direction. Rasmussen and Slaughter (1955, p. 23) say that the base of the Cretaceous dips between 58 and 146 feet per mile, the top of the Cretaceous from 15 to 59 feet per mile, and the top of the Tertiary System at less than 10 feet per mile. The sediments reach a thickness of 8,000 feet near the Atlantic Coast, of which about 5,600 feet are Cretaceous, about 2,200 feet are Tertiary, and about 200 feet are Quaternary (Rasmussen and Slaughter, 1955, pl. 1). Contours on top of the basement rocks (fig. 7) show a broad trough extending westward from Worcester and Wicomico Counties. Richards (1948, p. 54) refers to the structure as the Salisbury embayment. It was essentially filled and obliterated by the end of Eocene time. Large-scale faulting appears to be absent, as published works make no special reference to faults in the Coastal Plain of these two States.

Hydrogeology

Toward the southeast, as the topographic relief becomes subdued, the water table is almost flat and is near the land surface. A large proportion of water from precipitation seeps into the ground, but much of this recharge moves out of the ground within short distances, either as evapotranspiration or as seepage into streams. The water-table aquifer in southern Delaware and southeastern Maryland is one of the most productive surface sand aquifers along the Atlantic Coast.

The coastward-dipping beds of sands and clays of the Coastal Plain result in the choice of several artesian sands from which well water may be drawn (see fig. 20). Rasmussen and Slaughter (1955, p. 1) mention 14 aquifers in Somerset, Wicomico, and Worcester Counties. In many places as many as 10 artesian sand beds are subjacent to the water-table aquifer.

The volume of salty ground water may be less than the volume of fresh ground water; in fact, the relatively great depth to unpotable water is a striking feature of the hydrology. Some water, in Cretaceous deposits, lying between depths of 2,000 to 3,000 feet, is potable, and more than 90 percent of all water above 2,000 feet is potable.

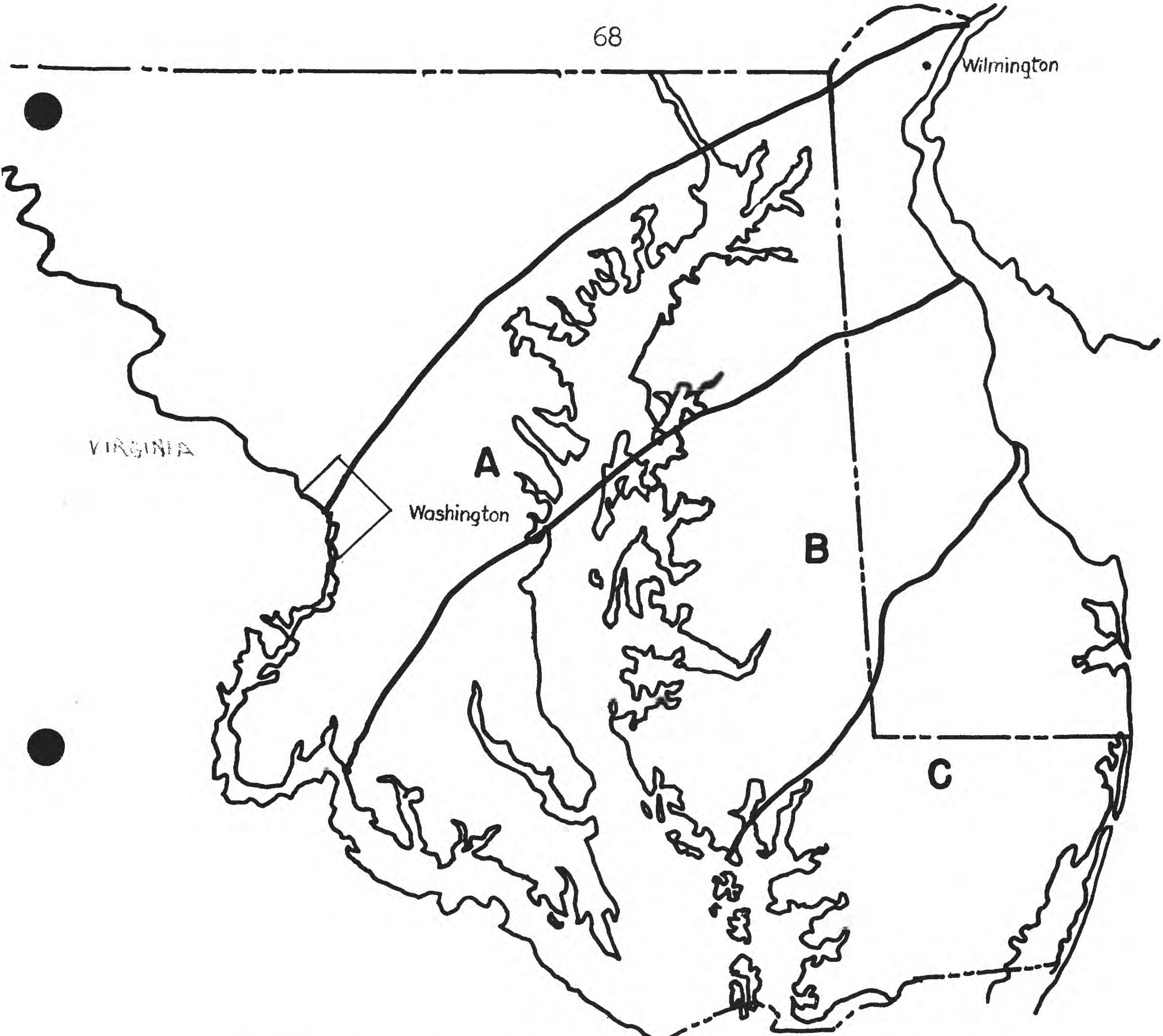


Figure 20. Map of Maryland and Delaware showing some hydrogeologic zones.

A. Cretaceous sands and clays, thickening to about 2000 feet near line separating areas A and B. Several artesian-sand aquifers, all containing fresh water.

B. Thick zone of fresh artesian water. Sands of Eocene age, commonly between depths of 200 to 600 feet, are chief aquifers. However, overlying sands of Miocene age and upper sands of Cretaceous age, which lie as deep as 1000 feet, also furnish fresh water. Aggregate thickness of interbedded sands and clays is about 4000 feet near southeast border.

C. Highly permeable surface sands yield much water. The Miocene contains important artesian aquifers. Eocene sediments are chiefly clay and fine sand. Upper part of Cretaceous system contains fresh water in places at depth of more than 1500 feet. Sediments no deeper than 3000 feet contain no appreciable thickness of consolidated beds.

Although the rate and direction of movement of water in each artesian aquifer may vary, the gross movement of artesian water is controlled by the regional homoclinal structure. Therefore, there is a general tendency for artesian water to move southeastward and to move upward into beds nearer the land surface. The movement is retarded by relatively impermeable deposits, and it is likely that natural movement in deep-lying Cretaceous beds is almost negligible.

VIRGINIA

Topography

The coastward outline of Virginia is irregular as a result of the presence of Chesapeake Bay and tributary salt-water estuaries, which appear to be drowned parts of drainage courses that rise in upland areas west of the Coastal Plain. The Coastal Plain scarcely reaches an elevation of 200 feet near its border with the Piedmont province. The topography is relatively flat except near streams, where hilly conditions prevail. Sluggish tidal rivers and stretches of flat land are characteristic.

Cretaceous System

Immediately overlying the basement rocks in Virginia is a succession of sands, clays, and gravels of Early and Late Cretaceous age which are commonly referred to as the Potomac Group. The sands contain varying proportions of weathered feldspar and kaolin, and the clays show a great variety of color and texture. The individual beds are not normally continuous over wide areas but tend to pinch out and give way to beds of some other type (Cederstrom, 1957, p. 16). Sediments of the Potomac Group crop out in some gullies and railroad cuts along the western edge of the Coastal Plain from Alexandria to Fredericksburg, and in the valleys of the James and Appomattox Rivers south of Richmond and east of Petersburg (Sanford, 1913, p. 14).

Many wells along the inner margin of the Coastal Plain yield water from Cretaceous sands that are interlayered with clay, but more than 15 to 25 miles east of the western edge of the Coastal Plain the sediments are buried beneath a thick cover of younger formations and are beyond the reach of all except the deepest wells. Some productive water-bearing strata are present, but little is known about the potential supplies that might be available in some central parts of the Coastal Plain (Cederstrom, 1957, p. 16). Near the coast, where the sediments of the Potomac Group reach a thickness of about 1,000 feet, the water is brackish, but westward the water is of good quality.

Tertiary System

Grouped in the Tertiary system as a unit are three formations of Eocene age and the Mattaponi Formation, which Cederstrom indicates is partly of Late Cretaceous and partly of Paleocene age (1957, p. 17). The Mattaponi is considered here with the Tertiary System only because lithologic features appear to resemble the Tertiary rather than the Cretaceous sediments. These four formations from lower to upper, in sequence--the Mattaponi, Aquia, Nanjemoy, and Chickahominy--contain conspicuous amounts of glauconite. Varying proportions of quartz and glauconite give the sands a pepper-and-salt, black, or green appearance. The sands are less abundant than blue and gray clays and marls, which almost everywhere are glauconitic to some degree (Cederstrom, 1957, p. 24). Some indurated layers of hard rock are scattered through the upper part of this unit. The four formations of this unit are not present everywhere, but some sediments of the unit are widespread, even lapping over the Cretaceous deposits along the inner margin of the Coastal Plain. The sediments thicken coastward only slightly, reaching a maximum thickness not greatly exceeding 400 feet.

Overlying the Eocene sediments are formations of Miocene age, which also extend over most of the Coastal Plain. Along the inner margin of the Coastal Plain the Miocene deposits are only a few tens of feet thick in places, but eastward they thicken to 400 feet at Newport News and 600 feet at Fort Monroe (Cederstrom, 1957, p. 29). The Miocene formations consist of gray and blue clay, sandy shell marl, sand, and shell beds. Clean sand is much less abundant.

Cederstrom (1957, p. 21) considers the Mattaponi Formation to be an excellent aquifer, and points out that wells from sands at West Point and Newport News yield 400 to 1,000 gallons a minute. The overlying Eocene

Formations yield moderate amounts of water from beds of glauconite and quartz sand, but these sands generally are fine grained. The uppermost Tertiary beds of Miocene age are, in aggregate, rather impermeable because of the predominance of clay and clayey sand; however, on the Eastern Shore peninsula fairly good water-bearing sands have been found between 80 and 300 feet below land surface in the Miocene deposits (Sinnott and Tibbitts, 1954, p. 15).

Quaternary System

The surface of the Coastal Plain in Virginia is coated with a veneer of sand and clay of Pleistocene age. In many places, especially toward the west, these deposits are no more than several feet thick, but on the Eastern Shore they reach a thickness of nearly 100 feet. These sediments are not everywhere distinguishable from the underlying weathered parts of the Miocene sediments. The unconfined ground-water body lies in the surface sands and clays, the water table generally occurring at a depth less than 15 feet.

General Statement

Geology

Clays and sands compose the bulk of the sediments in Virginia, but there are minor amounts of gravel and shell marl. The gravel occurs in significant amounts only near the base of the sedimentary wedge and in flood-plain deposits of the major streams along the inner part of the Coastal Plain. A surface veneer of nondescript sand and clay conceals the underlying formations except along the steep road cuts and stream beds.

Cretaceous sediments crop out along the inner margin of the Coastal Plain, which extends from Washington southward through Richmond to the North Carolina line. These sediments rest on a floor of crystalline rocks that slope seaward at an uneven rate which ranges from 30 to 65 feet per mile. The wedge of sediments thickens to a maximum of about 8,000 feet on the ocean side of the Eastern Shore, but the character of the sediments in the eastern and deeper parts of this wedge has not been determined. Cederstrom (1945b, p. 74-77) has logged a well at Fort Monroe, north of Norfolk, which is summarized as follows from top to bottom: 50 feet of Pleistocene material, chiefly sand; 560 feet of Miocene sand and clay; 830 feet of Eocene sand and clay; and 806 feet of Cretaceous sand and clay. The well, 2,254 feet deep, penetrated 8 feet of hard basement rock. This log and other logs listed in Cederstrom's report rarely mention rock or indurated layers. On the mainland, at least, the scarcity of consolidated and semiconsolidated rocks is striking, as is the scarcity of highly calcareous beds.

Contour maps relating to subsurface formations have been drawn by Spangler and Peterson (1950, p. 82-94). These maps and a report by Cederstrom (1945a) indicate several anomalous structural features, but these are not amenable to clear-cut interpretations without more subsurface data. Most of the abnormal structures are slight undulations in the surfaces of formations, resulting in thickening and thinning of overlying beds. However, Cederstrom (1945a, p. 71) mentions a fault in the basement rocks trending westward along the James River and approaching the Piedmont; the maximum displacement along the postulated fault, from 300 to 600 feet, occurs in the Hampton Roads area.

Hydrogeology

In almost all of the Coastal Plain of Virginia the relatively flat topography results in a high water table. The water table is so close to the land surface in many places that drainage is impeded, and much of the surface and near-surface water is removed by evapotranspiration. A large proportion of rural domestic water supplies comes from drive points and dug wells no deeper than 20 feet. The total use of this unconfined water is only a very small fraction of the available supply. Except within half a mile from the sea, the shallow water contains less than 50 parts per million of total solids.

Several artesian sand aquifers separated by beds of clay occur below the near-surface unconfined ground water. Although the permeabilities of these sands differ considerably, there is generally only a slight difference in artesian head between beds. The Cretaceous sands are used as a source of water supply in the west and central parts but tend to be buried so deeply toward the coast that they lie in a zone of highly mineralized water (see fig. 21). Cederstrom (1945c, p. 90-98) indicates the change in character of the water of the Cretaceous Formations as it

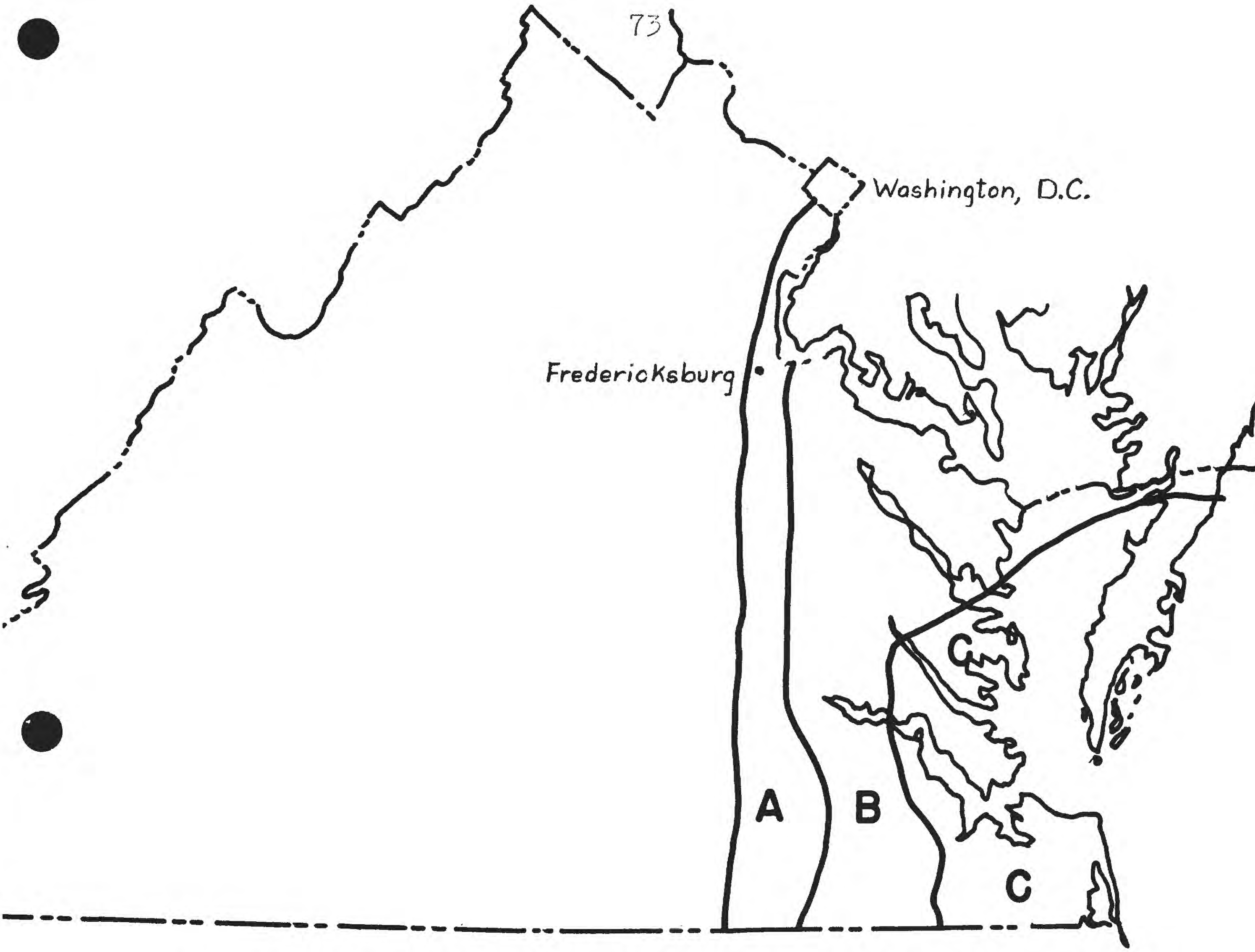


Figure 21. Map of Virginia showing some hydrogeologic zones.

A. Area where Cretaceous sands and clays lie at or near land surface. Includes belt of soft water of low mineralization along the west to belt of hard, bicarbonate water along east.

B. Cretaceous and Tertiary sands and clays. Artesian water is soft, sodium-bicarbonate type. Lowermost beds along the eastern border contain salt water.

C. Brackish water occurs everywhere at depths greater than 1000 feet - in many places below 600 feet and in some places below 300 feet. Usable aquifers are sands of shallow or intermediate depth. Deep-lying beds are chiefly sands and clays, and proportion of limestone and consolidated rock is slight.

moves coastward and downdip. From soft, low mineralized water in the western part of the Coastal Plain the water becomes hard as the calcium bicarbonate content increases toward the east; near the coast, ion exchange between the water and the sediments produces soft, sodium bicarbonate water.

North of the mouth of Rappahannock River fresh and potable water occurs to a depth of more than 600 feet; south of the river, toward Norfolk and vicinity, the depth to salty water commonly is less than 450 feet (Cederstrom, 1943, pl. 3).

Owing to the relatively low relief of the Coastal Plain in Virginia, the difference in pressure between water in various parts of the artesian system probably is not great. As a result of this condition, together with the thick and numerous clay beds, the natural movement of deep artesian water probably is infinitesimally slow. Some near-surface artesian water leaks out in the channels of the rivers.

NORTH CAROLINA

Topography

The Coastal Plain province occupies the eastern half of North Carolina. The plain has a smooth surface that rises from sea level at the coast to an elevation of more than 300 feet along its inner margin, where it borders the Piedmont province on the west. The extreme eastern part of the Coastal Plain is marked by a chain of off-shore bars, known locally as the Outer Banks. Separating this chain of islands from the mainland are two large inland waterways, Albemarle and Pamlico Sounds.

The major streams, and even most of the tributaries, flow southeastward or eastward. The Cape Fear, Neuse, Tar, Roanoke, and Meherrin Rivers have their head waters in the Piedmont, but collect most of the Coastal Plain drainage on their way to the sea. The dissection by streams is local to a great extent, and steep cliffs as much as 30 feet high are common near the streams. The upland inter-stream areas are relatively flat. Swampy flood plains border parts of the streams, and tidal estuaries with broad expanses of low swampy ground are common near the coast.

The Coastal Plain in North Carolina is underlain by beds of sand, clay, gravel, and limestone, which lie nearly flat but slope eastward at a rate that is only slightly greater in that direction than the slope of the land surface. The older beds, of Cretaceous age, crop out along the western or inner border of the province and become buried progressively deeper toward the coast. The younger beds, of Tertiary and Quaternary age, crop out southeast of the Cretaceous formations, and are buried less deeply near the coast. The sediments extend out to sea for many miles, as far seaward as the edge of the Continental Shelf (fig. 22).

Cretaceous System

Lying on the basement beneath the Outer Banks are more then 3,000 feet of sediments of Early Cretaceous age (Swain, 1952, p. 29). These sediments thin westward and presumably do not extend to the western margin of the Coastal Plain. The basal outcropping sediments have been assigned to the Tuscaloosa Formation of Late Cretaceous age. Overlying the Tuscaloosa are two younger Upper Cretaceous formations, the Black Creek and the Peedee.

The Tuscaloosa Formation crops out in the Sand Hills area south of the Neuse River and occurs in adjacent inland parts of the Coastal Plain at shallow depths. It is composed chiefly of beds of light-colored sand and clay, with some gravel near the base of the formation. The beds of sand and clay are lenticular and cannot be traced between wells as close as a mile apart. Beds of relatively pure clay and pure sand are common but are no less common than beds containing a mixture of sand and clay.

The Black Creek Formation either crops out or occurs at shallow depths in Greene, Wayne, Sampson, Bladen, and Robeson Counties. It is composed chiefly of beds and laminations of dark carbonaceous clays and fine to medium sands.

The Peedee Formation overlies the Black Creek and crops out east of the area of Black Creek outcrops. It is composed of dark-gray to green clays and sands. The sands almost everywhere contain considerable glauconite. Thin impure limestone beds occur locally in the outcrop area, these beds thickening toward the coast.

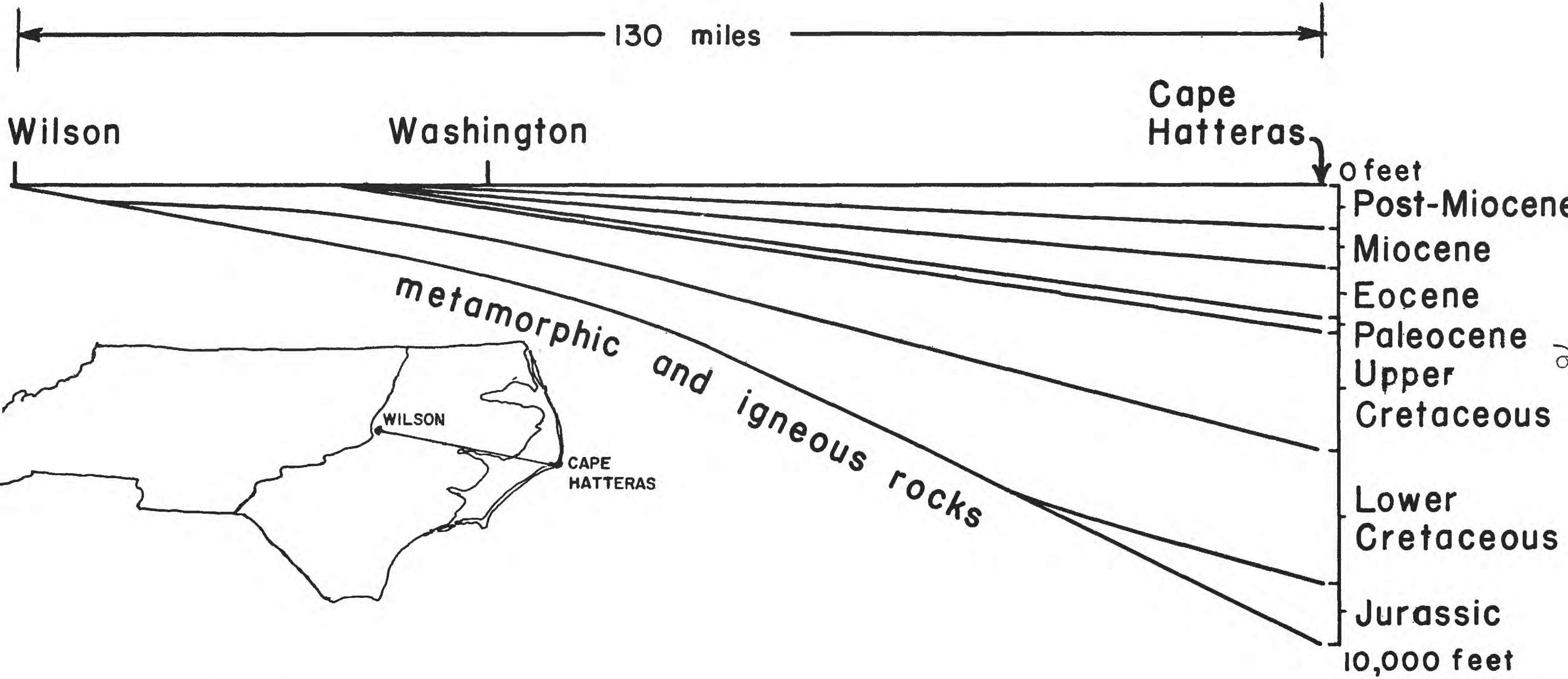


Figure 22.-- Cross section of the Coastal Plain of North Carolina.

