Artesian Water in Tertiary Limestone in the Southeastern States

By V. T. STRINGFIELD

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By V. T. STRINGFIELD

ABSTRACT

In Florida, southern Georgia, and adjacent parts of Alabama and South Carolina an artesian aquifer system of Tertiary age is the source of some of the largest groundwater supplies in the United States. The aquifer system consists of as many as eight formations, chiefly limestone. The area of this system discussed in this report includes all Florida and most of the Coastal Plain in Georgia as well as adjacent parts of South Carolina and Alabama and extends from the Atlantic coast as far inland as the Fall Line in a few places. The area is in the Atlantic and Gulf Coastal Plain province—a region of plains and low hills. Most of the region is covered by Pleistocene coastal terraces rising from sea level to as much as 270 feet above sea level; the higher hills between the terraces and the Fall Line are as much as 600 feet above sea level. Valleys are cut as much as 100 feet below some uplands. Some of the principal streams, such as the Savannah River, rise in the Piedmont province and flow across the Coastal Plain in Georgia and adjacent parts of South Carolina, Florida, and Alabama to the sea. The other streams rise within the area of the report.

The climate ranges from temperate in South Carolina and Georgia to subtropical in southern Florida. The average annual rainfall ranges from about 38 to 60 inches. The lowest rainfall is on the Florida Keys.

Sedimentary formations which crop out in this region range from Cretaceous to Recent in age. Igneous and metamorphic rocks underlie the Cretaceous formations and appear at the surface in the Piedmont province. The Cretaceous formations consist chiefly of sand, gravel, and clay in the areas where they are at or near the surface. The overlying Tertiary formations consist chiefly of limestone, dolomite, and marl, with some anhydrite and gypsum. Some formations grade into sands and other clastic material in western Florida, southeastern Alabama, the southwestern part of the Coastal Plain in Georgia, the northeastern part of the Coastal Plain in Georgia, and adjacent parts of South Carolina. Pleistocene and Recent deposits, consisting chiefly of sand and gravel, clay and shells, generally are less than 100 feet thick. In southeastern Florida the Pleistocene formations, however, include at least 250 feet of limestone, marl, sand, and shell beds.

The Tertiary formations are at or near the surface in belts approximately parallel to the Cretaceous outcrops and the Fall Line in Georgia and adjacent parts of Alabama and South Carolina. The Tertiary formations are also near the surface on some geologic structural features, such as the Ocala uplift in north-central Florida and on the Chattahoochee anticline in western Florida. Except where affected by local structural features, the formations dip gently toward the coast at right angles to the belt of outcrops. The formations dip in all directions from the Ocala uplift. In Florida, the thickness of the Tertiary formations ranges from less than 1,600 feet on the northwest side of the Ocala uplift to about 4,500 feet in western Florida. The thickness is about 2,500 feet in southern Georgia, 2,400 feet at Parris Island, S. C., and more than 5,500 feet in southern Florida. The oldest of the formations are at or near the surface in the belt of outcrops extending from northeastern Alabama into central Georgia. In Florida the Avon Park Limestone of middle Eocene age represents the oldest rocks exposed. These exposures are in a small area on the Ocala uplift. The Ocala Limestone and younger formations are exposed in large areas on the Ocala uplift and in Jackson and adjacent counties in western Florida.

The chief water-bearing limestones, ranging in age from middle Eocene to middle Miocene, form the principal artesian aquifer, which is the chief source of ground water in a large part of the region. The formations of the principal aquifer include, from bottom to top, the Lake City Limestone, Tallahassee Limestone, and Avon Park Limestone of middle Eocene age; Ocala Limestone of late Eocene age; Marianna and Suwannee Limestones of Oligocene age; and the Tampa Limestone of Miocene age. In part of the area the lower part of the Hawthorn of Miocene age forms the upper part of the principal artesian aquifer.

The formations yield water from permeable zones in the limestone and from solution cavities, some of which are filled with permeable sand. Some of the limestones grade into sandy formations in the subsurface in western Florida, southeastern Alabama, and in some areas of outcrops in Georgia and South Carolina. The shallow formations in southeastern Florida, consisting chiefly of cavernous limestone, ranging in age from late Miocene to Pleistocene, form a productive aquifer overlying the principal artesian aquifer. The shallow sands are good aquifers in the Pensacola and Cantonment areas in Escambia County, Fla.

In addition to the gentle homoclinal eastward dip of the beds, the geologic structural features include (1) the peninsular arch, (2) Ocala uplift and arch on its east flank, and (3) the Chattahoochee anticline. There are several embayments, including one in southwestern Georgia, which extends into the Apalachicola embayment in Florida and others in southeastern Georgia and southern Florida. Two joint systems are present in the limestone in most, if not all, of the region. Jointing and faulting on the Ocala uplift appear to reflect structural movement during the late Tertiary. Many solution cavities formed in the limestone and associated rocks, especially where they are at or near the surface. Sinkholes and vertical shafts extend from the surface to underground solution channels in some of these areas. In the lake regions in Florida and Georgia, the sinkholes, or vertical solution openings, extend through the Hawthorn Formation, which overlies the limestone of the principal artesian aquifer. Sinkholes also occur in the Gulf of Mexico area west of the Florida peninsula.

Although solution is continuous where there is circulation

of water, as at the present time, there is evidence that most of the solution in the water-bearing formations occurred in Pleistocene time. The principal artesian aquifer has cavities and solution channels probably comparable in size and extent to those in Mammoth Cave, Ky.

Water enters artesian aquifers in areas of relatively high altitudes where the aquifer is at or near the land surface or is overlain by permeable material. From such intake or recharge areas the water reaches the permeable rocks and gradually moves laterally downgradient into the aquifer under confining beds in response to pressure produced by recharge. All aquifers are both reservoirs and conduits. Under artesian conditions, however, they function chiefly as conduits in which water moves many miles from recharge areas to discharge areas.

The Tertiary limestones include many local aquifers and one principal aquifer. The principal aquifer, as much as 1,000 feet thick, underlies Florida, southern Georgia, and adjacent parts of South Carolina and Alabama. It is the source of nearly all the artesian water in Florida and southeastern Georgia. In Florida, it is commonly called the Floridan aquifer. The top of the aquifer ranges from more than 100 feet above sea level to as much as 1,000 feet below sea level. As a hydrologic unit, the principal aquifer is unusual in its thickness and areal extent. It is the source of the large springs in Florida and Georgia and yields water to thousands of artesian wells.

The piezometric surface, or the height (with reference to sea level) to which water in an artesian aquifer would rise in wells, shows the chief areas of recharge and discharge and direction of lateral movement of the artesian water. In general, the high areas of the piezometric surface indicate recharge, and the low areas indicate discharge. Recharge may, however, occur in some of the areas of relatively low pressure. The piezometric surface ranges from sea level near some coastal areas to more than 120 feet above sea level in the lake region of central Florida and in the Jackson County area in western Florida. The piezometric surface is as much as 250 feet above sea level in an outcrop area of the aquifer, extending from southeastern Alabama northeastward across Georgia to South Carolina. The aquifer is recharged, not only in areas where it is at or near the land surface, but also where the overlying beds have been penetrated by sinkholes. In general the piezometric surface slopes to the east, southeast, and south from the high area in Georgia. In the Valdosta area in Lowndes and Brooks Counties, where there is local recharge through sinkholes and drainage wells, the piezometric surface is as much as 100 feet above sea level.

The lateral movement of water is generally from the recharge areas. Although the lateral movement may be controlled over considerable distances by geologic structure and the movement may be parallel to the dip of the formations, the relative positions of the recharge and discharge areas are more important than the geologic structure in controlling the direction of the movement of the water in the area of this report. For example, the lateral movement of the water in the Polk County area, Florida, is in all directions from the recharge area, even though it is on the flank of the Ocala uplift.

Joints or fractures and bedding planes may have a pronounced effect on the patterns and movement of water in limestone and associated rocks. Solution features, such as vertical pipes or natural wells, in the limestone appear to have formed in the zone of aeration at the intersection of two sets of joints. Long shallow vertical openings were formed along some joint planes. Lateral movement may be locally along bedding planes, but the movement generally does not appear to be affected by regional structures. The cavities and horizontal solution channels were formed chiefly in the upper part of the zone of saturation, nearly parallel to the hydraulic gradient.

The chemical quality of the ground water may be divided into the following types: (1) Calcium bicarbonate water, its hardness ranging from about 50 to several hundred parts per million; most of the artesian water belongs to this type except in southern Florida and in some of the coastal areas where the fresh artesian water is mixed with remnants of sea water. (2) Calcium sulfate water, its hardness as much as 900 ppm (parts per million); some of the artesian water in southern Florida is of this type. (3) Sodium bicarbonate water, its hardness less than 50 ppm, the total dissolved solids being relatively high; this type of water occurs in the principal artesian aquifer in western Florida and adjacent parts of Alabama and Georgia. (4) Sodium chloride water in some parts of the coastal areas and southern Florida. (5) Soft water, its total dissolved solids less than 50 ppm in the surficial sands; the public supply of Pensacola and other supplies in Escambia County, Fla., are of this type, as are many of the shallow domestic supplies.

The temperature of ground water at depths of about 30 to 60 feet is generally about 2° to 3°F above the mean annual temperature. The temperature of water in the principal artesian aquifer, as measured at the mouth of flowing wells, ranges from about 62°F in South Carolina to 90°F in Martin County in southern Florida.

Salt water in fresh-water aquifers may be from (1) encroachment of sea water in the coastal areas, (2) originally entrapped sea water or sea water that entered the aquifer during a high stand of the sea in Pleistocene time, or (3) thin salt beds and sea water concentrated in tidal lagoons or other enclosed areas. Water having a relatively high chloride content is present in the artesian aquifer in coastal areas of Florida south of St. Augustine, in southern Florida, and also in the St. Johns River valley where the aquifer is near sea level.

The principal artesian aquifer is the source of many large springs. Silver Springs and Rainbow Springs in Marion County are the largest, their combined flow being 2,310 cfs (cubic feet per second). The largest known submarine spring is about 2½ miles east of Crescent Beach, Fla. There are many submarine springs from the principal artesian aquifer in the Gulf of Mexico on the coast from Pasco County to Wakulla County, where the aquifer forms the ocean floor.

Artesian wells range from 50 to more than 1,000 feet in depth and from 2 to more than 24 inches in diameter. Wells in the principal artesian aquifer are finished without screens except, in areas such as western Florida, where the water-bearing formations consist of sand and other unconsolidated material. The yield of natural-flow wells ranges from a few gallons to several thousand gallons per minute.

The principal artesian aquifer is the chief source of ground water for municipal, industrial, and irrigation supplies in the area of this report. Most of the public water supplies, including those for Savannah, Jacksonville, and St. Petersburg, are from the principal artesian aquifer. Supplies for the Miami area and Pensacola are from shallow aquifers overlying the principal artesian aquifer. The estimated quantity of water used in 1960 for public supplies in Florida, chiefly from the principal artesian aquifer, was 502 mgd (million gallons per day). The quantity for private supplies used for industrial and commercial purposes was 657 mgd. Large quantities of water are used for irrigation in Florida, especially for truck and citrus crops in the peninsula.

In Georgia the largest use of artesian water is in the coastal areas, where the estimated annual discharge was 279 mgd in 1960. Of that amount, 197 mgd was for industrial use, 31 mgd for public supplies, and 21 mgd for domestic supplies. About 30 mgd, a large part of which is not used, flows continuously for domestic and stock use and for game preserves. The quantity of water used for irrigation in Georgia is small in comparison with that in Florida and is only a fraction of 1 percent of the total discharge in Georgia.

Although the total quantity of water withdrawn from the principal artesian aquifer in the report area is large, it is only part of the billions of gallons of water naturally discharged each day. This abundant resource, which is not fully utilized in much of the region, will require continued systematic local and regional investigations of the geology and hydrology to provide the information required for its wise and full use.

INTRODUCTION

The area of this report (figs. 1, 2) includes Florida, most of the Coastal Plain in Georgia, and adjacent parts of Alabama and South Carolina. In this area, artesian water is the source of most of the large and many of the small supplies of water. Most of the potable artesian water in Florida and in part of southeastern Georgia is in limestone of Tertiary age. The limestone aquifer, composed of several formations, is overlain and underlain by formations of sands, clays, shales, and limestone. The limestone unit represents one of the most productive aquifer systems in the United States. Although there is an apparent abundance of ground water, the region has many problems, many of which relate to the quality of the water. The problems will increase, and the management of water resources is especially important because of the delicate interrelation of potable and impotable water in the aquifer. The main purpose of the report is to furnish background information to persons interested in ground-water conditions in the area.

This report is based on the results of fieldwork and reports of investigations, many of which are listed in the references. Discussions are included on counties for which ground-water reports are available. In addition to a regional description of the geologic formations and their water-bearing properties, artesian conditions and areas of recharge and discharge of the principal artesian aquifer are given. The discussion on the quality of water contains comments about radium, uranium, and tritium, in addition to the major chemical constituents. The distribution of salt water and its relation to fresh water in aquifers is described.

PREVIOUS REPORTS

Many publications relating to the report area of the U.S. Geological Survey, of the State Geological Surveys, and of other State agencies are included in the list of references. A list of publications on ground water from 1885 to 1957 is contained in bibliographies by Waring and Meinzer (1947) and Vorhis (1957). References to reports on ground water are contained in the U.S. Geological Survey's "Bibliography of North American Geology" published for the years 1785–1962.

Regional reports on geology of the report area include those by LeGrand (1961b and 1962), Applin and Applin (1944, 1947, and 1965), Toulmin (1955), Johnston, Trumbull, and Eaton (1959), and Murray (1961). Previous work on ground water is given in this report by States. Recent summaries by States are given by McGuinness (1963). Most of the investigations on ground water in Florida and Alabama have been by the U.S. Geological Survey and the State Geological Surveys. The work in Georgia has been chiefly by the U.S. Geological Survey and the Georgia Department of Mines, Mining, and Geology (Georgia Geological Survey). In South Carolina much of the work has been by the U.S. Geological Survey in cooperation with the South Carolina Development Board.

One of the earliest of the reports of the Florida Geological Survey is by Sellards (1908) on the underground water supply of central Florida. This bulletin contains discussions of deep and shallow wells, spring and artesian prospects, effects of underground solution, drainage of lakes, ponds and swamp lands, water analyses, and well records. A report on the underground water supply of west-central and western Florida (Sellards and Gunter, 1912) followed. A report by Matson and Sanford (1913) is one of the most comprehensive of the reports on the ground water of the entire State. In the same year a report by Sellards and Gunter (1913, p. 103–290) on the artesian water of eastern and southern Florida was published. A report by Gunter and Ponton (1931, p. 43–55) contains an article on the need for conservation of the water supply and a contour map that represents the height to which artesian water would rise in wells in the Ocala Limestone in part of Florida. It also includes a contour map (Malcolm Pirnie, written commun., 1927) showing the height to which water would rise in wells in the Ocala

FIGURE 1.—Counties in the Southeastern States.

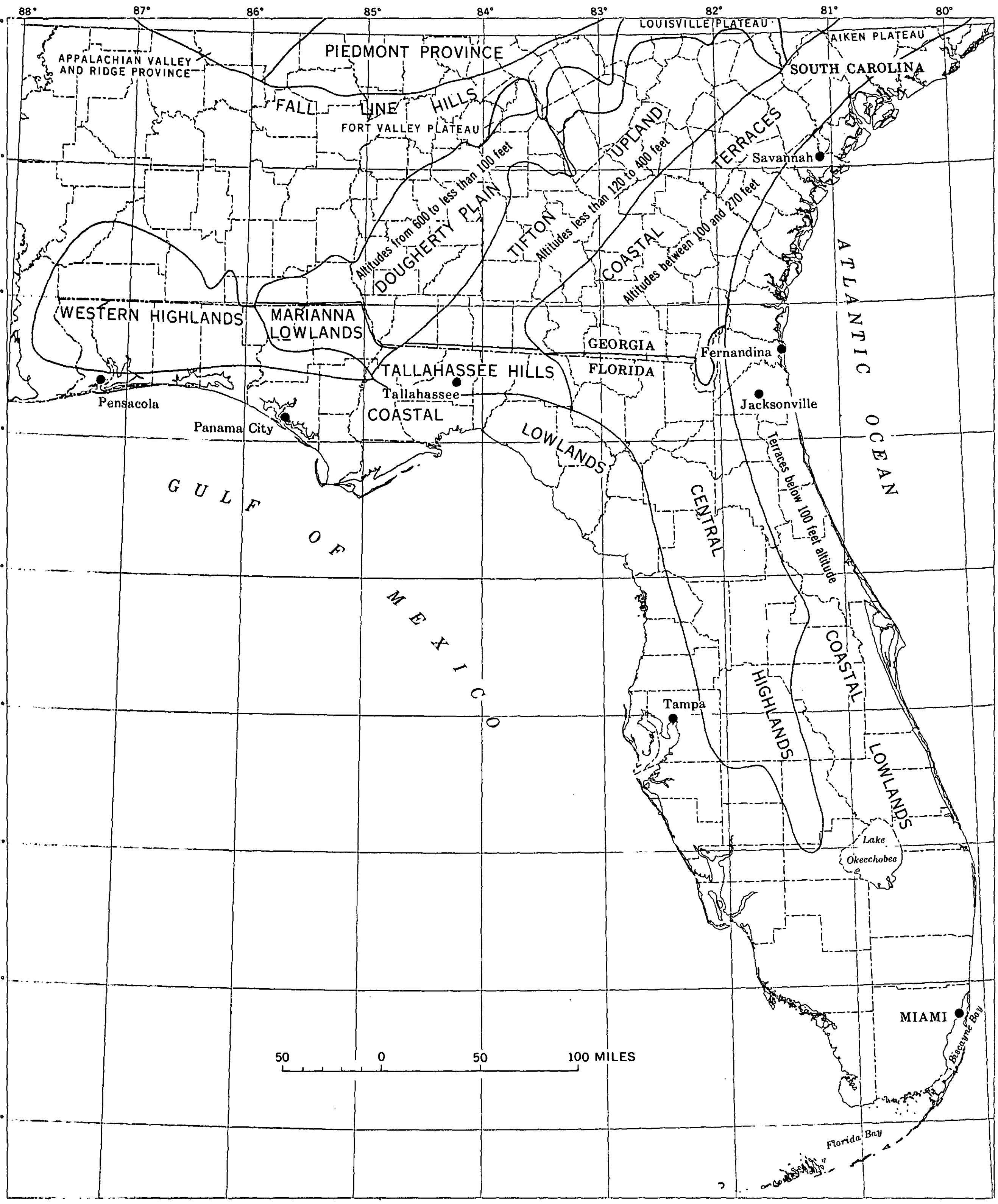

FIGURE 2.—Physical divisions (Cooke, 1939, p. 14; LaForge and others, 1925, p. 17; and Fenneman, 1938).

Limestone in the Jacksonville area. The original report by Pirnie, consulting engineer for the Water Supply Commission of Jacksonville, also includes a generalized contour map described as representing the ground-water table in part of Florida. It, like the contour map of Jacksonville, is based on water levels in the limestone instead of the water table.

One of the first county reports (Stringfield, 1933c, p. 121–194) on artesian water showed that the artesian water in Sarasota County, Fla., moves through the limestone from east to west, indicating that the water enters the limestone in an area east of the county. Previously, the available information on the artesian water and geology of Florida indicated that the limestone aquifer is recharged on the Ocala uplift in Marion County, north of Sarasota County in the vicinity of Ocala, where the limestone is at or near the ground surface and that the water moves downdip.

Stringfield's study in Sarasota County showed the need of a regional investigation of artesian water in order to obtain a better understanding of the recharge and discharge areas and the direction of movement of the artesian water. The work in Sarasota County and other parts of Florida also showed the value of obtaining additional information on the relation of the fresh artesian water to the salt water in the artesian aquifer. Therefore, a general survey of the artesian water in the Florida peninsula was undertaken in 1933, when Federal public works funds became available.

The results of that study (Stringfield, 1935, p. 524–529; Stringfield and Westendick, 1935, p. 5–16; Stringfield, 1936, p. 115–195) as stated by Vernon (1955, p. 39) showed that the artesian limestone is recharged in some of the lake regions through lakes that occupy sinkholes filled with unconsolidated permeable sand and silt. A piezometric map (Stringfield, 1936, pl. 12) representing the height to which water would rise in tightly cased wells in the artesian limestone aquifer showed extensive recharge and discharge areas and the general direction of movement of the artesian water throughout the Florida peninsula.

In 1936 Stringfield and Westendick mapped and described the piezometric surface of artesian water in the remainder of the State in an unpublished manuscript, "Artesian Water West of the Suwannee River in Florida." That map (combined with the maps of the Florida peninsula and southeastern Georgia and South Carolina) has been published with slight modification in different reports. With this new information on the artesian system in Florida came a better understanding of the occurrence and movement of the artesian water and the relation of salt water to fresh artesian water.

A report of the U.S. Army, Corps of Engineers (1933) at Jacksonville and a document (U.S. Congress, 1936) on routes for a ship canal across Florida contain information on the geology and ground water of the central and northern parts of the Florida peninsula. The reports include a map described as representing the water table in the peninsula. However, for much of the area the map represents the water in the limestone that is under artesian pressure throughout most of Florida. The water level in wells in the limestone is generally above or below the water table in the overlying formations.

Reports by Cooke and Mossom (1929, p. 29–228), Cooke (1945), and Puri and Vernon (1959) describe the geology of Florida. The report by Cooke and Mossom includes a geologic map of the State showing the distribution of the geologic formations at or near the surface. The 1945 report by Cooke also includes a geologic map of the State. Vernon and Puri (1956) summarized the geology of western Florida in a guidebook to surface exposures.

In their report on the subsurface stratigraphy and structure of Florida and southern Georgia, Applin and Applin (1944, p. 1674–1677) included a review of the most significant contributions to that subject in Florida and southern Georgia. The geologic structure is described in several reports including those by Mossom (1926, p. 171–268), Applin and Applin (1947), Pressler (1947), Toulmin (1955), and Vernon (1951). A comprehensive report by Parker, Ferguson, Love, and others (1955) gives information on the Cenozoic geology and hydrology of southeastern Florida.

During the past decade, 1955–65, detailed information on ground water by counties and local areas has been published by the Florida Geological Survey. These are included in the references at the end of this report.

Two of the earliest reports on artesian waters in the Coastal Plain in Georgia and South Carolina are by Darton (1896) and McCallie (1898). A preliminary report on the underground waters of Georgia by McCallie (1908) includes information on the artesian water in the Coastal Plain in Georgia. Stephenson and Veatch (1915) prepared the first comprehensive report on artesian water in the Coastal Plain in Georgia.