The interlayering of the Cretaceous sands and clays and their relatively simple homoclinal structure result in an artesian system in which multiple sands are the aquifers. An example of the use of more than one formation as a source of water supply is that of the town of Kinston, Lenoir County; the Kinston wells, about 500 feet deep, draw water from sands of the Peedee, Black Creek, and Tuscaloose Formations. Both the glauconite in the Peedee and the clays of the Peedee and Black Creek Formations have ion-exchange capacities, and there tends to be a change from calcium bicarbonate in the water as it moves eastward and downdip. Salt water occurs in the Cretaceous formations in the eastern counties and, consequently, very few wells have been drilled into these formations.

Tertiary System

The only Tertiary sediments that crop out in North Carolina are marls, sands, and limestones of Eocene age (Castle Hayne Limestone) and clays and marls of Miocene age (Yorktown Formation).

The Castle Hayne Limestone occurs within 20 feet of the land surface in much of the area shown as zone C in figure 23. It is variable in composition and in degree of induration. In places it consists of poorly permeable marl, in other places as sand, but most commonly as indurated shellrock or shell limestone. The proportion of limestone increases eastward.

North of the Neuse River the Yorktown is the formation most likely to be penetrated by a well deeper than 20 feet. It ranges in character from blue massive clay to lighter colored shell beds to sands and sandy clay. Toward the east the shell beds and their degree of induration increase to the extent that the Yorktown and underlying Castle Hayne cannot be separated easily.

Together the Castle Hayne and Yorktown Formations represent a limestone aquifer that is extensively used in the area of zone C shown in figure 23. The permeability varies greatly from place to place; where ground water has removed in solution some of the shells, the rock has interconnecting openings that render it very permeable. The limestone aquifer generally is covered by a relatively thin clay or sandy clay bed that tends to confine the water under slight artesian pressure; however, in many places it is under water-table conditions.

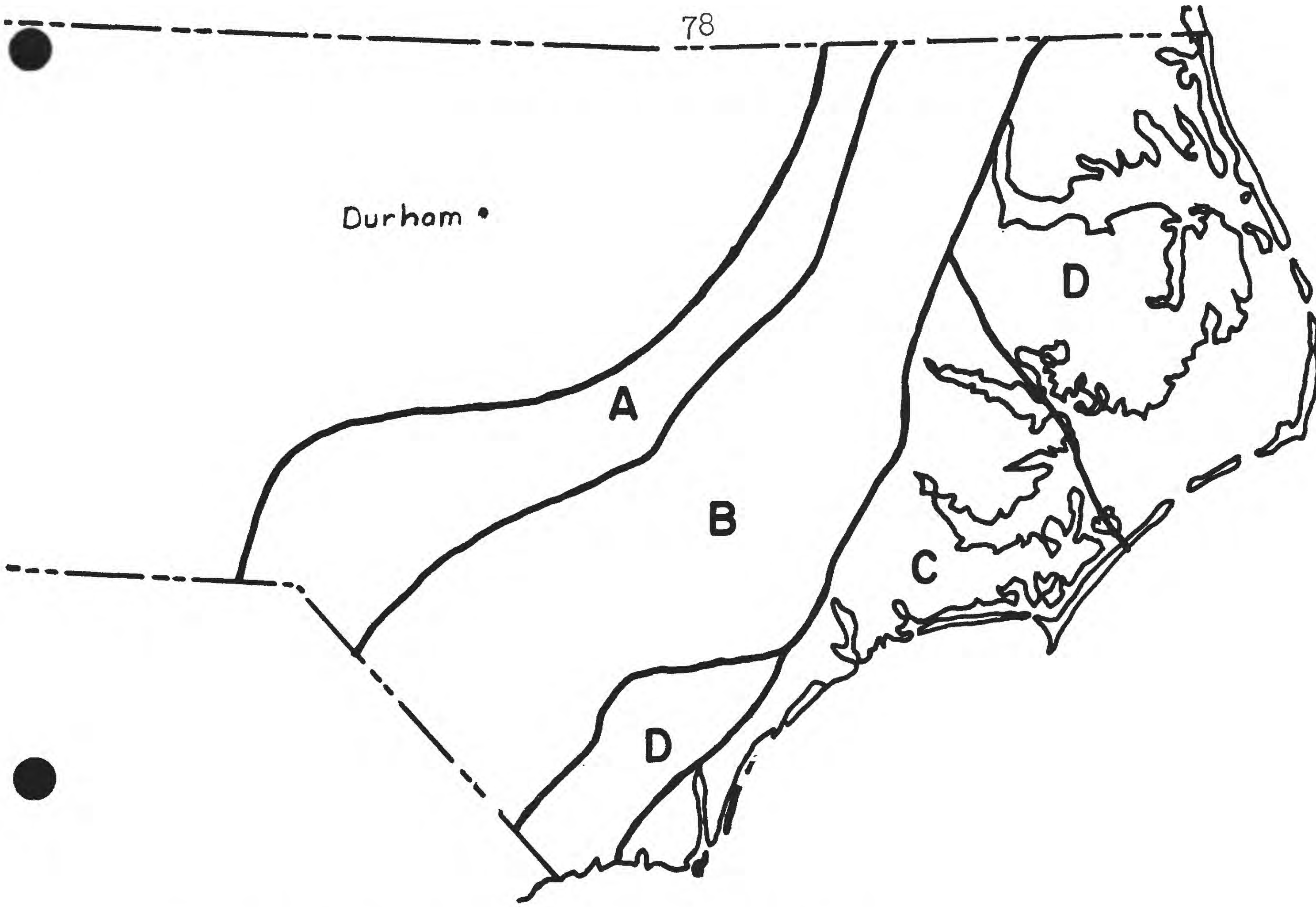


Figure 23. Map of North Carolina showing some hydrogeologic zones.

A. Sediments, chiefly sand and clay, are less than 400 feet thick. Permeable sand beds are scarce. All water is fresh.

B. Cretaceous-sand aquifer. Artesian water occurs chiefly in fine-to medium-grained sands separated by thick beds of clay. Artesian water is of soft sodium-bicarbonate type and is fresh to a depth greater than 500 feet.

C. Tertiary limestone-sand aquifer, top of which is less than 100 feet below ground. Permeability varies greatly but is good where hard shellrock prevails. Brackish water occurs in lower part of deposits and in upper part along salt-water estuaries.

D. Water supplies obtained from sands of shallow to intermediate depths. Water is brackish at depths greater than 600 feet - at many places at much shallower depths.

Quaternary System

A thin veneer of sand lies at the surface at most places. In some places it is apparent that the sand is the surface-soil horizon, and the underlying massive clay is a subsurface horizon formed on outcropping formations. In other places the surface materials are sedimentary deposits that are thought to be of Pleistocene age. It is generally difficult to distinguish between the base of the Pleistocene sediments and the weathered upper part of the underlying formation. The thickness of the Pleistocene and Recent sediments is less than 25 feet almost everywhere, except along a 10- to 20-mile coastal fringe where they tend to thicken. The water table lies in the surface sand and clay unit at a depth below land surface that is generally less than 20 feet.

General Statement

Geology

The surface of the Coastal Plain of North Carolina is covered almost everywhere by a layer of loose sand. The sand ranges in thickness from a few inches to several tens of feet and normally is underlain by clay. The sand and clay are not everywhere of the same age and character. Sands and clays form the bulk of the Cretaceous sediments, at least where they crop out or where they are covered by less than 1,000 feet of younger sediments. Gravel is not common, and its occurrence is almost restricted to thin, discontinuous zones near the base of one or more Cretaceous Formations and to the flood plains of present streams. The proportion of calcareous material increases coastward, and it is especially abundant in the Tertiary sediments. Studies of the oil tests at Cape Hatteras (Swain, 1951, 1952) at the eastern tip of the Coastal Plain serve to show the change in character of sediments and their degree of consolidation toward the coast. For example, the Cretaceous formations, which in the western, or outcrop, areas are represented by no more than a few hundred feet of sands and clays, at Cape Hatteras are more than 5,000 feet thick, and are characterized by dense shale, sandstone, and limestone beds. At Cape Hatteras the Tertiary sediments are chiefly limestones, with only a few scattered shale beds. Sediments that lie below 1,500 to 2,000 feet tend to be consolidated, and their original pore speces have been filled with cement or otherwise obliterated. Above this depth the sands and clays generally have not been greatly altered, and they retain their original porosity and permeability. Although shell and other calcareous deposits of the Tertiary System are easily consolidated at shallow depths, the limestone thus formed may be very permeable if ground-water circulation has been favorable for solution action.

The Coastal Plain sediments of North Carolina lie on a coastward-sloping basement of dense igneous and metamorphic rocks. The exact configuration of the basement is not known, but the homoclinal eastward slope steepens to more than 100 feet per mile in the extreme eastern part of the State (fig. 7). This break in slope in one of two major structural features involving the base of the sediments. The other is the Cape Fear arch, known also as the Wilmington anticline and as the Great Carolina ridge. It appears to be a wide southeast-trending uplift, the axis of which parallels the Cape Fear River. Arched around this axis at Wilmington and extending closer to the inner margin of the Coastal Plain on both sides of the axis are sediments of Eocene age. The subsurface aspects of the Cape Fear arch are not well known. The penetration of basement rocks at the relatively shallow depth of 1,100 feet below sea level in a well at Wilmington suggests that the arch indicates basement topography. The shallow basement at Wilmington interrupts the downdip, wedgelike thickening of formations recognized elsewhere in the Atlantic Coastal Plain. Although local faults of small displacement are not uncommon, the available evidence suggests that faulting on a large scale in the Coastal Plain of North Carolina is rare.

Hydrogeology

On the broad, flat interstream areas the water table is nearly flat and lies within a few feet of the land surface. Near the streams the water table has a steeper slope as it adjusts to the level of the surface stream. Much water is lost by evaporation and transpiration, although there is some discharge by seepage into the streams. In the Sand Hills evapotranspiration is slight, but ground-water discharge as seepage into the streams is steady and represents a high percentage of the total precipitation. Throughout the Coastal Plain the water-table aquifer is used widely for individual domestic-water supplies, but there is no significant use of this aquifer for industrial and municipal water supply. Except within half a mile from the sea, the shallow water contains less than 50 parts per million of total solids, but the low pH value makes it corrosive.

Two types of artesian systems characterize the Coastal Plain of North Carolina. These are the Cretaceous sand aquifer and the Tertiary limestone aquifer. The Cretaceous sand aquifer is used in a broad area, as shown in zones A and B of figure 23. It is represented by several sand beds that are confined beneath intervening beds of clay. Some industrial and municipal wells are developed from multiple screens, and water is drawn from several sand aquifers. Many of these wells yield more than 500 gpm with less than 100 feet of drawdown. The water commonly is of a soft sodium bicarbonate type. The limestone artesian aquifer lies east of the Cretaceous sand aquifer. Many wells, commonly of the open-end tubular type, obtain high yields from limestone. The water is of a hard, calcium bicarbonate type, but the total solids content commonly is less than 300 ppm.

In most places below a depth of about 500 feet, water is salty, although the boundary between fresh and salty water crosses formational contacts, and is very erratic. For example, near the mouths of the Cape Fear, Neuse, Tar, and Roanoke Rivers, salt water lies within 100 to 200 feet of the land surface. The saltiness tends to increase with depth, but only in the oil test at Cape Hatteras (table 1, analysis no. 14) is there a suggestion that the chloride content is greater than that of sea water.

Data are not available to indicate the direction and rate of flow in each of the many beds that compose the sediments in North Carolina. The artesian water in its downdip movement is slowed greatly be decreasing permeability of the sediments coastward, which precludes any significant concentrated discharge. Some artesian discharge occurs by upward leakage into aquifers with less artesian pressure. Leakage from the uppermost artesian aquifer is considerable near streams that have cut into the aquifer. These streams also receive drainage from the water-table aquifer. The leakage from the deep-lying beds is slight, and the movement undoubtedly is imperceptibly slow.

SOUTH CAROLINA

Topography

The Coastal Plain of South Carolina includes an area of more than 20,000 square miles, extending from the Atlantic Ocean inland a distance of 120 to 160 miles. Three moderately distinctive topographic areas exist. The Sand Hills division, along the inner margin of the Coastal Plain, is represented by rolling sand-covered hills reaching elevations of 400 to 600 feet above sea level. Coastward from the Sand Hills are the Red Hills, which are nearly level plateaus, underlain by stratified sands and clays into which streams have cut relatively narrow and deep valleys. The Upper and Lower Pine belts together may be considered as a division that is characterized by relatively flat interstream areas, extending inland from the coast for 70 to 80 miles.

The Coastal Plain is drained by three major streams, whose headwaters are in the Piedmont and Mountain provinces to the northwest; they are the Pee Dee, Santee, and Savannah. The Edisto and a few short streams flow directly to the ocean. Swampy, naturally vegetated flood plains bordering parts of swampy ground are common.

Cretaceous System

Three formations of Cretaceous age are represented in the Coastal Plain of South Carolina, and they compose more than three-fourths of the total volume of sediments in the State.

The Tuscaloosa Formation lies on the crystalline rocks and increases in thickness from a featheredge along the inner margin of the Coastal Plain to more than 800 feet in wells near the Coast (Siple, 1957, p. 284). The formation consists of light-colored sands and clays. Beds of pure sand and pure clay are common, but so are beds of clayey sand and sandy clay. Kaolin is the predominant clay mineral.

Uncomformably overlying the Tuscaloosa Formation are the Black Creek and Peedee Formations. The two formations are similar in lithology, especially toward the coast. Both formations are composed of dark-gray to black clays and interbedded dark-gray to light-gray or green sands. Cemented shell beds and limestone increase in number toward the coast. The combined thickness of the Black Creek and Peedee Formations reaches 1,400 feet in some wells in coastal areas (Siple, 1957, p. 284).

Cretaceous sands are used for water supply in all but the southern-most counties. Siple (1957, p. 292) indicates that the permeabilities of the sands, although varying considerably from place to place, generally are good. The coastward and downdip movement of water in the Cretaceous sands results in an increase in total dissolved solids but a decrease in hardness; the decrease in hardness is due to the exchange of calcium ions of the water with sodium ions of the clays and glauconite.

Tertiary System

The stratigraphy of the Tertiary sediments in South Carolina is not clearly established. In general terms, there are three major lithologic subdivisions, but the complete sequence of sediments is not everywhere present. The lower unit, overlying the Peedee Formation, consists of beds of the Black Mingo, Congaree, and McBean Formations; bedded marine clays predominate, although sand and limestone are common in the upper part. The Congaree and McBean Formations do not extend to the north and northeastern parts of the Coastal Plain. The middle subdivision is composed of calcareous materials and includes chiefly the Santee Limestone of Eocene age and the Cooper Marl of Oligocene age. The calcareous material ranges from a loose calcareous sand to limestone of varying hardness. The materials are commonly white to creamy yellow, and within 50 feet of the land surface they are sufficiently soft to move by pick and shovel. The soft limestone lies near the land surface in the southern halves of Orangeburg, Calhoun, and Clarendon Counties, and in almost all of Berkeley and Dorchester Counties. The sediments composing the uppermost subdivision do not blanket the underlying Tertiary sediments but occur in rather isolated patches; however, in the southern group of counties the clays of the Hawthorn Formation of Miocene age completely cover the limestone. Thin deposits of sand, clay, and loose shell beds of Miocene age represent the upper subdivision in the northeastern part of the State. These deposits lie on Cretaceous deposits in this area.

Limestone of the Santee and Cooper Formations is an aquifer, but it is much less productive than the limestone of Georgia, with which it is physically continuous. The limestone varies considerably in permeability, the soft, creamy, chalky material being almost impermeable. Sands of the McBean formation represent an important aquifer between the Savannah and Edisto Rivers.

Quaternary System

Encroachment of the sea during Pleistocene time resulted in the deposition of a veneer of unconsolidated sands and clays on the portion of the Coastal Plain that was drowned during that time. Retreat of the sea to its present position exposed these deposits, which cover more than two-thirds of the Coastal Plain of South Carolina (Cooke, 1936, p. 5). In most places they are less than 35 feet thick, and in some cases they are not readily distinguishable from the older underlying sediments.

Northwest of the known Quaternary deposits the land surface is higher but is underlain by sandy materials which appear similar to those nearer the coast. However, much of the loose, sandy surface material along the inner margin of the Coastal Plain may be a part of the soil profile of underlying sediments and may not be of Quaternary age. The water table lies in the "surface sand" unit.

General Statement

Geology

Sands and clays of Cretaceous age compose the bulk of sediments in South Carolina. A southward-thickening wedge of Tertiary sediments buries the top of the Cretaceous about 1,000 feet below sea level in the southernmost counties, but in more than half of the Coastal Plain the Cretaceous sediments are within 200 feet of the land surface. Perhaps more than half of the Tertiary sediments are limestone, the remainder being sand and clay. Gravels are extremely rare in the Tertiary deposits and are only slightly more common in Cretaceous and Quaternary deposits. Gravels occur in flood-plain deposits bordering the larger streams along the inner margin of the Coastal Plain.

Not enough information is available to determine whether the Cretaceous sediments change in character coastward. If there is a decrease in percentage of sand coastward it is less noticeable than in other States. The proportion of sediments that have become consolidated is surprisingly low, although there may be an increase in consolidation in the southeastern part of the State where the sediments are deeper than 3,000 feet. The Tertiary limestone is largely soft and unconsolidated, although local recrystallized limestone ledges occur, especially near stream valleys.

The basement rocks are chiefly igneous and metamorphic but red sandstones, presumably of Triassic age, have been penetrated below the Coastal Plain sediments at Summerville, Dorchester County (Cooke, 1936, p. 177), and at Florence, Florence County. The average slope of the basement-rock surface is 36 feet per mile to the southeast (Siple, 1959, p. 13). The Cape Fear arch apparently represents a broad, gentle southeast-trending arch, which causes the basement to slope more nearly southward in the northeastern counties. Some of the arching or uplifting presumably occurred in early or middle Tertiary time, because the Eocene limestone formations are absent on the arch but swing around it near the coast (fig. 7).

> "Faulting in the unconsolidated sediments, though not identified specifically or known to extend over large areas, is fairly certain to have taken place in some areas. Neither lateral nor vertical displacement is likely to have been large. Nevertheless, older residents of the State who remember the Charleston earthquake describe such phenomena as sand boiling up through cracks in the surface soil during and after the first shock. Therefore, it is not improbable that many fractures do exist in the sediments and that there has been displacement along some." (Siple, 1959, p. 16).

Hydrogeology

Within 50 to 80 miles of the coast, where broad flat interstream areas prevail, the water table is nearly flat and lies within several feet of the land surface. The water table commonly is in sand, but in parts of Berkeley, Dorchester, and Orangeburg Counties the soft limestone is within a few feet of the surface, and the water table lies in it. Much water is lost by evapotranspiration, although some water seeps into the streams to become stream flow. In the Sand Hills and Red Hills the topographic relief is greater, and the water table generally lies deeper than 15 feet below the surface--in many places deeper than 40 feet; in these sandy areas evapotranspiration is not great, but ground-water seepage into streams is steady and represents a great part of the precipitation. The water-table aquifer is used extensively for rural domestic purposes, the water containing only a small amount of dissolved solids.

Two major artesian systems occur in South Carolina. One involves sands of the Cretaceous formations and some thin beds of sand in the overlying Tertiary deposits; the other is the Tertiary limestone aquifer, which is confined to the group of counties in the southern part of the State (see fig. 24). Where multiple sands are screened in wells, yields of 400 to 1,000 gallons a minute can be developed. In general, the permeabilities of the artesian sand aquifers are good. Soft sodium bicarbonate waters are representative. The sand aquifers are used extensively in all but Jasper, Beaufort, and Charleston Counties. South of the 33° parallel the limestone artesian aquifer is used, although water from it is brackish in some places.

Water in the limestone aquifer in the vicinity of Beaufort County is brackish because the limestone is near the land surface and received seawater recharge during the relatively recent geologic past. The clays of the Hawthorn Formation, which represent a confining and protective blanket against the invasion of seawater to the limestone in coastal areas of Georgia, are either too thin or have been incised by the deep estuaries along the lower coast of South Carolina and therefore do not act as an effective barrier to movement of seawater. Deeper parts of the Cretaceous sediments contain brackish or saline water in wells near the coast, although at Charleston and Beaufort the Cretaceous sediments, to a depth of 1,970 feet, contain less than 300 ppm of chloride (Siple, 1946, p. 112-113). It is estimated that more than 70 percent of the total volume of sediments in South Carolina contains water having less than 500 ppm of chloride; thus, South Carolina may contain a larger percentage of usable water than any other coastal State considered in this report.

Only along the Savannah River have systematic studies of ground-water movement been made. Siple (1957, p. 289) shows that the Savannah River has incised the Tuscaloosa

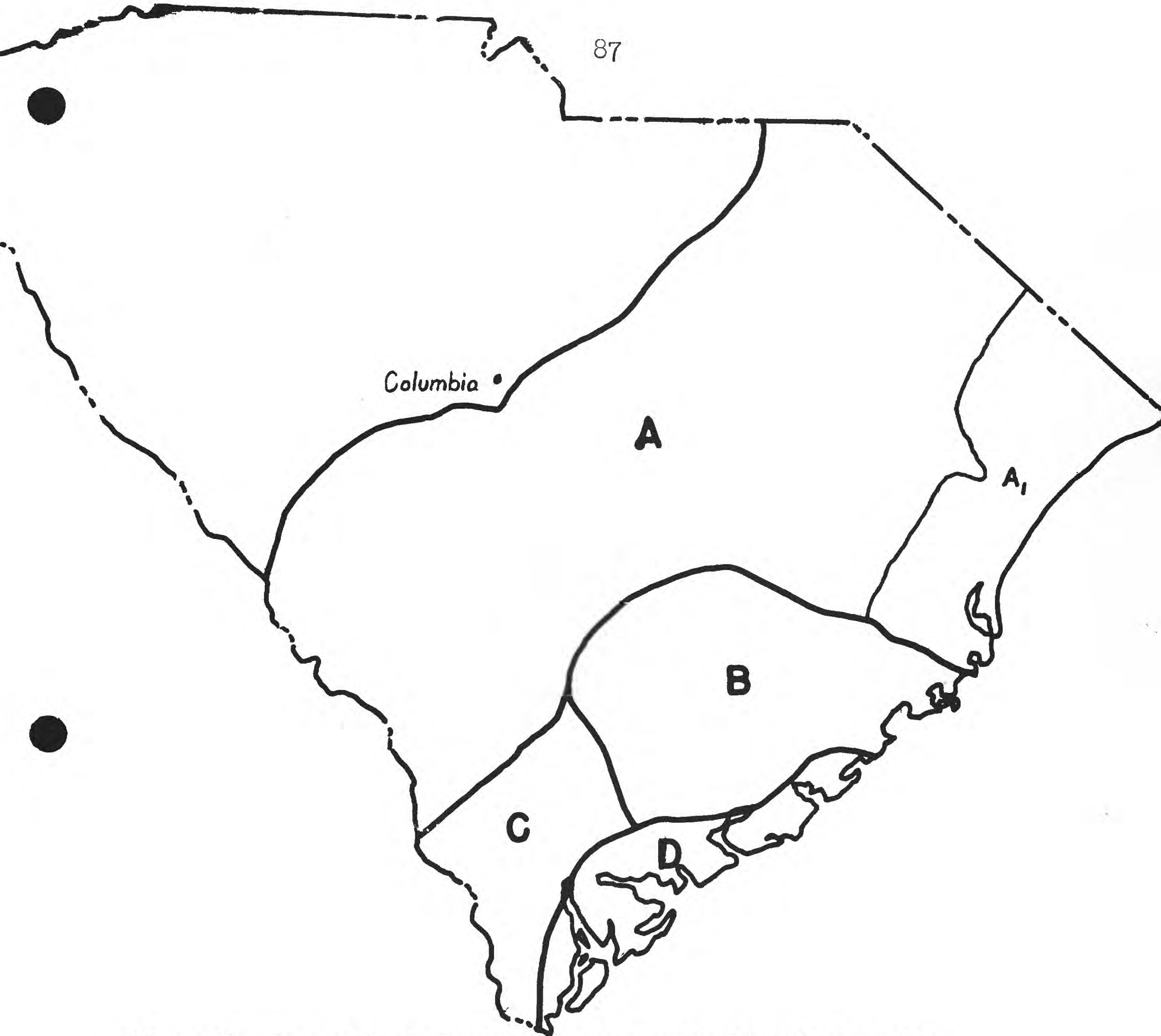


Figure 24. Map of South Carolina showing some hydrogeologic zones.

A. Cretaceous sand aquifer. Interbedded sands and clays. Multiple sands yield 300-1200 gallons a minute. Water soft and of good quality. Water to all depths is potable, except in Horry and Georgetown Counties where water below 700 feet may be brackish (zone A_1)

B. Tertiary limestone unit within 75 feet of land surface. Permeability varies from extremely poor (in the soft creamy marl) to moderately good (in the hard limestone along the southwest border). Water in limestone is fresh, as is water in upper part of underlying Cretaceous system.

C. Tertiary limestone. Confined beneath clay beds and sufficiently indurated and permeable to form a limerock aquifer. Water is fresh.

D. Tertiary limestone, the top of which has been incised by salt-water estuaries. Thus, brackish water occurs locally in the limestone. Some water in underlying Cretaceous deposits is fresh.

Formation and that the discharge of ground water under both water-table and artesian conditions from this formation along the Aiken County boundary is enormous. In this area the movement of water in this formation is southward to the river, but from Barnwell County southward the Cretaceous beds are not incised and the artesian movement is coastward. Warren (1944, p. 18a) shows that the limestone aquifer is incised by the Savannah River farther downstream, causing some water from the limestone to move toward the river. In much of the area underlain by the Tertiary limestone, either water-table or quasi-artesian conditions prevail because the limestone is near the surface and is only partly confined beneath less permeable materials. Where the limestone is near the surface and is soft and impermeable its properties for waste disposal might be favorable. The city of Charleston receives Edisto River water through an unlined tunnel in the limestone. The imperviousness of the limestone, the ease of digging, and the ease with which waste may be diverted or directed through tunnels to short unobtrusive coastal estuaries combine to make this area an interesting one in considering waste-disposal schemes.

GEORGIA

Topography

The Coastal Plain province occupies the southern half of Georgia. The Coastal Plain may be divided into several areas, each of which differs from the others in topography and in the kind of underlying rock. Along the inner margin are hills and valleys underlain by loose, light-colored sands and clays of Late Cretaceous age; this area, adjacent to the Piedmont province, is known as the Fall Line Hills. South of the Fall Line Hills, broad flat interstream areas are underlain by deep-red clays and sands of Eocene and Oligocene age. These areas are referred to as the Louisville Plateau (east of Oconee River) and to the Dougherty Plain, which occupies much of the drainage basin of Flint River. The Tifton Upland (which includes the Altamaha Upland) forms a strip about 45 miles in average width, extending across the middle of the Coastal Plain. It is a gently rolling upland, which has a thin sandy soil underlain by thick clays of the Miocene Hawthorn Formation. Between the Tifton Upland and the coast are the low coastal terraces that represent the slightly modified sea bottoms exposed since the retreat of the sea in Pleistocene time.

South-flowing streams drain the Coastal Plain, and the five largest--Savannah, Oconee, Ocmulgee, Flint, and Chattahoochee--have their headwaters in the Piedmont or Blue Ridge province. Although the streams are bordered along most of their reaches by flood plains, cliffs as high as 50 to 75 feet border parts of the major streams, especially the Savannah and Chattahoochee.

Cretaceous System

Sediments of Late Cretaceous age crop out or are buried beneath less than 500 feet of younger deposits in a belt about 50 miles wide that extends south of a line connecting Augusta, Macon, and Columbus. East of the Ocmulgee River light-colored sands and clays that are poorly stratified compose the outcropping beds. Between the Ocmulgee and Chattahoochee Rivers several formations having distinctive beds are present. Generally, the northernmost Cretaceous sediments, which also are the bottom sediments coastward, consist of medium- to coarse-grained sands and lenticular beds of clay. The overlying formations, south of a line connecting Macon and Columbus, commonly are more distinctly stratified beds of even-grained sands and clays; some impure limestone beds are present locally.

Sands of the Cretaceous formations represent an important ground-water unit in a belt 30 to 60 miles wide along the inner margin of the Coastal Plain (fig. 25). Interlayering of clay tends to separate the sand aquifers, but two or more sand beds are generally tapped by screened wells owned by municipalities and industries. The water normally is soft and low in dissolved mineral matter.

Tertiary System

The outcropping areas of formations of Oligocene and Eocene age are not clear-cut but approximately coincide with the Louisville Plateau and the Dougherty Plain (fig. 1). In their outcrop area these formations are composed of deep-red clayey sands and layers of limestone. Much of the red surficial material is considered to be a residuum of insoluble materials following the removal in solution

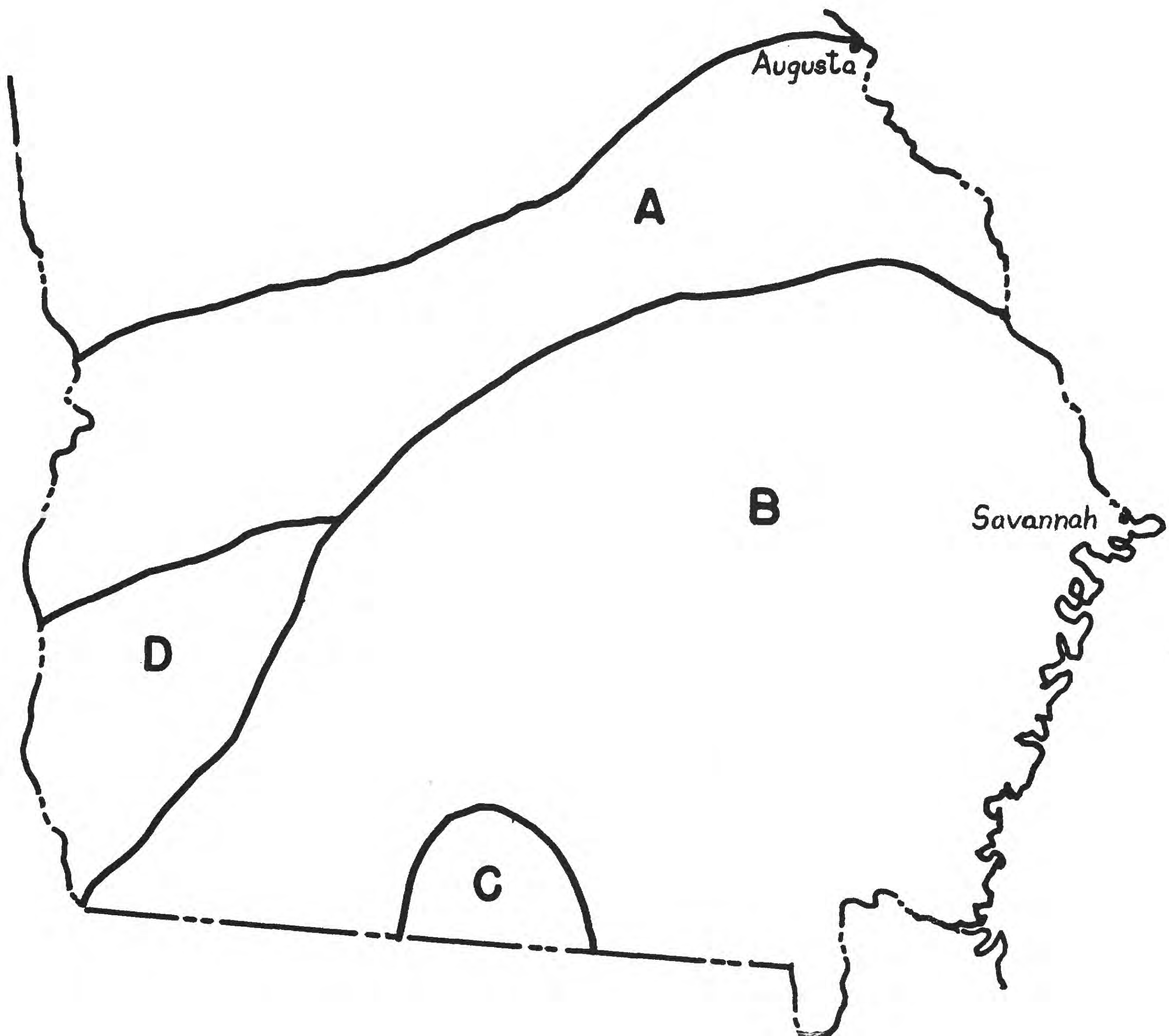
Figure 25. Map of Georgia showing some hydrogeologic zones.

A. Cretaceous sand aquifer. Alternating sand and clay beds. Sands vary in permeability from poor to excellent. Water fresh and low in mineral matter.

B. Tertiary limestone, or principal artesian, aquifer. An extensive, permeable, limestone aquifer confined beneath 100 to 500 feet of relatively impermeable Miocene deposits. Surface streams lie chiefly in clay and do not incise the limestone. Underlying Cretaceous sediments in southern and eastern counties contain brackish water.

C. Area where the Tertiary limestone is relatively close to the land surface and where the overlying clay is sufficiently breached to allow local recharge to the limestone.

D. Paleocene and Eocene limestone-sand aquifer. Uppermost artesian aquifer is either limestone of Paleocene age or sand of early Eocene age. Surface material is, in places, a nondescript clay and sand residuum of Eocene or Oligocene limestone, which once extended to this area but which has since been largely removed by solution.



of the limestone beds that may once have cropped out. Where the formations do not crop out at the surface the red residuum is not present, and the formation consists of limestone.

The Tertiary limestone unit, which is represented chiefly by the Ocala Limestone of late Eocene age, thickens southward as it becomes buried beneath the Tifton Upland. The Tifton Upland is underlain by the Hawthorn Formation of Miocene age, which consists of dark-green clays and sandy clays. The Hawthorn thickens coastward and is more than 500 feet thick in parts of McIntosh, Glynn, and Camden Counties.

Herrick and Wait (Thomson and others, 1956, p. 270) refer to deposits of the Midway and Wilcox Groups as the "Paleocene and Eocene limestone-sand aquifer." These deposits contain an aquifer in southwestern Georgia west of Flint River. Multiple-aquifer wells in this area commonly yield in excess of 500 gallons a minute.

The principal artesian aquifer, which is comprised mainly of the Ocala Limestone and to a lesser degree the Suwannee and Tampa Limestones, underlies about two-thirds of the Coastal Plain in Georgia and furnishes nearly 70 percent of the ground water used in the entire State, according to Herrick and Wait (Thomson and others, 1956, p. 277). The three limestone formations act as a single aquifer. The aquifer is confined above by clays of the Hawthorn Formation of Miocene age and below by clays and limestones of the Eocene McBean Formation. A piezometric map of the aquifer prepared by Warren (1944, p. 18a) indicates the general direction of movement of water. Much of the water enters the aquifer where the limestone is near the land surface, as on the Dougherty Plain and Louisville Plateau; some water enters the limestone through sinkholes in Brooks and Lowndes Counties and moves into the aquifer in all directions. Heavy withdrawal by water wells at Savannah has caused a large depression in the piezometric surface, and water levels have been lowered as far as 25 miles from the center of pumping. The dissolved solids in the water of the limestone consist chiefly of calcium bicarbonate, which tends to increase southward. The hardness commonly falls within the range of 150 to 300 ppm.

The Hawthorn Formation is not generally considered to be an aquifer, owing to the predominance of clay and sandy clay. However, in some places thin, moderately permeable sand beds are present which are capable of furnishing water to wells; moreover, dug wells in the clay furnish water for some rural domestic supplies.

Quaternary System

In a broad belt adjoining the ocean and approximately coinciding with the "Low Terrace" of figure 1, sands of Pleistocene age represent the surface material. Clay that underlies the surface sand also may be of Pleistocene age or may belong to the Hawthorn Formation of Miocene age. The topography of this area is nearly flat in the broad interstream areas; consequently, the water table commonly lies within 20 feet of the land surface.

General Statement

Geology

The coastward-dipping formations are exposed at the land surface in belts that extend across the State. Sands and clays of the Cretaceous System are exposed as the Fall Line Hills, along the inner, or northern, margin of the Coastal Plain. The area is hilly and is deeply incised by streams and tributary gullies. Southward, the Cretaceous formations become buried under a progressively thicker cover of younger deposits, and in the southern counties they are buried more than 2,400 feet below sea level. The loose sands and clays of the outcrop area grade into shales and sandstones, which in places are only semiconsolidated; limestone is a significant part of the Cretaceous rocks near the Florida line.

In spite of a thick homoclinal body of Tertiary limestone in the subsurface, surface exposures of limestone are rare for three reasons: (1) the naturally thinning wedge of rock units northward and updip, (2) the ubiquitous facies change coastward, from sands and clays in the outcrop areas to limestones and associated rocks seaward, and (3) removal in solution of some of the limestone that may have once been exposed. The Louisville Plateau, the Fort Valley Plateau (Peach County and vicinity), and the Dougherty Plain are underlain by relatively flat, red residual soils that appear to be, in part, the insoluble residue of former limestone beds. The Dougherty Plain, and to a lesser extent the Fort Valley Plateau and the Louisville Plateau, are bordered on the coastward side by an erosional scarp. Limestone and the overlying Hawthorn Formation compose the scarp, above which is the Tifton Upland.

Near the Florida boundary the Coastal Plain sediments approach their maximum thickness in Georgia; the sediments may be grouped as follows:

(1) From the surface to a depth of about 500 feet are undifferentiated clays and sands. With the exception of the material within 10 to 30 feet of the land surface, the sediments are characteristic clays of the Hawthorn Formation.

(2) Beneath the Hawthorn is the Tertiary limestone unit that is more than 1,000 feet thick.

(3) The basal unit is represented by Cretaceous sandstone, shales, and limestones. In parts of southern Georgia the Cretaceous deposits are more than 2,000 feet thick.

The characteristic homoclinal basement slope of the Middle Atlantic States is modified in Georgia by the Ocala-Peninsular arch, which extends northwestward from the vicinity of Ocala, Florida, to the central part of the Coastal Plain of Georgia (fig. 6). This peninsular uplift results in a basin on each side--the Southeast Georgia basin near Savannah, and the Southwest Georgia basin. The basin near Savannah is relatively shallow and broad, but the Southwest Georgia basin is more deeply embayed and contains about 9,000 feet of sediments in the extreme southwestern corner of the State. The uplift affects to a lesser extent in Georgia the uppermost Cretaceous and lowermost Tertiary sediments. The top of the Cretaceous sediments has a gentle, southeast slope of 12 to 20 feet per mile. The top of the Tertiary limestone unit slopes coastward, but not at a uniform rate. Faulting in the Coastal Plain is thought to be uncommon, and no faults with displacements of more than 100 feet are known.

Hydrogeology

In the Fall Line Hills the hilly topography and the loose, permeable sand causes the water to filter rapidly to the water table, which may be deeper than 30 feet on some upland surfaces. Poor fertility and rapid infiltration into the sand result in very slight loss of water by evapotranspiration. Ground-water discharge as seepage into streams is steady, and the sand-hill streams have good dry-weather flows. In the Dougherty Plain, Fort Valley Plateau, and Louisville Plateau the relatively flat topography results in a water table normally within 10 to 15 feet of the land surface, except near the streams where it may be deeper. In the Tifton Upland the water table generally is less than 20 feet below the surface and commonly is in clay rather than sand. Beneath the inner margin of the Tifton Upland, near the scarp that overlooks the plain to the north and west, the water table is perched above another water table in the limestone. Separating the two water tables are some clays of the Hawthorn Formation and some underlying air-filled, cavernous limestone. At Pelham, in Mitchell County, the writer and S. M. Herrick found the water table in the limestone to be 220 feet below the land surface and 150 feet below the top of the limestone. Southeastward from the scarp, the base of the Hawthorn Formation transects the water table in the limestone, and from this place coastward the limestone is completely saturated with water under artesian conditions. The water-table aquifers are tapped widely for rural domestic supplies, but the total use of ground water is small; very few of the shallow wells are equipped with electric pumps. Water in the surface sand and clay is soft and low in total dissolved solids.

The Cretaceous sand aquifer and the Tertiary limestone aquifer comprise the two major artesian systems (see fig. 25). As a result of the southeastward inclination, the Cretaceous sand aquifer is buried beneath the limestone and is not used where the limestone provides adequate water. Multiple sands, which require screened wells, characterize the Cretaceous sand aquifer. In the limestone aquifer the rock materials are consolidated, and the pore space is chiefly composed of small interconnecting solution openings; the uppermost part of the limestone tends to be more permeable than the lowermost part. Wells in limestone are of the open-end tubular type that are cased only to the top of the rock.

In most of the Coastal Plain of Georgia fresh water extends to a depth of 1,000 feet or more. Near the Florida line and along the coast salty water occurs in all the Cretaceous deposits, and the lowermost parts of the Tertiary limestone aquifer contain salty water in these areas also.

The over-all movement of artesian water is southeastward, but local variations are common (Warren, 1944, p. 18a). Information is not available to indicate the intricacies of the direction and rate of movement of water in the Cretaceous deposits; where buried beneath more than 300 feet of Tertiary deposits, the water in the Cretaceous Formations is so well confined that movement is slow. All the streams are, of course, fed by the water-table aquifers, and most streams receive leakage from the uppermost artesian aquifer. However, streams on the Tifton Upland have not cut through the clays of the Hawthorn Formation and do not bleed the limestone aquifer.

FLORIDA

Topography

Florida is a peninsula which is the emerged part of an extensive flat-topped plateau (fig. 6). It is underlain by a thick section of limestone rocks ranging in age from Early Cretaceous to Recent. Surface deposits of sand overlie the limestone, although in parts of the State clay beds separate the sand and limestone. The primary factors which determine the character of the landscape are: (1) terracing resulting from the advance and retreat of the sea during Pleistocene time; (2) the presence or absence of soluble rocks (limestone); (3) the thickness of sand or other covering of a buried soluble bed; (4) elevation above sea level sufficient to permit surface waters to descend and make solution possible; and (5) stream erosion (Fenneman, 1938, p. 46).

Lowlands border the entire coast of Florida and lie nearly everywhere less than 100 feet above sea level. These lowlands consist for the most part of nearly level plains, which have been covered so recently by the sea that great areas of them have suffered little dissection (Cooke, 1945, p. 11). A notable feature of the coastal lowlands is the Everglades,

> " . . . a flat, frequently flooded region commonly lower than 16 feet above sea level extending southward from Lake Okeechobee in Florida Bay and confined between slightly higher land on each side. The floor of the Everglades is composed of Pliocene and Pleistocene limestone and limey sandstone, covered by sheets or patches of peat and muck derived from sawgrass." (Cooke, 1945, p. 11).

The Pine Hills, or Western Highlands, extend from the Apachicola River westward to the western boundary between Florida and Alabama. The Western Highlands area consists of a southward-sloping plateau underlain chiefly by sands. Several large streams have cut deep flat-bottomed valleys, and the smaller streams have their heads in steep, narrow gorges.

The northern part of the peninsula may be divided into the Lime-sink district on the west and the Lake district on the east. Both extend slightly west of north from the latitude of Tampa. The Lime-sink district is characterized by a sandy cover over soluble limestone. No great area is without sinkholes; some contain water, but most of them are small, dry, sandy basins with rounded bottoms. The Lake district differs somewhat from the Lime-sink district on the west; Miocene clays separate the surface sands from the underlying limestone, and thus the downward movement of water in sinks is sufficiently retarded to result in lakes.

> "The relatively low relief of the land surface of peninsular Florida is conducive to the formation of slow-moving, meandering streams connected to or passing through numerous lakes. The stream gradients usually are slight with surface slopes as low as 0.07 feet per mile. The many lakes in the river systems act as reservoirs reducing the severity of flooding in wet seasons as well as sustaining the flow in dry seasons." (Florida's Water Resources, 1956, p. 26).

In the northern and northwestern parts of the State the land surface shows more relief, and stream gradients are steeper. Florida is noted for its large springs; these springs, in addition to large diffuse seepage from the permeable limestone, have great control over the stream flow, especially in northern Florida.

Cretaceous System

The Cretaceous rocks of Florida are buried so deeply that the only information about them comes from scattered test wells for oil. The top of the Cretaceous ranges from slightly more than 1,500 feet below the land surface in Gilchrist and adjacent counties in northern Florida to more than 6,000 feet in parts of southern Florida.

Applin (1952) has divided the Cretaceous sediments of Florida into two series--the Comanche and the Gulf--and has estimated their thicknesses in Florida and Georgia. From his studies it is estimated that between 40,000 and 60,000 cubic miles of Mesozoic sediments underlie Florida, of which the greater part belongs to the Cretaceous System. The sediments are thinnest on the "Peninsular arch" (Applin, 1951, p. 3), which is an anticlinal fold, or arch, approximately 275 miles long, trending south-southeastward, and forming the axis of the Florida peninsula as far south as the latitude of Lake Okeechobee. The Cretaceous sediments thicken around the arch and reach a thickness of more than a mile in southern Florida. In southern Florida the basal part of the Coastal Plain sediments has been tentatively classified as Jurassic in age.

The Cretaceous sediments, in general, are consolidated deposits represented by limestones, shales, and sandstones, although in northern Florida poorly consolidated sands and clays compose part of the section. In the northern part of the State varicolored shales interbedded with limestones and sandstones change southward into alternating beds of limestone, dolomite, and anhydrite. Salty water occurs through the Cretaceous sediments in Florida.

Tertiary System

At least a dozen formations compose the Tertiary system in Florida. None of these formations is sufficiently distinctive to justify a separate discussion for the purposes of this report. A major distinction exists between the Tertiary sediments in the Panhandle from those in Peninsular Florida. Those in the Panhandle consist of clays, sands, and some limestone, whereas those of Peninsular Florida consist almost entirely of organic limestones, in part dolomitized, and chemical precipitates, including evaporites (Toulmin, 1955, p. 233).

The eastern and the southern parts of the peninsula are underlain by relatively impermeable clay, marls, and silty, shelly sands; these deposits, chiefly the Hawthorn Formation of Miocene age, overlie the thick limestone beds.

The Tertiary limestome formations compose a productive artesian aquifer that underlies all but the extreme western tip of Florida. The aquifer was systematically studied by Stringfield (1936), who mapped its piezometric, or artesian pressure, surface. The piezometric surface of this aquifer in 1951 is shown in figure 26; as Stringfield and Cooper point out (1951, p. 811), the contours show the height to which water will rise above sea level in tightly cased wells that penetrate the aquifer. The contours also show the direction of movement of the water and show the areas in which water from the surface enters the aquifer and those in which water is discharged from the aquifer.