The work on the artesian water in Florida in 1933 showed that the piezometric surface of the artesian water in the principal limestone aquifer underlying Florida extends into Georgia. Therefore, in 1939 and 1940, Warren (1944) mapped the aquifer in Georgia and southeastern South Carolina in cooperation with Georgia Department of Mines, Mining and Geology. Herrick and Vorhis (1963) included maps showing the thickness and structure of the Tertiary and Cretaceous formations in Georgia.

Description of wells and other information on ground water by counties in the Coastal Plain in South Carolina are included in a report by Cooke (1936). Siple (1946) and (1957a) briefly outlined the geology and ground water in the Coastal Plain in South Carolina. The report in 1957 includes a map of the piezometric surface of artesian water in the Tuscaloosa Formation in parts of Aiken and Barnwell Counties, S.C., and in Burke County, Ga.

A report by E. A. Smith (1907) includes information on artesian water in the Coastal Plain in Alabama. Ground water in southeastern Alabama is described by LaMoreaux (Carter and others, 1949, p. 200–265). Cagle and Floyd (1957) described ground water in Escambia County with special reference to the Brewton area. Cagle and Newton (1963) also described the ground-water resources of Escambia County, Ala.

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J. W. Powell and John Newton in Alabama reviewed and revised the table of geologic formations in Alabama. George Siple prepared the table of geologic formations in South Carolina and contributed other information on geology and hydrology.

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Barbara Stringfield assisted in the preparation of the final draft of the manuscript. Verda M. Dougherty not only checked the geologic nomenclature and the references to the literature but also carefully reviewed the entire report.

SUMMARY OF GEOLOGIC HISTORY AND STRUCTURE

As the geologic history and structure of the region of this report had a significant effect on (1) the water-bearing properties of the geologic formations, (2) the quality of the artesian water, (3) the present topography, (4) drainage, and (5) areas of recharge of the aquifers, a brief summary is given here. Some of the effects of the regional structure on the distribution, thickness, and lithology of the sedimentary formations have been described by Applin and Applin (1965, p. 1–80). Their interpretation of the structure at different stages in the tectonic history of central and southern Florida is shown in the cross sections from Marion County on the north to Monroe County on the south (1965, pl. 11).

The sea advanced over the region and retreated many times in the history of the Coastal Plain. After each retreat of the sea, formations exposed at the surface were affected by weathering and erosion. As stated by LeGrand (1962, p. 24–26), after the Cretaceous formations were deposited and the sea withdrew, a gradual seaward tilting of the Coastal Plain caused the sea in Tertiary time to advance and deposit sediments, chiefly limestone in the area of this report. After being deposited, some limestone formations were exposed to erosion and solution during the time the sea retreated from the region. Like the underlying Cretaceous formations, the

Tertiary deposits, chiefly limestone with dolomite and anhydrite, thicken in a general downdip coastward direction. In the Florida peninsula anhydrite increases downdip from the Ocala uplift. Inland and updip the limestone merges with sands and other clastic material in western Florida and adjacent parts of Alabama and Georgia and also in areas of outcrop in Georgia and South Carolina.

The Quaternary Period, which includes the Pleistocene and Recent, is very short in comparison with the Tertiary and Cretaceous. However, the changes in sea level during Pleistocene time caused significant changes in the formations that compose the principal aquifers. The Quaternary deposits are relatively thin, forming a surficial blanket of sand and unconsolidated material. In a few areas, marine limestone and shell marl represent the Pleistocene, as along the east coast and in southern Florida. Maximum thickness of these deposits is in southeastern Florida where they may be as much as 250 feet thick.

The outstanding feature of Pleistocene time was extensive continental glaciation in the northern hemisphere. Although this glaciation did not extend to the South Atlantic States, worldwide changes of sea level were caused by removal of water from the sea to form the continental glaciers. At times when the glaciers melted, as described by Cooke (1939), water returned to the sea, causing a rise in sea level. The sea retreated when climatic changes caused ice to accumulate on the continental glaciers, or ice sheets. The glacial chronology of Cooke, accounting for the changes in sea level, also involves crustal changes in the ocean basins.

According to Cooke's sequence, the highest and earliest stand of the sea in Pleistocene time was at 270 feet above the present level during the Aftonian Interglaciation when the Hazlehurst (Brandywine) [1] shoreline was formed at that altitude. All Florida was covered by the sea except a few high areas in the center and in the west. The sea retreated to a low stand, below its present level, during the Kansan Glaciation. The low stand was followed by a rise to a height of 215 feet (Coharie shoreline) above the present level in the Yarmouth Interglaciation. This rise caused by melting of continental ice, was followed by intermittent emergence of at least 170 feet above the present level, resulting from crustal changes in the ocean basins. When the sea retreated during the Yarmouth Interglaciation, it paused long enough to form shorelines as follows: Sunderland, 175 feet above the present level; Okefenokee, 150 feet; Wicomico, 100 feet; Penholoway, 70 feet; and Talbot, 42 feet. Sea level declined during the Illinoian Glaciation. The decline was followed by a rise in sea level to 25 feet above the present level in the Sangamon Interglaciation when the Pamlico shoreline was formed. After the accumulation of continental ice during early Wisconsin time, the sea retreated. Partial melting of the ice sheet in middle Wisconsin time caused the sea to rise to a height of about 6 feet above the present level, forming the Silver Bluff shoreline at that altitude. During late Wisconsin time, the sea retreated again, when continental ice accumulated. In Recent time, the sea rose to its present level. Changes in sea level during Pleistocene time modified the recharge and discharge of the principal artesian aquifer from time to time. During lower stands of the sea, water discharged from the aquifer at lower levels, resulting in deeper circulation of the artesian water. During high stands of the sea, recharge areas of the aquifer were submerged and some sinkholes and solution cavities in the limestone were filled with unconsolidated sediments. Some of the salt water that entered the region during Pleistocene time has not been completely flushed from the aquifer.

In general, the geologic formations dip toward the coast except where interrupted by local structures. Major structures in Florida include the peninsular arch and the Ocala uplift. The peninsular arch extending from southern Georgia to the vicinity of Lake Okeechobee forms the axis of the Florida peninsula (Applin, 1951, p. 3). Its crest of Paleozoic sedimentary rocks is near the center of the northern part of the peninsula about 60 miles west of Jacksonville (Toulmin, 1955, p. 210). During Tertiary time, the Ocala uplift formed, parallel to and about 60–70 miles southwest of the peninsular arch. The crest of the uplift in Citrus and Levy Counties is as much as 150 feet above sea level. In that area erosion has removed the formations younger than middle Eocene, exposing middle Eocene rocks.

TOPOGRAPHY

The area of this report is in the Coastal Plain province—a region of plains and low hills that extends inland to the Piedmont province, which forms the foothills of the mountainous regions farther inland. The Piedmont province is underlain by igneous and metamorphic rocks that extend under the sedimentary rocks of the Coastal Plain. In Alabama the Coastal Plain cuts across the south end of the Piedmont province. A belt of hills corresponding approxi-

[1] The name Hazlehurst was proposed by Cooke in 1925 but was rejected in favor of Brandywine. In 1952 Cooke replaced the term "Brandywine" with the term "Hazlehurst" to designate the 270-foot terrace.

mately to the inner border of the Coastal Plain is known as the Fall Line Hills because streams entering the Coastal Plain from the Piedmont form falls, or rapids, where they flow from the hard rocks of the Piedmont to the softer, more easily eroded rocks in the Coastal Plain.

Most of the area of this report is covered by coastal terraces of Pleistocene age which have been described by Cooke in South Carolina (1936, p. 2–9), in Georgia (1943, p. 103–116), and in Florida (1939, p. 11–59). These terraces range from a few feet above sea level along the coast to 270 feet above sea level in the interior. In some areas the lower terraces have been only slightly modified by erosional processes. In areas where limestone is at or near the surface, however, solution has resulted in sinkhole or karst topography. In the Fall Line Hills northwest of the terraces, some altitudes are as much as 600 feet above sea level.

The sinkhole or karst areas form the lake regions in the uplands extending from southern Florida into southern Georgia. There are no sinkholes east of these regions on the lower terraces in the area of artesian flow in southeastern Georgia and northeastern Florida. A few sinkholes are present on the coast in southwestern Florida. North of Tampa Bay the sinks become more numerous and are abundant in Citrus and Levy Counties. In the coastal areas sinkholes were submerged and filled with sediments when the sea covered the area in Pleistocene time. In the areas where the limestone is near the surface, however, the sediments in many of these filled sinkholes were removed by circulating water after the sea retreated.

PHYSICAL DIVISIONS

For convenience in the following discussion, the report area is divided into physical divisions (fig. 2).

DIVISIONS IN FLORIDA

In describing the topography of Florida, Cooke (1939, p. 14) divided the State into five divisions: (1) Coastal Lowlands, or Coastal Terraces, extending northward to Georgia and South Carolina on the Atlantic coast and to Alabama on the gulf coast, (2) Central Highlands extending from southern Florida into southern Georgia, where the division merges with the high coastal terraces, (3) Tallahassee Hills, a strip about 25 miles wide and 100 miles long bordering Georgia between the Withlacoochee River on the east and the Apalachicola River on the west and extending northward into the Tifton Upland in southern Georgia, (4) Marianna Lowlands in Jackson, Holmes, and Washington Counties in western Florida and in Georgia merging with the Dougherty Plain, which extends northeastward to the Louisville Plateau in eastern Georgia, (5) Western Highlands extending westward from the Apalachicola River to the Perdido River, the boundary between Florida and Alabama. The westernmost part of the Western Highlands extends northward to the Alabama line, and the easternmost part forms a narrow belt between the Marianna Lowlands and the Coastal Lowlands.

COASTAL LOWLANDS

The altitude of the Coastal Lowlands bordering the Atlantic and gulf coasts ranges from sea level to about 100 feet above sea level. In the Florida panhandle, areas west of Tallahassee and south of the Tallahassee Hills are in this division. The area consists chiefly of nearly level plains or terraces formed during Pleistocene time by invasions of the sea which left shorelines at 100, 70, 42, 25, and about 6 feet above the present sea level. The marine terraces corresponding to these shorelines are named, from highest to lowest, the Wicomico, Penholoway, Talbot, Pamlico, and Silver Bluff. The Pamlico terrace is the most extensive and least dissected. The Coastal Lowlands are widest in southern Florida. They are narrowest on the gulf coast in Citrus and Hernando Counties and in the area west of Choctawhatchee Bay in Walton County. At Pensacola, they are only 10 to 12 miles wide.

On the Coastal Lowlands in southern Florida, the Everglades, a frequently flooded region of about 4,000 square miles generally not more than about 16 feet above sea level, extends southward from Lake Okeechobee to Florida Bay. West of the Everglades is Big Cypress Swamp. Details of Coastal Lowlands in southern Florida and a contour map showing the elevation of the limestone floor of Lake Okeechobee and the Everglades are given by Parker (in Parker and others, 1955, p. 147–155).

CENTRAL HIGHLANDS

The Central Highlands extends from the Florida peninsula to the Okefenokee Swamp in southern Georgia. The altitude ranges from less than 40 feet in some valleys to 325 feet on the top of Iron Mountain near Lake Wales in Polk County, Fla. The division includes high hills, swampy plains, and thousands of lakes. Sinkholes and sinkhole lakes are present in most of the region, including the Valdosta area in Georgia.

As stated by Cooke (1945, p. 8), the most extensive plain in the Central Highlands is the Sunderland terrace formed when the sea stood approximately 170 feet above its present level. The terrace covers several counties in the northern part of Florida and adjacent parts of Georgia and includes the Okefenokee Swamp. The Sunderland terrace is well developed in Manatee, Hillsborough, and Polk Counties; there are small remnants scattered throughout the Central Highlands. The Sunderland sea covered Florida, except a few islands in the Central Highlands and part of western Florida adjacent to the Georgia and Alabama State lines. The largest of these islands, in the northwestern part of Putnam County, Fla., extended as a sandy peninsula and bar into Georgia (Cooke, 1939, p. 35, fig. 12). The remnant of this sandy peninsula is now known as Trail Ridge.

TALLAHASSEE HILLS

The Tallahassee Hills ranges in altitude from less than 70 to about 340 feet above sea level. As shown by topographic maps, the highest point near Dog Town in the northern part of Gadsden County seems to be remnants of a plain, about 330 to 240 feet above sea level, underlain by red sand mapped by Cooke (1945, p. 9) as the Citronelle Formation. The rest of the area generally consists of rolling hills cut into the Citronelle and the underlying clayey sand and fuller's earth of the Hawthorn. Some large lake basins formed by solution in the limestone are near Tallahassee. The Tallahassee Hills merges with the Tifton Upland, which extends northeastward across Georgia between the Coastal Terraces on the southeast and the Dougherty Plain and Louisville Plateau on the northwest.

MARIANNA LOWLANDS

The Marianna Lowlands (including Jackson, Washington, and Holmes Counties) is underlain by the Ocala and other limestones of the principal artesian aquifer. The division in Florida is bounded by the Alabama State line on the north, by the Apalachicola River on the east, and by the Western Highlands on the south and west. The Ocala Limestone crops out in several areas, the largest of which is north of Marianna, where many springs flow into the Chipola River. A large part of the Marianna Lowlands is underlain by the Suwannee Limestone. The Tampa Limestone is present in a narrow band around the south margin (Cooke, 1945, p. 10). Limestone solution accounts for the low rolling hills and hollows. There are many shallow sinkholes and depressions resulting from sinks. Many sinks contain ponds or small lakes. Altitudes range from less than 50 feet along the Apalachicola River to as much as 209 feet near Marianna. The Marianna Lowlands extends into Alabama and Georgia. In Georgia it merges with the Dougherty Plain in the Flint River valley.

WESTERN HIGHLANDS

The Western Highlands, between the Perdido and Apalachicola Rivers, extends inland from the Coastal Lowlands to the Alabama State line, except in a narrow belt south of the Marianna Lowlands. The division includes the valleys of the Escambia and Yellow Rivers and several other streams. The altitudes range from sea level to more than 300 feet above sea level. One of the highest points (a few miles southeast of Chipley in Washington County) is 340 feet above sea level. This place seems to be part of the same plain, represented in a small area near Dog Town in the Tallahassee Hills. The northern part is hilly, the altitude being about 300 feet; the southern part is a broad, gently rolling upland ranging in altitude from approximately 100 to 270 feet above sea level. The plateau is deeply trenched by narrow, steep-walled valleys which cut down almost to sea level. The areas below 270 feet include remnants of three marine terraces—Hazlehurst (Brandywine), Coharie, and Sunderland (Cooke, 1939, p. 17). The heads of several streams in the northern part of the De Funiak Springs quadrangle are circular depressions that seem to have formed as sinkholes or lakes; they were later captured by headward growth of surface streams. Cooke lists Lake Sylvia, 4 miles west of De Funiak Springs, as an example of a sinkhole lake on the verge of being captured by Fish Pond Branch. Lake Sylvia is about 60 feet below the upland in a funnel-shaped sink. There are many sinkhole lakes ranging from about 75 feet above sea level in the Coastal Lowlands to more than 100 feet above sea level in the Western Highlands.

Youthful tributaries of the Yellow River and young streams flowing southward to the Coastal Lowlands in Santa Rosa and Okaloosa Counties have valleys with steep walls at their heads which are known as steepheads. These features have given rise to such geographic names as Mossy Head, Bear Head, Deer Head, White Head, and Deep Head. As described by Sellards (1918, p. 27), Cooke (1939, p. 17), Vernon (1942, p. 28–29), and Moore (1955, p. 17), steepheads form in areas underlain by permeable sand overlying a clay bed or less permeable zone. Precipitation on the surface moves downward instead of flowing over the surface of the ground. After reaching the less permeable zone, the water moves laterally and forms a spring where the less permeable beds crop out. The flow of the spring causes the permeable sand at the head of the spring to slump into the spring, and the flow carries it downstream. The headward movement of the spring forms the steephead. A waterfall may form in an area where the less permeable beds have sufficient resistance and are far above the zone of saturation in the underlying sand.

DIVISIONS IN GEORGIA

In Georgia, Cooke (in LaForge and others, 1925, p. 21–42) divided the Coastal Plain into: (1) Coastal Terraces that cover about half of the Coastal Plain, (2) Tifton Upland, a belt about 45 miles in average width adjacent to the Coastal Terraces, (3) Dougherty Plain and Louisville Plateau, adjacent to the Tifton Upland, (4) Fort Valley Plateau, and (5) Fall Line Hills.

COASTAL TERRACES

This area in Georgia and South Carolina includes the Pleistocene terraces ranging from sea level to about 270 feet above sea level. The terraces represent sea bottoms laid bare by the retreat of the sea to successively lower levels. The inner margin passes from the Florida State line at Ochlockonee River near Thomasville and thence northeastward to the Savannah River at Sylvania. A large embayment of the Pleistocene sea extended up the Flint River valley from Florida and covered part of the Dougherty Plain. In Florida and Georgia the coastal terraces below 100 feet are shown as the Coastal Lowlands (fig. 2). The terraces above 100 feet in Florida are included as parts of the topographic divisions at higher levels because they have been dissected more than those in Georgia and South Carolina.

TIFTON UPLAND

The Tifton Upland is bordered by the Coastal Terraces on the southeast and the Dougherty Plain and Louisville Plateau on the northwest. It occupies a broad band crossing the middle part of the Coastal Plain. The Hawthorn Formation underlies the upland and extends coastward beneath the Coastal Terraces. The more resistant and less soluble sands of the Hawthorn overlying the limestones of the principal aquifer form a northwestward-facing scarp along the northwest edge of the upland, adjacent to the Dougherty Plain and Louisville Plateau. West of Pelham the altitude of the Dougherty Plain is 175 feet. Altitudes in the Tifton Upland range from less than 120 feet to about 400 feet, the maximum relief being 240 feet. However, the hills are generally about 100 feet high. Between Cordele and Waynesboro, the thickness of the Hawthorn decreases, and the Tifton Upland merges with the Dougherty Plain and Louisville Plateau where the Ocala Limestone grades into sand. Depressions caused by the solution of limestones beneath are scattered over much of the area. Shallow sinkholes occur along the escarpment adjacent to the Dougherty Plain and in other areas where the limestone is near the surface. They are circular, elliptical, or elongated depressions ranging from less than an acre to many acres in extent.

DOUGHERTY PLAIN AND LOUISVILLE PLATEAU

As described by Cooke (in LaForge and others, 1925, p. 40) the Dougherty Plain slopes from nearly 600 feet above sea level along the northwest border adjacent to the Fall Line Hills to about 160 feet at the edge of the Tifton Upland. The lowest point is about 50 feet above sea level at the mouth of the Flint River. The northwestern part of the plain is rolling; the wider areas between streams are generally flat, as in Sumter County. In a large area in the Flint River valley where limestone is at or near the surface, sinkhole topography was modified by an embayment of the Pleistocene sea which extended up the Chattahoochee-Flint River basin. The plain has many shallow, saucer-shaped sinks or depressions that have been formed by the collapse of caverns in the soft soluble limestone. Most of the drainage is underground.

The Louisville Plateau, an area of wide flat uplands, between the Fall Line Hills and the Tifton Upland extends about 90 miles from the Oconee River to the Savannah River. Its maximum width is about 20 miles. The altitudes of a typical upland in Jefferson County range from about 500 feet above sea level to about 320 feet in the vicinity of Louisville. Some valleys are cut as much as 100 feet below the uplands. The plateau at Louisville is shown on the map of Stapleton quadrangle. The outline of the plateau is determined in part by the distribution of the red sand of the Barnwell Formation, which is easily distinguished from the gray sands of the Hawthorn Formation of the Tifton Upland.

FORT VALLEY PLATEAU

The Fort Valley Plateau, also underlain by the red clayey sand of the Barnwell Formation, occupies an area of about 300 square miles between the Flint and Ocmulgee Rivers. It adjoins the Fall Line Hills on the west, north, and northeast and the Dougherty Plain on the southeast and south. The plateau is nearly flat but slopes gently southeastward. The town of Fort Valley, after which the plateau was named, is 522 feet above sea level (LaForge and others, 1925, p. 42). On the west the plateau descends about 300 feet to the Flint River Valley.

FALL LINE HILLS

The area of hills and valleys, corresponding approximately to the outcrop of the Upper Cretaceous sands and clays, extends across Georgia adjacent to the Piedmont province. The area ranges in width from about 80 miles along the Chattahoochee River to a minimum of 3 or 4 miles east of the Flint River.

DIVISIONS IN SOUTH CAROLINA

In South Carolina the Coastal Plain, 120 to 150 miles wide, includes an area of more than 20,000 square miles. Cooke (1936, p. 3) divided the Coastal Plain into five parts: (1) the Coastal Terraces which cover more than two-thirds of the Coastal Plain, (2) the Aiken Plateau, (3) the Richland Red Hills, (4) the High Hills of Santee, and (5) the Congaree Sand Hills.

The Coastal Terraces extend inland from the seashore about 90 miles. The altitudes range from sea level to about 270 feet above sea level. Each terrace is defined by the level shoreline at which the sea stood when the terrace was under water.

Between the valleys of the Savannah and Congaree Rivers, the Aiken Plateau extends northwestward from the edge of the Coastal Terraces to the Piedmont Plateau in Edgefield and Saluda Counties and to the Congaree Sand Hills in eastern Aiken County and in Lexington and Calhoun Counties. The Aiken Plateau slopes southeastward from 660 feet above sea level west of Trenton in Edgefield County to about 270 feet at the point where it merges with the Coastal Terraces. Near Aiken, the plateau ranges in altitude from 550 to 500 feet. It is separated from the Louisville Plateau in Georgia by the Savannah River. The less dissected parts of the Aiken Plateau contain undrained depressions that appear to be shallow sinkholes. Cooke suggested that they may have resulted from solution of marl or limestone. Smith (1931, p. 641–652) and other investigators have suggested that they are caused by solution of iron and aluminum from sandy sediments. The Aiken Plateau is underlain chiefly by the Barnwell and McBean Formations, both of which contain calcareous beds. There are similar depressions on the Louisville Plateau, which also is underlain by the Barnwell. Many shallow depressions on the Pamlico and other Pleistocene terraces are surficial irregularities formed on the floor of the ocean or in shallow water of tidal marshes when the sea stood at a higher level. These shallow surficial depressions, many of which are partly enclosed by low sandy ridges, include Carolina Bays (Cooke, 1936, p. 7; 1954, p. 195–205).