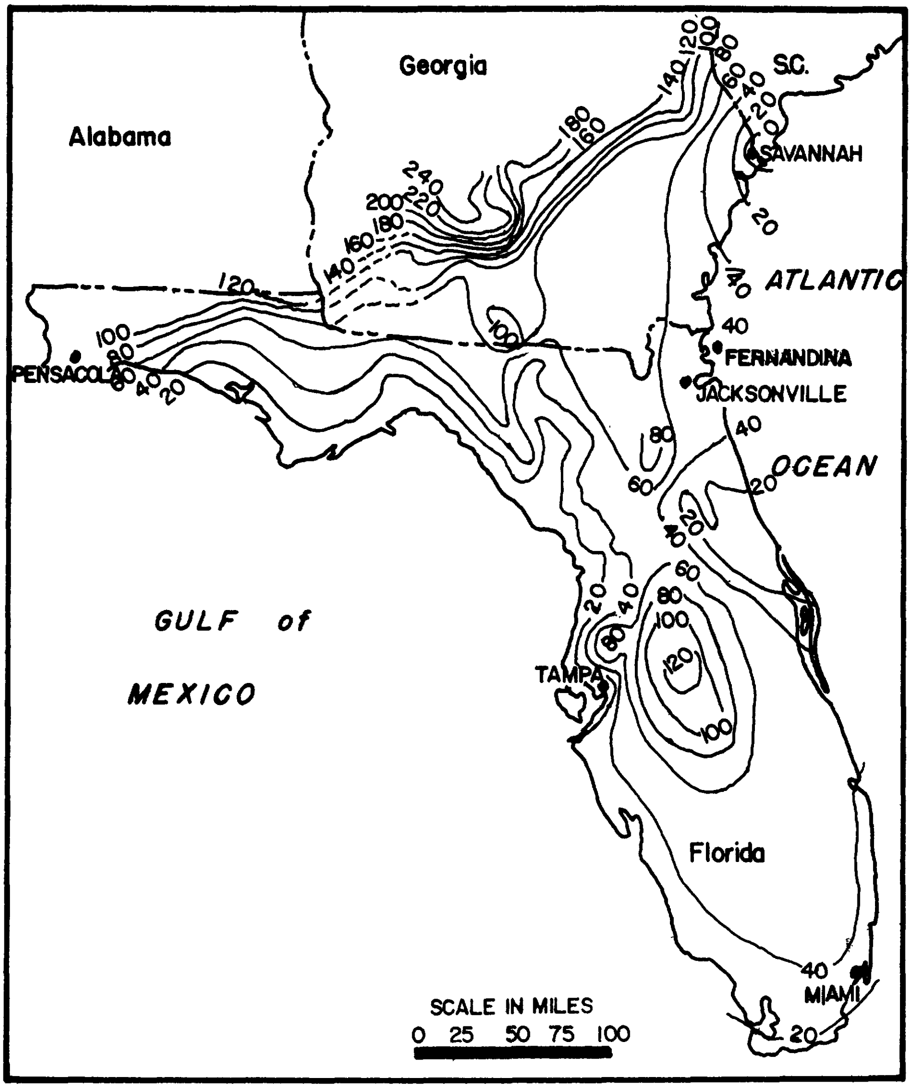
The limestone aquifer has a thickness of more than a thousand feet throughout much of Florida (Stringfield, 1936, p. 132). It is exposed or covered with relatively thin, sandy deposits in the north-central and northwestern parts of the peninsula, but throughout much of the State its top is several hundred feet beneath the land surface and separated from the surface by relatively impermeable materials. The aquifer is the source of water for Florida's large springs and for many thousand wells. It is one of the most permeable aquifers of the country. It yields hard water, the bulk of the total dissolved solids being calcium bicarbonate.

Quaternary System

The land surface at most places in the State is underlain by Pleistocene deposits (Cooke, 1945, p. 15). These deposits are of two general types. The most widespread is represented by sands that were deposited as a result of the last submergence by the sea. The other type is limited to the east coast and southern part of the State, and consists of limestones and sands in varying degrees of consolidation. The major part of the Biscayne aquifer in southeastern Florida is of Pleistocene age.

A characteristic feature of the surface and near-surface materials is their relatively high permeability. In most places in Florida the precipitation seeps readily into the coarse, sandy soils. The water table lies in the sand in relatively flat areas, particularly where the sand is underlain by clay. Where limestone immediately underlies the surface sand the water table may lie in either the sand or limestone.

Figure 26. Piezometric surface of the Tertiary limestone aquifer of Florida and Georgia, 1951. Lines connect points of equal head on the ground water, in feet above sea level (Stringfield and Cooper, 1953).



General Statement

Geology

Sands occurring at the land surface throughout Florida are in contact with underlying limestone in the north-central and northwestern part of the Peninsula. Elsewhere, relatively impermeable clay beds separate the sand from the underlying limestone. Limestone of Tertiary age underlies all of Florida, although in the extreme western part of the State limestone is subordinate in quantity to sand and clay. In the southern half of the Peninsula almost all the Tertiary sediments are limestones and dolomites, with subordinate amounts of anhydrite. Cretaceous deposits in northern Florida are chiefly shales and sandstones, somewhat more dense and compacted than sands and clays of equivalent age in central Georgia.

The character of the rocks beneath the Coastal Plain sediments is not well known. Formations of Jurassic or Triassic age are throught to be the basal Coastal Plain deposits in southern Florida. Igneous and metamorphic rocks are the underlying basement materials in a broad area surrounding Cape Canaveral, but Applin (1951, p. 1-28) describes some Paleozoic sedimentary rocks that have been penetrated by several oil tests in other parts of the State.

Some semblance of a peninsula, or platform, has occupied the Florida area since early Cretaceous time, but its shape has been modified many times as the sea advanced and retreated. The behavior of this peninsula accounts for the distribution of Cretaceous and Tertiary sediments. Owing to its elevation above sea level during some of the time, the Peninsular arch is responsible for the relative thinness of Cretaceous sediments in the north-central part of the peninsula; here they are less than 2,000 feet thick, compared to more than 7,500 feet in the southwestern part of the State. Almost parallel to the Peninsular arch, but unrelated to it, according to Applin (1951, p. 3-5), is the Ocala uplift. The Ocala uplift trends northwestward through Citrus and Levy Counties (Vernon, 1951, p. 55) and represents a slight arch in the Tertiary beds. As a result of the Ocala uplift, the Tertiary sediments are thinner than normal in the northwest and north-central parts of the peninsula, and Eocene limestones which are buried in southern Georgia reach the surface in the Lime-sink district. The combined effects of the Peninsular arch and Ocala uplift tend to accentuate the thickening of sediments around this positive structure. For example, figure 8 shows that sediments increase in thickness away from the Peninsular arch--Ocala uplift in the extreme northeastern corner of the State (Southwest Georgia basin), in the Tallahassee area (Southeast Georgia basin), and in the southern Florida (South Florida basin). The nature of the faulting in Florida has not been fully evaluated. In fact, faulting had not been recognized prior to the work by Vernon (1951, p. 47), who mapped several faults in Citrus and Levy Counties and postulated others in surrounding areas. These faults involve Eocene limestone formations.

Hydrogeology

A discussion of the hydrology of Florida must focus attention on the Tertiary limestone formations that act as a single aquifer (see fig. 27). The aquifer, as a whole, is (1) very permeable, (2) essentially full of water, and (3) capable of taking enormous amounts of water from precipitation; these conditions result in enormous discharge from the aquifer through large springs, by leakage into streams and beneath the sea, and by evapotranspiration. Many of the streams north of the latitude of Tampa Bay are fed by discharge from the limestone. The limestone is readily dissolved by circulating water and, consequently, there are many sinkholes and lakes in the northern part of the peninsula. These undulations in topography and a trend toward underground drainage result in a scarcity of surface streams; moreover, many of the existing surface streams are fed by artesian springs whose water is derived from rain falling in the drainage basin of another stream.

Although the thick Tertiary limestone formations are generally considered as a single, permeable hydrologic unit, they have different water-transmitting properties. Water moves freely through some beds and with difficulty through others. The fact that the upper part of the Tertiary limestone unit contains some very permeable layers is well established. The lower part of the limestone unit, for example, the part more than 1,000 feet below sea level, contains some permeable layers also; however, there is reason to believe that the average permeability decreases with depth. This thought applies also to the underlying Cretaceous limestone formations in the southern half of the peninsula. Reports that solution

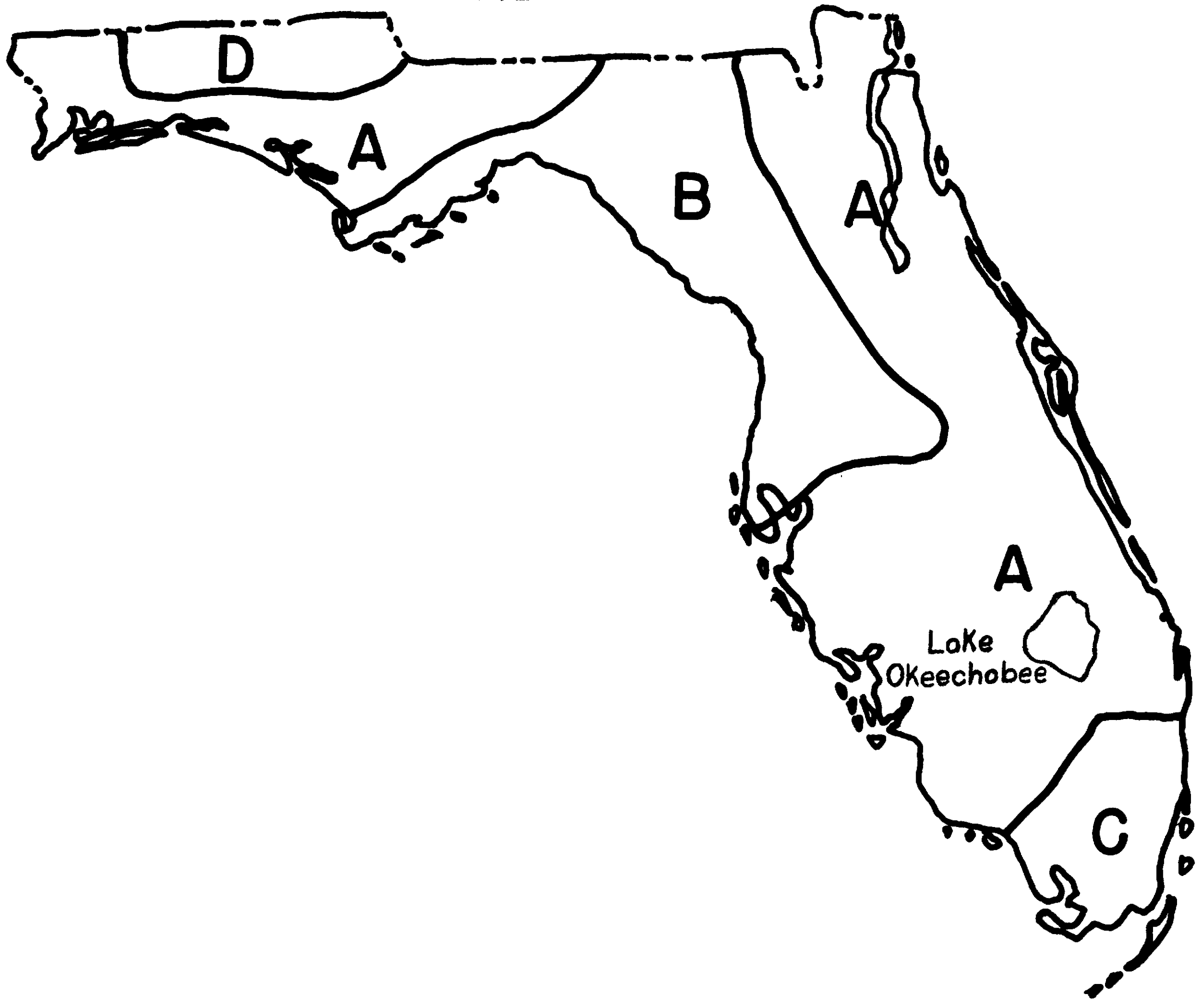


Figure 27. Map of Florida showing some hydrogeologic zones.

A. Tertiary limestone artesian aquifer. Overlain by relatively impermeable clays and surface sand. Top of limestone is more than 100 feet below sea level and artesian pressure is above sea level in most places. South of Lake Okeechobee the top of the limestone is more than 400 feet below sea level, and almost all the Tertiary and Cretaceous sediments (more than 10,000 feet thick) are composed of limestone and dolomite; water below 500 feet south of Lake Okeechobee is salty.

B. Tertiary limestone aquifer lies at or near the ground surface. Discharge from the limestone into streams and the Gulf is heavy.

C. Biscayne aquifer, composed mainly of sandy limestone and calcareous sandstone, is an extremely permeable water-table aquifer.

D. Principal water-bearing formations are sands and gravels of Miocene age 100 to 300 feet thick. They occur within 500 feet of ground surface and yield soft, low-mineralized water.

cavities have been penetrated by oil tests at a depth of several thousand feet in southern Florida does not weaken the belief that the deep-lying limestones are relatively impermeable--at least in comparison with the near-surface Tertiary limestone formations. Perhaps the limestones below a depth of 5,000 feet are more permeable than sandstone and shales of equivalent depth elsewhere.

All water in the Cretaceous section and in the lower part of the Tertiary section is salty. This water has been entombed almost since the enclosing sediments were deposited and, as far as is known, there is very little movement of water in these rocks. In contrast is the part of the Tertiary limestone which lies no deeper than a few hundred feet below sea level; water in this shallow limestone zone moves at varying rates. Water in the surface sands is disposed of in the following ways: (1) Where the sands are in contact with underlying Tertiary limestone, as in the Lime-sink area, the water enters the limestone or is sloughed off in low areas as ground-water discharge, (2) where the sands are underlain by clays, as in parts of extreme western Florida and the eastern part of the peninsula, most of the water is sloughed off above the clay in the form of leakage into streams and the sea, and as evapotranspiration, and (3) where the land is relatively flat and the sands are underlain by extremely permeable limestone beds, as in southern Florida, the water table is so near the land surface that evapotranspirtation is relatively great; yet seepage into the sea and surface bodies of water and pumpage from wells also are significant.

In the Miami area in southern Florida the top of the limestone artesian aquifer is about 1,000 feet below sea level, and its water is brackish. However, the Biscayne aquifer is the one in which most wells are developed in this area. It is composed mainly of sandy limestone and calcareous sandstone, with beds and pockets of quartz sand (Parker and others, 1955, p. 2). It is a water-table aquifer of large permeability. Parker indicates (p. 2) that an average well, 6 inches in diameter and 50 feet deep, will yield 1,000 to 1,500 gpm with a drawdown of less than 4 feet. The Biscayne aquifer is composed of beds of several formations ranging in age from Miocene to Pleistocene.

The percentage of rainfall that becomes ground water in Florida is very great. Some of the ground water moves only short distances before it discharges, whereas some becomes a part of a great underground circulatory system in which it is transmitted through permeable limestone formations for considerable distances--perhaps irrespective of surface-drainage systems.

ALABAMA

Topography

The Coastal Plain of Alabama includes roughly the southern half of the State. The inner part, underlain by formations of Late Cretaceous age, forms a concentric pattern that trends westward across the middle of the State and swings northwestward into Mississippi. Several distinctive topographic belts occur, corresponding to outcrop areas of certain formations. The inner margin of the Coastal Plain is represented by the Fall Line Hills; this belt is underlain by basal Cretaceous sands and clays into which valleys have been carved as much as 100 to 200 feet below the upland level. Coastward is the Black Belt, a prairie underlain by black, fertile residual soils formed on chalky deposits of the Selma Group. It is a plain of faint relief nearly 25 miles wide, extending from eastern Alabama into Mississippi. South of the Black Belt is the Ripley Cuesta, formed on relatively resistant and partly indurated Cretaceous sands and clays; the scarp, facing north, rises as much as 200 feet above the Black Belt. The outcrop belt of some lower Tertiary sediments corresponds with the Red Hills; the Red Hills is a gently coastward-sloping plain 400 to 600 feet above sea level, which has been deeply eroded, and which is characterized by red soils. The Red Hills are somewhat modified in western Alabama in the vicinity of Choctaw County by the surface expression of the Hatchetigbee anticline. In southern Alabama the Pine Hills are underlain by sandy clays and correspond to the Tifton Upland of Georgia.

Much of the State is drained by the Chattahoochee River in the east and the Tombigbee and Alabama Rivers in the west. A large area separates these south-flowing streams; smaller south-flowing streams are located in the large area separating the basins.

Cretaceous System

Sediments of the Cretaceous System crop out in a crescent-shaped belt about 70 miles wide, that extends westward across the middle of the State and northwestward into Mississippi. The northernmost sediments--those lying on the dense, consolidated Paleozoic rocks--consist of sands and clays of the Tuscaloosa Group. The Eutaw formation of Late Cretaceous age overlies the Tuscaloosa Group, and in eastern Alabama is overlain by the Blufftown Formation which is composed chiefly of irregularly bedded sand and clay. The Selma Group overlies the Eutaw Formation in west-central Alabama. It consists of massive chalk with some thin-bedded chalky marl and has a thickness of more than 600 feet in much of its area of outcrop. In central and eastern Alabama the Selma Group grades laterally into the Blufftown Formation and the Cusseta Sand Member of the Ripley Formation (Carlston, 1944, p. 29). A striking feature of the Cretaceous outcrop area is the progressive change in character of sediments westward. The interbedded sands and clays (and interspersed limestone beds) in the east grade into chalk and other calcareous beds in the west.

The area in which water is extensively withdrawn from Cretaceous sands is shown as zones A and B in figure 28. South of zone C, in the southern and southwestern counties, water in Cretaceous formations is salty. Significant water-bearing sands occur in the Tuscaloosa Group and the Eutaw and Ripley Formations of western Alabama and in the Tuscaloosa Group, Eutaw, Cusseta, Ripley, and Providence Formations of eastern Alabama (LaMoreaux, 1948, p. 16). The coastward movement of water in the Cretaceous sands results in an increase in total dissolved solids but a decrease in hardness; the decrease in hardness is due to the exchange of calcium ions of the water with sodium ions of the glauconite and clay.

Tertiary System

Tertiary formations crop out in the southern two-thirds of the Coastal Plain province in Alabama. They lie on Upper Cretaceous deposits and have an approximate regional dip of 25 feet per mile or more to the south and southwest (LaMoreaux, 1948, p. 16). Sediments of the Tertiary system, like those of the Cretaceous System, change in lithologic character considerably from east to west. These changes have been illustrated in a generalized diagram by Toulmin (1955, fig. 4) and are indicated in tables 12 and 13 in the pocket, which was adapted from LaMoreaux (1948, p. 14-15). Tertiary sediments are composed

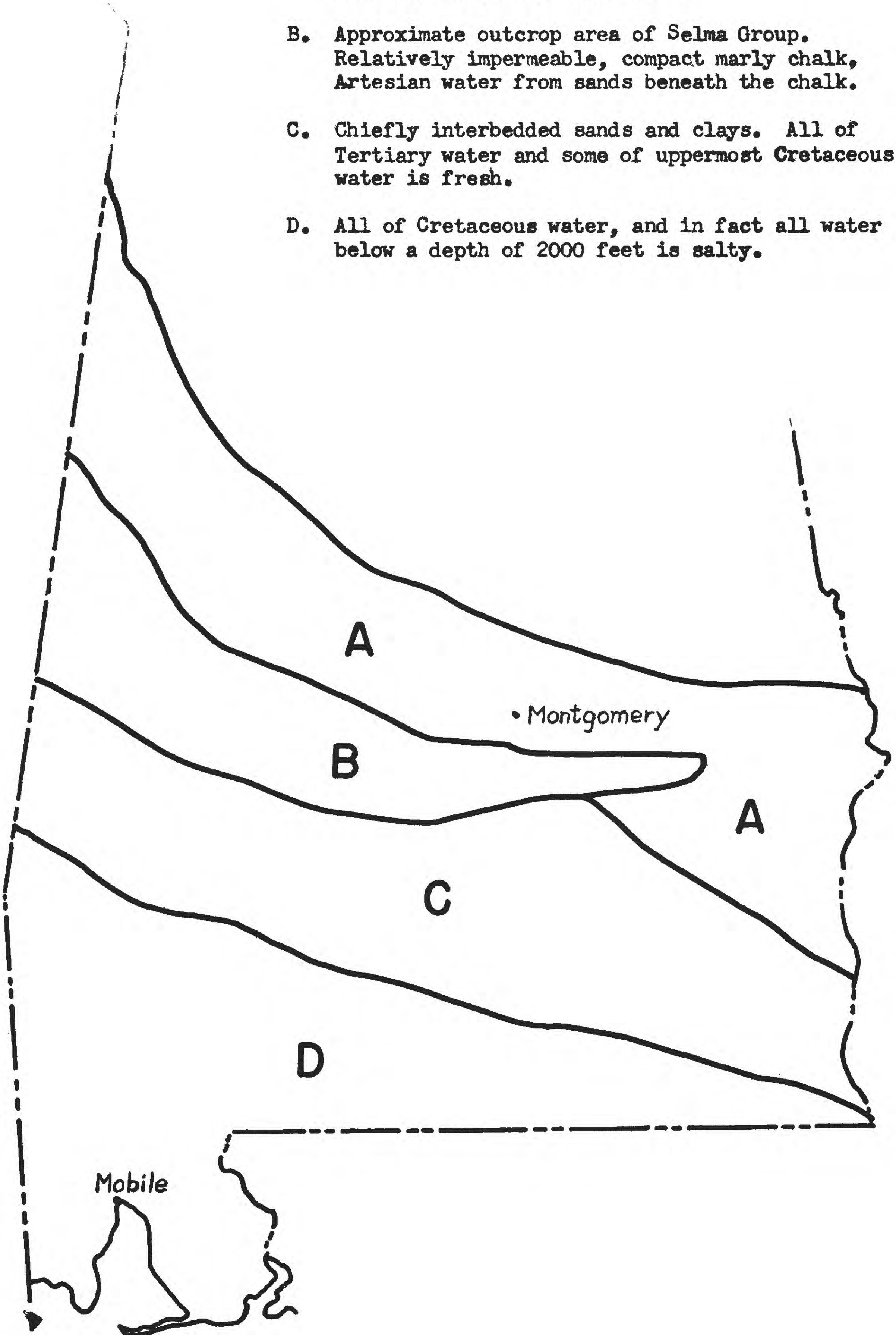
Figure 28. Map of Alabama showing some hydrogeologic zones.

A. Area of bedded sands and clays. Almost all sediments contain fresh water.

B. Approximate outcrop area of Selma Group. Relatively impermeable, compact marly chalk, Artesian water from sands beneath the chalk.

C. Chiefly interbedded sands and clays. All of Tertiary water and some of uppermost Cretaceous water is fresh.

D. All of Cretaceous water, and in fact all water below a depth of 2000 feet is salty.



of beds of fine- to medium-grained quartz and glauconite sands, clays, marls, calcareous clays and sands, and limestone. Most Tertiary formations have at least one sand or limestone bed that is a potential source of ground water (LaMoreaux, 1948, p. 16). The Porters Creek Formation, which lies near the base of the Tertiary in western Alabama, is sufficiently impermeable to effectively separate Cretaceous and Tertiary water.

Quaternary System

Although the Citronelle Formation is of Pliocene age, it is not readily distinguished from Pleistocene surface deposits in Alabama and is here included with the Quaternary System. The Citronelle and associated deposits cover the Tertiary sediments in southwestern Alabama. The deposits consist of lenticular beds of coarse to fine sand and varicolored clay, reaching a maximum thickness of less than 100 feet in Washington, Escambia, Clark, Mobile, and Baldwin Counties (LaMoreaux, 1948, p. 22). The sands and gravels near the base of these "surface deposits" furnish soft water for several public supplies in these counties.

General Statement

Geology

Where the Cretaceous sediments are exposed, they have a regional southward dip of about 35 feet per mile. Under cover of Tertiary deposits they are more steeply inclined, and the base of the Coastal Plain is more than 15,000 feet below sea level in the southwestern part of the State. The Tertiary sediments thicken to the south and southwest, reaching a thickness of more than 1,500 feet in the southeastern corner of the State and more than 5,000 feet in the southwestern corner.

The basement underlying the southeastern part of the Coastal Plain is composed of igneous and metamorphic rocks, but underlying the western part are sedimentary rocks of Paleozoic age.

The character of sediments of the same age changes significantly from the east to the west. However, the gross changes in lithology of the Tertiary deposits are not as great as the changes in the formational names suggest. For example, beds of fine quartz and glauconite sands, clays, marls, and other soft calcareous sediments prevail in both the east and west parts of the Tertiary. A decrease in the quantity of limestone beds in the outcrop area to the west is apparent; also, the Porters Creek, a relatively impermeable clay at the base of the Tertiary in western Alabama, thickens westward. Sands and clays prevail along the entire northern half of the Cretaceous outcrop belt; the southern half of the Cretaceous outcrop belt consists chiefly of chalky deposits in the west, and sands and clays with thin limestone beds in the east prevail.

In most of the Coastal Plain of Alabama the sediments are inclined gulfward as a homoclinal unit. However, the southwestern part of the State contains structures that are common to the Gulf Coast geosyncline (fig. 6). Significant among them is a series of gravity-strike faults trending southeastward from the vicinity of Choctaw County toward Florida. These faults have caused a great thickening of sediments toward the southwest. The Hatchetigbee anticline occurs in the vicinity of Choctaw, Washington, and Clarke Counties; it affects an area at least 50 by 20 miles in extent and represents an uplift of several hundred feet, bringing to the surface formations that are slightly buried 10 or more miles to the north. One salt dome has been found in southwest Alabama, salt being reached at a depth of only 410 feet (Braunstein, 1959, p. 12). The upward intrusion of salt in this dome, and perhaps in other deeper undiscovered domes, has arched and uplifted the adjacent sediments.

Hydrogeology

The depth to the water table varies greatly from place to place in the Coastal Plain of Alabama. Beneath some steep hills the water table is more than 80 feet below the land surface, but beneath flood plains and broad, relatively flat areas it is within 10 feet of the surface. As a whole, the surface deposits are sufficiently sandy to allow water to move into the soil and downward to the water table. Some of the water in the upper part of the zone of saturation is available to feed the underlying artesian aquifers, but the relative fullness of these beds allows much of the water to move laterally to valleys, where it is lost by evapotranspiration or seepage into streams. The interlayering of sands and clays results in water being deflected laterally to valleys at somewhat higher topographic locations than would be the case were the deposits composed of homogeneous sands. Springs are numerous but small, only a small percentage yielding more than 10 gallons a minute. The chalk that underlies the Black Belt is relatively impermeable. Water-table aquifers are used extensively throughout the Coastal Plain for rural domestic supplies of water.

Every formation of the Cretaceous and Tertiary Systems in Alabama has a permeable bed capable of yielding artesian water, with the exception of the Porters Creek and the underlying chalky formations. Most of the permeable beds are composed either of quartz sands or quartz and glauconite sands. The beds of sand vary greatly in thickness, areal extent, and permeability. Many industrial and municipal wells yield several hundred gallons a minute, although the total withdrawal of artesian water is only a fraction of that available. Most of the artesian aquifers yield soft water, either containing very little mineral matter or containing a moderate amount of sodium and bicarbonate as the chief dissolved constituents. Flowing wells can be had in most of the lowland areas, and the artesian pressures of the deeper aquifers commonly are higher than those of the shallow aquifers.

Salty water occurs in the Cretaceous and lower Tertiary aquifers where they are buried deeply near the coast (see fig. 28). In the southeastern counties water to a depth of almost 1,000 feet is fresh, but in some southwestern counties the depth to brackish water is less than 1,000 feet.

Almost all of the ground-water circulation occurs at shallow depth--either in the water-table aquifer or in the uppermost artesian aquifers. The relatively deep incision of streams into the formations results in a water-table gradient toward the streams, as is the case, of course, in all parts of the Coastal Plain province where humid conditions prevail. In addition, the deep stream incision allows some near-surface artesian water to leak out into the streams. The movement of artesian water tends to be gulfward in the permeable layers except where diverted to discharge areas in some valleys. It is likely that the deep artesian water has an infinitesimally slow movement gulfward down the dip of the formations.

MISSISSIPPI

Topography

Coastal Plain sediments cover all of Mississippi except small areas of Tishomingo County in the northeastern part of the State. The Coastal Plain may be divided into several distinct physiographic districts. The relative altitudes and the landforms shown by all but two of these districts have resulted from the differing effects of erosion on the sediments that immediately underlie the land surface. The areas where the sandy formations crop out stand as hilly uplands, whereas the areas underlain by clay and chalk are moderately rolling low plains between the hilly districts (Stephenson and others, 1928, p. 2). From northeast to southwest the belts of uplands and lowlands in sequence are as follows: Fall Line Hills, underlain by predominantly sandy strata of the Tuscaloosa Group and the Eutaw Formation; Black Belt, underlain by chalk south of Lee County and calcareous clay northward into Tennessee; Pontotoc Hills, underlain by sands of the Ripley Formation and limestone of the Clayton Formation; Flatwoods, underlain by the Porters Creek Clay; Red Hills, underlain by interbedded sands and clays of the Wilcox and Claiborne Groups; Jackson Prairie, underlain by predominantly clayey materials of the Jackson Group; and the Pine Hills, underlain by sandy soils of late Tertiary age. The upland parts of the Coastal Plain have a general south and southwest slope, ranging from an elevation of about 600 to 700 feet on the Fall Line Hills to about 100 feet on the Pine Hills. Topographic relief on each of the alternate hilly belts is relatively great, some of the hills being as much as 200 feet above the adjacent valleys. The two districts whose main features are not chiefly governed by erosion are the Yazoo basin and the Coastal Pine Meadows (Stephenson and others, 1928, p. 2). The Coastal Plain Meadows is a belt about 20 miles wide bordering the coastal Part of the State. The Yazoo basin is a relatively flat alluvial plain in northwestern Mississippi. Rising 150 to 250 feet above the Yazoo basin on the east is a rather abrupt escarpment composed of calcareous loess. This upland belt of loess, about 5 to 15 miles wide, is characterized by steep slopes and by narrow ridges and intervening valleys.

The Gulf of Mexico receives all the drainage of Mississippi. The surface waters of the eastern, south-central, and southern parts of the State flow to the Gulf through three principal streams--Tombigbee, Pascagoula, and Pearl Rivers. The drainage of the northern, north-central, and western parts flows into the Mississippi River. The main streams have fairly low gradients and have sluggish, meandering courses.

Cretaceous System

The Paleozoic sedimentary rocks that crop out in small areas in the northeastern part of the State are overlain by formations of Late Cretaceous age. The outcrop belt of the Cretaceous formations trends southward but swings southeastward as the Alabama line is approached. The formations dip gently toward the west and southwest and pass under Tertiary sediments near the 89° meridian of longitude. The Tuscaloosa Group and Eutaw Formation, which comprise the basal sediments, contain irregularly bedded clays, sands, and gravels. In aggregate, they are slightly more than 500 feet thick in their outcrop area, but they thicken progressively southwestward and down the dip. The Selma Group overlies the Eutaw Formation and is more than 600 feet thick near the Alabama border. It consists chiefly of soft, more or less clayey and sandy limestone of a fine chalky texture, but northward near Tennessee the proportion of clay and sand increases greatly. Therefore, the low plain characterizing the outcrop of the chalk fades out before reaching Tennessee. The Ripley Formation of the Selma Group, composed of compact to loose sand, sandstone, sandy chalk, and clay, ranges in thickness from about 100 feet near the Alabama line to about 400 feet near the Tennessee line (Stephenson and others, 1928, p. 39).

Sand aquifers occur in the Tuscaloosa Group and the Eutaw Formation, and, to a lesser extent, in the Ripley Formation. Each formation contains clay beds that tend to confine water under artesian pressure, and the Selma Group contains chalky deposits that are relatively impermeable. Water from each permeable formation is used both in its outcrop area and west of it. In a general sense, the belt of utilized artesian water from any given Cretaceous aquifer is about 30 miles wide and lies slightly west or southwest of its outcrop area; at greater distances each aquifer commonly is more than a few hundred feet below the ground and either contains highly mineralized water or is buried beneath a shallower aquifer from which water can be developed more cheaply. Water from the Cretaceous aquifers normally is soft and low in dissolved mineral matter at depths no greater than 500 feet. There is a gradual increase in total dissolved solids downdip, and in southern Mississippi all water in Cretaceous beds is salty.

Tertiary System

As a result of the intensified exploration for oil in Mississippi since 1940, the Tertiary formations have received considerable study. The basal Tertiary formations crop out in arcuate bands west and south of the Cretaceous deposits, extending southward from the Tennessee line, and then southeastward into Alabama. The lowermost beds, belonging to the Clayton Formation of the Midway Group, consist of about 30 to 60 feet of hard limestone and greenish-gray glauconitic sandy marl (Stephenson and others, 1928, p. 44). Overlying the Clayton Formation is the Porters Creek Clay, consisting of about 500 feet of dark-gray clay. It represents an important and extensive aquiclude separating Tertiary and Cretaceous water. Overlying the Porters Creek Clay are interlayered sands and clays of the Wilcox Formation. In this formation beds of fine to coarse sand alternate with layers of clay and lignite. In aggregate, sands of the Wilcox Formation are important aquifers in the north-central, northwest, and central parts of the State (fig. 29). Eocene sediments above the Wilcox Formation have a broad outcrop belt in central and north-central Mississippi and extend as a thick wedge to the south and southwest; these deposits consist of sands, clays, and marls of the Claiborne and Jackson Groups. These deposits reach a thickness of several hundred feet in their outcrop areas. Beds of permeable sands are subordinate (Water for the Future in Mississippi, 1955, p. 16-17), but important sand aquifers are present. The southern one-fourth of the State is underlain by Miocene deposits that thicken greatly to the south. The basal formation of probable Miocene age is the Catahoula Sandstone. It consists of irregularly bedded deposits of sand, sandstone, clay, and gravel; the formation yields large supplies of water at Hattiesburg, Laurel, and in the surrounding areas. The overlying Pascagoula and Hattiesburg Formations of Miocene age are composed of blue and gray clay, sandy clay, and sand. Beds of sand are sufficiently thick and permeable to constitute important aquifers in much of the southern part of the State.

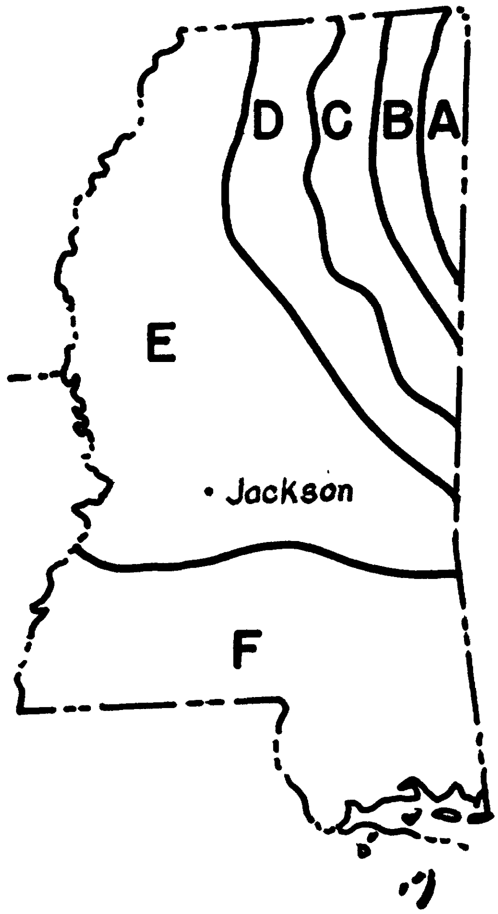


Figure 29. Map of Mississippi showing some hydrogeologic zones.

A. Outcrop and recharge areas of Tuscaloosa and Eutaw formations. Several permeable sand beds present.

B. Relatively impermeable compact marly chalk of the Selma group. Proportion of chalk decreases and sand increases near the Tennessee border. Artesian water from sands beneath chalk.

C. Pontotoc Ridge and Flatwoods area. Outcrop area of impermeable Porters Creek clay and Ripley formation. Ripley sands yield some water north of Oktibbeha County. As a whole the area is underlain by few permeable beds.

D. Area in which sands of the Wilcox Group crop out or are buried at shallow depths. Wilcox is principal aquifer.

E. Wilcox sands chief aquifer in north part of area. Sparta sand and sands of Cockfield formation chief aquifer in south part. Cretaceous water in this area and in area F is salty.

F. Chief aquifers are sands in the Catahoula Sandstone, and Pascagoula and Hattiesburg formations, which contain fresh water to depths ranging between 1000 and 2500 feet. Underlying aquifers contain salty water.

Quaternary System

The Quaternary deposits of Mississippi may be grouped as follows: (1) the alluvial material of the Yazoo basin and the thinner alluvial deposits bordering other streams, (2) loess and brown loam, which forms a mantle on the older formations on the upland bluffs that overlook the Mississippi River bottom, from the Tennessee State line in De Soto County to the Louisiana State line in Wilkinson County, and (3) Citronelle Formation and terrace deposits that border the Gulf Coast. The Citronelle is considered to be of Pliocene age by the U. S. Geological Survey (Matson and Berry, 1916, and Stringfield and LaMoreaux, 1957, p. 742). Some workers have considered it to be Pleistocene (Doering, 1956, p. 1893). It is included in the Quaternary here only for convenience of discussion.

The terrace deposits that border the coast in Jackson, Harrison, and Hancock Counties are underlain by deposits of loam, sand, and clay. They increase in thickness from only 20 or 30 feet along their northern border to 200 feet or more at the coast (Stephenson and others, 1928, p. 61). The Citronelle Formation rises from beneath the terrace deposits in the coastal counties and covers most of the area south of the latitude of Vicksburg and Jackson in the west and south of the latitude of Quitman in the east. The Citronelle consists largely of sand and gravel, although subordinate amounts of clay occur.

The loess forming the bluffs ranges in thickness from 50 to 100 feet, or more, but toward the east it becomes thinner and gradually disappears. The typical loess is gray to yellow and brown, massive, calcareous silt. Although the loess is porous and capable of absorbing water readily, it does not yield large amounts of water to wells.

The alluvial plain of the Mississippi River in northwestern Mississippi, about 6,600 square miles in extent, is underlain with an average thickness of 140 feet of alluvial materials (Brown, 1947, p. 9). The alluvium forms the Yazoo basin, which is a flat expanse of farm land crossed by natural levees along old stream channels. Many large-capacity wells (1,000 to 5,000 gallons per minute) produce water from the alluvial sands of the basin for irrigation and industrial cooling; many public and industrial supplies, however, are from the artesian sands of the underlying Eocene beds.

General Statement

Geology

The Coastal Plain sediments in northern Mississippi are influenced by the downwarping that attended the formation of the Mississippi embayment. Cretaceous and lower Tertiary sediments form the east limb of this trough in northern Mississippi as they dip westward toward the Mississippi River. Southern Mississippi forms a part of the Gulf Coast geosyncline, and contemporaneous subsidence and sedimentation has resulted in an immense thickening of the sediments toward the south. Thus, in southern Mississippi the sediments tend to dip southward and southwestward.

In the northern half of Mississippi the Cretaceous deposits dip to the west and southwest at the rate of about 20 to 35 feet per mile. Interbedded sands and clays and chalky deposits of the Selma Group are characteristic. In the southern half of the State, Cretaceous formations are covered by several thousand feet of Tertiary deposits; in aggregate, the Cretaceous deposits reach a thickness of more than 10,000 feet along the Louisiana border where they are composed chiefly of limestones, shales, and fine-grained sands.

Like the underlying Cretaceous formations, the formations of the Tertiary System dip toward the west in northwest Mississippi and toward the southwest in the southern part of the State. Where buried near the coast the sediments are chiefly clays, fine sands, and calcareous deposits.

In addition to the Mississippi embayment and the Gulf Coast geosyncline, which are major downwarps in the basement rocks that caused the westward and southward thickening of sediments, other structural features are noteworthy. A subsurface dome about 30 miles across occurs in the vicinity of Jackson; this dome brings Jurassic and Lower Cretaceous formations several thousand feet closer to the land surface than normally expected (Eardley, 1951, p. 552). A broad zone of downfaulting or downflexing occurs across Mississippi from about the 33d parallel on the west to the 32d parallel on the east (fig. 6). Murray (1957, p. 254) associates this belt of faulting with thickening and heavy loading of sediments southwestward and gulfward. At least 54 salt domes have been discovered in Mississippi. Sediments surrounding each dome have been arched upward, and the intrusion of salt has caused other complex local structures to develop. Other local structural features occur in southern Mississippi, but in the northeastern part of the State the sediments have been relatively undisturbed and tend to retain their homoclinal dip.

Basement rocks in Mississippi consist of shales, limestones, and sandstones of Paleozoic age. They dip under the Cretaceous deposits in northeastern Mississippi and become more deeply buried toward the west and south. Although most of the beds are dense and impermeable, some limestone and dolomite beds are sufficiently permeable to form reservoirs for oil.

Hydrogeology

Fresh artesian water from at least one bed of sand is available in all of Mississippi, except in a few square miles in the northeastern corner of the State. Interlayering of sand aquifers and clay and chalk aquicludes results in a choice of aquifers in most places, although the west and southwest inclination of the strata causes the youngest and uppermost aquifers to the most commonly developed (see fig. 29).

Ground water is so readily available and so widespread in occurrence that about 98 percent of the public water supplies in the State are from wells, and more than 85 percent of all water used for municipal, industrial, and irrigational purposes comes from wells. Although artesian water is used predominantly by municipalities and industries, shallow non-artesian water is used in great amounts for irrigation of rice in the Yazoo basin. During the growing season of rice in 1954, nearly 1,200 million gallons of shallow ground water were used per day in the Yazoo basin (Water for the Future in Mississippi, 1955, p. 15).

Brackish or salty water occurs at some depth in all the Coastal Plain except in the extreme north and northeastern parts of the State. Almost everywhere the water to a depth of 1,000 feet is fresh. Sands of the Wilcox Formation in the northwest and central parts of the State and sands of Miocene age in the south generally contain water that is relatively fresh to a depth of more than 2,000 feet. In spite of a relatively thick body of fresh water, more than 80 percent of the Coastal Plain sediments in southern Mississippi contain salty water.

It is difficult to make a general statement concerning the movement of ground water in Mississippi because of the complexities of such controlling factors as topography, structure, and withdrawal of water from wells. In the shallow water-table aquifers, the movement of water normally is toward the nearest stream valley. Even in the uppermost artesian aquifers there is some diversion of water from the normal downdip direction toward a stream valley. The deep aquifers that contain salty water have their water almost completely sealed in, and probably there is almost no deep subsurface movement. The artesian pressures of the deep aquifers are generally greater than pressures of the near-surface artesian aquifers. Flowing wells are common in the Yazoo basin and in other low areas.

LOUISIANA

Topography

Although a great variety of topographic conditions exists in Louisiana, they may be divided conveniently into two major groups. One group includes the low, rather flat areas underlain by relatively recent alluvium which lie below an elevation of 100 feet. The other group includes the rolling upland areas lying roughly between 100 and 400 feet above sea level.

The lowland area lying west of the Mississippi River in northern Louisiana is commonly referred to as the Tensas basin (Fenneman, 1938, p. 93). It is a flood plain extending from Arkansas to the Red River and is similar to the Yazoo basin of western Mississippi. The Atchafalaya floodway, below the mouth of the Red River, is a low alluvial plain composed of prairies and wooded plains between elevations of 5 and 50 feet above sea level. Farther south, along the coast, are marshes and lakes; the elevation along the coastal areas commonly is less than 20 feet above sea level. The water table in much of the low alluvial plains is within a few feet of the land surface.

Three moderately well-drained upland areas occur in Louisiana. They include the Pine Hills belt in the eastern part of the State north of the Mississippi delta, the low rolling hills between Ouachita and Red Rivers, and the broad interstream areas of western Louisiana. A close network of streams is actively eroding the characteristically sandy upland areas.

Jurassic and Cretaceous Systems

Sediments of Jurassic age, immediately overlying the Paleozoic basement rocks in Louisiana, are buried beneath about 5,000 feet of younger sediments in northern Louisiana and become more deeply buried southward. They are composed chiefly of shales, limestones, and evaporites. The evaporites consist of anhydrite, gypsum, and salt. Imlay (1940, p. 1) points out that the salt is variable in thickness throughout the area of its occurrence in southern Arkansas and northern Louisiana. Although not penetrated by drilling farther south, it is thought that this same bed or approximately the same bed or beds of salt is the "mother salt," which is the source of the salt forming the salt domes of the Gulf-coast region.

Cretaceous deposits, which overlie rocks of Jurassic age, are not exposed at the surface in Louisiana except in the vicinity of a few salt domes. The top of the Cretaceous is slightly less than 300 feet below the land surface in the northwestern part of the State near Shreveport, but near the Gulf of Mexico the Cretaceous deposits are buried beneath more than 500 feet on the Monroe uplift in northeastern Louisiana to an undetermined thickness--perhaps in excess of 8,000 feet near the gulf. The Cretaceous formations in aggregate contain sands, shales, limestones, and some beds of anhydrite.

Throughout Louisiana the water in Cretaceous and Jurassic sediments is salty and is not used. Although some permeable beds occur in northern Louisiana, where oil is produced from Cretaceous and Upper Jurassic sediments, the ratio of impermeable to permeable beds probably is great.

Tertiary System

During Tertiary time Louisiana was the depositional center for large amounts of deltaic sediments. Subsidence of the Gulf coast geosyncline and accelerated deposition that accompanied the subsidence led to an almost unparalleled accumulation of sediments in southern Louisiana. An idea of the great thickness of sediments can be had from logs of an oil well 22,570 feet deep, about 35 miles south of New Orleans which bottomed in sediments considered to be of Miocene age (Murray, 1957, p. 262); by subtracting a small thickness of

Quaternary sediments at the top of the section and by adding a few thousand feet of pre-Miocene sediments of Tertiary age not yet reached by wells but considered to be present, it appears that the total thickness of Tertiary sediments in southern Louisiana is more than 25,000 feet.

Tertiary sediments crop out in the northwestern part of the State, but elsewhere they are covered by Quaternary alluvial deposits. North of the 31st parallel the basal Tertiary sediments are represented by several hundred feet of the Porters Creek composed chiefly of clay. The Porters Creek is overlain by interlayered sands and clays of the Wilcox Group. Overlying deposits of the Wilcox Group is the Cane River Formation of the Claiborne Group, an extensive formation of clay, especially in northeastern Louisiana. Above the Cane River are interlayered sequences of sands, clays, and marls, representing several formations of the Tertiary. According to Murray (1952, p. 1184) the late Tertiary sequence "is characterized by great thickening of individual units and by rapid facies changes to thick, marine shales downdip." The early Tertiary deposits, including those of Paleocene and Eocene age, also show a change to thick shales and limestones coastward, although their character is not known near the Gulf Coast.

From a consideration of water supply, the Porters Creek Clay may be considered the basal formation in Louisiana because no fresh water occurs below it. The base of the fresh-water zone lies in different Tertiary formations at variable depths (Rollo, 1960), except near the Gulf Coast, where in most places all the Tertiary deposits contain salty water.

Quaternary System

Pleistocene and Recent sediments occur in the Tensas basin, in the Atchafalaya basin, and along the coastal margins of the State. These sediments are alluvial and deltaic deposits. They consist of alluvial deposits bordering stream valleys and belts of deposits bordering the present coast. Alternating sand and clay beds are common, and gravel deposits are prominent, especially in the principal stream valleys. No group name has been assigned the thick mass of sediments of Pleistocene age in southern Louisiana (Jones and others, 1956, p. 72). Near the axis of the Mississippi structural trough in St. Mary Parish (see fig. 6) the thickness of these sediments exceeds 3,000 feet (Fisk, 1944, fig. 70). The alluvial deposits of the river valleys in northern Louisiana are commonly within the range of 50 to 200 feet in thickness.

The Quaternary sands and gravels are important sources of ground water. The alluvium in the northern part of the State represents a highly productive aquifer containing hard water, which overlies several artesian sand aquifers of the Tertiary System that generally contain softer water. In southern Louisiana the sands and gravels are commonly very permeable and are extensively developed as a source of water. These deposits have been investigated in detail and are referred to as the Chicot reservoir (Jones and others, 1956, p. 214). According to Jones, water in this reservoir is soft and low in mineral matter in the recharge area of Beauregard and Allen Parishes but is considerably harder eastward and southward.

General Statement

Geology

Subsidence along the northern border of the Gulf of Mexico since Early Cretaceous time has resulted in very thick sedimentary deposits, especially in southern Louisiana. An effect of downwarping has been the gulfward thickening of beds, the older deposits dipping southward more steeply than the younger beds that overlie them. The almost universal gulfward dip of the beds is altered locally where stable areas developed, of which the most important are the Sabine uplift of northwestern Louisiana and the Monroe uplift of north-central Louisiana (Jones and others, 1956, p. 93). The magnitude of the downwarping of the Gulf coast geosyncline has somewhat obscured the effects of the Mississippi structural trough, the axis of which extends roughly northward through St. Landry Parish. Some formations tend to dip toward the axis of this trough, but the tendency is less marked than in States farther north in the embayment.

Downwarping and regional faulting are common in Louisiana. Many of the faulted beds are displaced downward to the south as a result of adjustments to subsidence in the Gulf Coast geosyncline. Murray (1957, p. 254) has termed them "down-to-basin" strike faults and calls attention to the relation of these fault zones to salt domes. Salt domes, as well as the major structural anomalies, occur in the northern and southern parts of the State; a broad belt extending eastward through the center of the State contains no known salt domes.