The Richland Red Hills in the eastern part of Richland County and the High Hills of Santee in the western part of Sumter County and the southwestern part of Lee County are on opposite sides of the Wateree River between the Coastal Terraces and the Congaree Sand Hills. They are underlain by the hard clayey sand of the Black Mingo Formation of early Eocene age. The altitudes are as much as 400 feet above sea level. The High Hills of Santee rises as a low ridge above the gently sloping coastal terraces.

The Congaree Sand Hills, extending from the Aiken Plateau in Aiken County into North Carolina, adjoins the Piedmont Plateau on the northwest. On the southeast, it adjoins the Aiken Plateau, the Coastal Terraces, the Richland Red Hills, and the High Hills of Santee. They correspond approximately to the area in which the Tuscaloosa Formation of Late Cretaceous age is at or near the land surface, similar to the Fall Line Hills in Georgia.

DRAINAGE

RELATION OF DRAINAGE TO THE PRINCIPAL ARTESIAN AQUIFER

Streams of two general types drain the Coastal Plain—through-flowing streams and streams that rise within the Coastal Plain. All the through-flowing rivers have deep, wide, flat-bottomed valleys. Water in the streams from the Piedmont is generally colored with yellow or red mud. The streams that rise in the Coastal Plain are seldom muddy, but in many of them the water is brown or black because of the color received from leaves, straw, and other vegetable matter.

Stringfield (1964, p. 164–169) described the relation of artesian water to surface drainage. The main source of several limestone springs and of some streams is discharge from the principal artesian aquifer where it is at or near the surface. During flood stage, water from the larger streams may enter the aquifer, but recharge is chiefly in interstream areas. In recharge areas, the water level in the principal aquifer may represent the water table, but in other areas, there is a separate water-table aquifer, wherein the water table may be above or below the piezometric surface of the artesian water.

Natural discharge of the principal aquifer occurs through springs, in surface streams (at places where the aquifer is exposed), in the ocean, and by upward leakage into the overlying formations. Movement of water in the principal aquifer in coastal Georgia is northeastward toward a submarine discharge area northeast of Savannah. In the Flint River valley in Georgia and in some areas in north and north-central Florida, the major streams occupy channels cut into the aquifer, and water discharges from the aquifer into the stream. In the discharge areas, the chemical quality of the artesian water affects the quality of the surface water.

Drainage patterns, except on the Coastal Terraces, were well established before the beginning of the Pleistocene Epoch and probably have undergone little change since that time. As stated by Cooke (1936, p. 13), during the Pliocene Epoch the seashore probably lay somewhere within the area now occupied by the Coastal Terraces, at least the part covered by the Waccamaw and other marine formations of Pliocene age. Cooke suggested that the sea may have stood about 100 feet higher upon the land than it does today. Widespread earth movements at the end of Pliocene time depressed the land about 170 feet and left the sea at the Hazlehurst (Brandywine) shoreline, about 270 feet above the present level. Wide valleys of streams flowing from the Piedmont province to the Coastal Plain were converted to bays heading at the Fall Line. Tidewater extended up the valleys. When the sea retreated in Pleistocene time, the large rivers appear to have reoccupied their partly silted valleys and flowed across the newly exposed ocean floor, following the slope of the land. This process was repeated during each subsequent lowering of the sea. During each interglaciation, when the sea flooded the land, coastal features such as bars, islands, and spits were built along the shore. These features diverted many of the smaller streams from their direct course to the sea. The courses of some of the streams, like the St. Johns River in Florida, were influenced by tidal lagoons where there were offshore islands and bars parallel to the coast. As stated by White (1958, p. 17) and Cooke (1939, p. 109), most of the valleys parallel to the coast seem initially to have been long narrow lagoons, bays, or sounds behind offshore bars. The larger streams, like the St. Johns, probably resembled the present Indian River and similar lagoons, which closely parallel the present east coast of Florida.

The stream patterns and drainage have been influenced by underground solution in some areas where the limestone is at or near the surface. The streams that rise in the Piedmont province and flow across the Coastal Plain province into the Atlantic Ocean include the Savannah River, the Ogeechee River, and the Oconee and Ocmulgee Rivers which join to form the Altamaha in the Coastal Plain of Georgia. The major stream entering the Gulf of Mexico is the Chattahoochee or Apalachicola River. The river, called the Chattahoochee in Alabama and Georgia and the Apalachicola in Florida, rises in the Piedmont province and flows across the Coastal Plain into the gulf where it forms a delta. The Flint River, a tributary of the Chattahoochee in Georgia, has cut its channel at least 15 feet below its flood plain. The Flint, flowing on the principal artesian aquifer in much of its lower course, has been a factor in the formation of the escarpment that separates the Tifton Upland from the Dougherty Plain.

Streams in the Coastal Plain rise in the area underlain by Tertiary formations. The Conecuh River, which forms one of the principal drainage systems in south-central Alabama, rises in the area where Cretaceous formations are at or near the surface, flows southwestward to the Florida State line, thence southward as the Escambia River to the gulf. The Pea River and some of its tributaries in southeastern Alabama rise in the Cretaceous area. They flow southward across the Tertiary formations in Alabama to the Florida State line near Geneva, Ala., where they join to form the Choctawhatchee River, which has built a large delta at the head of Choctawhatchee Bay (Cooke, 1939, p. 105) on the gulf.

Among the streams that drain western Florida and south-central and southeastern Alabama are: the Perdido and Yellow Rivers, which rise in Alabama, and the Chipola River, which rises in an area where the principal artesian aquifer is at or near the surface (as in Jackson and Washington Counties, Fla.; and adjacent parts of Alabama) and flows into the Apalachicola River. The Apalachicola is formed by the confluence of the Chattahoochee and the Flint at the southwest corner of Georgia.

The Ochlockonee River, the Aucilla, and the Suwannee and its two principal tributaries—the Withlacoochee and the Alapaha—rise in southern Georgia and flow southward across Florida to the gulf. The Santa Fe River is a tributary of the Suwannee in Florida. South of the Tallahassee Hills, between Ochlockonee and Suwannee Rivers, much of the drainage is underground through sinks and channels in the limestone of the principal aquifer.

The St. Marys River rises on the Coastal Terraces in Georgia and flows southward, before turning northward and eastward along the Florida-Georgia boundary to reach the Atlantic Ocean. The Satilla River, which drains southeastern Georgia, rises within the area underlain by the Tertiary formations and discharges into the Atlantic Ocean at a point north of the St. Marys River.

SUWANNEE, WITHLACOOCHEE, AND SANTA FE RIVERS

The Suwannee River heads in the Okefenokee Swamp in southern Georgia and northern Florida, flows southward nearly to White Springs, then turns northwestward to its junction with the Alapaha. It flows southwestward past Dowling Park, circles southeastward to the mouth of the Santa Fe, then southward to the Gulf of Mexico (Cooke, 1939, p. 106). Cooke suggests that, when the Sunderland terrace emerged from the Pleistocene sea, natural drainage toward the east was blocked by Trail Ridge, which impounded the water in Okefenokee Swamp. The overflow from this swamp followed the natural slope of the land southward until it was diverted westward by the higher ground surrounding Lake City. Beyond White Springs the overflow was influenced by underground drainage into cavernous limestone, by oscillations of the sea level, and other factors. Over most of its course the Suwannee flows on limestone of the principal artesian aquifer. Above White Springs the Suwannee, having cut through the thin deposits of the Sunderland terrace, flows on the Hawthorn Formation. Below White Springs the Suwannee flows in a channel in the Suwannee Limestone. Beyond the mouth of the Withlacoochee it has cut through the Suwannee Limestone into the Ocala Limestone. There is an exchange of water between the river and the cavernous aquifer; the direction of exchange depends on the stage of the river with reference to the piezometric surface of the artesian water along the river. This relationship is also present on the lower part of the Withlacoochee and the Santa Fe Rivers.

The Santa Fe River rises east of the Suwannee and flows westward in an upland region in Florida where the Hawthorn Formation overlies the principal artesian aquifer. In its lower course it flows on and in the limestone of the principal artesian aquifer. As described by Clark and others (1962, p. 39–48), the flow characteristics in the upper part and the lower part of the Santa Fe basin differ considerably. The flow characteristics change abruptly in the vicinity of O'leno State Park, about 6 miles north of High Springs, where the river disappears underground, then reappears about 3 miles away. Below that point streamflow increases rapidly as the river flows through a channel cut in the principal artesian aquifer. Almost all the pickup in flow in the lower basin is from the artesian aquifer. Few tributary streams feed the lower river except those that flow from springs, such as the Ichatucknee Springs near Hildreth. In the lower part of the basin the section of the river between High Springs and Fort White has an average annual runoff of 84.7 inches per square mile—more than 1½ times the annual rainfall on the 130-square-mile area. This runoff is the highest of any area of like size in Florida.

The upper part of the river is fed by tributaries that drain almost the entire area of Bradford and Union Counties and the northern part of Alachua County. Much of the streamflow occurs as direct runoff from lakes, lowland areas, and overland flow. Small headwater streams cease flowing during extended periods of deficient rainfall. The average annual runoff at the Worthington gaging station is 8.4 inches per year, based on 27 years of record.

STREAMS SOUTH OF THE SUWANNEE RIVER

Six major streams discharge into the Gulf of Mexico on the west coast of the Florida peninsula. The Withlacoochee River rises in Polk County, flows westward, turns to a generally northerly course past Tsala Apopka Lake, then turns westward to the gulf. The Hillsborough and Alafia Rivers enter Hillsborough Bay at and near Tampa. The Manatee and Little Manatee enter Tampa Bay south of Hillsborough Bay. The Peace River rises in Polk County and flows southward into Charlotte Harbor. The Myakka River rises in Manatee County and flows southwestward, thence southeastward parallel to the coast into Charlotte Harbor. The Caloosahatchee River flows from Lake Okeechobee to the gulf. The upper part of the Caloosahatchee River is connected to the lake by a canal forming part of the Okeechobee Waterway that crosses Florida through Lake Okeechobee. The Kissimmee River rises in Orange County in central Florida and flows southward to Lake Okeechobee, which flowed southward into the Everglades before levees for flood control were constructed on the south side of the lake.

As described by White (1958, p. 27–33), the Kissimmee River is in consequence to an emergent marine surface. The drainage formed as the Pleistocene sea retreated from the Wicomico shoreline about 100 feet above the present sea level. The lower part of the valley and southern Florida were covered by the sea again during Pamlico time. The discharge from Lake Okeechobee is now through canals to the gulf through the Caloosahatchee River and to the Atlantic Ocean through the St. Lucie River and canals. The canals are controlled by locks. A levee on the border of the south half of the lake from Moore Haven to Port Mayaca prevents the lake from flooding the adjacent areas during tropical storms that used to sweep the water of the shallow lake over its natural levee. Also a levee has been constructed along the north shore to protect the low area between the lake and the town of Okeechobee, which is on high ground. Levees around the remainder of the lake are authorized and partly under construction (Nevin Hoy, written commun., 1962). The Miami canal extends from the south end of the lake into the Everglades. Although the middle section of the canal has not been excavated, the south end of the canal passes through Miami and drains water from the Everglades to Biscayne Bay at Miami.

WITHLACOOCHEE RIVER

Two streams in the area of this report are named Withlacoochee; one is a tributary to the Suwannee in Georgia, and the other is in Florida. The Withlacoochee River and Peace River in Florida are the longest streams south of the Suwannee. White (1958, p. 19–27) gives a description of the Withlacoochee in Florida and its relation to the Hillsborough River with a profile of the Withlacoochee, a planimetric map, and an aerial photograph of the area in which the Hillsborough reaches the Withlacoochee. The Ocala Limestone and the Suwannee Limestone of the principal artesian aquifer are at or near the surface in the area through which the Withlacoochee flows from Hernando County to the gulf. The Tampa Limestone of the principal aquifer is at or near the surface in the area of the lower course of the Hillsborough River. Solution of the limestone in both areas has influenced the course of the rivers. As suggested by White, it is entirely possible that the upper course of the Withlacoochee was formerly a part of the Hillsborough River. Sinkhole topography formed in the areas where the limestone was at or near the surface during a low stand of the sea in Pleistocene time. Probably most of the drainage was through sinkholes. The areas through which both rivers flow at the present time were covered by the Pleistocene sea when it stood about 100 to 150 feet above the present sea level. During that time sinkhole topography which had formed in the area of Lake Tsala Apopka was covered by sediments on the ocean floor. As the sea withdrew, Lake Tsala Apopka and the northward route of the Withlacoochee formed along with the capture of the upper part of the Hillsborough River.

The lower courses of the Withlacoochee and the Hillsborough Rivers in the area, less than about 25 feet above sea level, were covered by the Pamlico area. When the Pamlico sea retreated to a position below the present sea level, the lower course of the Withlacoochee was formed. In discussing Lake Tsala Apopka, the Withlacoochee River, and other streams in Citrus and Levy Counties of Florida, Vernon (1951, p. 29–37) explained the influence of jointing and faulting and other structures on the courses of some streams. He stated that the Withlacoochee is clearly antecedent and the fold of the Ocala uplift has ponded the river above Dunellon, forming Lake Tsala Apopka. However, the present writer prefers the explanation in which solution of the limestone and influence of eustatic changes of sea level were controlling factors in the formation of the lake.

ST. JOHNS RIVER

On the east coast of Florida, the St. Johns River is the dominant stream. It flows northward through a wide shallow valley nearly 275 miles from its headwaters in the Coastal Lowlands to Jacksonville, thence eastward into the Atlantic Ocean (Cooke, 1939, p. 108–109). At its source, it is approximately 20 feet above sea level (D. W. Brown and others, 1962, p. 7). In the headwaters of the basin the stream forms a definite channel at Lake Hellen Blazes. The stream channel is interrupted by many lakes. The river flows northward to Lake Harney in Seminole County, then turns westward to Lake Monroe. From there it continues its general northward course to Jacksonville where it turns eastward and enters the Atlantic at Mayport. The main use of the St. Johns River is for navigation (Clark and others, 1962, p. 39). The controlled depth of channel from the ocean to Jacksonville (25 miles) is 30 feet; from Jacksonville to Palatka (55 miles), 13 feet; from Palatka to Sanford (90 miles), 8 feet; and from Sanford to Lake Harney (26 miles), 5 feet. The channel between the ocean and Jacksonville is relatively narrow and well defined, rarely exceeding 30 feet in depth. At Jacksonville the width of the river is reduced to about 500 yards, and the channel is scoured by tidal currents to a depth of about 70 feet (Cooke, 1939, p. 108). Between Jacksonville and Palatka, the river has no well-defined channel. It ranges in width from nearly a mile to more than

3 miles. The depth rarely exceeds 30 feet, and near the shores it is 10 feet or less. As stated by Cooke, tidal marshes between Palatka and Lake George narrow the river to a relatively uniform width, averaging 400 or 500 yards, the maximum depth of 37 feet being below Murphy Creek. The river is about 6 to 7 miles wide in Lake George and 9 to 11 feet deep. The lake is about 11 miles long. Between Lake George and Lake Harney, the river is not more than 100 yards wide and 8 to 20 feet deep, with expansions in width at Lake Dexter (2 to 20 feet deep). The range of the tide at Palatka is 2.9 feet (Cooke, 1939, p. 108). At times the chloride content of the water is relatively high because of tidewater in its lower course and discharge of springs, like Salt Springs near Lake Kerr and many small springs along the river between Lake George and Lake Harney where beds overlying the principal aquifer have been cut by the river.

Cooke suggests that the valley of the St. Johns River above Lake Harney came into existence in late Pleistocene time, when a barrier island, now on the east bank of the river, accumulated in the Pamlico sea. The remainder of the valley also consisted of lagoons and sounds during Pamlico, but, as Cooke states, these depressions had an earlier origin. At the time of a low sea level, 300 or more feet below the present sea level, sinkholes and large lake basins formed in the areas where the limestone was at or near the surface and where the Hawthorn Formation was thin or had been removed by erosion. Because the St. Johns valley from Palatka to Lake Harney is a region of sinkholes and solution basins, it seems plausible that the present channel was formed by solution and erosion. After the Continental Shelf was exposed as the sea reached lower levels, probably most of the drainage in that part of the valley was underground through sinkholes and lake basins. In northeastern Florida and southeastern Georgia, where the Hawthorn Formation is as much as 500 feet thick, erosion did not expose the limestone of the principal aquifer as it did farther south. Therefore, the surface streams were not affected by the artesian aquifer.

The discharge of the St. Johns River onto the gentle slope of the Continental Shelf might suggest that no deep river channels would be cut in areas offshore from northeastern Florida and southeastern Georgia, where the soluble limestone has not been exposed to surface streams. However, it seems likely that these stream channels were cut on the Continental Shelf but are now covered by sediments on the ocean floor. The channels of some of the drowned valleys along the coast, as that of the St. Johns and Nassau Rivers, show that they were cut to at least 60 feet below sea level. A river channel, probably an ancestral channel of the Susquehanna River, was cut to a depth of 200 feet below sea level in Chesapeake Bay at the Annapolis Bridge crossing (Hack, 1957, p. 817–830) in Maryland. Another river channel was cut 370 feet below sea level at Cape Henry (Harrison, 1962, p. 47, 52, 53) during Pleistocene time. It seems reasonable therefore that there are buried Pleistocene channels both under the coastal terraces and offshore in the report area.

OKLAWAHA RIVER

As stated by Cooper and Kenner (1953, p. 151), not only the Oklawaha River but most of the major streams in central and northern Florida, including the Suwannee, Santa Fe, St. Johns, Withlacoochee, and Hillsborough Rivers, receive a large part of their flow from artesian springs. The flow of the Oklawaha is sustained at medium and low stages by Silver Springs. The Oklawaha rises in a group of large lakes including Lake Griffin, Lake Eustis, Lake Harris, and Lake Dora in Lake County. It flows northward across Marion County and turns eastward to the St. Johns River between Lake George and Palatka. As suggested by Cooke (1939, p. 109–110), the Oklawaha is older than the St. Johns River, and some of its headwaters probably have been in existence since the Sunderland terrace emerged from the sea. The Oklawaha valley was filled with unconsolidated sediments which have remained to the present time. The area of the St. Johns valley remained submerged until the retreat of the Talbot sea. During the low stand of the sea after Talbot time, sediments in the channel of the St. Johns River probably were removed. The valley was covered again by the sea in Pamlico time, but the channel was not completely filled or was reopened to a depth of as much as 60 feet during a low sea level in the late Pleistocene.

LAKES

Lakes are especially numerous in Florida, where it is estimated there are 30,000 named lakes (U.S. Cong. Senate Select Comm., 1960, p. 40). Of about 250 fresh water lakes in the United States, with a surface area of 10 square miles or more, 19 are in Florida (Bue, 1963, p. 18). Lake Okeechobee in Florida is the second largest fresh-water lake in the United States. Many of these large lakes in Florida occupy solution basins in limestone. Lake basins in the area of this report may be placed in two groups according to origin. One group is formed chiefly by the solution of limestone or other soluble rocks; the other group is formed by forces working on surficial material, which include original depressions and hollows on the former ocean floor that is exposed by the retreat of the sea. Lakes that were formed chiefly by solution include those affected by jointing or faulting. The lakes formed by solution of limestone are especially significant in a study of the principal artesian aquifer because the lake basins may be recharge areas under certain conditions. Under other conditions if there were a lowering of sea level, as in Pleistocene time, many of the larger artesian springs in sinkholes—such as the two salt springs in Sarasota County—would stop flowing and form lake basins. Also, some submarine springs, discharging from sinkholes off the coast of Florida at the present time, would form lakes.

Most, if not all, of the lakes in the areas where the limestone of the principal aquifer is at or near the surface are in basins formed chiefly by solution of the limestone and collapse of a section of a cavern roof. Most of the lakes in the lake region in the Central Highlands of Florida occupy old partially filled sinkholes. They range in size from mere ponds to lakes several miles wide, such as Lake Apopka. Many lakes have no surface outlets, but some are connected and drain into rivers, or they form part of the river such as the lakes through which the St. Johns flows. Most of the lakes are shallow, although some of the sinks that have not been filled with sediments have deep water. The solution basins extend into western Florida, southeastern Alabama, and southwestern Georgia, including the large lake basins at the south edge of the Tallahassee Hills. The large lakes in central Florida, including Lake Apopka, Lake Harris, and others at the head of the Oklawaha River, appear to occupy solution basins similar to those near Tallahassee.

As stated by Cooke, (1939, p. 101), Crescent Lake, Lake George, and a series of smaller lakes that form expansions of the upper reaches of St. Johns River are remnants of Pamlico estuaries. However, except possibly for the lakes south of Lake Harney, the writer is of the opinion that all the lakes in the valley, including Crescent Lake, are in basins that originally were formed by solution of limestone during a low stand of the sea in Pleistocene time. The relatively high salinity of the artesian water southeast of Crescent Lake seems to indicate that sea water entered the aquifer through these sinks during a high stand of the sea.

The altitudes of the lakes in solution basins range from approximately sea level to more than 120 feet above sea level. The highest of these lakes in central and north-central Florida are in areas where sinkholes penetrated the Hawthorn or other relatively impervious beds overlying the principal artesian aquifer. In north-central Florida, Clark, Musgrove, Menke, and Cagle (1962, p. 19–38) reported that the lakes in Alachua, Bradford, Clay, and Union Counties range from about 175 feet to about 55 feet above sea level.

The lake basins formed by agents other than solution of limestone include Lake Okeechobee which occupies about 730 square miles. As stated by Cooke (1939, p. 101), the basin seems to have originated during late Pleistocene time as a slight depression in the bottom of the Pamlico sea. After the sea retreated, solution of the shell marl and other calcareous material at or near the surface may have occurred in the lake and its natural spillway in the Everglades to the south.

Apparently, as suggested by Cooke, Lake Istokpoga, Lake Kissimmee, and other lakes in the Kissimmee River basin in southern Florida originated as depressions in the ocean floor. However, lakes such as Lake Kissimmee and Lake Tohopekaliga in the northern part of the Kissimmee River valley, near areas where lake basins were formed by solution of underlying limestone, may also have originated as solution depressions that were filled and sealed by sediments on the ocean floor.

SWAMPS AND THE EVERGLADES

There are many areas with poor drainage on the Coastal Terraces, chiefly in the swamps and low grassy plains, which are called the Everglades in southern Florida. Locally, there are many swamps along the flood plains of streams and bordering tidal marshes.

The Big Cypress Swamp in northern Collier County in southern Florida and the Okefenokee Swamp in southern Georgia and northern Florida are the principal swamps of the region. In southern Florida the Everglades occupy a nearly level plain about 40 miles wide underlain by organic soil; the land slopes from about 15 feet above sea level at the south side of Lake Okeechobee to sea level at the tip of the peninsula, a distance of more than 100 miles (Cooke, 1939, p. 55). As the name implies, the Everglades are open grassy meadows. Much of the land is covered by tall sawgrass and other vegetation characteristic of organic soil. On the west the Everglades merge with the Big Cypress Swamp, which is on higher ground. The Everglades extend to the gulf coast south of the swamp. An arm of the Everglades extends northward between Lake Okeechobee and the Atlantic Coastal Ridge. Before parts of the Everglades were drained by canals and converted into farming land, water from Lake Okeechobee overflowed through a gap in the natural levee on its south side into the Everglades and passed southward across the Everglades to the Bay of Florida and Gulf of Mexico. In wet seasons, the Everglades are covered by water except for islands of higher ground. Unlike swamps, the Everglades have few trees.

In the Miami area, the Everglades are bordered on the east by a rim a few miles wide of white cross-bedded oolitic limestone of the Miami Oolite. North of the Miami area, oolite and the Anastasia Formation form the rim. Parker and Cooke (1944, p. 47, 51) show by contours the rock floor of the Everglades including Lake Okeechobee. They show by arrows the direction of surficial drainage in the Everglades and the Big Cypress Swamp. Before drainage canals were dug, part of the natural drainage of the Everglades between Miami and West Palm Beach was to the Atlantic through natural courses crossing the east rim of the Everglades, known as the Atlantic Coastal Ridge. A large part of the drainage is to the south and southwest to the Gulf of Mexico.

The Big Cypress Swamp is bounded on the east and southeast by the Everglades. On the south and southwest, it merges with the low-lying coastal marshes and mangrove swamps. Sandy flatlands border it on the north and west. The area to the north is slightly higher than the swamp; the area to the west is lower than the swamp. The drainage of the Big Cypress Swamp is to the east and south into the Everglades. North of the swamp and west of the Everglades in the Devils Garden in Hendry County, part of the drainage is northward to the Caloosahatchee River. The swamp is underlain by limestone riddled by solution at the surface. However, the limestone is thin, and the underlying Hawthorn Formation contains relatively impervious beds that separate the shallow limestone in southern Florida from the limestone of the principal artesian aquifer, the top of which is as much as 1,000 feet below sea level. Therefore, the solution cavities do not extend below the shallow limestone. Only five deep sinkhole lakes, all west of the Everglades, have been discovered in southern Florida, but there may be others filled with sand or other material. The sinkholes pass through the shallow limestone but appear to terminate in a permeable limestone zone of the Hawthorn.

The Okefenokee Swamp on one of the higher terraces in southern Georgia and northern Florida is the largest of the swamps. It covers an area of about 660 square miles (LaForge and others, 1925, p. 52) extending from a point about 5 miles south of Waycross southward beyond the Florida State line. Parts of several sand terraces extend around the swamp. The most prominent, known locally as Trail Ridge, marks the eastern extent of the swamp. The west margin is irregular because of tributary streams, as shown on the Valdosta topographic map, scale 1:250,000, U.S. Geological Survey, and by Fortson (1961, p. 6). The swamp slopes from about 120 feet above sea level in the northeastern part to about 100 feet above sea level in the southwestern part. Most of the water drains westward into the Suwannee River and to the Gulf of Mexico, but part of it drains southward to the headwaters of the St. Marys River, which cuts across Trail Ridge and to the Atlantic. The swamp contains many islands, remnants of sand terraces. Much of the swamp is forested, but there are areas of grassy prairie like the Everglades. On the lower ground are pond cypress, black gum, and several kinds of bay trees (LaForge and others, 1925, p. 53). Although there are lakes in Okefenokee Swamp, none is comparable in size to Lake Okeechobee in the Everglades or Lake Drummond in the Dismal Swamp of Virginia and North Carolina. Cooke (1939, p. 106) stated that when the area emerged from the sea in Pleistocene time, its natural drainage toward the east in the area of the Okefenokee Swamp was blocked by Trail Ridge, which prevented or retarded surface water drainage to the east. An exception is the St. Marys River which rises in the swamp and cuts across the ridge. The overflow of the swamp followed the natural slope of the land southward and formed the headwaters of the Suwannee River.

Cooke (1945, p. 313) suggested that some of the upland swamp, notably Okefenokee Swamp, has been in existence, probably with little change, since the Illinoian Glaciation, possibly earlier. During the time when the sea stood about 120 feet above its present level, the area of the swamp was part of a shallow sound bounded on the east by a bar, now Trail Ridge. The water in the sound rarely was deeper than 40 feet, but on the east side of Trail Ridge the water deepened rapidly to 100 feet or more. Parts of the swamp are underlain by peat deposits (Fortson, 1961, p. 1–21), some of which may be in sinkholes which were covered and filled by the Pleistocene sea. Peat is present in sinkholes in Lowndes County west of the swamp and also in depressions that appear to be filled sinks in Effingham and Screven Counties, Ga., north of the swamp near the South Carolina State line.

CLIMATE

The climate in this region ranges from temperate in the northern part of the report area to subtropical in southern Florida (U.S. Weather Bureau, 1958, p. 3). Annual precipitation ranges from about 50 inches in the northern part to 60 inches or more along the coast of Alabama and in some parts of Florida. The average rainfall for Florida is 53 inches. South of Miami the annual rainfall decreases to a minimum of 38 inches at Key West. Precipitation in southern Florida, within the belt of the northeast trade winds in the summer, reaches a peak in June. A larger peak in September and October is caused in part by hurricanes. The Caribbean and Atlantic hurricanes generally occur in later summer and autumn. At times rainfall exceeds 20 inches in 24 consecutive hours near the storm center. Thunderstorms during the summer months frequently result in heavy downpours, locally more than 20 inches in 24 hours. More than 90 thunderstorms per year have been reported in northwestern Florida, June and July being peak months.

Ferguson (in Parker and others, 1955, p. 54–56) estimated that evaporation losses from water bodies in Florida average 40 to 45 inches a year. He reported that the estimated mean annual evapotranspiration from sawgrass land in the Everglades near Belle Glade is about 60 inches a year. Fred M. Elliot showed that evapotranspiration was about 110 inches in a year by a test with paragrass growing in muck in a tank. The water level ranged between 0 and 12 inches below the top of the muck. During the same period a tank having water levels 30 to 36 inches below the top of the muck showed a loss of 50 to 60 inches.

The details of the climate in this region are given in reports of the U.S. Weather Bureau, Washington, D.C. Details of the climate in southeastern Florida are given by Ferguson (in Parker and others, 1955, p. 15–56).

SOILS AND THEIR RELATION TO AQUIFERS

There are many soils in the Coastal Plain, and their character and composition result in part from the geologic conditions during the deposition of the surficial formations and the nature and intensity of their weathering and erosion (LeGrand, 1962, p. 35).

Where topographic relief is adequate and the water table is not near the land surface, there is a tendency for dissolved solids and suspended matter to move downward from the surface soil and to be deposited in the subsoil. For example, the rolling Sand Hills region along the inner margin of the Coastal Plain in Georgia and South Carolina (Fall Line Hills, fig. 2) has a well-developed sandy soil separate from the clayey subsoil. However, where the land is flat and poorly drained, there is a tendency for the soil profile to be poorly developed.

A mature soil (Bryan, 1962, p. 5–6) is represented by layers or horizons of different thicknesses and colors. The upper layer may range from a few inches to several feet; it is known as the A horizon, or zone of leaching. The second layer, which has different thicknesses and colors, is known as the zone of accumulation, or B horizon. The parent material from which the soil develops is known as the C horizon. In the Coastal Plain, the thickness of the soils generally is greatest on the upland ridges, where they may be several feet thick with loose sandy subsoils. In Florida (Bryan, 1962, p. 12) reported that the Lakeland soil in the upland lake region of central Florida may have a depth of as much as 6 feet and that the Kershaw soils are deeper and less coherent than the Lakeland soils.

Much of the region of this report is blanketed by sandy soils underlain by a subsoil zone of clay, sandy clay, or clayey sand. Silica is the predominant mineral of the sand. Harper (1910, p. 40) stated that about 80 percent of the State of Florida could be roughly classified as sand, 3 percent as red clay, 12 percent as muck, and the remainder as limestone and marl. Bryan (1962) described various groups of soils with subdivisions and showed the distribution of 10 of these groups on a map (1910, p. 49). Soil maps and reports for many counties in the Coastal Plain have been published by the U.S. Department of Agriculture. Some reports include information on the percolation rates of water in undisturbed saturated cores. In general, the rates range from about 2.5 inches to 10 or more inches per hour. The rate for many of the soils was 10 or more inches per hour.

The 1938 yearbook of the U.S. Department of Agriculture (p. 1065–1122) showed seven categories of soils in the region of Tertiary formations in the southeastern States. The following discussion is chiefly from that report. Two of the most extensive of these groups of soils are the Leon-Bladen soils of the coastal terraces and coastal lowlands and the Norfolk-Ruston soils on the uplands.

COASTAL TERRACES AND COASTAL LOWLANDS

The area of the Leon-Bladen soils is chiefly on the coastal terraces (fig. 2). It includes the greater part of the flatwoods of Florida and Georgia and extends inland into the central uplands of Florida and the higher coastal terraces of Georgia. In northeastern Florida and southeastern Georgia, the area of these soils surrounds the peat and muck soils in the Okefenokee Swamp. In coastal Georgia the soils merge with another group of sandy soils that extends along the low terraces in South Carolina. The area is characterized by a dominantly flat to undulating surface, numerous low sand ridges, hummocks, ponds (some containing grass pondweed), swamps and marshes, and numerous tidal streams and estuaries. Natural drainage is poor except for the sand ridges. A characteristic feature of the Leon soils is a well-defined black to brown hardpan layer consisting of sand cemented by organic matter or other material. The Leon soils are light gray to gray fine sand, 4 to 8 inches thick, overlying light gray sand, 12 to 30 inches deep, resting on the hardpan. In some places there are two hardpans.

Bryan (1962, p. 23–28) described the Leon soils and three other series having hardpan as imperfectly drained acid soils. He included the Bladen soils with a series of poorly drained acid soils underlain by plastic sandy clay. The relatively impervious hardpan retards vertical movement of water and reduces recharge to the shallow aquifers. Locally, water under the hardpan is under slight artesian pressure. The hardpan makes conditions favorable for surface irrigation by means of shallow ditches and subirrigation as in the Sanford celery area in Seminole County, Fla.

The Leon-Bladen soils in Georgia and in eastern and southern Florida are underlain by the Hawthorn Formation and younger material. In the area on the west coast from Tampa Bay to Wakulla County, Fla., and extending inland to the Central Highlands and Tallahassee Hills, the soils are underlain by Eocene limestones and younger formations. In that area some soils are changed by the limestone formations containing phosphatic material. Parent materials of soils in the region covered by the Pleistocene sea may include Pleistocene deposits, chiefly sand and clay and material of older formations reworked by the sea.

The soils on the coastal terraces in the southern part of Florida, south of Lake Okeechobee, consist chiefly of peat and muck in the Everglades, extending southward from the lake almost to the coast. The area bordering the Everglades and extending to the coast in southern Florida is Perrine silt loam and rock land, where the Miami Oolite and other limestone and marl of post-Miocene age are at or near the surface. Bryan showed similar soils in an area adjacent to the north shore of Lake Okeechobee and along much of the shell ridge on the east coast, also in areas on the west coast. The Perrine silt loam, known locally as marl land, may be as much as 30 inches thick. However, there are extensive areas with covering of fine loose sand of very shallow silt loam and areas of mangrove swamp at tide level. In the vicinity of Redland there are small areas of brown or reddish-brown soil a few inches thick overlying the limestone. In addition to the large areas of muck land in the Everglades and Okefenokee Swamp, there are muck areas in the middle and upper St. Johns River valley. There are many smaller areas in sinkholes, ponds, and local depressions on the coastal terraces. Truck crops are grown in many of these areas, as in the Everglades and elsewhere, where the water level in the muck is controlled by drainage and irrigation. During wet seasons the water table may rise to the land surface in poorly drained muck areas. Some of the underdrained areas are covered with water. In the Okefenokee Swamp in southern Georgia and northern Florida, where peat and muck fill sinkholes, water may pass through these materials to the underlying Tertiary limestones of the principal artesian aquifer. Water in the shallow sands of the poorly drained areas may have relatively high organic color and iron.

UPLANDS

In the uplands (fig. 2), which includes the areas above the Coastal Terraces and Coastal Lowlands, the Norfolk-Ruston soils are the most extensive. Bryan (1962, p. 13–19) grouped these soils as well-drained acid soils. In the central Highlands in north-central Florida, the Norfolk-Ruston soils merge with the Norfolk-Blanton soils that occupy the upland lake region. The outstanding features of these soils are their extremely sandy texture, small amounts of organic matter, and strongly acid reaction. Drainage is good or excessive, except in some flat areas and slight depressions. The Norfolk soil, the predominant type, consists of a light-gray or yellowish-gray fine sand underlain at a few inches by yellow loose fine sand that at 3 to 4 feet grades into brownish-yellow loose fine sand. The sand at 5 to 10 feet is usually underlain by mottled yellow, light-gray, or brown fine sandy clay. Blanton soil differs from the Norfolk in being lighter colored in both surface and subsurface zones. In Florida Bryan groups the Blanton soils with Lakeland and other sandy soils in upland areas. On the northwest border at the Norfolk-

Ruston soil area is a narrow belt of Norfolk sand in the Fall Line Hills (fig. 2). The sands are yellowish gray to light gray underlain by pale-yellow loose incoherent sands to a depth of 3 to 80 feet.

Within the large area of the Norfolk-Ruston soils are the Greenville-Magnolia soils and the Tifton-Irvington soils. The Greenville-Magnolia soils extend from the Dougherty Plain in southwestern Georgia into Alabama and the Marianna Lowlands in Florida, where the Tertiary limestone is at or near the surface. A smaller area of these soils is on the Georgia-Florida State line where the Tifton Upland and Tallahassee Hills merge. The Hawthorn Formation of Miocene age is at or near the surface in that area. Several areas of these soils are in Florida west of Tallahassee. On the Dougherty Plain and Marianna Lowlands, these soils may be influenced by the underlying Tertiary limestone. However, at least part of the area was covered by the Pleistocene sea which reworked the unconsolidated material. The areas in Florida are underlain by the Hawthorn Formation and younger deposits. The soils are developed from limestone and beds of noncalcareous heavy sandy clay and clay. The surface soils are predominantly sandy with a moderately low mineral content and organic matter. They are mildly to strongly acid in reaction. Greenville soils have brown to reddish-brown surface soils and red to deep-red, or maroon, heavy sandy clay subsoil which may be influenced by limestone (Bryan, 1962, p. 16). Magnolia soils differ essentially from Greenville in having light-brown to gray surface soils and yellowish-brown subsurface layers.

The Tifton-Irvington soils occupy an area on the Tifton Upland (fig. 2) in southwestern Georgia underlain by the Hawthorn Formation. The surface is almost level, undulating, or gently sloping about 300 to 400 feet above sea level. The parent material is from unconsolidated beds of mottled red, light-gray, yellow, and purple hard brittle sandy clay. Outstanding characteristics are the large quantities of small rounded brown to almost black pebbles of ironstone one-eighth to one-half inch in diameter on the surface soil and to a less extent in the subsoils. Tifton soils differ from the Norfolk in having finer texture and iron pebbles throughout the profile. The Tifton soils, the dominant soils of the area, are grayish-brown to gray loamy sandy soils, 4 to 6 inches deep. The subsurface layers are yellow to brownish-yellow light-textured sandy loam. The subsoil begins at depths of 8 to 15 inches and extends to 30 to 36 inches. Irvington soils, which are not extensive, differ from Tifton soils in having a compact or cemented layer below the subsoil. Alluvial soils are present in flood plains of river valleys. Colluvial soils, brought down from higher elevations by either gravity or water, occur in depressions and along some streams.

In general, the sandy soils of the region are favorable for recharge of the water-bearing formations. Recharge through sandy soils underlain by permeable limestone is excellent because there is no runoff and little or no transpiration. The soils having hardpan or clayey subsoil retard the movement of water to the underlying aquifer. However, the hardpan makes it possible to irrigate the sandy soils. The clayey subsoils may be helpful in removing objectionable constituents during the movement of the water to underlying aquifers. In the area of sluggish drainage on the coastal terraces, a large part of the water evaporates or is transpired by vegetation instead of moving downward to an aquifer. Water from peat or muck acid soils may have relatively high organic color. The exceptions are those soils developed from beds of sands mixed with shells or beds of sand on limestone or marl.

GEOLOGIC FORMATIONS AND THEIR WATER-BEARING PROPERTIES

GENERAL FEATURES

The geologic formations that crop out in this area range in age from Late Cretaceous to Recent. They consist chiefly of alternating beds of limestone and marl with some sand, gravel, and clay. The outcrops, in general, are belts approximately parallel to the Fall Line, the inner boundary of the Coastal Plain. Except where affected by local structural features, the formations dip gently toward the coast at right angles to the belt of outcrops (fig. 3). This pattern of outcrops is broken by local geologic features, such as the Ocala uplift in Florida. The formations dip in all directions from the Ocala uplift.

Cretaceous formations underlying the Coastal Plain form the inner belt of outcrops adjacent to the area of this report. The altitude on top of the Cretaceous is indicated approximately by contours on the tectonic map of the United States. In northern Florida the top ranges from less than 2,000 feet below sea level in the panhandle to more than 6,000 feet in southern Florida. Along the Fall Line in Georgia, Cretaceous formations are as much as 600 feet above sea level (Herrick and Vorhis, 1963, fig. 14). They dip southeastward to more than 2,800 feet below sea level in southeastern Georgia. The Cretaceous formations overlie igneous and metamorphic rocks, as shown by Applin (1951, p. 5–17).

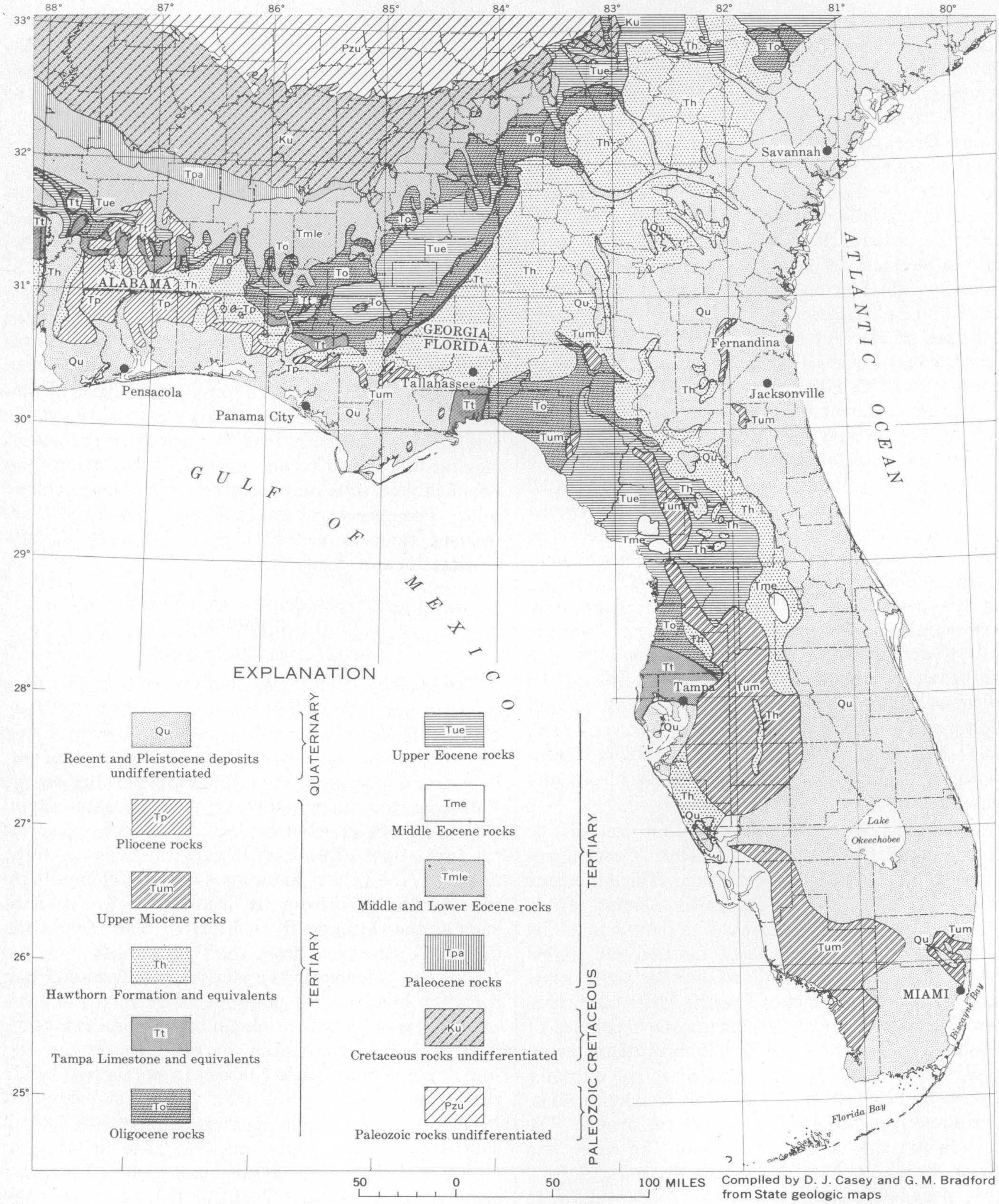

FIGURE 3.—Generalized geologic map of the Coastal Plain of the Southeastern States.

The igneous and metamorphic rocks (also known as crystalline rocks) are at or near the land surface in the Piedmont province and at the Fall Line. The surface formed by the top of the crystalline rocks under the Coastal Plain, as shown by Applin (1951, fig. 2), ranges from a few hundred feet above sea level along the Fall Line to more than 13,000 feet below sea level in southern Florida. In north-central Florida on the crest of the peninsular arch, the surface is about 3,500 feet below sea level. A table of well data by Applin (1951, p. 19–25) shows that the rocks include granite, diorite, biotite gneiss, schist, tuff, and volcanic agglomerate of rhyolitic composition, quartzitic sandstone, shale, and dolomite. Some of the data on Florida from Applin's report are tabulated by Puri and Vernon (1959, p. 8–16).