Because of the deep burial near the Gulf of Mexico, the character and thickness of Jurassic and Cretaceous sediments are not known in the southern part of Louisiana. Near the base of the Coastal Plain section is the Louann salt, which occurs at a depth of several thousand feet in parts of northern Louisiana; it may be the source bed from which the salt domes have migrated.

Almost all of the Tertiary and Quaternary sediments either are unconsolidated or poorly cemented. They are composed almost entirely of sands, clays, and gravels. It is generally recognized that the thickness of the Tertiary and Quaternary deposits beneath the coast of southern Louisiana is 30,000 feet or more.

Hydrogeology

Although at least one fresh-water aquifer is present almost everywhere in Louisiana, water in more than 95 percent of the total volume of sediments is much too salty for human use. All water below the base of the Tertiary is salty, and in the southern half of the State the fresh water map in Louisiana (Rollo, 1960) indicates great irregularities in the depth to salty water. For example, fresh water extends to a depth of more than 3,000 feet in parts of St. Tammany, Livingston, and East Baton Rouge Parishes; in adjacent parishes to the south fresh water extends to less than 1,000 feet, and even to less than 300 feet in the coastal areas in eastern Louisiana.

The coastward dipping and interlayering of predominantly sand and clay formations of Tertiary age in the northern part of the State result in several artesian aquifers (see fig. 30). In the southern half of the State thick beds of sand and gravel are common. "The sand and gravel

> aquifers of the Chicot reservoir of southwestern Louisiana are among the thickest, uniformly permeable granular water-bearing beds in the United States." (Jones and others, 1956, p. 216).

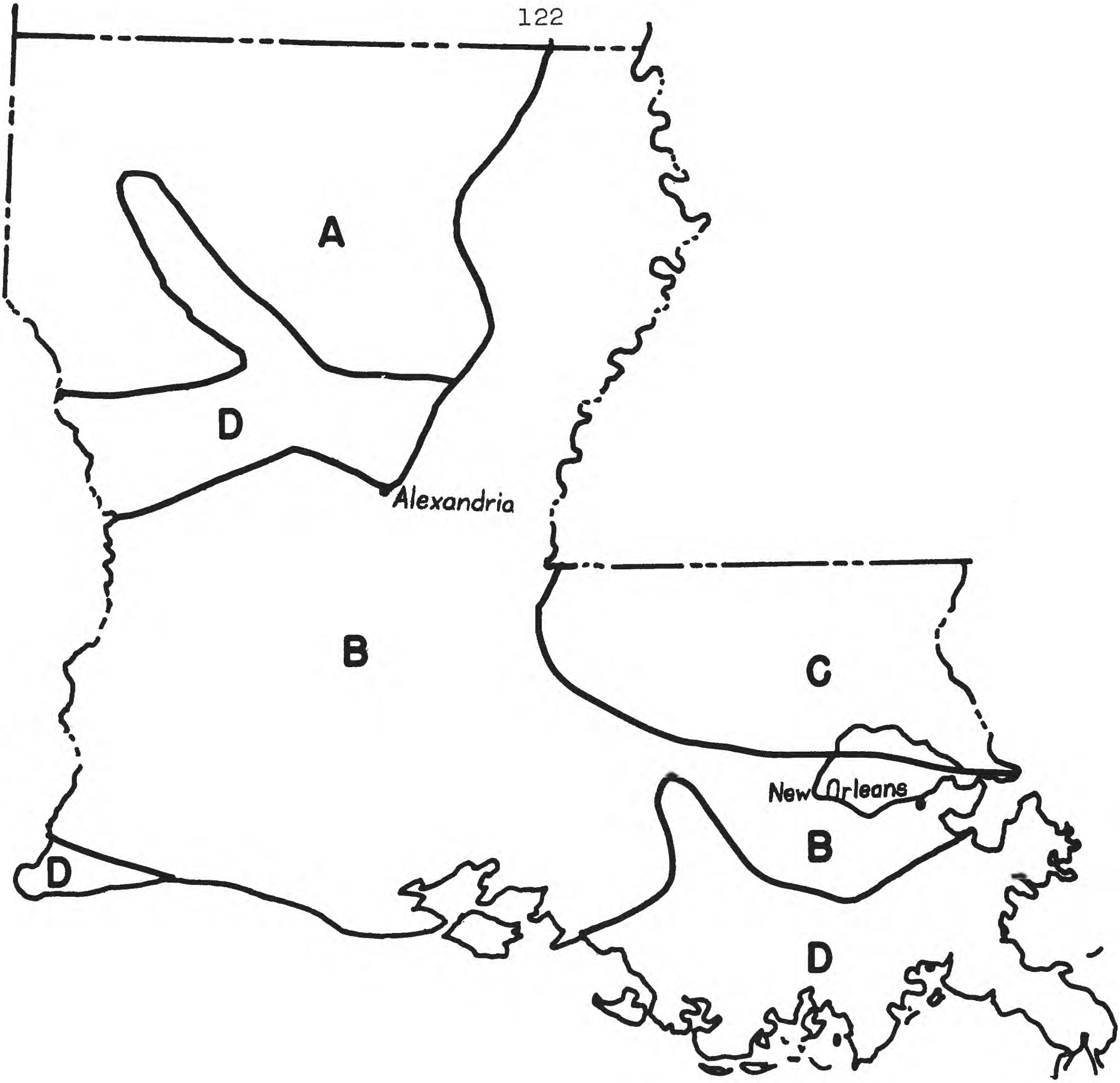


Figure 30. Map of Louisiana showing some hydrogeologic zones.

A. Interbedded sands and clays of Tertiary age. Artesian sands yield fresh water to depths ranging between 200 and 1100 feet.

B. Chiefly sands and gravels yielding moderate to large quantities of water.

C. Wells yield large quantities of soft water from sands and gravels. Fresh water extends to a depth of 3000 feet in much of area.

D. Only small to moderate quantities of fresh water available. Depth to salt water is less than 500 feet, commonly less than 200 feet.

Most of the circulation of ground water occurs in the surface and near-surface formations--in the water table and uppermost artesian aquifer. Water from precipitation moves downward to the water table. Much of the water from the water-table aquifer drains into streams or is lost through evapotranspiration in low, swampy ground. In general, the deep water is confined beneath rather impermeable beds. Structural features, such as faults, folds, and salt domes, have affected movement in the past. Jones (Jones and others, 1956, p. 201) points out that faults control the movement of ground water by "offsetting aquifers and abutting

> them against less permeable clay or shale or by bringing two different aquifers into hydraulic connection. Folds do so by upwarping beds and facilitating their exposure to recharge, as a result of accelerated local stream erosion, or by downwarping the aquifer and bringing the fresh water into contact with highly mineralized water in the downdip part of the aquifer."

ARKANSAS

Topography

The Coastal Plain of Arkansas represents the southeastern half of the State and may be subdivided topographically into uplands and lowlands. The uplands coincide with areas where Cretaceous and Tertiary sediments are exposed. They are characterized by irregular and rolling hills rising 100 to 200 feet above the flat-bottomed stream valleys which extend in various directions. Veatch (1906, p. 15) states that "the unequal hardness of the underlying

> beds has given rise to several transverse ranges of hills, which are more or less persistent for many miles and follow the general strike of the formations producing them."

This is especially true in the Cretaceous outcrop area which has a nearly eastward trend in the southwestern part of the State. The uplands south of the Arkansas River are broad and extensive, but northward only a thin but pronounced upland belt exists. Known as Crowleys Ridge, it extends almost continuously from Stoddard County, Mo., to Phillips County, Ark. The lowlands are broad, undulating plains underlain by alluvial and terrace materials. They are constructional plains representing partially filled valleys that were cut by the Mississippi River in its earlier courses, and by other streams flowing southward and eastward.

Jurassic System

The basal Coastal Plain sediments of Arkansas are of Jurassic age. They do not crop out and occur only at depth in a belt along the Louisiana State line. In aggregate they are composed of red shales, sandstones, limestones, anhydrite, and salt (Murray, 1952, p. 1180-1181). The most important feature of the sediments is the presence of the Louann salt, which may be the source of the salt plugs that have intruded and domed up overlying sediments in certain places.

Cretaceous System

The Cretaceous sediments are exposed in southwestern Arkansas only in a belt scarcely 80 miles long, which extends westward from the Ouachita River. The Lower Cretaceous Series lies on consolidated Paleozoic rocks and dips southward about 80 to 120 feet per mile (Counts and others, 1955, p. 8). The Lower Cretaceous deposits range in thickness from about 500 feet in the outcrop area to more than 6,000 feet near the Louisiana border. Upper Cretaceous formations dip to the southeast at a rate ranging from 40 to 80 feet per mile. They are buried beneath more than 1,500 feet of Tertiary sediments at the Louisiana border. The Cretaceous System in Arkansas is composed of about 15 formations, which are described by Dane (1929). They consist largely of unconsolidated sand, clay, and marl (Dane, 1929, p. XI) but include some beds of limestone, sandstone, and chalk.

In the Lower Cretaceous, sands of the Trinity Group furnish water to wells in central Sevier County and southern Howard County (Counts and others, 1955, p. 23). Farther south the water tends to be excessively mineralized. In the Upper Cretaceous, sands of the Tokio Formation and the Nacatoch Sand yield as much as 300 gallons of water per minute in some places several miles southeast of their outcrop areas. Two factors combine to make the Cretaceous sediments relatively poor aquifers in Arkansas; these are (1) the preponderance of relatively impermeable materials such as clay, chalk, marl, and fine sand, and (2) the presence of salty water at relatively short distances (10-25 miles) south and southeast of the outcrop areas of the sands.

Tertiary System

Several formations compose the Tertiary system of Arkansas, and some of the beds have extensive outcrop areas. They lie on Cretaceous deposits and conceal them, except in a small area along the inner margin of the Coastal Plain. They have a regional dip to the south and southeast. The basal part of the Tertiary is composed of clay and limestone of the Midway Group. The overlying Wilcox Group consists of interlayered sands and clays, some of the clays containing lignite. Above the Wilcox are several formations of middle and late Eocene age which are composed essentially of sands and clays.

The Midway deposits represent widespread confining beds that effectively separate water in the Eocene sands from that in underlying Cretaceous formations. The "1,400-foot" sand of Memphis extends into northeastern Arkansas (Baker, 1955, p. 4), where it yields large amounts of water of good quality. This sand unit is buried several hundred feet below sea level near the Louisiana line and contains salty water there. The Sparta sand and sand of the Cockfield Formation of the Claiborne Group yield large quantities of good water, although water in the Sparta is highly mineralized in parts of southern Arkansas (Baker, 1955, p. 5).

Quaternary System

During the latter part of the Tertiary and early part of the Quaternary Period Arkansas was elevated above sea level, and the Coastal Plain was entrenched by gulfward-flowing streams. "The bottom lands along the larger

> streams, the ancient Mississippi, Arkansas, Ouachita, and Red Rivers, were about 100 feet below the present flood plains." (Veatch, 1906, p. 47).

Subsequently, the rivers became less capable of carrying their loads to the sea, and a period of filling of lowland areas has followed. These deposits of Quaternary age occur in a large part of the Coastal Plain and in the valleys of the Saline, Ouachita, Red, and Arkansas Rivers (Baker, 1955, p. 5). They are commonly less than 200 feet thick and consist of clays, loams, sands, and gravels. There is a general downward gradation from fine silts or loams at the surface through "compact clays and fine sands to coarse sands and gravels at the base" (Stephenson and Crider, 1916, p. 115).

According to Baker (1955, p. 5), the Quaternary deposits are by far the most important sources of ground water in Arkansas as to both presently developed supplies and undeveloped reserves. The quality of water varies considerably from place to place; in general, the water is moderately hard and high in iron. Prior to the heavy withdrawal of water, chiefly for rice irrigation, the water level in the Quaternary deposits was generally within 25 feet of the land surface. However, the water level in much of Arkansas, Monroe, Prairie, and Lonoke Counties is now more than 50 feet below the ground surface (Baker, 1955, fig. 2).

General Statement

Geology

The basal Coastal Plain sediments, including the buried Jurassic and Lower Cretaceous rocks and the outcrop belt of Lower Cretaceous sediments in the southwestern part of the State, dip southward toward the Gulf. The Upper Cretaceous and the Tertiary sediments were influenced to a great extent by the downwarping in the Mississippi embayment, and they have a more general southeastward dip than the underlying sediments (fig. 7). The Quaternary deposits occur as a thin surface veneer bordering wide expanses of the major rivers.

Although the character of sediments varies considerably from place to place and also with time of deposition, some general comments may be made. The deep-lying Jurassic formations in the southern part of the State contain shales, sandstones, limestones, and salt beds. Lower Cretaceous formations contain sands, shales, limestones, and some anhydrite. Upper Cretaceous sediments consist of sands, clays, shales, and limestones. The Tertiary formations are composed chiefly of beds of sand and clay, the basal part consisting chiefly of clay of the Midway Group. The

Quaternary deposits are not as well stratified as the underlying marine sediments; they commonly consist, in descending order, of silt and fine sand, coarse sand, and gravel.

The south and southeast homoclinal tendencies prevail in the Coastal Plain sediments in Arkansas, but there are many other significant structural features. Only a small proportion of beds in the subsurface extend to the surface. An increase in number of beds and in thickness of individual beds downdip and to the south is related to downwarping of the Gulf Coast geosyncline. The pre-coastal basement rocks lie at a depth of more than 10,000 feet in the extreme southern part of the State; extending eastward through this area is the great coastal zone of downfaulting (Murray, 1957, fig. 5). In fact, the southern and eastern boundaries of the State are marked by unusual conditions. The Monroe uplift along the southeastern boundary was an uplifted area during much of the Cretaceous (Murray, 1957, figs. 8, 9, 10, and 11) and, to a lesser extent, during parts of the Tertiary. The Desha basin (Murray, 1957, p. 260-263), which lies in and around Desha County, appears to be a slight irregularity in the downwarped Mississippi embayment; it contains as much as 4,000 feet of Tertiary sands and clays, which is more than that in the surrounding area.

Hydrogeology

The depth to the water table varies greatly in the Coastal Plain of Arkansas. It lies at or near the surface in low ground near many streams, but beneath elevated ridges and interstream areas and in areas where water is withdrawn from shallow aquifers, it lies as much as 50 to 75 feet below the surface. The water table lies in the Quaternary deposits in more than half of the Coastal Plain, but it is in the Cretaceous and Tertiary deposits in the interstream areas near the southern part of the State. Water in the Quaternary sands and gravels is confined to a great extent beneath the prevailing surficial impermeable clays (Klein and other, 1950, p. 25), and is more generally under artesian pressure. Downward percolation of water from precipitation through clay is slow, a condition that has contributed to a general decline of water levels in the Grand Prairie region where well water is used for irrigation of rice (Baker, 1955, p. 7).

At least one fresh-water and one or more deeper salt-water artesian aquifers occur in most of the Coastal Plain (see fig. 31). In the northeastern counties the 1,400-foot sand at Memphis is an important aquifer. It occurs at a depth of about 1,000 feet and contains water of good quality (Baker, 1955, p. 4); farther south it is more deeply buried and contains salty water. The Cockfield Formation contains fresh artesian water in the Grand Prairie region, and the Sparta Sand is an important source of ground water in south-central Arkansas. Along the Louisiana border the fresh- and salt-water boundary lies in the Sparta Sand, ranging in depth below the land surface from about 300 to more than 800 feet. The Midway Group extends beneath eastern and southern Arkansas and tends to separate the underlying salty Cretaceous water from water in the Tertiary beds, most of which is fresh except in the extreme southern part of the State. Water from the Cretaceous formations is used in the outcrop belt in southwestern Arkansas and for several miles downdip and southeastward. Farther to the south and east the water is highly mineralized.

The streams receive drainage from the uppermost aquifer that they incise. Data are not available to indicate the direction and rate of flow in the Tertiary and Cretaceous beds. Some water from the near-surface beds leaks upward into Quaternary deposits, and doubtless there are many places where water does not move southward and southeastward in a normal downdip direction.

TENNESSEE, KENTUCKY, AND MISSOURI

Topography

Coastal Plain sediments of the Mississippi embayment extend into southeastern Missouri, the southern tip of Illinois, southwestern Kentucky, and the western part of Tennessee. The topography of the Coastal Plain in these States varies from gently rolling or hilly surfaces in the interstream areas to flat flood plains along the main rivers and their tributaries. The flat alluvial plain is mainly west of the Mississippi River in Missouri, where only a few upland remnants rise a few tens of feet above the plain. East of the Mississippi River, bluffs rise from 100 to 180 feet above the flood plain. "These bluffs are cut by

> narrow ravines, or 'gulfs,' as they are called locally, into steep-sided hills whose upper portions are largely vented from weathering back into gentler slopes by a capping of 20 to 80 feet of loess . . ." (Glenn, 1906, p. 18).

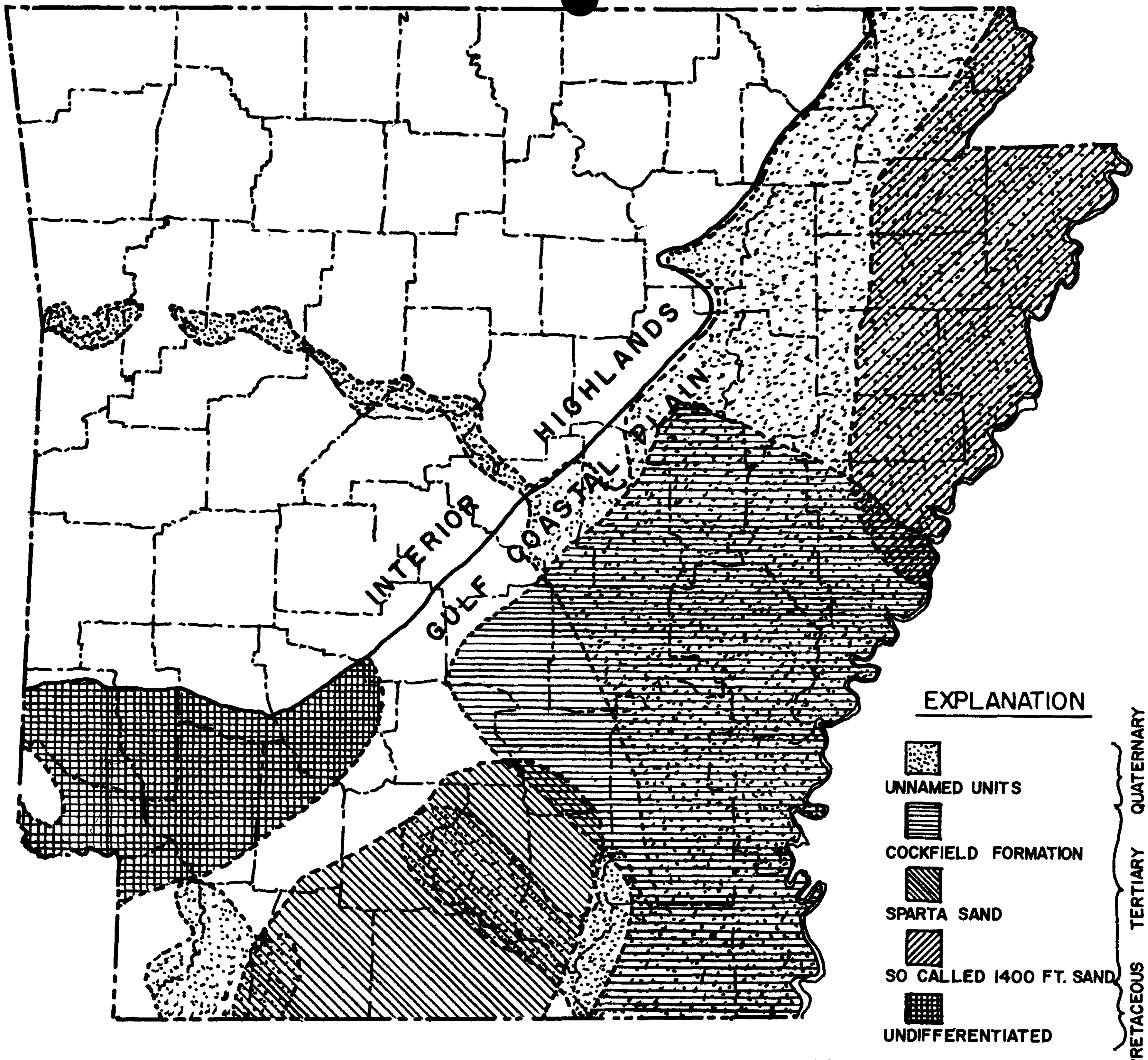


Figure 31. Approximate productive areas of the most important aquifers in the Coastal Plain of Arkansas (Baker, 1955).

The upland area between the Mississippi and Tennessee Rivers is dissected by many small tributary streams. The major drainage divide lies relatively close to the Tennessee River. Thus only short and small streams flow eastward to the Tennessee River.

Cretaceous System

Upper Cretaceous formations form the basal Coastal Plain sediments in the upper part of the Mississippi embayment. The Upper Cretaceous formations in the Missouri part of the Mississippi embayment are the Owl Creek Formation and McNairy Sand; in the Kentucky part, the McNairy Sand and the Tuscaloosa Formation; and in the Tennessee part, the Owl Creek Formation, the Ripley Formation (McNairy Sand Member and Coon Creek Tongue), the Selma Clay, the Coffee Sand, the Eutaw Formation, and the Tuscaloosa Formation. The Selma Group has not been recognized in Tennessee, Kentucky, and Missouri. However, the term "Selma" is used in this report to include clays and subordinate materials of Selma age. They lie below a depth of 2,000 feet in the center of the basin several miles west of Memphis (Stearns and Armstrong, 1955, pl. 14), but some of the Cretaceous beds rise almost to the land surface around the western rim of the embayment. The Eutaw Formation does not extend into Kentucky and Missouri. In southwestern Tennessee, it is composed chiefly of alternating layers of sand and clay, carbonaceous material being abundant (Wells, 1933, p. 71). Equivalents of the Selma Group range from about 200 to 400 feet in thickness in southwestern Tennessee, but they thin northward and extend only slightly into Missouri and not at all into Kentucky; the sediments of the Selma Group equivalents are chiefly clay and chalk. The uppermost Cretaceous deposits are represented in Missouri by the Owl Creek Formation, in Kentucky by the McNairy Sand, and in Tennessee by the Owl Creek Formation and the Ripley Formation.

Water from the Cretaceous deposits is used widely in the upper part of the embayment. The McNairy is an important aquifer in southeast Missouri, southwest Kentucky, and in most of the Coastal Plain of Tennessee west of its area of outcrop. The water from the McNairy generally contains less than 100 ppm of total dissolved solids, although in the vicinity of Memphis where the top of the McNairy Sand Member of the Ripley Formation lies below 2,000 feet the mineral content reaches about 1,000 ppm (Wells, 1933, p. 85). The remainder of the Ripley Formation and the underlying clay and chalk of Selma age are relatively impermeable. The Eutaw Formation contains a few water-bearing beds of sand, but water from them is used only in the Cretaceous outcrop area.

Tertiary System

Tertiary sediments filled the former embayment or basin to about its present surface level, and only a thin veneer of Pleistocene and Recent sediments now conceal the uppermost Tertiary formation in this part of the Coastal Plain (fig. 3). Clay is predominant in the basal part, especially in Tennessee where the Porters Creek Clay of Paleocene age is an extensive, impermeable formation more than 200 feet thick (Schneider and Blankenship, 1950). In the Wilcox group, which represents the middle section of the Tertiary, is the "1,400-foot" sand of Memphis. This sandy zone, from which large quantities of water are withdrawn at Memphis (Schneider, 1947, p. 631), extends for considerable distances and occurs in Arkansas, Missouri, Tennessee, and Mississippi. The "1,400-foot" sand rises to higher elevations eastward from Memphis and presumably reaches the land surface in Hardeman, Madison, Carroll, and Henry Counties in Tennessee. A series of clay beds separates the "1,400-foot" and "500-foot" sands at Memphis. The "500-foot" sand presumably extends northward into Kentucky and Missouri. At any rate, sands that appear to be equivalent in age to those at Memphis extend into Kentucky and Missouri. It is overlain in Tennessee by clays considered to be of late Eocene age.