CRETACEOUS SYSTEM

Applin and Applin (1944, p. 1708–1723) briefly described the subsurface stratigraphy of the Cretaceous System in Florida and southern Georgia. Applin (1952; 1965) described the geology in more detail and designated the Early Cretaceous as comanche Series and the Late Cretaceous as Gulf Series. As described by Applin (1952, p. 1159, 1164), rocks of the Comanche Series do not crop out in the Southeastern States, because they are overlapped by deposits of the Gulf Series. Well data are insufficient for more than an approximation. However, formations of the Comanche Series are present in the subsurface throughout most of Florida and the Coastal Plain in Georgia, but they are absent on the crest of the peninsular arch in northern Florida and in southeastern Georgia. Both clastic and nonclastic facies are recognized in Florida. The nonclastic facies in southern Florida is composed chiefly of alternating beds of limestone, dolomite, and anhydrite. The total thickness of the Comanche Series is at least 6,250 feet, as indicated by the record of a well on Big Pine Key, Monroe County, Fla., in the southern Florida basin. In western Florida a well in Jackson County penetrated approximately 5,000 feet of Comanche beds. No fresh water has been reported in the Comanche Series in the area of this report.

Formations of the Gulf Series crop out in an irregular belt along the inner margin of the Coastal Plain. Except for the Atkinson Formation, each stratigraphic unit includes both a clastic and nonclastic facies. In western Florida and most of southern Georgia, a clastics facies, similar in its broader aspects to the sedimentary rocks of the western gulf coast, is chiefly shale and sand containing some limestone and chalky marl. In most of the Florida peninsula, the sedimentary section of the Gulf Series is predominantly nonclastic chalky limestone and dolomite. The Gulf Series has a maximum thickness of 3,000 feet in the southern Florida basin. It yields large supplies of fresh water in parts of the Coastal Plain in Georgia, Alabama, and South Carolina. However, the water in the Gulf Series is salty in most, if not all, of Florida and southeastern Georgia. Fresh water is present in the Cretaceous formations on the coast at Parris Island, S.C. Further discussion of the Cretaceous is not given here because this report is on the artesian water in the Tertiary formations overlying the Cretaceous.

TERTIARY SYSTEM

Formations of Tertiary age consist chiefly of limestone in most of Florida and southeastern Georgia. Some of them grade into sands and other clastics in western Florida, southeastern Alabama, southwestern Georgia, and in the northern part of the Coastal Plain in Georgia and adjacent parts of South Carolina. The Tertiary rocks are underlain by Cretaceous sedimentary rocks, except in a few places along the Fall Line in eastern Georgia where Eocene rocks overlap the Cretaceous and rest on igneous and metamorphic rocks, which are at or near the surface in the Piedmont province. A sketch map of Florida and adjacent States showing structure contours on top of the Eocene formations is shown in figure 4. The sedimentary rocks extend oceanward to the edge of the Continental Shelf. The large projection of the continent, separating the deep water of the Gulf of Mexico from the deep water of the Atlantic Ocean, is the Floridian Plateau named by Vaughan (1910, p. 99). The plateau includes not only the State of Florida but an equally large or larger submerged area less than 50 fathoms (300 feet) deep (Cooke, 1945, p. 3). A photograph of a relief model of the plateau is shown in figure 5.

The distribution and thickness for each series of the Tertiary are shown by Toulmin (1952, p. 1165–1175) for Florida, Georgia, and adjacent parts of Alabama and South Carolina and by Herrick and Vorhis (1963) for Georgia. A comparison of the geologic formations along the Chattahoochee River in southeastern Alabama and southwestern Georgia with those in central Alabama (Toulmin and LaMoreaux, 1963, p. 385–403) shows changes in thickness and lithology in the east-west transition from the clastic facies to limestone in Georgia and Florida.

Toulmin (1955, p. 208, fig. 1; 1952, p. 1165–1175)

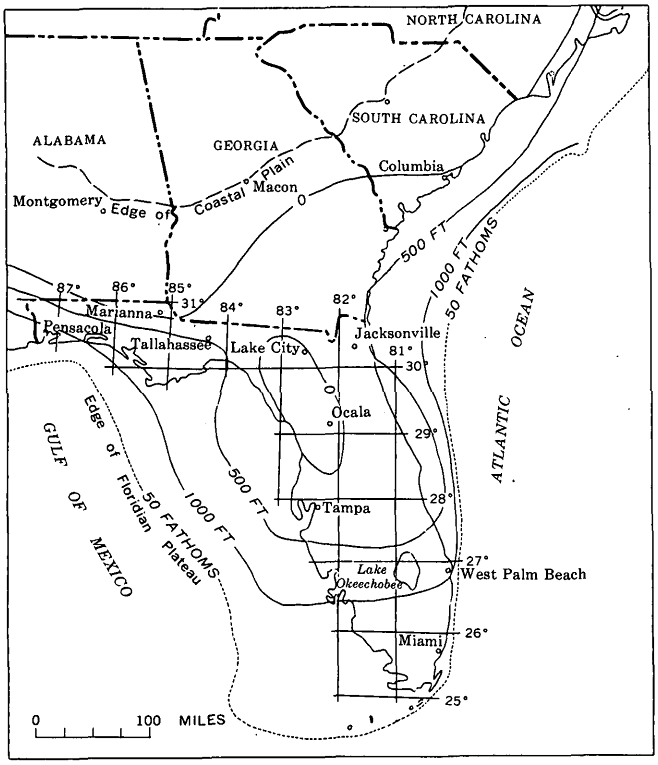

FIGURE 4.—Sketch map of Florida and adjacent States showing Floridian Plateau and top of Eocene formations. (From Cooke, 1945, p. 6.)

showed the total thickness of the formations of the Tertiary and Quaternary Systems in the report area. As the Quaternary System is only a few feet thick in most of the area, the probable maximum thickness being about 200 feet in a few places, the thickness shown for the Cenozoic (fig. 6) represents in a general way the thickness of the Tertiary. The thickness in Florida ranges from less than 1,600 feet in Lafayette and Suwannee Counties on the northwest side of the Ocala uplift in north-central Florida to about 4,500 feet in western Florida. North of the Ocala uplift in southern Georgia, the thickness increases to about 2,600 feet and then decreases to zero northward in the belt of outcrops adjacent to the Fall Line. Southward from the Ocala uplift, the Tertiary formations thicken to about 5,500 or more feet in the southern Florida embayment. In southeastern Alabama the maximum thickness is about 3,000 feet. In southeastern South Carolina the Tertiary deposits are about 2,400 feet thick. A geologic section from Hancock County, Ga., to Monroe County, Fla., is shown in figure 7.

The Tertiary formations are the chief source of large ground-water supplies (both artesian and nonartesian) in the area of this report with the following exceptions: (1) In some of the outcrop areas of the Tertiary in Alabama, Georgia, and South Carolina, where the underlying Cretaceous sands may be the chief source of water, (2) in the Miami area, where part of the ground-water supply is from Pleistocene formations, (3) at Pensacola, where part of the supply is from sand of Pleistocene age, and (4) in areas where many shallow domestic wells are in Pleistocene and Recent sands. The Tertiary formations and their water-bearing properties are described in the next section of this report. The following tables (1 to 5) show the geologic correlation and some of the water-bearing properties of the formations by States.

PALEOCENE SERIES

MIDWAY AGE

Clayton, Porters Creek, and Naheola Formations

In southeastern Alabama, the Clayton, Porters Creek, and Naheola Formations represent the Midway Group. The Porters Creek does not, however, crop out in that area, and the Naheola pinches out to a few feet of sand and clay. The Clayton Formation extends into Georgia and possibly into South Carolina. The Paleocene Series in southeasternmost South Carolina is not named, but S. M. Herrick (written commun., 1956) has applied the name Clayton to subsurface rocks in South Carolina (Counts and Donsky, 1963, p. 19). Cooke and MacNeil (1952, p. 21) indicated that the deposits that have been mapped in South Carolina as Black Mingo of early Eocene age should, in part, be considered of Paleocene age. The Paleocene deposits in the report area in South Carolina are dark-gray to black laminated shale with limestone facies in the south coastal areas.

In Florida there were two basins of deposition—one contains chiefly clastic deposits; the other contains carbonate rocks. The rocks of Midway age are represented by the Cedar Keys Limestone, or its clastic equivalent, in Florida and adjacent parts of Alabama and Georgia. Cooke (1945, p. 16) suggested that the clastic facies in western Florida represents the Porters Creek Formation. The distribution and thickness of the formations of Midway age in Florida and Georgia are shown by Toulmin (1952, fig. 2). The distribution and thickness of Paleocene deposits in Georgia are shown by Herrick and Vorhis (1963, fig. 12).

In central Alabama the Clayton Formation thickens greatly eastward. The Porters Creek Formation thins eastward and the lithologic character changes. The lower part grades into calcareous clay, and the upper part, into calcareous silt and fine sand. In eastern Alabama the Clayton Formation makes

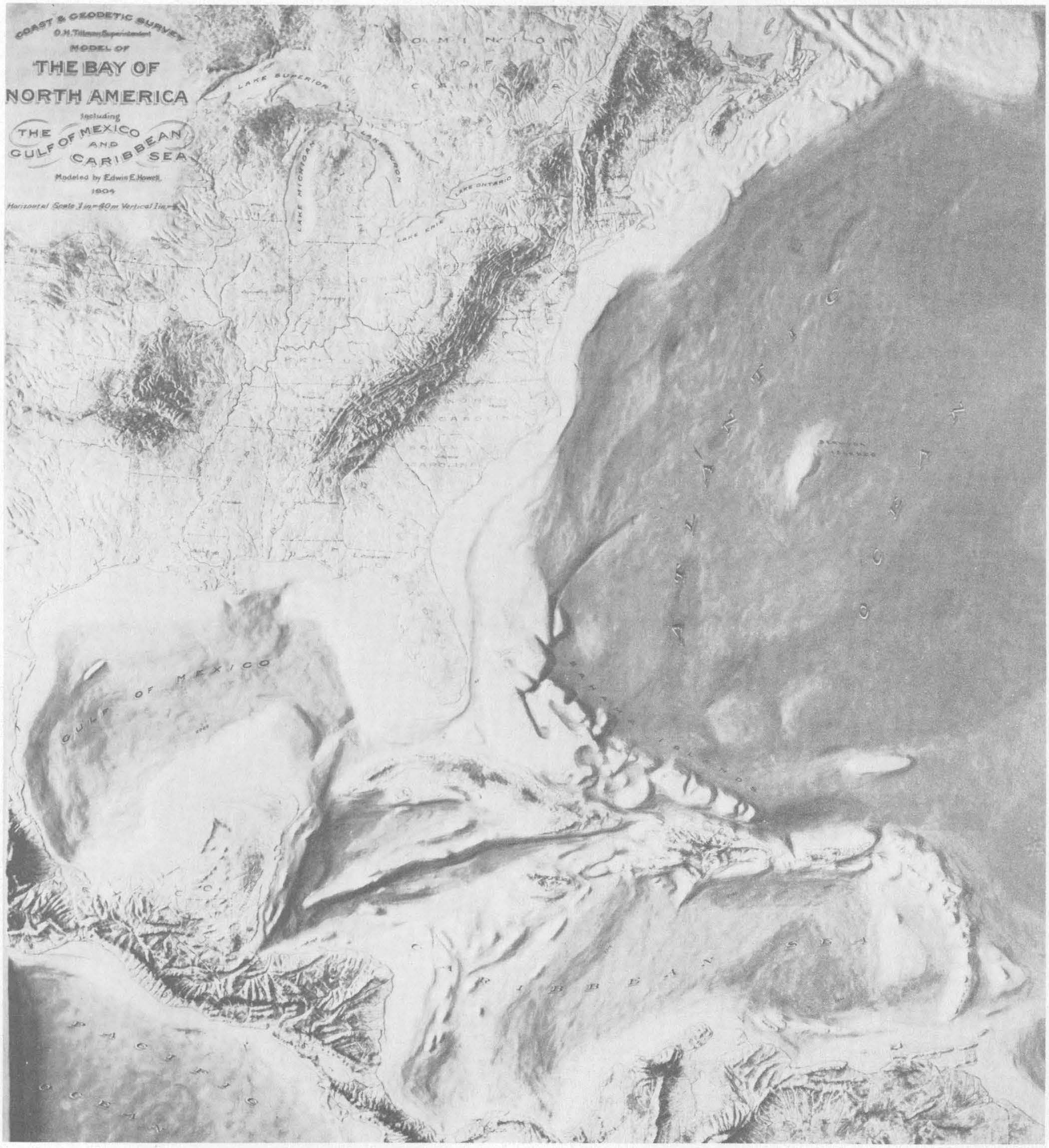

FIGURE 5.—Photograph of relief model of Floridian Plateau. (After Cooke and Mossom, 1929, pl. 1.)

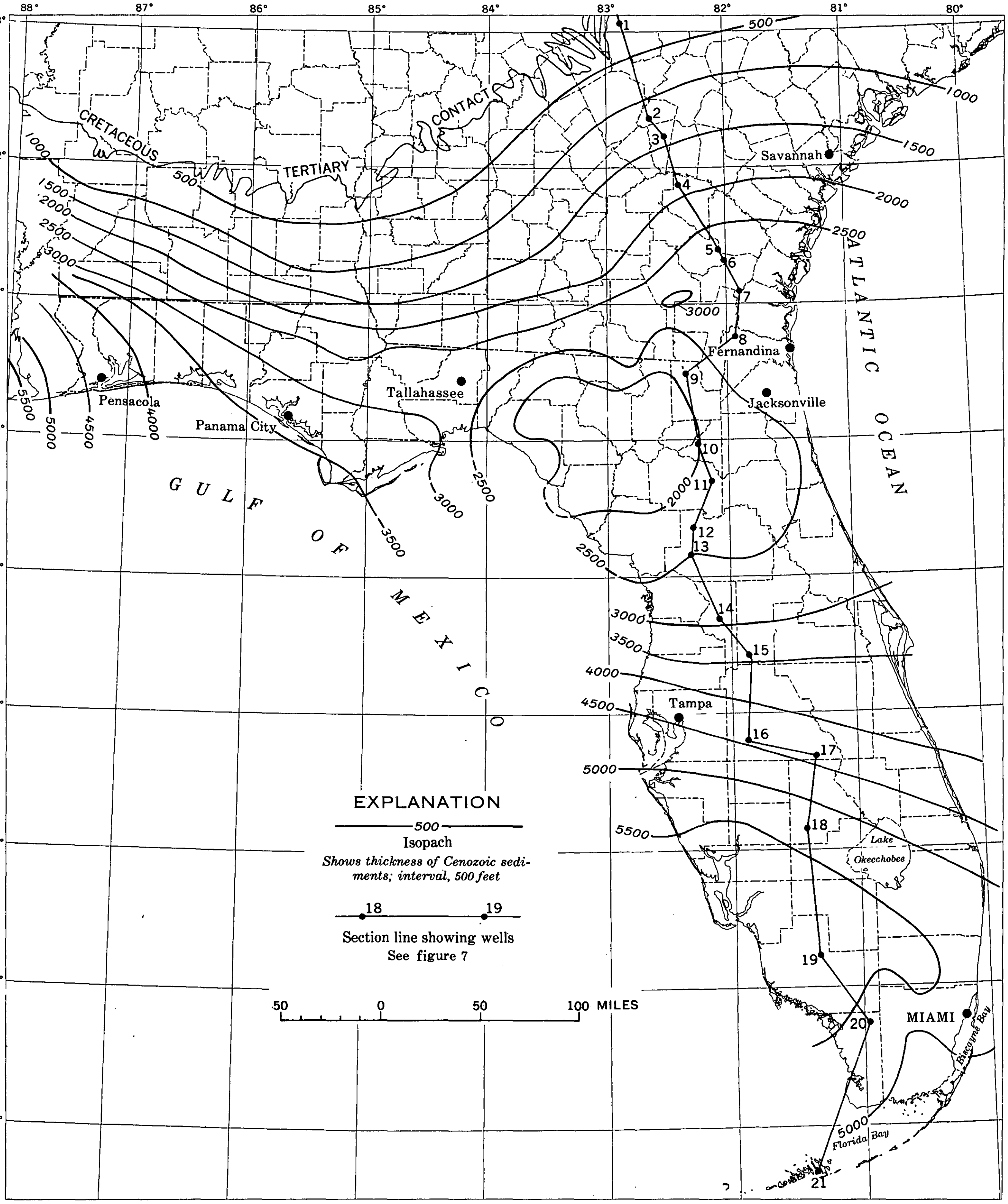

FIGURE 6.—Isopach map of Cenozoic sediments in Florida, Georgia, and adjacent parts of Alabama and South Carolina. (From Toulmin, 1955, p. 208.)

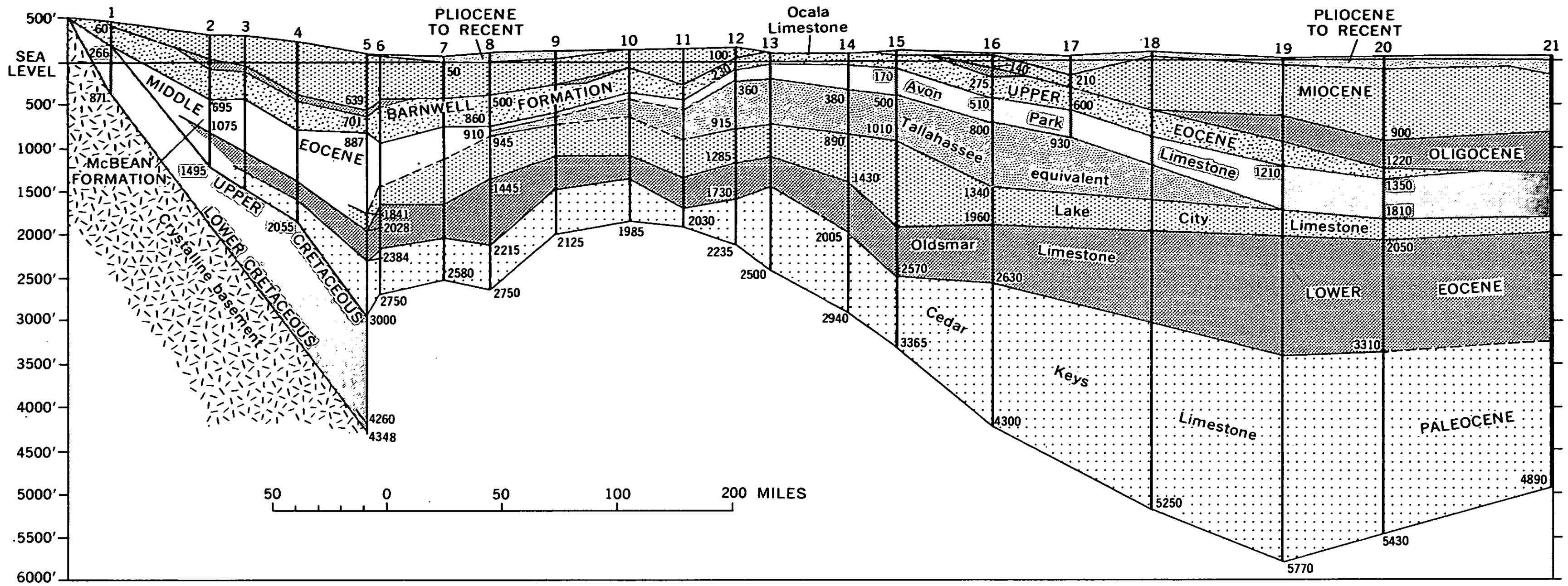

FIGURE 7.—Geologic section from Hancock County, Ga., to Monroe County, Fla. (From Toulmin, 1952, p. 1165–1175.) See figure 6 for location of section.

EXPLANATION OF WELL NUMBERS IN FIGURES 6 AND 7

1. Sandersville Public Water Well 51, Washington County, Ga. (LaMoreaux, 1946, p. 121).
2. Glen Rose, Fowler 1, Treutlen County, Ga. (Richards, 1945, p. 923).
3. Weatherford, Wilkes 1, Montgomery County, Ga.
4. Felsenthal, W. Bradley 1, Appling County, Ga.
5. W. B. Hinton (Clark), Adams McCaskill 1, Pierce County, Ga. (Applin and Applin, 1944, p. 1744).
6. Pan Am., Adams McCaskill 1, Pierce County, Ga.
7. California, John A. Buie 1, Camden County, Ga.
8. St. Marys River Oil Corp., Hilliard 1, Nassau County, Fla. (Cole, 1944; Applin and Applin, 1944, p. 1734).
9. Hunt Oil Co., Hunt 1, Baker County, Fla.
10. Tide Water Associated Oil Co., M. F. Wiggins 1, Bradford County, Fla.
11. Tide Water Associated Oil Co., J. A. Phifer 1, Alachua County, Fla.
12. J. S. Cosden, Inc., W. L. Lawson 1, Marion County, Fla. (Applin and Applin, 1944, p. 1739).
13. Ocala Oil Corp, York 1, Marion County, Fla.
14. Dundee Petroleum Co., Bushnell well, Sumter County, Fla. (Applin and Applin, 1944, p. 1734).
15. Oil Development Co. of Florida, South Lake 2, Lake County, Fla. (Applin and Applin, 1944, p. 1734).
16. Pioneer Oil Co., Hecksher-Yarnell 1, Polk County, Fla. (Applin and Applin, 1944, p. 1735).
17. Avon Park Bombing Range Water Well, Polk County, Fla. (Applin and Applin, 1944, p. 1740). Florida Geol. Survey W-668.
18. Humble Oil and Refining Co., C. C. Carlton Est. 1, Highlands County, Fla.
19. Humble Oil and Refining Co., Gulf Coast Realties 1, Collier County, Fla.
20. Peninsular Oil and Refining Co., J. W. Cory 1, Monroe County, Fla. (Cole, 1941; Applin and Applin, 1944, p. 1735).
21. Gulf Oil Corp., State of Florida J. P. Scranton 1, Monroe County, Fla.

TABLE 1.—*Correlation of Tertiary formations in south-central and southeastern Alabama, Florida, Georgia, and southeastern South Carolina*

[Based on information in separate tables for each State. For Quaternary System, Pleistocene and Recent Series, see discussion for particular State, p. 29, 30, 32, and 34]

Series	South-central and southeastern Alabama	Florida (*, panhandle; †, peninsula)	Georgia	Southeastern South Carolina
Pliocene	Citronelle Formation	Citronelle Formation Caloosahatchee Marl	Charlton Formation	Waccamaw Formation[1]
Miocene	Catahoula Sandstone Paynes Hammock Sand	Duplin Marl *Choctawhatchee Formation[2] | †Tamiami Formation[2] *Alum Bluff Group | *Shoal River Formation with Oak Grove Sand Member; Chipola Formation | †Hawthorn Formation Tampa Limestone	Duplin Marl Hawthorn Formation Tampa Limestone	Duplin Marl Hawthorn Formation Tampa Limestone
Oligocene	Chickasawhay Limestone Byram Formation Marianna Limestone and Red Bluff Clay undifferentiated	Suwannee Limestone *Byram Formation Marianna Limestone | Absent	Flint River Formation Suwannee Limestone Cooper Marl	Flint River Formation Cooper Marl
Upper Eocene Jackson Group in Alabama	Ocala Limestone Yazoo Clay Moodys Branch Formation	*Ocala Limestone[3] | †Upper member (Crystal River) †Lower member (Williston and Inglis)	Ocala Limestone, upper member and lower member (grades updip into Barnwell Formation)	Barnwell Formation
Middle Eocene Claiborne Group in Alabama	Gosport Sand Lisbon Formation Tallahatta Formation	Avon Park Limestone Tallahassee Limestone Lake City Limestone	*SW. Georgia*: Gosport Sand; Lisbon Formation | *SE. Georgia*: Sandy limestone; McBean Formation Tallahatta Formation	Castle Hayne Limestone McBean Formation and Santee Limestone Warley Hill Marl Congaree Formation
Lower Eocene Wilcox Group in Alabama	Hatchetigbee Formation Tuscahoma Sand Nanafalia Formation	*Undifferentiated clastics | †Oldsmar Limestone	*SW. Georgia*: Hatchetigbee Formation; Tuscahoma Formation; Nanafalia Formation | *SE. Georgia*: Limestone undifferentiated where present	Black Mingo Formation
Paleocene Midway Group in Alabama	Naheola Formation Porters Creek Formation Clayton Formation	*Undifferentiated clastics | †Cedar Keys Limestone	Clayton Formation	Undifferentiated
Cretaceous and older				

[1] DuBar (1962, p. 23) believes that the Waccamaw Formation is Pleistocene.

[2] The Choctawhatchee in western Florida is recognized by Florida Geol. Survey as the equivalent of the Tamiami Formation in southeastern Florida.

[3] The Ocala Group and its subdivisions as described by Puri (1953) has been adopted by the Florida Geol. Survey. The U.S. Geol. Survey has not adopted the names Crystal River, Inglis, and Williston.

TABLE 2.—*General stratigraphic section and water-bearing properties of Tertiary formations in south-central and southeastern Alabama*

[After LaMoreaux (1948, p. 15), LaMoreaux (in Carter and others, 1949, p. 204), Cagle and Floyd (1957, p. 12), Cagle and Newton (1963), Mac Neil (1946, 1947)]

System	Series	Stratigraphic unit	Thickness (feet)	Lithology	Water-bearing properties
Quaternary	Recent and Pleistocene	Undifferentiated	0–100	Chiefly sands, gravel, and clay.	Yield small supplies to shallow wells. Potential source of large quantities of water where deposits are hydrologically connected to streams.
Tertiary	Pliocene	Citronelle Formation	0–150	Lenticular beds of sand, gravel, and variegated clay.	Gravel beds in the basal part of formation are a source of water for domestic, industrial, and municipal wells.
	Miocene	Catahoula Sandstone and Paynes Hammock Sand undifferentiated	0–650	Sand, white to pink; gravel, sandstone, and varicolored clay.	Source of moderate to large water supplies for municipal, industrial, and domestic use.
	Oligocene	Chickasawhay Limestone	0–70	Greenish-gray, dolomitic, fossiliferous limestone; contains a few beds of fine glauconitic sand.	Solution cavities in limestone supply water to domestic and stock wells. Sand beds yield small quantities of water to flowing wells in Brewton.
		Byram Formation (Bucatunna Clay Member, marl member, and Glendon Limestone Member undifferentiated)	0–100	Dark-gray to brown sandy lignitic clay; contains some fine glauconitic sands.	Generally not important as a source of water supply. Sands in upper part yield small quantities of water to flowing wells in vicinity of Brewton.
		Marianna Limestone and Red Bluff Clay undifferentiated	0–40	Light-gray fossiliferous limestone and clayey marl.	Solution cavities in limestone supply moderate quantities of water to domestic, industrial, municipal, and some irrigation wells.
	Upper Eocene Jackson Group	Ocala Limestone	0–60	Light-gray limestone and clayey fossiliferous marl.	Water-bearing properties similar to those of overlying Marianna Limestone.
		Yazoo Clay	0–70	Greenish-gray clay and fine to medium glauconitic sand.	Sand beds are sources of small quantities of water.
		Moodys Branch Formation	0–55	Grayish-green to white glauconitic fossiliferous limestone and marl.	Relatively impermeable but may be source of small quantities of water.
	Middle Eocene Claiborne Group	Gosport Sand and Lisbon Formation undifferentiated and Tallahatta Formation	0–325	Fine to medium and coarse glauconitic sand, marl, and clay, generally abundant fossils, and tan siliceous claystones.	Massive sands are an important source of ground water.
	Lower Eocene Wilcox Group	Hatchetigbee Formation and Tuscahoma Sand	0–175	Interlaminated and interbedded fine olive-gray sand, sandy clay, and a few glauconitic fossiliferous sand beds.	Some massive sands are a source of small water supplies.
		Nanafalia Formation	0–100+	Greenish-gray to gray fossiliferous coarse glauconitic sand, sandstone, marl, and clay.	Sand beds are very permeable and form an excellent aquifer.
	Paleocene Midway Group	Naheola Formation	0–25	Interbedded gray sandy clay and fine gray sand.	Not a source of water supplies.
		Clayton Formation Westward the Clayton intertongues with the Porters Creek	0–130	Chiefly light-gray smooth-textured argillaceous limestone containing solution cavities.	Some water obtained from solution cavities and permeable limestone, although the formation is relatively impermeable.
Cretaceous					Important source of water both nonartesian and artesian.

TABLE 3.—*General stratigraphic section and water-bearing properties of Tertiary formations in Florida*

[Geology is based in part on reports, including Applin and Applin (1944), Parker, Ferguson, Love, and others (1955), Cooke (1945), Puri and Vernon (1959), and Toulmin (1955), with revisions by D. W. Brown (1962)]

System	Series	Stratigraphic unit		Thickness (feet)	Lithology	Water-bearing properties
Quaternary	Recent and Pleistocene	See discussion of Pleistocene units (p. 68).		0–250	Chiefly sands, gravel, clay, shells, limestone, and marl. See discussion of geologic formations.	Yield water to shallow wells. Miami Oolite and Fort Thompson Formation are part of the shallow productive aquifer (Biscayne) in the Miami area.
Tertiary	Pliocene	Citronelle Formation		0–100	Chiefly sands, gravel, and clay.	Yields large quantities of water of good quality.
		Caloosahatchee Marl and Charlton Formation		0–50	Shells, sands, and marl.	Yields water to shallow wells.
		Alachua and Bone Valley Formations		0–100	Chiefly phosphatic sand and clay. Occur only in the phosphate area of the Florida peninsula.	Yields small to moderate quantities of water to shallow wells.
	Miocene	Western Florida: Choctawhatchee Formation (of former usage)[1]	Tamiami Formation in southeastern Florida (late Miocene)	0–150	Consists chiefly of limestone, sand, and marl.	Upper part of formation is very permeable. Forms lower part of the Biscayne aquifer. Lower part, with the Hawthorn, confines water in the underlying principal artesian aquifer.
		Alum Bluff Group: Shoal River Formation with Oak Grove Sand Member. Chipola Formation	Hawthorn Formation	0–550	Sand, clay, and marl. Hawthorn consists chiefly of interbedded sand, clay, and limestone and sandy phosphatic limestone and marl.	Yields small to moderate quantities of artesian and nonartesian water. Major part of Hawthorn forms the confining layer for the underlying artesian water, but lower part forms the upper part of the principal artesian aquifer.
			Tampa Limestone	0–250	Limestone with sands, silts, and clay. Some parts of the limestone are silicified. The formation contains many solution cavities in recharge area.	Yields large quantities of water in west-central Florida, but the yield is generally lower in other parts of the State.
	Oligocene	Suwannee Limestone		0–450	Limestone containing many solution cavities in recharge areas.	Yields moderate amounts of water but generally less than underlying Eocene formations.
		Byram Formation chiefly in western Florida		0–40	Limestone, marl, and clay.	Yields moderate amounts of water.
		Marianna Limestone in western Florida		0–60	Limestone.	Yields moderate amounts of water.

TABLE 3.—*General stratigraphic section and water-bearing properties of Tertiary formations in Florida*—Continued

System	Series	Stratigraphic unit		Thickness (feet)	Lithology		Water-bearing properties
Tertiary—Continued	Upper Eocene	Ocala Limestone[3]	Upper member	0–380	Consists chiefly of chalky fossiliferous limestone. Equivalent of Crystal River Formation of Ocala Group of Florida Geological Survey.	Principal artesian aquifer[2]	Ocala Limestone is one of the most productive formations of the principal artesian aquifer.
			Lower member	0–150	Consists chiefly of calcitic limestone. Equivalent of the Williston and Inglis Formations of Ocala Group of Florida Geological Survey.		Upper member is more productive than lower member. Formation contains many solution cavities in recharge areas.
	Middle Eocene	Undifferentiated clastics in western Florida	Avon Park Limestone	0–845	Cream-colored to brown chalky limestone and dolomite. Contains gypsum and chert.		Avon Park and Tallahassee Limestones are principal source of water in areas where overlying limestone is thin or absent.
			Tallahassee Limestone	0–650	Limestone similar to overlying Avon Park Limestone.		
			Lake City Limestone	110–990	Alternating beds of dark-brown dolomite and chalky limestone. Gypsum is present in central part of peninsula and in the Tallahassee area.		Oldest formation of the principal artesian aquifer and an important source of artesian water in some areas.
	Lower Eocene		Oldsmar Limestone	250–1,000	Limestone containing chert and gypsum in central part of peninsula. Grades into sandy facies in western Florida.		Contains salt water.
	Paleocene	Undifferentiated clastics in western Florida	Cedar Keys Limestone	165–2,250	Gray and cream-colored to white limestone containing gypsum and some anhydrite stringers and oolitic lenses. Grades into sand, sandy clay, and marl in western Florida.		Contains salt water.
Cretaceous and older							Contains salt water.

[1] Florida Geological Survey regards the Choctawhatchee (of former usage) in western Florida as the age equivalent of the Tamiami in the Miami area.
[2] The principal artesian aquifer (Floridan) is the source of water for the artesian wells and large springs and includes overlying formations up to middle Miocene (p. 30).
[3] Florida Geological Survey uses Ocala Group, including Crystal River, Williston, and Inglis Formations.

TABLE 4.—*General stratigraphic section and water-bearing properties of Tertiary formations in Georgia*

[Based in part on the following references: Cooke (1943), Herrick and Wait (in Thomson and others, 1956), Wait (1960a), and Counts and Donsky (1959)]

System	Series	Stratigraphic unit	Thickness (feet)	Lithology	Water-bearing properties
Quaternary	Recent and Pleistocene	See discussion of Pleistocene units (p. 68).	0–100	Chiefly sands, gravel, and clay	Yield small supplies to shallow wells. Potential source of large quantities of water where deposits are hydrologically connected to streams.
Tertiary	Pliocene	Undifferentiated sands and gravel	0–150	Lenticular beds of sand, gravel and variegated clay.	Gravel beds in the basal part of formation are a source of water for domestic, industrial, and municipal wells.
		Charlton Formation[1]	0–20	Fine sands interbedded with clay and marl which is fossiliferous in some places.	Yields water to shallow wells.
	Miocene	Duplin Marl	0–100	Hawthorn Formation consists of marl, clay, sand, limestone, interbedded with pale to dark-green phosphatic sandy clay and sandy limestone. Tampa Limestone consists chiefly of limestone.	Hawthorn yields as much as 200 gpm to wells from sands which are little used but are a potential source of water. Some of the water is artesian. Tampa Limestone yields as much as 200 gpm. The water is artesian except in outcrop areas. The lower part of the Hawthorn Formation and the Tampa Limestone where present form the upper part of the principal aquifer of Tertiary age.
		Hawthorn Formation and Tampa Limestone	0–600		
	Oligocene	Suwannee Limestone and Flint River Formation Cooper Marl[2]	0–200	Limestone, ranging from soft, chalky, and fossiliferous to dense calcitized, saccharoidal, and unfossiliferous. Flint River is cherty limestone that consists chiefly of residual flint and chert in the Flint River valley of Georgia.	Suwannee Limestone yields as much as 500 gpm. The water is artesian except in outcrop areas. Yields large supply to wells in southwestern Georgia where it and formations of principal aquifer yield as much as 2,100 gpm in Valdosta area. The Suwannee and Flint River are part of the artesian aquifer.
	Upper Eocene	Ocala Limestone, upper unit	0–155	Upper unit differentiated only in northeastern Coastal Plain of Georgia. Dull white limestone, fossiliferous, somewhat calcitized, and crystalline, glauconitic at depth. Lower unit is cream-colored soft granular limestone. Thin layers and tongues of dense pale-blue calcitized limestone and silty and clayey limestone or marl. Maximum thickness of undifferentiated limestone, 575 ft. Ocala grades into Barnwell Formation updip. Barnwell Formation (0–200 ft. thick) is sandy facies of Ocala.	Major part of principal artesian aquifer in coastal area of Georgia. In the Savannah area the upper unit of the Ocala and the overlying Oligocene deposits apparently are the most permeable parts of the aquifer. The aquifer yields as much as 4,200 gpm to wells. Water is moderately hard in Savannah area.
		Ocala Limestone, lower unit	0–283		

TABLE 4.—*General stratigraphic section and water-bearing properties of Tertiary formations in Georgia*—Continued

System	Series	Stratigraphic unit	Thickness (feet)	Lithology	Water-bearing properties
Tertiary—Continued	Middle Eocene	Gosport Sand	0–100	Calcareous sand or very sandy limestone, fossiliferous and glauconitic at depth. Avon Park Limestone in Florida and southeastern Georgia.	Reported to yield as much as 650 gpm to wells from thick sections in Savannah area. Water is moderately hard. Has high chloride in coastal counties. Lowest formation of principal artesian aquifer along coast and southeastern Georgia. It is an important part of principal aquifer in southwestern Georgia.
		Lisbon Formation / McBean Formation	0–600	Marl or soft glauconitic limestone, white, gray and buff; some sand. Facies change from limestone on west to clayey marl with some limestone on east. Avon Park and Lake City Limestones in Florida. McBean Formation in outcrop.	Forms lower confining bed of principal artesian aquifer in some places in southeasten Georgia but generally is part of the aquifer.
		Tallahatta Formation	0–200	Pale green glauconitic marl and buff silty clayey fossiliferous limestone. Lake City Limestone in Florida.	Forms lower part of principal Tertiary aquifer in southwestern Georgia and southeastern Alabama but is part of confining beds below aquifer in southeastern Georgia and Florida. Lisbon and Tallahatta Formations yield as much as 1,200 gpm in Dougherty County. Principal source of water at Albany and Cordele. Contains saline water at Thomasville.
	Lower Eocene	Hatchetigbee Formation Tuscahoma Formation, and Nanafalia Formation in southwestern Georgia; undifferentiated in southeastern Georgia	0–400	Alternating micaceous lignitic clay, marl, and sandy and minor amounts of gray crystalline glauconitic sandy limestone. Equivalent to Oldsmar Limestone in Florida.	Source of potable water in outcrop area in southwestern Georgia, but water is salty in coastal areas, southeastern Georgia, and Florida peninsula.
	Paleocene	Clayton Formation	0–380	Mostly gray crystalline glauconitic fossiliferous limestone and minor amounts of clay and sand.	Important source of water in southwestern Georgia and southeastern Alabama. It contains salty water in coastal areas, southeastern Georgia, and Florida, except in Jackson County, Fla. Water in basal sand yields soft sodium bicarbonate water in some areas. The type of water in the overlying limestone is calcium bicarbonate. Much of the artesian water in the Cretaceous aquifers is soft sodium bicarbonate water.
Cretaceous and older					

[1] S. M. Herrick (written commun., July 1962) believes that the Charlton may be part of the Duplin Marl.
[2] Herrick and Vorhis (1963) describe the Cooper Marl as upper Eocene in Georgia.

TABLE 5.—*General stratigraphic section and water-bearing properties of Tertiary formations in South Carolina*

[By G. E. Siple, written commun., 1964]

System	Series	Stratigraphic unit	Thickness (feet)	Lithology	Water-bearing properties
Quaternary	Recent and Pleistocene	See discussion of Pleistocene units (p. 68).	0–100	Chiefly sand, gravel, and clay.	Yields small supplies to shallow wells.
Tertiary	Pliocene	Waccamaw Formation (early Pliocene[1])	0–40	Blue-gray to yellow and brown sandy marl, gray to buff fine loose quartz sand.	Water usually hard and having some H_2S odor. Fair to large yields.
	Miocene	Duplin Marl (late Miocene)	0–50	Buff sandy friable shell marl and loose sand.	Yields small supplies of hard water.
		Hawthorn Formation (early and middle Miocene)	0–150	Hard brittle shale, gray to black, resembling stratified fuller's earth and sandy phosphatic marl.	Sparse available data indicate the unit is relatively impermeable, but in some areas small yields of hard water may be obtained.
		Tampa Limestone (early Miocene) (subsurface)	0–40	Greenish phosphatic sandy clay and coarsely phosphatic limestone.	Small to moderate amounts of water, moderately hard to hard.
	Oligocene	Flint River Formation	0–50	Reddish-yellow sand and lumps of yellow vitreous chert.	No data available.
		Cooper Marl undifferentiated limestone	0–200	Grayish-green to brown phosphatic, sometimes sandy, marl.	Yields little or no water.
	Upper Eocene	Barnwell Formation	0–100	Deep-red to brown fine to coarse massive sandy clay and clayey sand. Scattered thin lenses of buhrstone.	Small yields, sufficient for domestic and stock use.
		Ocala Limestone	0–400	White to cream-colored calcitized fossiliferous limestone; saccharaoidal, nodular, and recrystallized; contains numerous bryozoan remains.	Large water yields in southern part of State. Water hard to moderately hard.
	Middle Eocene	Castle Hayne Limestone	0–800 (?)	Buff-gray tough to hard crumbly fossiliferous limestone in upper part underlain by soft fine-grained granular limestone.	Very permeable in southern part of State where yields of 2,000 gpm have been obtained. Water moderately hard and may be high in iron or H_2S.
		McBean Formation	0–250	Fine to medium greenish-yellow quartz sand; green glauconitic marl, silicified beds of coquina, and clayey sand interbedded with red, brown, ochre, and yellow plastic clay. Light gray fuller's earth and siltstone.	Moderate to good yields—50–300 gpm. Water generally soft but may be high in iron, dissolved oxygen, or carbon dioxide.
		Santee Limestone	0–325	Pure white to creamy-yellow fossiliferous and party glauconitic limestone containing numerous Bryozoa.	Water yields moderate to high. Water moderately hard to hard.

TABLE 5.—*General stratigraphic section and water-bearing properties of Tertiary formations in South Carolina*—Continued

System	Series	Stratigraphic unit	Thickness (feet)	Lithology	Water-bearing properties
Tertiary—Continued	Middle Eocene—Continued	Warley Hill Marl	0–200(?)	Fine, green to yellow glauconitic sand, reddish-yellow massive argillaceous sand, and gray-green glauconitic marl.	Aquifer potential uncertain but regarded as poor.
		Congaree Formation	0–80	Green to gray brittle nonplastic clay interbedded with thin fine semiconsolidated sands and fuller's earth.	Clay beds function primarily as aquiclude but some sandy parts may yield moderate quantities of soft water which may be high in iron.
	Lower Eocene	Black Mingo	0–250	Upper red to brown sandy clays and partly indurated fine white to yellow sands underlain by gray to black clay having conchoidal fracture.	Upper sands have limited water supply. Lower unit serves as aquiclude. Quality moderately soft and may be high in iron.
	Paleocene	Undifferentiated; in subsurface only	0–200	Dark gray to black laminated shale with limestone facies in south coastal areas. (May be in part Black Mingo of early Eocene age.)	Very low permeability. Of no known significance as aquifer.
Cretaceous and older					

[1] DuBar (1962, p. 23) believes that the Waccamaw Formation is Pleistocene.

up the entire Paleocene Series. The Clayton Formation is exposed as far east as central Georgia where it is overlapped by younger formations. Downdip in southeastern Alabama the upper part of the Paleocene Series consists of limestone that is correlated with the upper limestone of the Clayton Formation. The lower part of the Paleocene Series is made up chiefly of fossiliferous marl and gray calcareous clay. In southeastern Alabama the Clayton Formation, as described by LaMoreaux (Carter and others, 1949, p. 210), is the oldest and basal Tertiary formation having an estimated thickness of 130 feet along the Chattahoochee River. It consists chiefly of argillaceous limestone containing solution cavities. In some places there may be basal sands. To the west, the upper part of the Clayton becomes sandy and glauconitic and intertongues with the Porters Creek Formation, which consists chiefly of clay. Ground water is present in the solution cavities in the limestone and in the sand beds of the Clayton.

In southwestern Georgia and southeastern Alabama the Paleocene is thickest of any place in the Coastal Plain. The Paleocene in this area consists of limestones with some clays and sands, which are correlated with the Clayton Formation. The Paleocene in southeastern Georgia is considered equivalent to the Cedar Keys Limestone of Florida (Counts and Donsky, 1963, p. 19). In southwestern Georgia (Wait, 1960a, p. 8) the Clayton is a light-gray fine sand near the top, white crystalline limestone in the middle part, and light-gray conglomeratic feldspathic sand near the bottom. It is the major aquifer in Clay, Randolph, Terrell, Lee, Calhoun, Dougherty, and Early Counties. Yields of wells range from 250 to 1,700 gpm. The limestone yields a calcium bicarbonate water. The basal sand may yield soft sodium bicarbonate water. Wait reported that in Georgia the first flowing artesian well drilled in 1881 near Albany yielded water from limestone of the Clayton Formation.

Counts and Donsky (1959, p. 99; 1963, p. 19) reported that the Clayton is as much as 385 feet thick in the Savannah area, Georgia, where it consists of sandy limestone and calcareous glauconitic sand. In the coastal area of Georgia and South Carolina, the aquifer contains salt water. The thickness of the Paleocene in Georgia (Herrick and Vorhis, 1963, fig. 13) increases from a few feet in its area of outcrop to 600 feet in southern Georgia.