All water in the Tertiary deposits in Tennessee, Kentucky, and Missouri is fresh and relatively low in dissolved mineral matter. The "1,400-foot" sand and the "500-foot" sand of Memphis are excellent artesian aquifers that are extensively used. Recharge to these aquifers is largely through precipitation on the Tertiary outcrop areas in Tennessee and through leakage from overlying and underlying beds that are poorly permeable rather than impermeable.

Quaternary System

Deposits of Pleistocene and Recent age form a thin veneer over the older sediments. They include discontinuous patches of sand and gravel, loess deposits, and alluvial deposits that cover the lowland areas. The loess extends

20 to 30 miles eastward from the edge of the bluffs overlooking the Mississippi River in Tennessee and Kentucky (Glenn, 1906, p. 49). It is commonly 50 to 75 feet thick in the bluffs but thins eastward. The loess also is widespread in Missouri and blankets Crowleys Ridge (Grohskopf, 1955, p. 24). Alluvial, or flood-plain, deposits cover all the lowland areas, covering almost all of the Coastal Plain of Missouri and the low areas between the Mississippi River and the bluffs in Tennessee and Kentucky. They are composed of clays, sands, and gravels. There is a tendency for the sands and gravels to lie at or near the base of the alluvial deposits. In many places the alluvial deposits are between 100 and 200 feet thick.

The water table lies in the alluvium. In many places it lies in relatively impermeable clays, resulting in semiartesian conditions for the water in the underlying sands and gravels. Wells yielding 250 to 500 gallons per minute are not uncommon from the alluvial deposits in Missouri (Grohskopf, 1955, p. 33), but the water generally is high in iron content.

General Statement

Geology

The Coastal Plain sediments of southeast Missouri, the southern tip of Illinois, southwest Kentucky, and western Tennessee were deposited in the northern end of a gently subsiding sedimentary trough, known as the Mississippi embayment. Therefore, the Upper Cretaceous and Tertiary sediments that fill this part of the trough dip toward the center, which nearly coincides with the Mississippi River. The beds dip westward in Tennessee, southwestward in Kentucky, southward in the southern tip of Illinois, and southeastward in Missouri. In spite of the concentric structure, outcropping formations do not extend around the axis of the embayment. For example, the north-trending Cretaceous outcrop belt in Tennessee extends into Kentucky and southern Illinois but thins to the northwest and west; in Missouri the Cretaceous formations are concealed by overlapping Tertiary and Quaternary deposits. The dips toward the center of the basin range from about 25 to 40 feet per mile, the deeper-lying Cretaceous beds having a slightly steeper dip than the Tertiary beds. The basin is open southward, and there is an over-all component of dip toward the Gulf.

The sediments at Memphis are about 3,000 feet thick, whereas farther northward along the axis of the basin in southwest Kentucky they are about 2,000 feet thick (fig. 7). Consolidated sedimentary rocks of Paleozoic age underlie the Coastal Plain sediments. Some degree of faulting and subsidence since early Cretaceous time is indicated by the basin-filling sediments. The New Madrid earthquake of 1812 suggests that movement in the underlying Paleozoic rocks may not yet be ended.

Two features of the Coastal Plain sediments in the upper Mississippi embayment are noteworthy. These are the relatively loose and unconsolidated nature of the sediments and the preponderance of sands and clays. Calcareous material is rare, being confined chiefly to the chalky and marly beds of Selma age and to thin limestone beds of the Clayton Formation near the base of the Tertiary deposits.

Hydrogeology

The water table lies in loose sand or clay, commonly between a depth of 10 to 25 feet beneath the low alluvial plain, and commonly between a depth of 15 to 50 feet beneath upland areas. Well points and other types of shallow wells draw water from the water-table aquifers. Some of the shallow ground water is used for irrigation and some for rural domestic supply.

Several artesian sand aquifers separated by zones of clay occur below the water-table aquifer. Near the center of the embayment sands of Tertiary age furnish much water. These include the "500-foot" sand and the "1,400-foot" sand of Memphis. The "1,400-foot" sand, or its approximate equivalent, furnishes water to a large area in western Tennessee, southeastern Missouri, and southwestern Kentucky. Water from these aquifers is low in total dissolved solids. Even water in the Cretaceous beds below 2,300 feet at Memphis contains very little chloride, and perhaps all Coastal-Plain water in the three States is fresh.

The natural movement of water in the artesian aquifers is known only in a general sense. The Cretaceous and Tertiary formations crop out in relatively high areas between the Tennessee and Mississippi River. It is thought that in Tennessee water moves through the sand beds from the outcrop areas westward toward the Mississippi River. However, the river is reported to be entrenched in Tertiary clays (Elliott Cushing, oral communication, 1960), and thick clay beds separate the major sand aquifers. Even though the Mississippi River appears to be sealed from the artesian sands, some artesian water probably is leaking through clay beds into the River. As the basin is open and somewhat depressed toward the south, doubtless there is a southward component of movement of artesian water from the upper part of the embayment. The heavy withdrawal of water from wells at Memphis has caused water from the "500-foot" sand and the "1,400-foot" sand to flow more rapidly toward Memphis from the surrounding areas.

TEXAS

Topography

The Coastal Plain of Texas is a broad region extending inland from the Gulf of Mexico for distances ranging from about 150 to 400 miles. The gulfward slope of the land surface averages less than 5 feet per mile. The regional slope of the underlying beds of clay, sand, and limestone is from 10 to more than 200 feet per mile. Thus, the somewhat bevelled edges of different formations, representing outcrop areas, occur as bands that extend northeastward and roughly parallel the coast line. At their outcrop areas the formations differ as to the extent and trend of exposure, as to the type of materials, and as to degree of consolidation. Hence, the materials resist erosion and dissection unequally (Johnson, 1931, p. 47). Thus, there is a variety of topographic features that may be related to geologic formations. The following table was revised from Fenneman (1938, p. 104). (See also fig. 1)

Formations of the Texas Coastal Plain and their Topographic Relations

Formation	Belts
Pleistocene	
Beaumont Clay	Pleistocene terraces
Lissie Formation	Pleistocene terraces
Pliocene	
Willis Sand	

(continued)

Formation	Belts
Miocene	
Lagarto Clay	
Oakville Sandstone	Kisatchie cuesta
Catahoula Tuff	
Oligocene	
Frio Clay	Lowland
Eocene	
Jackson Group	Lowland
Claiborne Group	Nacogdoches cuesta
Wilcox	Margin of E. Texas Timber Belt
Paleocene	
Midway Group	Black Prairie (less typical)
Cretaceous	
Navarro Group	Black Prairie (less typical)
Taylor marl	Black Prairie (typical)
Austin chalk	White Rock escarpment and Black Prairie
Eagle Ford shale	Eagle Ford Black Prairie
Woodbine Formation	Eastern Cross Timbers
Washita Group and Fredericksburg Group	Grand Prairie and Edwards escarpment
Trinity Group	Western Cross Timbers

For a distance of 50 to 75 miles inland from the coast the land is rather flat and generally lies below an altitude of 100 feet. This land was submerged at one or more times during the Pleistocene Epoch, but the withdrawal of the sea to its present position left a low plain crossed by streams flowing to the Gulf. Fine-textured clayey soils on which tall grasses are common tend to characterize this area, which is known as the Coastal Prairies (Johnson, 1931, p. 70).

From the low coastal prairies the land rises to elevations of several hundred feet near the inner margin of the Coastal Plain. Two distinctive types of topography are noted in the interior zone--elongated lowlands and intervening ridges. The outcropping beds show different degrees of resistance to the agents of erosion, some sandstone and hard limestone beds standing as ridges above the lowland plains. To a great extent the ridges tend to be escarpments or cuestas facing inland and overlooking prairies of relatively low relief. All the prairies except the coastal prairies are the result of erosion on relatively non-resistant materials such as marls and limey clays.

The Coastal Plain has been incised by gulfward-flowing streams. The Rio Grande, Nueces, Guadalupe, Colorado, and Brazos Rivers rise in regions to the north and west, but other streams drain only the Coastal Plain. Both precipitation and runoff as streamflow are greater east of the 97th meridian than west of it. In the subhumid region of southwestern Texas some streams, including the Nueces and Frio Rivers, cease flowing at times along some stretches as river water drains downward to a lower-lying water table.

Jurassic System

Sediments of Jurassic age do not crop out and, in fact, do not occur within 5,000 feet of the land surface in the Coastal Plain of Texas (Colle and others, 1952, p. 1196). Yet they represent the basal part of much of the Coastal Plain. The northern extremities of Jurassic deposits contain red, coarse clastic materials, but gulfward and downdip thick deposits of limestone, dolomite, and evaporites are characteristic (Murray, 1957, p. 259). Thick beds of salt, probably of Jurassic age, underlie northeastern Texas. The character of Jurassic sediments beneath the coastal areas is now known.

Cretaceous System

Both Lower and Upper Cretaceous formations occupy thick sections of the Coastal Plain sedimentary sequence and both have extensive outcrop areas. Some Lower Cretaceous sedimentary rocks underlie higher plains northwest of the Coastal Plain, but they are not considered in this discussion. The outcrop area of Lower Cretaceous deposits north of the Brazos River is included in the Coastal Plain. The Lower Cretaceous deposits generally are referred to as the Comanche Series and include, in descending order, the Washita, Fredericksburg, and Trinity Groups; each of the groups contains several formations. The Upper Cretaceous deposits are known as the Gulf Series, and include, in descending order, the Navarro Group, Taylor Marl, Austin Chalk, Eagle Ford Shale, and Woodbine Formation.

The outcrop belt of the Gulf Series extends eastward from the Rio Grande to the vicinity of Guadalupe County, where it turns northeastward and widens toward the Oklahoma and Arkansas boundaries. Formations of both the Comanche and Gulf Series dip coastward at an angle slightly greater than that of the land surface and are buried by successively younger formations toward the coast. Some of the formations are several hundred feet thick in their outcrop areas, and there is a tendency for them to thicken toward the coast beneath younger sediments. A great variety of sediments compose the Cretaceous System of Texas. Sands, clays, marls, and limestones are predominant, and some gypsiferous sediments occur in the western part of the Coastal Plain. A coastward change in character of sediments, especially toward finer materials, is characteristic.

In southern Texas water from the Cretaceous System furnishes large potable water supplies from the Edwards and associated limestone formations in a belt about 300 miles long extending eastward from near the Rio Grande and southward from the Balcones escarpment for 10 to 20 miles (Broadhurst and others, 1950, p. 5). Coastward from this zone all the Cretaceous water is highly mineralized. In the northeastern part of the Coastal Plain sands of the Trinity Group and the Woodbine Formation are important aquifers. Sediments of the Austin Chalk and the Navarro Group consist chiefly of clay, marl, and chalk. They are relatively impermeable, and the belt of their outcrops is marked by relatively low-yielding wells (fig. 32).

Tertiary System

Tertiary formations are exposed in a northeast-trending belt south and east of the Cretaceous outcrop belt. The Tertiary sediments dip generally toward the coast and, in aggregate, represent an exceptionally thick sedimentary section. The following units, in ascending order, have been recognized: Midway, Wilcox, Claiborne, and Jackson Groups, Frio Clay, Catahoula Tuff, Oakville Sandstone, Lagarto Clay, Goliad Sand, and the Willis Sand. The basal Tertiary sediments of the Midway Group are chiefly shales, chalks, and marls. The Wilcox and Claiborne Groups contain a variety of shales and sands. In fact, sands and shales are characteristic of all the Tertiary sediments. Most formations generally retain their surface lithologic character to a depth as great as they have been drilled, except that some of the sandy formations become finer grained toward the coast (Colle and others, 1952, p. 1195).

Almost all aquifers of the Tertiary System in Texas consist of loose sands. The Wilcox and Claiborne Groups contain widespread aquifers with interbedded clays, but other Tertiary sands also yield much water (Sundstrom and others, 1948, p. 1; Broadhurst and others, 1950, p. 1). Characteristically impermeable materials compose the Midway Group and, to a lesser extent, some beds of late Eocene and Miocene age in southern Texas. Several Tertiary formations are important producers of oil.

Quaternary System

The Quaternary deposits of Texas consist of the Lissie Formation, the Beaumont clay, and alluvium. The Lissie Formation and Beaumont clay may be considered as the uppermost Coastal Plain deposits, extending in a belt along the coast and ranging in width from about 40 to 100 miles. Each formation reaches a thickness of more than 1,000 feet in places near the coast. Considered together, they are composed of assorted deposits of sands and clays, with subordinate amounts of shell beds, gravels, and carbonaceous materials. Caliche occurs in the southwestern part of Texas. Alluvium is relatively thin except near the present coast line and in and near the lower reaches of the larger streams such as the Brazos and Rio Grande.

The water table lies in the Quaternary deposits on the coastal prairies. Where the deposits are thick, water in the deep-lying sands is confined under pressure. Some of the sands, together with the Willis and Goliad Sands, furnish large supplies of water. Wood (1956, pl. 20) shows by means of profiles that the fresh- and salt-water contact lies in the Quaternary deposits in the coastal region and that this contact rises to the land surface near the coast.

General Statement

Geology

The Coastal Plain of Texas is underlain by an immense wedge of sediments that thicken coastward, and extend beneath the Continental Shelf and Gulf of Mexico. The simple homoclinal structure so characteristic of the Atlantic Coastal Plain and parts of the Gulf Coastal Plain is not typical in Texas. The major structural features have been discussed by Sellards and Baker (1934) and summarized by

Murray (1957, p. 254-258). Murray points out that structural anomalies appear to result from isostatic adjustment to thick sedimentary accumulations, from emplacements of large igneous or salt masses, or from movements related to warping or displacement of basement rocks.

The coastward dip of the formations is modified by four major structural features, two appearing as depressed areas and two as uplifted or arched areas. The Rio Grande embayment and the East Texas embayment (fig. 6) have complex histories as downwarped basins (Sellards and Baker, 1934, p. 39-44) that are separated by pre-coastal plain rocks of the Llano region. A southeastern and subsurface extension of the Llano uplift is the San Marcos arch. Sellards and Baker (1934, p. 44) report that it "was not an arch of

> slight width but was rather a broad positive element resulting in the thinning especially of the Upper Cretaceous formations in several counties including Travis, Hays, Comal, Caldwell, Guadalupe, Bexar, and Medina."

In easternmost Texas (fig. 6) is a large, gentle dome known as the Sabine uplift; some doming started in Cretaceous time, but upward movement during middle or late Tertiary time is reflected in the outcropping of lower Eocene beds nearer to the coast than is normal.

Gravity faulting and downwarping are widespread features of the Coastal Plain of Texas. The Balcones fault zone lies along the inner margin of the Coastal Plain and consists chiefly of "down-to-the-coast (down-to-basin) faults, with complementary faults occasionally forming grabens" (Murray, 1957, p. 254). The Luling and Mexia fault systems are similar and locally contain grabens, or down-faulted blocks. Extending to the Gulf are northeast-trending zones of gravity faulting or down-flexing. On the seaward side, where older strata are downwarped steeply, are centers of considerable deposition (Murray, 1957, p. 254). The younger sediments thicken greatly coastward of these downfaulted or downwarped zones.

The salt domes of the Coastal Plain in Texas appear to trend with the regional fault systems, suggesting that "the

> domes may have been positioned at depth by the faults and that they grew in these zones in association with (1) weaknesses created by the faulting, and (2) great increases in sedimentary thicknesses,

local or regional, which occur across many of the fault zones." (Murray, 1957, p. 254).

The salt domes were derived from a deep-lying thick bed or beds of salt, but in most places the bedded salt has not been reached by drilling.

A result of the down-to-coast faulting and downflexing is the great accumulation of sediments near the Texas coast, generally considered to be a minimum of 30,000 feet. The volume of sediments beneath the land area of 90,000 square miles of the Coastal Plain of Texas has been calculated as 453,000 cubic miles (Colle and others, 1952, p. 1193). With such great thickening coastward, and downdip, it is to be expected that only a small proportion of beds in the deep subsurface extend to surface outcrop areas. In fact, the existence in the subsurface of beds not present on the outcrop is a significant feature of the geology (Colle and others, 1952, p. 1195).

There is some variation in character of sediments. Where the beds crop out or are covered by no more than a few thousand feet of sediments they consist chiefly of sands, clays, shales, marls, and limestone. Downdip, and with great depth, coarse sand beds become rare and the proportion of shale and limestone increases.

Hydrogeology

Ground-water conditions vary greatly in the Coastal Plain of Texas, and it is beyond the scope of this report to comment on the complex details of each locality. U. S. Geological Survey Water-Supply Papers 1047 (Sundstrom and others, 1948) and 1070 (Broadhurst and others, 1950) discuss the public ground-water supplies in eastern and southern Texas, respectively, and refer to more detailed published reports and unpublished open-file reports.

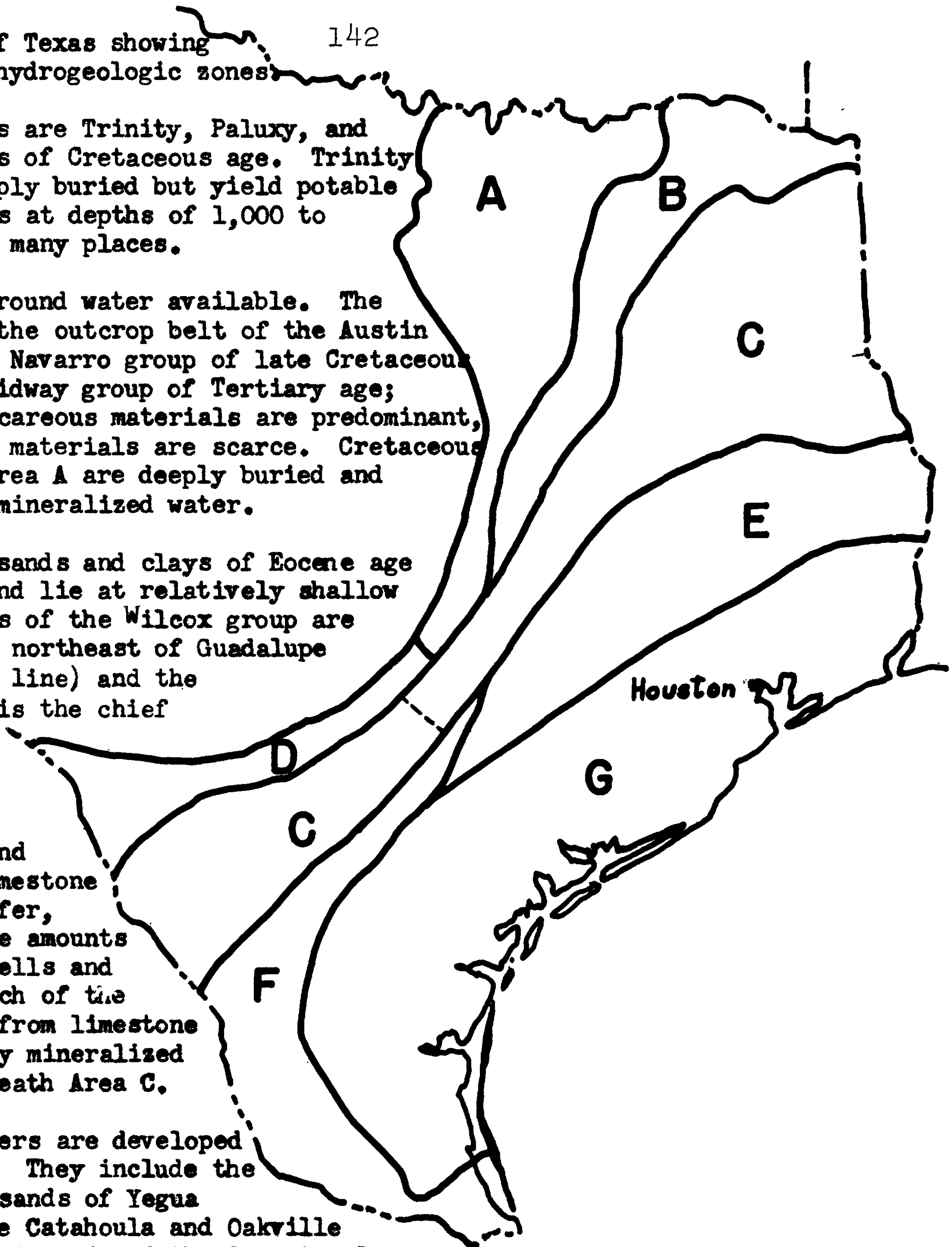
Almost all of the water is under artesian conditions, occurring in beds which dip southeastward beneath younger formations to increasingly greater depths. The overlying water-table body extends across many diverse formations and topographic features. It is locally discontinuous across some escarpments and other topographic breaks.

Outcrop areas and moderately shallow subsurface parts of formations contain fresh water. In aggregate, the fresh-water body extends somewhat lens-shaped in cross section toward the Gulf, pinching out along the western margin where the sediments thin to a featheredge and thinning near the coast, where the salt-water zone rises to about sea level (fig. 18). The fresh-water zone tends to be thickest in the interior, especially where the buried, thick, permeable beds extend to broad and elevated outcrop areas. In the Houston area fresh water extends to a depth of more than 2,000 feet (Broadhurst, 1953, p. 60). At Garland, in Dallas County, sands of the Trinity Group of Cretaceous age yield water that is satisfactory for public supply at a depth of 3,633 feet (Sundstrom and others, 1948, p. 4). From cross sections showing the quantity of fresh ground water in transient storage, Wood (1956, p. 31) indicates that beneath the coastal counties of Calhoun and Nueces the fresh-water zone is extremely thin. As is the case in other parts of the Gulf and Atlantic Coastal Plain, the fresh-water zone of each aquifer or formation is restricted to its outcrop area and a belt no greater than a few tens of miles downdip and coastward from its outcrop area (fig. 32).

The amount of water in natural storage underground in Texas is enormous. Water in the water-table and uppermost artesian aquifers is in "transient storage," as it is moving toward areas or points of discharge. The deeper water is almost stationary, or is moving at imperceptibly slow rates because it has no good avenues for escape. The withdrawal of water from wells has disturbed the natural state of dynamic equilibrium in the vicinity of centers of withdrawal. Withdrawals are attended by reduction in hydrostatic pressure, extending to relatively great distances in the artesian systems; therefore, the development of ground-water supplies is altering the natural movement of water in Texas more than is generally believed.

The contrast in climate between the northeastern and southwestern parts of the Coastal Plain of Texas is reflected in the behavior of the water table and of stream discharge. In eastern Texas, where the annual precipitation averages more than 40 inches a year, the water table stays at a relatively high stage beneath the interstream areas. Water moves out of the water-table aquifer into the stream valleys and is lost by evapotranspiration or to furnish perennial flow of the streams. During parts of the year the aquifer is over-full and there is an excess of water, insofar as the needs for recharge are concerned. In contrast is southern Texas near the Mexican border, where the annual precipitation averages less than 30 inches a year and where the water table normally is depressed to low levels. In this case, all water that infiltrates downward through surface materials

Figure 32. Map of Texas showing some hydrogeologic zones.



A. Chief aquifers are Trinity, Paluxy, and Woodbine sands of Cretaceous age. Trinity sands are deeply buried but yield potable water supplies at depths of 1,000 to 2,000 feet in many places.

B. Very little ground water available. The area lies in the outcrop belt of the Austin chalk and the Navarro group of late Cretaceous age and the Midway group of Tertiary age; clays and calcareous materials are predominant, and permeable materials are scarce. Cretaceous aquifers of Area A are deeply buried and contain only mineralized water.

C. Interlayered sands and clays of Eocene age are exposed and lie at relatively shallow depths. Sands of the Wilcox group are good aquifers northeast of Guadalupe County(dashed line) and the Carrizo sand is the chief aquifer southwestward in this area.

D. The Edwards and associated limestone is chief aquifer, yielding large amounts of water to wells and springs in much of the area. Water from limestone becomes highly mineralized southward beneath Area C.

E. Several aquifers are developed in this area. They include the Sparta sand, sands of Yegua formation, the Catahoula and Oakville sandstones, and sands of the Lagarta clay.

F. Much of area is underlain by clay and fine sands of either late Eocene or Miocene age. Very little potable ground water available.

G. Several permeable beds of sand are generally widespread from Quaternary and uppermost Tertiary formations. Abundant supplies exist in many places. Near the coast the fresh-water zone is extremely thin, but inland it is commonly several hundred feet thick.

(Information adapted from Sundstrom and others (1948) and Broadhurst and others (1950)).

is accepted by the aquifer. In addition, the water table in many places lies below the base of streams, resulting in movement of water from the stream to the water-table aquifer. Much of the streamflow in the subhumid part of southern Texas is derived from discharge of springs along the Balcones fault zone near the inner margin of the Coastal Plain. Much water emerges from the cavernous Edwards and associated limestones through springs in the Balcones fault zone.

The public ground-water supplies in the eastern and humid part of the Coastal Plain generally are relatively low in dissolved mineral matter. Dissolved solids are less than 1,000 ppm in more than 90 percent of the water, and the average hardness is about 80 ppm (Sundstrom and others, 1948, p. 2). The public ground-water supplies in the south and subhumid part of Texas contain more dissolved mineral matter. Only about one-fourth of the waters have less than 500 ppm of total solids, and almost half have more than 1,000 parts (Broadhurst and others, 1950, p. 2). The streams in southern Texas also contain much more mineral matter in solution than do streams in humid parts of the Coastal Plain.

SUMMARY OF GEOLOGY AND HYDROLOGY

In summarizing the geology and hydrology of the Atlantic and Gulf Coastal Plain certain facts may be set forth and others, perhaps equally significant, must be omitted. Some selected facts that may be important in the management of radioactive wastes are listed below:

1. The Coastal Plain is composed chiefly of nearly horizontal beds of sands, clays, and calcareous materials. The beds are inclined coastward at a rate only slightly greater than the slope of the land surface. Beds tend to thicken seaward, and beds that do not crop out tend to occur at depth near the coast. The greatest thickness of the wedge of sediments tends to be near the present coast line--perhaps a few tens of miles out to sea. However, the sediments extend out many tens of miles to the edge of the Continental Shelf before thinning to extinction.

2. The sediments are grouped according to the geologic period in which they were deposited. From top to bottom they include the Quaternary, Tertiary, Cretaceous, and (to a lesser extent) Jurassic

Systems. The sediments are further divided into formations according to their lithology or character of the constituent materials. Many formations occur, each supposedly having distinctive characteristics where it is typical. Although some beds may be traced for many miles, there is a tendency for beds to be lenticular, as gradations of materials inevitably occur. The sediments tend to be finer-grained downdip and coastward; within some formations there is a change from coarse sand to fine sand, to clay, and to limestone toward the coast.

3. Below the water table all the sediments are saturated with water. The water table in flat, low areas is commonly within a few feet of the land surface. Places where the water table lies within 30 feet of the land surface are extremely common, and places where it lies below 100 feet are relatively scarce. There are no dry openings or caverns at great depth.

4. The homoclinal coastward-dipping beds are ideally suited for the occurrence of artesian water. Water is confined under pressure beneath clays and other relatively impermeable beds. The permeable beds, called aquifers, are commonly sands and certain limestones. The close interlayering of relatively impermeable and permeable beds results in several separate artesian aquifers where the sediments are thick. Deep-lying artesian water is confined so well that it has no means of escaping readily; therefore, its natural circulation may be so slow that the rate of movement may be considered in terms of a few feet per year or, more likely, a few feet per century. The uppermost artesian aquifer commonly is separated from the near-surface water-table aquifer by an impermeable layer. Water moves vertically, even through seemingly impermeable beds, so that there is a slow exchange of water between aquifers--from one of higher head to one of lower head. The uppermost artesian aquifer is an important distributor of water for the entire artesian system; some of its water discharges into stream valleys. In most places the head of the deeper aquifer is greater than that of its overlying aquifer. Water tends to have both a downdip and an upward component of movement in the artesian aquifers; but there are many exceptions to this tendency.

5. "Aquifers are recharged by precipitation, streamflow and underground percolation. Discharge occurs as springs, seeps, underground leakage, evaporation, and transpiration. From an aquifer not affected by wells, the amount of ground water discharged naturally is equal to the amount entering it in the recharge area, except for temporary differences due to storage changes. Withdrawal of water from wells is balanced by a decrease in the amount of water in storage, a decrease in discharge or a combination of these." (Stringfield and Cooper, 1951, p. 814-815).

6. Almost all the sand and clay, and some of the calcareous material no deeper than 1,500 feet are unconsolidated. With increasing depth, especially below 3,000 feet, many beds are consolidated. The deep-lying beds generally have finer-grained material than their inland and shallow counterparts. Thus, the permeability of the deep-lying beds almost invariably is less than that of beds near the surface.

7. Clays are extremely common as beds in the sedimentary sequence. They are common also in the soil profile where suspended matter has moved downward and accumulated in a shallow subsurface horizon. The clays are important with regard to sorption of cations and anions of radioactive wastes.

8. Calcareous materials occur as limestone, marl, chalk, and finely dispersed ingredients in some sands and clays. North of North Carolina calcareous material is scarce. Limestone and other carbonate rocks compose the bulk of sediments of Florida. Limestone occurs elsewhere in scattered formations near the land surface, and the amount of limestone tends to increase toward the coast with depth. The Tertiary limestone unit of Florida and Georgia contains many permeable beds, and other limestone formations show a wide range of permeability. Marls and chalks of South Carolina, Alabama, Mississippi, and Texas are noteworthy because of their relatively low permeability.

9. Bodies of salt occur in parts of the Gulf coast and in southern Florida. Salt occurs (1) as deep beds having a lateral extent of more than 100 miles, and (2) as intruded masses or domes rising

above the source bed of salt. Near the coast of the Gulf of Mexico the bedded salt lies at a depth greater than 20,000 feet, but some of the salt domes rise within a few feet of the land surface. More than 200 domes have been located. They are somewhat circular and range in diameter from less than 1 mile to more than 4 miles.

10. The basal sediments in the coastal regions contain salty water. In considering the entire volume of Coastal Plain sediments, the volume containing salt water greatly exceeds that containing fresh water. The contact between the fresh-water zone and the underlying salt-water zone is erratic and is not amenable to brief accurate description. In general, the deepest fresh-water zones are in the hinterland. The fresh-water zone is somewhat lens-shaped in cross section. At many coastal points it is less than 100 feet thick; at places in the hinterland it is several hundred feet thick; and along the inner margin it thins as the sediments thin in a featheredge.

11. The largest streams rise in the interior of the United States and flow completely across the Coastal Plain to the sea. These streams and their tributaries form the bulk of the drainage. All streams, except perhaps those in extreme southern Texas are effluent, or "gaining" streams; typically, the water table beneath the interstream areas is higher than the stream level, and ground water moves toward the valleys to contribute water to the streams. Throughout most of the Coastal Plain the valleys are incised in loose sands and clays, which tend to disperse ground-water discharge as seepage or small springs into streams. Only where limestone is the near-surface aquifer, as in the northwestern peninsula of Florida, are large springs noteworthy.

RADIOACTIVE WASTES

Introduction

An attempt to evaluate the waste-disposal characteristics of separate areas within the Coastal Plain would make the report unduly long. The main body of the report contains no discussion of radioactive materials but stresses features of the hydrology and geology that seem important to the management of wastes. This section of the report contains a discussion of nuclear wastes and highlights factors and conditions that are favorable or unfavorable to the management of wastes on or in the ground; this section refers to specific areas in the Coastal Plain. By studying the entire report the reader can draw reasonable inferences about the handling of wastes in the Atlantic and Gulf Coastal Plains.

Nuclear reactors, chemical reprocessing plants, and other nuclear facilities produce unwanted waste products that are complex mixtures of radioactive and stable elements. Two important ways in which these wastes differ from those of trade industries are their hazardous nature, even at extremely low concentrations, and the long radioactive life of many of the isotopes. Some wastes are liquids and some are solids. They vary between extremely wide limits in the intensity of their radioactivity. The intensity of radioactivity decreases with time; some radioisotopes decay to innocuous levels in a very short time, whereas others retain their radioactivity for millenia.

One classification of wastes is based on the great variability in their degree of radioactivity; this classification aids in planning the management of the wastes. Low-activity wastes may include large volumes of air, gas, or liquor. Many low-activity wastes are deliberately released to the natural environment by such methods as controlled discharges to the ground, rivers, lakes, and the atmosphere. The radioactivity of high-activity wastes may be sufficiently great even after a few years of temporary storage or retention that diluting and dispersing processes in the environment would not reduce the radioactivity to acceptable limits. To a great extent the problem can be focused on the following statement:

> Many low-activity wastes, particularly those in liquid and gaseous form, cannot be economically concentrated and contained. High-activity wastes cannot be practically and safely dispersed and diffused in the natural environment.

The principal bulk of high-level wastes is now in liquid form, stored temporarily in steel tanks at chemical plants where fuel elements from reactors are reprocessed. The Savannah River Operations area in Aiken and Barnwell Counties, South Carolina, includes the only chemical reprocessing plant in the Atlantic and Gulf Coastal Plains. The many problems involved in the handling of these wastes have been discussed by several workers (U. S. 86th Congress, 1959). Any scheme of disposal to the ground must provide isolation from potable water supplies, because some long-lived isotopes remain radioactive for hundreds to thousands of years. Radioactive wastes may reach the ground or a body of water deliberately or by accident. No high-activity wastes are deliberately released, and only under certain controlled conditions are low-activity wastes intentionally released to the natural surroundings. We are concerned here, (1) with the fate of the wastes deliberately released, (2) with the fate of those that may be released accidentally, and (3) with schemes that may result in burial or disposal of the radioactive wastes which will prevent them from moving into a circulating water system.

The consequences that could result from accidental release of radioactive materials to the ground or a body of water are so serious that extreme caution must be exercised to prevent such a release. Accidental release could result from failure of equipment, errors in design, human errors, and natural disasters. The probability of occurrence of a publicly hazardous accident in a year at any nuclear site is exceedingly unlikely, but low probability does not warrant disregard of the roles that the geology and hydrology have in preserving or threatening the health and safety of people in a large area.

Sufficient data are available to predict the general fate of most radioactive species in most circumstances if they came in contact with the ground in the Coastal Plain; the course and fate of all radioactive ions in some circumstances can be accurately predicted within narrow areal and volumetric limits. Consoling though these statements seem to be, no formula involving the geologic environment could give a quick answer to the bulk of questions arising from the disposal of radioactive wastes. Knowing the course or fate of most radioactive ions in a particular release may not be significant if the remaining ions represent a health hazard. Also, as Nace has indicated (1959, p. 2586), even it we know the answers to some of the questions, we have then described only some conditions. Knowing the answers, of course, will pave the way for solving the problems.

Two characteristic features of earth materials must be reckoned with where radioactive materials come in contact with the ground. Radioactive materials tend to disperse in the natural environment; they tend to be adsorbed by mineral particles. The radioactive ions gain mobility and are dispersed in surface waters and in the ground where subsurface water circulates. Sorption thwarts and limits dispersion.

What is the shape and nature of a contaminated zone? Let us examine two extreme cases. In the one case the wastes remain near the place where they first make contact with the ground. They may be buried below the zone of normal circulation of subsurface water, or they may lie within this zone of circulation but be adsorbed on mineral particles in the ground; either the confining features of the enclosing geological material or the confining capacity of man-made containers are depended on to keep the radioactive ions immobilized in the ground. In the other case the wastes extend as a trail down gradient in a hydrologic environment from a point of origin; if the point of origin is the ground, the trail may be broadened as the wastes are diffused in the ground water, but if they persist in the ground-water discharge upon reaching a stream the trail may extend to the sea.

Various schemes for deliberately burying high-level wastes have been considered. Some schemes involve transformation of the wastes into solids that can be handled more readily than raw wastes. Burial of solid wastes in bodies of natural salt seems to be a promising possibility (Struxness and others, 1960, p. 494). A report by Pierce and Rich (1958) gives specific information about the occurrence of salt in the United States. Figure 11 shows areas where salt bodies underlie the Coastal Plain. Disposal of liquid wastes through deep wells into formations below the zone of ground-water circulation also has been considered.

Deep-Well Disposal

Can radioactive liquid waste be disposed of safely through wells into deep permeable beds? A search is now being made throughout the United States for deep zones where liquid wastes may be buried permanently. Attention is centered chiefly on closed structural sedimentary basins, the premise being that the closed basins tend to restrict circulation of fluids at considerable depth. Although the Gulf Coastal Plain is slightly synclinal, neither the Gulf nor Atlantic Coastal Plain is a closed basin. Nevertheless, certain features of the region seem favorable for deep-well disposal.

It might be well to give less consideration to the inner part of the Coastal Plain than to the outer part. Beneath the inner part--that nearest the interior of the country--there is a tendency, (1) for the total sedimentary sequence to be thin, (2) for much of the ground water to be fresh, and (3) for ground-water circulation to be appreciable. In contrast, beneath the coastal margin: (1) the sediments are several thousands of feet thick, except near Wilmington, N. C.; (2) only the uppermost part of ground water is fresh--less than 10 percent of the total volume in most coastal places; (3) many hundreds of feet of impermeable beds, composed chiefly of clay, overlie some permeable sand beds, except in peninsular Florida, where limestone predominates; (4) in many places the water at great depth may have been trapped by burial for hundreds or thousands of years, and may be immobile. Another consideration concerns the possibility that wastes may come in contact with the land surface or water table. Precautions would be taken to prevent high-level wastes from reaching the land surface or the water table, and contamination either by surface spillage or upward migration of wastes from a suitable zone of deep burial would be extremely unlikely. If contamination occurred, however, the consequences would be less severe along the coast than similar contamination elsewhere, in the inland country, because no inland aquifer and no important fresh-water surface stream would be contaminated.

Some coastal strips appear to be less favorable than others. Much of the Gulf coast is unfavorable because of the oil- and gas-bearing potentials of the area. The peninsular part of Florida is difficult to appraise because data do not clearly indicate whether local clay beds and dense limestone beds are sufficiently impermeable to confine wastes that might be injected in permeable limestone beneath them. Parts of South Carolina may be relatively unfavorable because the fresh-water zone is thick and the salt-water zone relatively thin. The coastal fringe between Cape May, N. J., and Cape Lookout, N. C., appears favorable, especially the area between Cape Lookout and the mouth of Chesapeake Bay in Virginia. The following factors tend to make northeastern North Carolina and southeastern Virginia rather favorable for deep-well disposal of liquid wastes:

(1) The population is sparse.

(2) No prolific fresh-water aquifers are present. In most of the area water below the 200-foot depth is salty.

(3) No public water supply could be contaminated. (No fresh-water streams are present and no ground water moves inland.)

(4) Permeable salt-water sand aquifers lie below great thicknesses of impermeable clay.

(5) The plain is flat and low as far inland as the Piedmont province, and the differences in hydrostatic pressure between beds are slight.

(6) The conditions noted in items (4) and (5) favor entrapment of deep water and insignificant circulation.

(7) The sediments enclosing the aquifer have great ion-exchange capacity. They contain a wide variety of clay minerals, and glauconite and phosphate are abundant in some sand and clay beds. Owing to the ion-exchange capacity of the enclosing sediments, absolute containment of waste liquid may be less imperative in many places than it would be where the ion-exchange capacity is small.

Adsorption of Radioactive Ions

Much has been learned about the capacity of some earth materials to retain radioactive ions by adsorption or ion-exchange. Laboratory experiments, passing solutions of single ionic species through columns composed of a single mineral, have established quantitative values for sorption capacities in simplified and idealized situations. However, different ionic species are not sorbed to the same degree and the sorptive characteristics of various foreign ionic species interfere mutually one with another and with natural ions in solution in subsurface water (Simpson, 1960, p. 527).

Thomas and Coleman (1959) have commented on the complexities of the natural ion-exchange phenomena.

> "For the past decade large volumes of medium- to low-activity radioactive wastes have been disposed of at Hanford and Oak Ridge in pits, cribs, and lagoons, which function either as storage basins or as ion-exchange columns" (Struxness and others, 1960, p. 487).

To a lesser degree, soils and near-surface clay beds at the Savannah River Plant are relied on to extract and retain the radioactivity of some low-activity waste.

What is the ion-exchange capacity of Coastal Plain materials and how can this capacity be utilized? No other section of the country of comparable size approaches the Coastal Plain in the abundance of materials which have high capacity for ion exchange. Two principal factors make this true: (1) The enormous volume of pore space in unconsolidated sediments, which provide opportunity for ion exchange; and (2) the great mass of clay minerals distributed throughout the province and lesser amounts of glauconite and phosphate, where are effective ion-exchange hosts. A distinction needs to be made as to whether we are concerned with the entire prism of sediments extending to the basement rocks or only with materials above the water table and a short distance below it. Insofar as deep disposal is concerned, the exchange capacity of sediments overlying the disposal zone could be utilized if complete containment or confinement were not possible. This is a safety factor if deep-well disposal is undertaken in the Coastal Plain.

If radioactive materials come in contact with the ground surface in the Coastal Plain, the radioactivity may be dispersed by water before the full ion-exchange capacity can be utilized. For example, much of the shallow ground water, and consequently much of the waste that might be with it, moves laterally toward nearby stream valleys, in many places rather rapidly. Even if it moved exclusively through good ion-exchange clays, the removal of radioactivity might not be effective. Moreover, water and waste would move, preferentially, through the more permeable local materials, chiefly sands, which have very low sorption capacity. An environment which was not saturated in its natural state, such as the zone above the water table, is considered to be desirable and ideal for ion exchange. This zone is thick in many arid regions like Hanford, where the thick zone of sorptive materials above the water table is a fortunate circumstance. In the humid part of the Coastal Plain the water table is near the land surface, and it tends to be closer to the land surface in clays than in sands. In brief, everywhere in the Coastal Plain some radioactivity would be sorbed and retained in the ground, but at most places some radioactivity would be dispersed by naturally circulating water. By carefully selecting sites where radioactive materials might reach the ground, and by considering earth-moving schemes to improve the efficiency of local ion exchange, some problems of waste management might be solved.

Storage of Wastes in Impermeable Beds

The subject of salt bodies as environments in which high-level wastes may be buried is important, but will not be discussed here because abundant information has been published.

Relatively impermeable beds of clay and marl are common throughout the Coastal Plain. Many of these probably would confine liquid waste if it were injected in permeable zones between or below the confining layers. "Confinement," however, is a relative term. What would be essentially complete confinement from the standpoint of conventional hydrology might involve unacceptable leakage from the waste standpoint. The risk of imperfect containment in beds stratigraphically associated with fresh-water aquifers may be unacceptably high. Therefore, the sedimentary formations of the inner part of the Coastal Plain seem to be unfavorable for the injection of high-level waste liquids. The so-called crystalline basement rocks beneath the sedimentary formations are a separate and entirely different problem.

One region which may be favorable for permanent disposal of solid high-level wastes is the seaward part of the Coastal Plain in southeastern South Carolina, where the top of the Cooper Marl lies only about 100 feet below the land surface. The marl is essentially impermeable and can be excavated easily. At some places, (1) no fresh-water streams lie at the land surface above the marl; (2) no fresh-water aquifers underlie the marl; (3) no important fresh-water aquifer overlies the marl; and (4) the surface-water and ground-water flow both are seaward, so there is no possibility, if waste migration occurs, of contaminating inland fresh-water supplies. The conditions enumerated may be thought of as safety factors, because the properties of the marl itself probably are adequate to permanently contain the radioactive constituents of solid wastes. Careful, detailed study of the hydrogeology of this area would be appropriate.

Movement of Wastes in Water

Movement of water in the hydrologic cycle gives mobility to unconfined radioactive materials. Knowledge of the direction and rate of movement that wastes would take is a primary objective. Throughout this report we emphasize the movement of subsurface water, because (1) radioactive solutes move in the same general direction as subsurface water, and (2) the solutes move no faster than the host water; generally they move much slower.

From point sources or small areas where waste reaches the land surface or water table it would tend to move in a dispersive trail to or toward a nearby topographically lower area, commonly a valley. Almost all the waste that is not sorbed en route would discharge in the stream or be retained in the soil and vegetation of the flood plains. Artesian beds which lie at some depth in the Coastal Plain are essentially full of water and tend to reject recharge. Indeed, at many places these aquifers are full and are under sufficient hydraulic head that water "leaks" out of them and upward through imperfectly confining sediments. Most of the unconfined shallow ground water moves laterally toward surface streams. Thus, at most places of the humid part of the Coastal Plain, because of the nature of hydraulic heads, only a small fraction of the waterborne wastes in or on the ground could enter artesian beds. Wastes that lie in a drainage basin in most cases will not reach an adjacent basin. The Coastal Plain sediments are almost flat, but the slight inclination of the beds of varying permeability tends to guide the movement of water. Where the near-surface beds are inclined in a direction opposite that of the water table (and also the land surface) some water may be deflected toward an adjacent drainage basin. In some circumstances it becomes buried below the valley in the underlying artesian system. Local observations by a trained hydrogeologist would indicate whether contaminated materials could move through a drainage divide and enter a different drainage basin.

Favorable Earth Considerations for Management of Wastes

The most favorable geologic and hydrologic conditions for handling wastes are those that prevent hazardous radioactive materials from entering the present or future water and mineral supplies, and from entering populated parts of the biosphere. It is difficult to find the ideal hydrogeologic setting. No environment at existing nuclear facilities approaches an ideal, although every facility has some favorable features. Without making an exhaustive appraisal of environmental criteria, the following considerations appoach an ideal for handling radioactive wastes:

1. Deep water table
2. Great sorptive capacity of surface or near-surface materials
3. Permeability (a dependent consideration, varying from low permeability being favorable for some situations to high permeability for other situations)
4. Great distance from surface streams
5. Absence of fresh water in surface streams
6. Absence of fresh ground water

1. Deep Water Table.--Depth to the water table in various parts of the Coastal Plain is an important consideration noted throughout this report. Frequency and intensity of precipitation, topography, and permeability are principal factors which control the depth to water. All the area excepting southwestern Texas has a humid climate. Owing to the abundance of recharge and the relatively low topographic relief in much of the region, the water table generally is shallow. Where the water table is deep, movement of water to the land surface is delayed. Therefore, if the water were contaminated there would be opportunity for some radioactive decay. Where materials above the water table have effective sorptive properties, wastes which percolate through them would tend to be absorbed and might not reach the zone of saturation. Depth to the water table exceeds 75 feet beneath only a very small part of the humid Coastal Plain. A deep water table generally indicates (a) high permeability, which may accompany low ion-exchange capacity, and (b) nearness to a surface stream or flood plain.

2. Sorptive Capacity.--(discussed on page 151).

3. Permeability.--Permeability must be considered jointly with other factors. Highly permeable materials in the zone of aeration would tend to conduct waste quickly underground and to the water table. The water table commonly lies deeper in permeable than in impermeable materials but this favorable circumstance is offset to some extent by the fact that the least permeable materials generally are clays, which have a capacity for ion exchange many times that of the more permeable sands.

Two permeability characteristics in the Coastal Plain are especially important. One is the great contrast between relatively impermeable clays and highly permeable sands. Another is the horizontal layering of alternating zones of differing permeability. Where valleys cut through clay beds, wastes above the clay might move laterally to the land surface above a stream level; in that case, the likelihood would be great that radioactive contaminants would reach land biota on lowland slopes and flood plains. In the deep zones of the Coastal Plain a permeable zone which is overlain by thick beds of clay is favorable for the disposal of liquid waste.

4. Distance from Surface Streams.--The movement of subsurface water is many times slower than that of surface water. Thus, great distance from the nearest surface stream is an advantage in disposal sites because of the increase in decay and the increase in opportunity for sorption en route. It is realized that the movement of waste under ground removes from use parts of some aquifers, but the proportions of ground-water contaminated by radioactive wastes has been infinitesimally small. Owing to high precipitation in most of the Coastal Plain, the drainage network is dense. Places as much as one mile from a perennial stream are unusual.

5. Quality of Water in Streams.--Present and potential uses of water downstream from the general area at which wastes may be in contact with the ground is an important consideration. The coastal margin is favorable in this regard because many coastal streams contain brackish water for some distance above their mouths, and little direct use is made of this water.

6. Quality of Ground Water.--The tendency for wastes to be dispersed in ground water causes some parts of aquifers to be contaminated. Fresh-water aquifers are relatively

scarce along the coastal margin. Almost nowhere is there a significant ground-water gradient inland. Thus, contact of waste with the ground along the coast will not contaminate the aquifer in the interior.

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