Cedar Keys Limestone

As described by Applin and Applin (1944, p. 1704) and Toulmin (1955, p. 216), the Cedar Keys Limestone is a white, cream-colored, or gray finely granular to fragmental limestone, microcoquina, and dolomite. The name Cedar Keys Formation was proposed by Cole (1944, p. 27) for limestone of Paleocene age in a deep oil test at Cedar Keys, Fla. The limestone has thin stringers of anhydrite, which increases in thickness in southern Florida. Commonly, gypsum in the pores of the limestone gives it a spotted appearance. In some places the limestone is oolitic. The thickness of the formation ranges from about 165 feet in northern Florida to about 2,250 feet in southern Florida. The maximum thickness of the clastic equivalent in western Florida is about 1,000 feet.

Water from the Cedar Keys Limestone is salty. Three samples of water from the Cedar Keys in the South Lake well in Lake County at depths of 2,470, 2,590, and 2,593 feet had chloride contents of 23,020, 310, and 12,000 ppm, respectively. A sample from a depth of 3,419 feet in the Lawson Limestone of Late Cretaceous age, at or near the contact with the overlying Cedar Keys Limestone, had a chloride content of 58,100 ppm as indicated by unpublished tests made in the quality of water laboratory of the U.S. Geological Survey.

EOCENE SERIES

WILCOX AGE

Nanafalia, Tuscahoma, and Hatchetigbee Formations

The Eocene Series includes, in ascending order, formations of Wilcox, Claiborne, and Jackson age. Formations of the early Eocene (Wilcox age) crop out in a belt south of the Paleocene Series, extending across Alabama into western Georgia, east of which they are overlapped by middle Eocene formations. In Alabama the group is represented by three formations from bottom to top as follows: the Nanafalia Formation, the Tuscahoma Sand, and the Hatchetigbee Formation. The Bashi Marl Member forms the lower part of the Hatchetigbee.

The Nanafalia Formation in southeastern Alabama and southwestern Georgia, as described by Toulmin (1955, p. 219), consists of as much as 100 feet of greenish-gray fossiliferous coarse glauconitic sand, sandstone, marl, and clay. The sands are very permeable and form an excellent aquifer. Downdip in southeastern Alabama and the Florida panhandle, the Nanafalia grades into the Salt Mountain Limestone, a white chalky fossiliferous massive biohermal limestone of irregular thickness and sporadic occurrence. In Florida the Nanafalia ranges in thickness from 70 to 90 feet in Walton and Bay Counties; it is absent near the coast in Gulf County and in the Tallahassee area.

The updip clastic facies of the formations of early Eocene age in southwestern Georgia correlate with the formations in Alabama (Herrick and Vorhis, 1963, p. 32), whereas the downdip limestone equivalent in southeastern Georgia and the Florida peninsula correlates with the Oldsmar Limestone. As shown on a map by Herrick and Vorhis (1963, fig. 11), the lower Eocene deposits increase in thickness from a few feet in the outcrop area to more than 400 feet in southeastern Georgia.

In South Carolina, the deposits of Wilcox age are represented by the sandy clays and sands of the Black Mingo Formation, which is as much as 250 feet thick. Siple considers the Black Mingo Formation equivalent to the Tuscahoma and Nanafalia Formations of the Gulf Coast. The Foraminifera obtained from outcrop areas of the Black Mingo Formation have not indicated decisively whether the formation is of Wilcox or Midway age.

Oldsmar Limestone

The carbonate facies of the formations of Wilcox age extends from southeastern Georgia throughout the Florida peninsula and is known as the Oldsmar Limestone, which Toulmin (1955, p. 270) and Puri and Vernon (1959, p. 30) regarded as essentially a faunal rather than a lithologic unit. The name was proposed by Applin and Applin (1944, p. 1699) for limestone of Wilcox age in a test well for oil near Oldsmar, Hillsborough County, Fla. The upper and lower boundaries of the formation may not be the same as those of the clastic facies in the Florida panhandle where the Salt Mountain Limestone faunal zone is included in the lower division of the clastic facies. That zone is included as the upper part of the Oldsmar Limestone in the peninsula.

As described by Toulmin (1955, p. 220), the Oldsmar in the northern and central parts of the Florida peninsula is a tan to brown permeable granular chalky limestone interbedded with brown permeable coarsely crystalline dolomite. The bottom part of the formation is chiefly soft permeable foraminiferal microcoquina. In southern Florida the Oldsmar is cream-colored permeable chalky nodular limestone and tan hard vuggy granular dolomite. The entire section is gypsiferous. The Oldsmar Limestone is lithologically similar to the overlying middle Eocene Lake City Limestone. It is less than 250 feet thick in the northern part of the peninsula over the peninsular arch, but it increases in thickness southward to more than 1,000 feet in the southern part of the peninsula. It is 925 feet thick in the Oldsmar well and 1,200 feet thick in the Peninsular Oil and Refining Co. well J. W. Cory 1 in Monroe County.

Little information is available on the water-bearing properties of the Oldsmar Limestone. In Florida most, if not all, of the water in the Oldsmar is salty. A sample of water from the Oldsmar at a depth of 2,258 feet in the South Lake well in Lake County, Fla., had a chloride content of only 781 ppm. However, samples from depths of 2,300 feet and 2,352 feet in the Oldsmar Limestone had a chloride content of 6,020 ppm and 6,290 ppm, respectively.

CLAIBORNE AGE

In southeastern Alabama and Georgia, the formations of Claiborne age (middle Eocene) include, from bottom to top, the Tallahatta, Lisbon, and Gosport Formations. The McBean Formation, which has been correlated with the *Ostrea sellaeformis* zone of the Lisbon Formation in southwestern Georgia, appears to be present only in northern and eastern Georgia. Thus, tentatively at least, the Lisbon Formation will be used in southern and southwestern Georgia and the McBean Formation in northern and eastern Georgia. In Florida, formations of Claiborne age are represented chiefly by the Lake City and Avon Park Limestones in the peninsula and by undifferentiated clastics in the panhandle. The Tallahassee Limestone occurs in part of the panhandle.

Along the Georgia-South Carolina State line, deposits of Claiborne age are undifferentiated in the subsurface. In South Carolina, deposits of Claiborne age are represented by the Congaree Formation at the bottom overlain by the Warley Hill Marl—both included in the McBean by Cooke (1936)—Santee Limestone, and the McBean Formation with the Castle Hayne Limestone at the top. H. E. LeGrand (oral commun., 1963) believes that the Warley Hill Marl is a facies of one of the formations.

In eastern Alabama, as described by LaMoreaux (in Carter and others, 1949, p. 212), the Tallahatta Formation is sandy and glauconitic in the upper 50 or 60 feet and in the lower 10 or 20 feet. The two sandy units are separated by about 30 feet of siliceous claystone. Overlying the Tallahatta, the Lisbon consists of a very glauconitic, in part fossiliferous, gray sand and clay. The combined thickness of the two formations in the outcrop area is less than 200 feet. The Gosport Sand, the stratigraphic equivalent of the upper part of the Cockfield Formation in Mississippi (Toulmin, 1955, p. 220), about 30 feet thick in western Alabama, consists of yellow to orange crossbedded glauconitic fine to coarse sand and brown carbonaceous nonmarine clay. Some sandy layers contain marine shells. The formation is absent on the Chattahoochee River in southeastern Alabama (Toulmin and LaMoreaux, 1963, p. 338). In Escambia County, Ala., the formations of Claiborne age have a total thickness of about 325 feet. The thickness increases toward the coast and becomes at least 1,000 feet in the central part of the panhandle of Florida.

As described by Toulmin (1955, p. 220), the formations of Claiborne age in the subsurface in southern Alabama and the Florida panhandle are predominantly marine clastics. They grade into limestone downdip in the Apalachicola area of Florida and eastward in the eastern part of the panhandle and the peninsula. The Tallahatta is composed chiefly of glauconitic sand that contains in some areas beds of light-green siliceous claystone and a little white sandy glauconitic limestone. Siliceous claystone is common in Okaloosa and Walton Counties, Fla., but pinches out eastward, and in Jackson County the Tallahatta consists of loose glauconitic quartz sand. In Gulf County, Fla., the lower part of the Tallahatta is cherty and contains small amounts of glauconite. The Tallahatta ranges in thickness from 175 feet in northern Okaloosa County to nearly 500 feet in Gulf County, Fla. (Rainwater and others, 1945, p. 50).

The Lisbon Formation in southern Alabama and adjacent parts of Florida consists chiefly of calcareous glauconitic sand, hard glauconitic sandy limestone, soft sandy glauconitic marl and chalk, and minor beds of glauconitic sandy shale and brown crystalline limestone. The formation becomes cherty downdip. In Gulf County, Fla., the limestones are partly dolomitized. The thickness of the Lisbon ranges from approximately 300 feet in Bay County, Fla., to 430 feet in Jackson County (Rainwater and others, 1945, p. 49).

In the Tallahassee and Apalachicola areas Toulmin (1955, p. 222) described the Claiborne deposits as consisting of three formations: (1) the Lake City Limestone, probably equivalent to the Tallahatta Formation and most of the Lisbon; (2) the Tallahassee Limestone, restricted to the Tallahassee area, apparently equivalent to the upper part of the Lisbon, and (3) the Avon Park Limestone, possibly equivalent to the Gosport. The Lake City and Avon Park are present in southern Georgia and throughout the

Florida peninsula, except in a small area in northern Florida where the Avon Park is absent (Applin and Applin, 1944, fig. 3).

In Georgia, Herrick and Vorhis (1963, p. 25) included the Gosport Sand with the Lisbon Formation because of lack of fossils to differentiate the two formations. They considered the Lisbon and Tallahatta Formations as the updip clastic facies of the middle Eocene in Georgia and correlated them with these formations in Alabama. They also correlated them with the downdip limestone equivalents, the Avon Park and Lake City Limestones of peninsular Florida. Counts and Donsky (1963, p. 22) used Lisbon Formation to include the rocks in the subsurface between the Tallahatta and the Gosport and stated that it was considered to be equivalent in age to the McBean Formation in the outcrop area. Veatch and Stephenson (1911, p. 237) regarded the Lisbon Formation as the subsurface equivalent of the McBean Formation in eastern Georgia. As originally defined, the McBean included some beds of upper Eocene (Herrick and Vorhis, 1963, p. 25). As used by Cooke (1943, p. 54), the McBean included some beds of the Tallahatta west of the Flint River. In order to eliminate the inconsistencies Herrick and Vorhis (1963) and Herrick (1961) used the names Lisbon and Tallahatta throughout Georgia.

The downdip limestone facies of the Tallahatta Formation is similar to that of the overlying Lisbon but is much more dolomitized and considerably more glauconitic. The middle Eocene gradually increases in thickness from a few feet in its outcrop area to more than 1,300 feet in southeastern Georgia (Herrick and Vorhis, 1963, p. 28). In South Carolina, the Lisbon is represented by the McBean Formation, which grades into the Santee Limestone farther north. Counts and Donsky (1963, p. 22) considered the Lisbon Formation in the Savannah area to be equivalent in age to the McBean Formation which occurs in updip exposures. In outcrops the Lisbon (McBean) Formation consists of fine to medium sand with fossiliferous clay beds containing hard lime nodules.

Lake City Limestone in Florida

The name Lake City Limestone was given by Applin and Applin (1944, p. 1694–97) to limestone of Claiborne age penetrated between depths of 492 and 1,010 feet in a city well at Lake City, Columbia County, Fla. The formation consists of alternating beds of dark-brown dolomite and chalky fossiliferous limestone. The limestone is tan to cream colored with pasty to fragmental matrix in which are embedded many foraminifers, crystals of calcite, fragments of echinoids, and, commonly, peat fragments. Applin and Applin reported that a bed of lignite 25 feet thick was penetrated near the top of the limestone in a well in Marion County, Fla. Peat and lignite beds, clay and sand stringers, and phosphorite and limonite nodules are present at the unconformable contact of the Lake City and the overlying Avon Park Limestone, as described by Puri and Vernon (1959, p. 35). Rock samples from some wells show signs of oxidation and weathering of the Lake City Limestone at the contact with the Avon Park. Vernon (1951, p. 92) noted that the peat content increases toward the unconformable contact of the underlying Oldsmar Limestone.

As described by Applin and Applin (1944, p. 1693), in northern Florida including the northern half of the peninsula, the Lake City Limestone underlies the Tallahassee and the equivalent nonfossiliferous limestone. Along the northeastern coast of Florida and in the southern half of Florida, the Lake City underlies the Avon Park. In western Florida where the Avon Park and the Tallahassee Limestones are absent, the Lake City underlies the Ocala Limestone.

Commonly, the Lake City is impregnated with anhydrite and gypsum. The limestone is irregularly dolomitized; dolomitization is present in all stages from incipient dolomite crystals in the matrix to complete dolomite (Vernon, 1951, p. 91–92). The change is usually accompanied by decalcification of the fauna to a degree comparable to the amount of dolomitization. Such decalcification is present in stages from unaltered fossils, calcite dust retaining some of the fossil forms, to molds surrounded by crystalline dolomite. The complete removal of fossils sometimes results in a dolomite that retains the texture of a former granular limestone, in which the matrix and interiors of the fossils have been filled by dolomite and calcite shells removed to form a very permeable scab and skeletal spongy texture (Puri and Vernon, 1959, p. 33–34). In some places the limestone is essentially a coquina of foraminifers. The coquina is so impregnated with gypsum that the fossils appear to be embedded in gypsum in a few places. Beds with diagnostic lithology occur throughout the formation, but many are concentrated at the top and the bottom. These beds include a pseudo-oolite, a brown to coffee-colored chert, a clay that appears to be bentonitic, and a brownish-gray laminated, finely crystalline dolomite containing seams of black carbon and flattened decalcified fossils, which give the dolomite a mottled and laminated appearance. Chert is present in rock samples from some wells, especially in the Tallahassee area.

Applin and Applin (1944, p. 1694) reported that in the Tallahassee area and in the northern part of the peninsula, the Lake City is 400 to 500 feet thick, but in Pierce County, Ga., and in the southern part of the Florida peninsula it is about 200 to 250 feet thick. In the central part of the Florida peninsula in Lake County the Lake City is about 990 feet thick, the top about 1,010 feet below sea level. In Polk County it is 420 feet thick, the top about 1,540 feet below sea level. Gypsum has been noted in wells in the central part of the peninsula, in the Tallahassee area, and in southeastern Georgia. The thickness of the clastic facies in western Florida increases from about 575 feet in Jackson County to about 780 feet in Walton County.

The following table from Applin and Applin (1944, p. 1695) gives the thickness of the Lake City penetrated by deep wells.

Counties	Florida Geol. Survey well	Depth (feet)	Thickness (feet)	Total depth of well (feet)
Limestone facies				
Brevard	W-104	756- 872	116	872
Broward	W-150	2,127-2,500	373	3,010
Columbia	W-299	492-1,010	518	1,012
Dade	W-215	2,490-2,737	247	5,432
Dixie	W-636	525-1,085	560	4,776
Duval	W-304	805-1,005	200	1,005
	W-581	965- 980	15	908
Hillsborough	W-8	1,910-2,165	255	3,255
Jefferson	W-19	1,740-2,223	483	3,838
Lake	W-275	1,010-2,000	990	6,120
Leon	W-32	1,600-1,995	395	3,755
Levy	W-166	811-1,308	497	5,266
Marion	W-901	915-1,285	370	4,334
Monroe	W-445	1,810-2,050	240	10,006
	W-2	1,740-1,920	180	2,310
Nassau	W-336	945-1,370	425	4,821
Polk	W-61	1,540-1,960	420	4,540
	W-668	930-1,040	110	1,040
St. Johns	W-236	590-1,350	760	1,350
Sumter	W-3	890-1,430	540	3,070
Suwannee	W-6	475- 650	175	650
Wakulla	W-12	1,750-2,169	419	2,169
	W-440	1,750-2,122	372	5,746
Clastic facies				
Calhoun	W-7	1,000-1,320	320	1,320
Escambia, Ala.	Applin 31[1]	646-1,350	704	6,025
Jackson	Applin 34	200- 776	576	5,022
Walton	Applin 32	755-1,536	781	5,337
Washington	W-1	375- 970	595	4,912

[1] Well number assigned by Florida Geological Survey.

Chemical analyses of water (Wyrick, 1960, p. 37-38) include analyses of samples from three wells that end in the Lake City Limestone. As the wells are not cased below the top of the Avon Park Limestone, the samples are a composite of water from the Avon Park and Lake City. Water from both formations is hard, containing calcium and bicarbonate as the chief constituents, except in areas where the water has a relatively high chloride content. The low magnesium content of the samples from wells in the Lake City suggests that the water is from the permeable limestone bed instead of the dolomite.

Where the chloride is relatively low, the hardness of the water sampled ranges from about 125 ppm to several hundred parts per million. The salt water is much harder. The softest water is in areas where local recharge of the aquifer through sinkholes has flushed out the salt water. The fresh water in recharge areas has had less time to receive hardness from the limestone than water which has moved through the limestone.

The Lake City Limestone is the oldest and deepest of the water-bearing formations that form an important part of the principal artesian aquifer in Florida and southeastern Georgia. In a few places the underlying Oldsmar Limestone may yield fresh water. In the clastic facies of the water-bearing formation in southeastern Alabama and Georgia the formations equivalent in age to the Oldsmar are good sources of water. Special comments about the ground-water conditions in counties where studies have been made are described below.

HIGHLANDS COUNTY

Bishop (1956, p. 18) reports that the Lake City is a permeable, very productive water-bearing formation in Highlands County, Fla., and is utilized to a large extent wherever large quantities (500 to 1,500 gpm) of ground water are needed for municipal and irrigation supplies. In Highlands County, the reported thickness ranges from about 200 to 350 feet. The top of the formation ranges from about 900 feet below sea level in the northern part of the county to about 1,100 feet below sea level in the southern part. The average dip is about 5 feet per mile to the south. According to Bishop, the permeability of the formation compared with overlying formations is indicated by pumping tests made by Briley and Wild, consulting engineers of Daytona Beach, during the drilling of well 403, 10 inches in diameter, 1,301 feet deep at Avon Park. Pumping tests show that 90 feet of penetration into the Lake City Limestone, after the well had penetrated 915 feet of overlying water-bearing formations, increased the yield from 463 to 636 gpm (gallons per minute) with a drawdown of 25 feet for each test. At a depth of 1,301 feet with

175 feet of the Lake City penetrated the yield was 818 gallons with a drawdown of 35 feet.

Bishop stated that in Highlands County the quality of water in the Lake City Limestone ranges from soft to hard, the hardness increasing toward the south end of the county. The chief constituents are calcium and bicarbonate. Locally there is more than 0.3 ppm of iron, some of which may be from well casings, but in general, the water is satisfactory. In seven samples reported by Bishop from wells 150 feet to 1,550 feet deep using the Lake City Limestone as the principal source of water, the hardness of the water ranged from 50 ppm to 85 ppm. Only two of these contained iron, suggesting the iron is from the well casings. Both samples had 0.38 ppm iron. One sample had a color of 2, and two had a color of 7. As the wells are cased only to the top of the principal artesian aquifer, the samples are composites of the formations. The relatively low hardness suggests local recharge. The highest hardness is from the deepest well. As the color is present in the water with the greatest hardness, the color is apparently from peat in the Lake City Limestone instead of recharge of colored surface water. The temperature of the water from different wells ranged from 77° to 82°F.

INDIAN RIVER COUNTY

Wells penetrate the Lake City Limestone at a depth of about 600 feet in the southern part of Indian River County but do not penetrate the entire thickness (Bermes, 1958b, p. 10). Bermes showed several faults with small displacement in the Lake City and overlying Eocene limestones, but these faults do not extend upward into the Hawthorn Formation. These faults seem to have little or no effect on the piezometric surface of the artesian water.

PUTNAM COUNTY

Leve (1958, p. 7) reported that one well in Putnam County slightly more than 700 feet deep reached the Lake City Limestone at a depth of about 550 feet. A current-meter survey of the velocities of the well when flowing showed that little or no water entered the bottom part of the well. Most of the water was from the overlying Avon Park Limestone.

SEMINOLE COUNTY

In the southwestern part of Seminole County as described by Barraclough (1962, p. 12–13), the top of the Lake City was penetrated about 600 feet below sea level. Only a few wells have been drilled into the Lake City in Seminole County because adequate supplies are obtained from the overlying Avon Park and Ocala Limestones of the principal artesian aquifer. However, the Lake City appears to be very productive. The largest yield pumped from a well in Seminole County was reported to be 8,100 gpm. The well penetrated more than 400 feet of Lake City Limestone and less than 200 feet of the overlying Avon Park Limestone. Barraclough reported that the mineral content of the water from the Lake City is less than that from Avon Park and Ocala in the southwestern part of Seminole County and the northern part of Orange County. He suggested that this difference may be due to the large percentage of dolomite in the limestone of the Lake City (the dolomite being less soluble than the limestone).

VOLUSIA COUNTY

Wyrick (1960, p. 17–18, table 1) reported six wells in Volusia County that reached the Lake City Limestone. The deepest of these wells penetrated 380 feet of the Lake City without passing through it. The Lake City is about 280 feet below sea level near De Land and about 315 feet below sea level near the coast. The top of the formation slopes toward the east at about 3 feet per mile. At some wells the unconformity separating the Lake City from the overlying Avon Park Limestone is marked by a thin layer of rounded phosphatic pebbles, and the record of one well reveals a 6-foot layer of brown clay and peat.

Tallahassee Limestone

Applin and Applin (1944, p. 1688) proposed the name Tallahassee for limestone penetrated by eight wells near Tallahassee, Fla. As described by Cooke (1945, p. 49), it consists chiefly of cream-colored, tan crystalline limestone and some soft clayey limestone. He regarded it as the equivalent of the Lisbon. It contains tan clay, chert, and gypsum. Its thickness ranges from about 75 feet in wells near its west edge to 650 feet in Jefferson County. The Tallahassee extends from Calhoun County on the west to Leon and Wakulla Counties on the east. Northward it extends to Decatur County, Ga. Eastward and southward it merges with nonfossiliferous limestone (Applin and Applin, 1944, p. 1690, fig. 4) and is present in the north half of the peninsula except along the east coast. The texture ranges from hard dense limestone to saccharoidal limestone. Gypsum and chert occur commonly. Thin streaks of carbonaceous clay are present. A 40-foot bed of lignite was penetrated at the base of the limestone in J. S. Cosden's Lawson well 1, Marion County. The limestone unit wedges out along the eastern and southern limits of the Tallahassee but in the central part of the peninsula reaches a thickness of 1,200 feet in the Oldsmar well, Hillsborough County. It is 50 to 100 feet thick in northern Florida and 950 feet thick in Pierce County, Ga.

As stated by Applin and Applin, the generally dome-shaped configuration of the nonfossiliferous limestone, its location over the Ocala uplift, and its lithologic character suggest that it may be an algal reef. The Tallahassee Limestone overlies the Lake City Limestone and underlies the Avon Park Limestone. The water-bearing properties of the Tallahassee Limestone apparently are similar to those of the Avon Park Limestone.

In recent geologic reports, including one by Puri and Vernon (1959), the name Tallahassee Limestone has not been used. Apparently, the limestone has been included as part of the Avon Park Limestone. However, in Levy County, Fla., Vernon (1951, p. 88–89, 95) stated that 411 feet of dolomite penetrated by a well and assigned by Applin and Applin (1944, p. 1738) to the nonfossiliferous limestone, is part of the Lake City Limestone in which dolomitization may have destroyed fossils.

Avon Park Limestone in Florida

The name Avon Park Limestone was proposed by Applin and Applin (1944, p. 1680) for limestone of Claiborne age penetrated between depths of 600 and 930 feet in a well drilled at the Avon Park Bombing Range (sec. 31, T. 32 S., R. 30 E.) in Polk County, Fla. At the type locality the formation is a cream-colored limestone that contains a very distinct microfauna of middle Eocene age.

As described by Toulmin (1955, p. 223), the Avon Park is a cream-colored to brown chalky limestone and dolomite that is present in the eastern part of the panhandle of Florida from Gulf County eastward into southern Georgia and throughout the peninsula except in an area in Columbia and Suwannee Counties. Surface exposures of this formation have been found only on the Ocala uplift in Citrus and Levy Counties, Fla. (Vernon, 1951, p. 95). The Avon Park is 50 feet or less thick in the northern part of the peninsula, 150 to 300 feet in the central part, and 450 to 650 feet thick in the southern part (Applin and Applin, 1944, p. 1687). However, H. G. Stewart (1959, p. 19) indicated a thickness of more than 845 feet in Polk County. It lies unconformably on the Lake City Limestone in the Florida peninsula and is overlain unconformably by the Inglis Formation of the Ocala Group (Puri, 1953, p. 130).

As described by Puri and Vernon (1959, p. 37), several general lithologic types, all carbonates, are present in the exposures in Citrus and Levy Counties and in wells that penetrate the formation. Three types as described by Vernon (1951, p. 96–98) are as follows:

1. Marine limestone, cream to brown, highly fossiliferous, fragmental to pasty; weathers cream to white and is tinted purple. The bed contains abundant specimens of mollusks, foraminifers, and corals. Its permeability and fossils resemble a reef. It grades laterally and vertically through a tan to brown dense brittle thin lithographic limestone, a 4- to 6-inch layer of "fucoid-Cerithium" fragmental dolomite, an irregular lens of lignite and a dolomitic clay with foraminifers, and into the other rock types.
2. Marine limestone (not exposed), cream to brown, pasty and fragmental, peat-flecked and seamed, very fossiliferous. Well-preserved bryozoans, foraminifers, and ostracods are abundant. The fossils are concentrated and somewhat deformed along thin beds that are interbedded with peat and pasty limestone seams which give the rock a laminated and mottled appearance, to which the term "molasses and butter" has been applied by some geologists.
3. Marine dolomite, tan to brown, finely crystalline. Molds of characteristic Avon Park foraminifers are common. The dolomite is composed of euhedral silt-sized crystals of dolomite, interbedded with layers of lignite and carbonaceous plant remains, each layer being commonly one-sixteenth to one-fourth inch in thickness. The structure of the rock resembles varves. Poor consolidation and grain size cause the rock to resemble siltstone.

Vernon reported that the Avon Park Limestone has been dolomitized since deposition and that any of the general types may be irregularly or completely dolomitized, although the original structures and composition of the rock have been preserved. Encircling Polk County and including most of Citrus and Levy Counties, the Avon Park Limestone is a shallow-water marine deposit made of a coquina. The laminated dolomite appears to have been formed in a partially landlocked shallow marine basin in which the seaweed and other marine plants flourished. In western Florida the Avon Park Limestone consists of glauconitic and calcareous sand, hard glauconitic sandstone, soft sandy glauconitic and cherty limestone, and fossiliferous bentonitic clay. These beds are correlated with the Gosport Sand and the Lisbon Formation in part, although they differ from the formations at the type sections.

The Avon Park Limestone is very permeable and cavernous in some areas. It is one of the most productive water-bearing formations of the principal artesian aquifer in Florida and southeastern Georgia. However, in some areas it is reported to be less productive than the underlying Lake City and overlying Ocala Limestones, as may be noted in the discussion of the Avon Park in Highlands County. In the Fernandina area, Florida, it appears to be less productive than in some other areas.

BREVARD COUNTY

D. W. Brown, W. E. Kenner, and Eugene Brown (1957, p. 22) reported that the Avon Park Limestone, more than 300 feet thick, is the principal source of water for the deeper artesian wells in Brevard County where the formation consists chiefly of white soft dense chalky limestone; it ranges in color from white to light brown or ash gray. Its composition ranges from chalky limestone to a loose coquina of foraminifers, echinoids, and other marine shells. In some places, the Avon Park has been largely altered to dolomite. Such alteration of the limestone may have changed the permeability of the formation. Some of the dolomite is hard and relatively impermeable. The Avon Park Limestone is less than 300 feet below sea level in the central part of the county east of the St. Johns River but is more than 600 feet below sea level along a fault on the west side of the St. Johns River.

Chemical analyses of artesian water from the Avon Park Limestone and the overlying limestone indicate a hard calcium bicarbonate water mixed with remnants of connate water. The chloride content of the water samples reported by Brown, Kenner, and Brown (1957, p. 85) ranged from about 290 ppm to more than 2,000 ppm. The carbonate hardness ranged from about 380 to more than 1,000 ppm. The temperature of the water ranged from about 73° to 81°F.

HIGHLANDS COUNTY

Bishop (1956, p. 19) reported that the Avon Park in Highlands County, Fla., is not an important source of large water supplies but is utilized locally in the vicinity of Avon Park. In other parts of the county it yields some water to wells that reach the underlying Lake City Limestone. The Avon Park Limestone in Highlands County ranges from about 200 to 350 feet in thickness. The top of the formation slopes to the south about 10 feet per mile from about 500 feet below sea level in the northern part of the county to about 900 feet below sea level in the southern part. Bishop (1956, p. 53) included analyses of one sample from the Avon Park from a well 750 feet deep. The water is similar to that in Lake City Limestone with a hardness of only 66 ppm.

HILLSBOROUGH COUNTY

Peek (1959b, p. 13) reported that the Avon Park Limestone is the oldest formation penetrated by water wells in southwestern Hillsborough County, where the top of the formation ranges in depth from 575 feet below sea level in the northern part of the area to about 900 feet in the southern part. The estimated thickness is 600 to 700 feet. Although the formation is permeable and contains solution cavities that yield large quantities of water, relatively few wells penetrate the formation in the coastal area because the water is salty. Water of better quality is obtained from the younger formations at shallower depths in that area. The upper part of the Avon Park consists predominantly of white to tan soft chalky and granular limestone containing many foraminifers and other fossils. The lower part is principally a tan to dark-brown hard crystalline dolomite containing carbonaceous material but very few fossils.

MANATEE COUNTY

In Manatee County, the Avon Park Limestone, as described by Peek (1958a, p. 16–17), is about 700 feet thick and probably is a productive water-bearing formation throughout the county because of extensive solution channels. It is the oldest formation penetrated by water wells in Manatee County. The water probably is salty in the coastal area. The formation ranges from white or tan fairly soft coquinoid or granular limestone to dark-brown hard crystalline dolomite. Most of the formation has been dolomitized to some extent. A northwest to southeast section from Tampa Bay to the southeast corner of the county by Peek indicates the top of the Avon Park ranges from less than 1,000 feet to a little more than 1,000 feet below sea level.

The wells described by Stringfield (1933c, p. 222–227) in Sarasota County, except one, are less than 1,000 feet deep and probably do not reach the Avon Park. However, current-meter measurements of a few wells show that the Ocala Limestone which overlies the Avon Park yields little or no water to wells. The water is from the Tampa Limestone and the lower part of the Hawthorn Formation.

MARTIN COUNTY

As described by Lichtler (1960, p. 14, 15), the Avon Park Limestone in Martin County is generally a cream to tan, hard to medium soft, rather pure chalky to finely crystalline limestone. No known wells pass through the Avon Park in this county, but Lichtler estimated the thickness to be at least 400 feet. Current-meter tests in wells show that very permeable zones are separated by less permeable zones. Where the salt content of the water is relatively low, the Avon Park is a source of water for irrigation. Judging from a contour map showing the top of the Ocala Limestone (Lichtler, 1960, p. 17), the top of the Avon Park Limestone ranges from about 700 feet to more than 1,200 feet below sea level. The greatest depth to the Avon Park is in a belt about 5 miles wide along the coast, which is in the downthrown block of a northwestward- to southeastward-trending fault parallel to the coast with a vertical displacement of 300 to 400 feet.

Chemical analyses (Lichtler, 1960, p. 52) of samples of the artesian water from the Avon Park Limestone and the overlying limestones indicate a calcium bicarbonate water mixed with remnants of salt water. Lichtler (1960, p. 63) believed that connate water was flushed from the formation and that sea water entered the aquifer during Pleistocene time when the sea covered much of Florida. However, Pleistocene sea water entered aquifers in some parts of Florida, but in Martin County the Avon Park Limestone is so deeply buried that it probably was not exposed to Pleistocene sea water, except at the edge of the Continental Shelf where the head in the aquifer probably was sufficient to prevent salt-water encroachment.

The chloride content of samples of artesian water from the principal artesian aquifer, which includes the Avon Park Limestone in Martin County, ranges from about 300 ppm to several thousand parts per million. In the eastern part of the county two samples had chloride contents of from 3,200 to 4,050 ppm. The highest of these is from the deepest well—1,315 feet deep. The degree of mineralization of the water differs in different parts of the county and in different zones within the water-bearing formations. As suggested by Lichtler (1960, p. 81), the zones of lowest mineralization probably correspond to the more permeable limestone where the greatest flushing of the salt water has occurred.

POLK COUNTY

In northwestern Polk County, Fla., H. G. Stewart (1959, p. 17–19) described the Avon Park Limestone as the most productive formation in the area. It is a cream to dark-brown hard dense fine-grained, locally crystalline limestone, but in some places it is chalky, dolomitic, gypsiferous, or cherty. Many rock fragments from wells at depths of 400 to 900 feet contain many small solution cavities. About 6 miles northeast of Lakeland a large industrial well 26 inches in diameter and 1,200 feet deep penetrated the top of the Avon Park at a depth of 355 feet but apparently did not pass through it. This indicates a thickness of more than 845 feet, the maximum reported for this formation.

A table by H. G. Stewart (1959, p. 14) showing solution cavities penetrated by wells in limestone in Polk County includes cavities with vertical dimensions that range from 2 to 20 feet in the Avon Park Limestone at depths from 458 to 805 feet. The cavity at a depth of 805 feet is 6 feet in diameter. The 20-foot cavity is at a depth of 482 feet. At a depth of 700 feet in one well, the driller's log showed a honeycomb zone 20 feet thick. Only the upper part of the wells are cased, and generally more than one water-bearing formation yields water to a well. Under these conditions, samples of water from a well and the yields represent a composite of more than one formation. However, pumping tests on several deep wells, in which the Avon Park is the principal water-bearing formation, give some indication of the water-bearing capacity of the Avon Park in Polk County.

A 6½-hour pumping test (Stewart, 1959, p. 39–40) at a rate of 6,500 gpm on the well 26 inches in diameter and 1,200 feet deep with 292 feet of casing gave a transmissibility of 1,000,000 gpd per ft. (gallons per day per foot) for the Avon Park and the overlying limestone of the lower member of the Ocala Limestone. Because the well was cased to a depth of 292 feet and reached the top of the Avon Park at 355 feet, only 63 feet of the Ocala Limestone may yield water to the well. During the pumping test at 6,500 gpm beginning with a static level of 14.7 feet below the land surface, the drawdown was 11.6 feet, or a specific capacity (yield in gpm per ft. of drawdown) of 560.

Assuming equivalent efficiency of the wells, differences in the permeability of the limestone in different areas are indicated by results of the pumping tests on three wells 24 inches in diameter having specific capacities of 73, 100, and 200. The wells having specific capacities of 73 and 100 were the deepest wells, 1,285 feet and 1,220 feet, cased to depths of 285 and 294 feet, respectively. The well having a specific capacity of 200 was 1,037 feet deep with 118 feet of casing. These results suggest not only differences in the permeability of the Avon Park Limestone but also that the overlying Ocala Limestone may yield a large part of the water in the well with the smallest amount of casing. Calcium and bicarbonate are the principal constituents of the water as shown by chemical analyses of samples from 66 wells (Stewart, 1959, p. 43) from the northwestern part of Polk County. Samples of water show that the magnesium and sulfate are low, indicating the water is from relatively pure limestone.

The hardness of samples from five wells ranged from 148 to 260 ppm. Three of the wells are more than 1,000 feet deep, and two were 811 and 824 feet deep. These wells may obtain a large part of their water from the Avon Park. Chemical analyses (Black and Brown, 1951, p. 94, 95) of samples of water from wells throughout the county show that the hardness of the water which may be from the Avon Park ranges from 92 ppm from a well 1,063 feet deep having 950 feet of casing at Lake Wales to 314 ppm from a well 1,201 feet deep having 300 feet of casing at Lakeland. The sample from the well at Lakeland has a sulfate content of 100 ppm. The low hardness of 92 ppm at Lake Wales indicates local recharge of the aquifer. The temperature of the water from the principal artesian aquifer ranged from 76°F in a well 108 feet deep to 81°F in a well 635 feet deep (H. G. Stewart, 1959, p. 44).

PUTNAM COUNTY

Leve (1958, p. 7) reported that the Avon Park Limestone is a predominantly tan dense hard finely crystalline dolomite in Putnam County. It is about 235 feet thick in the central part of the county. Some of the water wells penetrate the Avon Park, but the chief yield to wells apparently is from the overlying Ocala Limestone.

SEMINOLE COUNTY

Barraclough (1962, p. 14) stated that the Avon Park Limestone is the shallowest formation of the principal aquifer that underlies Seminole County. It is the chief source of artesian water. The overlying Ocala Limestone is absent in part of the county.

VOLUSIA COUNTY

In Volusia County, Wyrick (1960, p. 20) described the Avon Park Limestone as a tan limestone about 280 feet thick, some of it chalky white to ash gray or light brown. Some beds, especially near the top, are composed of a loose coquina of cone-shaped foraminifers, small echinoids, and other fossils. The Avon Park is generally dolomitized. Wyrick found that replacement of calcium in the limestone by magnesium changed the permeability of the limestone in many places. Dolomitization of loosely packed coquina makes it dense and less permeable. However, selective dolomitization of the limestone makes it very permeable with a spongy honeycomb appearance.

The Avon Park is the principal source of water in the western part of the county where the overlying Ocala Limestone is thin or absent. Many of the deeper wells along the coast yield water from the Avon Park. Wyrick (1960, p. 21) reported that chemical analyses of water from different depths in the same well show that the hardness of water from isolated sections of the Avon Park Limestone is less than that from the overlying limestone. He suggested that this may be due to the fact that dolomitic rocks are commonly less soluble in water than limestone. The Avon Park, the underlying Lake City, and overlying Ocala contain hard dense layers that are relatively impervious. These layers retard upward or downward movement of the water.

JACKSON AGE

As described by Toulmin (1955, p. 224), the formations of Jackson age (late Eocene) are separated from those of the middle Eocene by an inconspicuous disconformity. In southeastern Alabama, the formations include the Moodys Branch Formation at the bottom, overlain by the Yazoo Clay and the Ocala Limestone (Cagle and Floyd, 1957, p. 12). The Moodys Branch Formation, maximum thickness about 55 feet, consists of greenish-gray to white fossiliferous glauconitic limestone and marl. It is relatively impermeable but may be the source of small quantities of water. The Yazoo Clay, maximum thickness about 75 feet, consists of greenish-gray clay and fine to medium glauconitic sand. The sand beds are the source of small quantities of water. The Ocala Limestone, maximum thickness about 60 feet, consists of light-gray limestone and clayey fossiliferous marl (John G. Newton, written commun., 1962). Solution cavities in the limestone supply moderate quantities of water to wells. In the outcrop area in east-central Georgia, the Ocala merges laterally with the Barnwell Formation, a marine pebbly sand and sandy limestone. Downdip in Georgia and South Carolina, the Barnwell grades into the Ocala Limestone.

The Cooper Marl, a finely granular olive-drab to brown marl in South Carolina, has been considered to be Eocene and Oligocene at different times by different investigators. Herrick and Vorhis (1963, p. 18) assigned it to the Eocene in Georgia. It is included as part of the early Oligocene in the present report. In southeastern Georgia and Florida, rocks of Jackson age are represented by the Ocala Limestone.

The stratigraphic nomenclature in Florida and southern Georgia, as proposed by geologists of the U.S. Geological Survey and the Florida Geological Survey (Peek, 1959b, p. 14), is as follows:

U.S. Geological Survey			Florida Geological Survey			
Cooke (1945)	Applin and Applin (1944)		Vernon (1951)		Puri (1953, 1957)	
Ocala Limestone	Ocala Limestone	Upper member	Ocala Limestone restricted		Ocala Group	Crystal River Formation
		Lower member	Moodys Branch Formation	Williston Member		Williston Formation
				Inglis Member		Inglis Formation

The Florida Geological Survey uses Ocala as a group name as proposed by Puri (1953) and divided into three formations as shown in the preceding table. Cooke (1959, p. 3) proposed the use of Inglis Formation as the equivalent of the Inglis and Williston Formations of the Florida Geological Survey. Cole and Applin (1964, p. 1) found no faunal (foraminiferal) breaks between the Inglis Limestone and the underlying Avon Park Limestone and recommended that Inglis beds be included with the Avon Park Limestone. However, Vernon (1951) reported that the Inglis is separated from the Avon Park by an unconformity.

In Jackson County, Fla., Moore (1955, p. 21) divided the Crystal River Formation into the Bumpnose Member and the lower member. In the southeastern part of the county, he called the Crystal River the Gadsden Limestone. However, these names have not been adopted by the Florida and U.S. Geological Surveys. The Ocala as a formation name, with an upper member and a lower member, is used in the present report, in accordance with the official nomenclature of the U.S. Geological Survey.

Ocala Limestone in Florida

The Ocala Limestone was divided into an upper and a lower member by Applin and Applin (1944, p. 1679) on the basis of lithologic and faunal differences. They found that at least in the Florida peninsula it was generally possible to separate the Ocala into two members. However, in western Florida where the Ocala is chiefly cream-colored chalky limestone, they could not recognize the two members.

Vernon (1951, p. 111–171) separated the limestone unit into the Ocala Limestone (restricted to the upper part) and the Moodys Branch Formation. He divided the Moodys Branch into the Inglis Member at the bottom and the Williston Member at the top. Puri (1953, p. 130) changed the Ocala Limestone (as restricted by Vernon) to the Crystal River Formation. Later Puri (1957, p. 24–30) gave the rank of formation to the Williston and Inglis Members of the Moodys Branch and proposed that the name Ocala be used for a group consisting of the Crystal River, Williston, and Inglis Formations.

The Ocala Limestone is about 100 to 300 feet thick in much of the panhandle of Florida but is much thicker in the Apalachicola embayment in western Florida. It is thin in most of the central and northern part of the peninsula but reaches a thickness of 400 feet in the northeastern part. In the southern part of the peninsula, it is generally 200 feet thick or less and probably is absent in the vicinity of Miami and Key West. A map by Toulmin (1952, p. 1171) shows the extent and range in thickness of the Ocala Limestone in Florida, Georgia, and adjacent parts of South Carolina and Alabama. It is as much as 575 feet thick in the Savannah area, Georgia (Counts and Donsky, 1959, p. 98; 1963, p. 24). A map by Herrick and Vorhis (1963, p. 21) shows that the upper Eocene deposits in Georgia increase in thickness from their area of outcrop to more than 500 feet in some of the coastal counties and 700 feet in the southwestern part of the State.

In addition to a belt of outcrops extending from Alabama into Georgia, the Ocala Limestone crops out in two large areas in Florida. The largest area borders the gulf coast in the northwestern part of the Florida peninsula on the Ocala uplift. The other area is in western Florida in the northern half of Washington and Jackson Counties and the eastern part of Holmes County. The Ocala extends from this area into southeastern Alabama and southwestern Georgia. The Ocala merges with the Barnwell Formation in east-central Georgia. The Barnwell in the outcrop area and the Ocala downdip in Georgia extend into South Carolina.

As indicated by Toulmin's map and by Vernon (1951, pl. 2), the Ocala in Florida is absent in small areas in northern Seminole County, Volusia County, southern Orange County, northern Osceola County, Lake County, Marion County, and southern Levy County. Applin and Applin (1944, fig. 2, p. 1684) showed that the upper member of the Ocala is absent in a large area extending from the Atlantic Coast to Lake County. North to south it is absent from St. Johns County to Osceola County. The central part of this area is on the New Smyrna arch extending from the Ocala uplift to the Atlantic Ocean. This area also is on the Sanford high and Kissimmee flexure as mapped by Vernon.

In the peninsula and northern Florida, the Ocala overlies the eroded surface of the Avon Park Limestone except at Live Oak, Suwannee County, and at Lake City, Columbia County, where the Avon Park is absent and the Ocala rests on the nonfossiliferous lower unit of the late middle Eocene (Applin and Applin, 1944, p. 1683). In Duval and Clay Counties, the Ocala rests on the basal part of the Avon Park. In western Florida, Applin and Applin reported that where late middle Eocene beds are absent the Ocala apparently was deposited on early middle Eocene beds.

The upper member of the Ocala is the typical limestone at the outcrops on the Ocala uplift. It is the equivalent of the Crystal River Formation of Puri (1953, p. 130), which Vernon and Puri (1956, p. 35, 38) proposed for 108 feet of limestone exposed in the Crystal River Rock Company quarry in Citrus County, Fla. The Crystal River is synonymous with Ocala Limestone (restricted) of Vernon (1951). It is soft white chalky permeable coquina consisting chiefly of large foraminifers. It contains chert and silicified limestone. The basal part may contain a few beds of secondary dolomite, as much as 12 feet thick (Puri and Vernon, 1960, p. 12). The youngest part of the upper member of the Ocala Limestone has been removed by erosion in the area of outcrop. Puri (1957, p. 31) reported that 310 feet of the member was penetrated in a well in Polk County. The upper member of the Ocala is more than 300 feet thick in the subsurface in Jackson County in western Florida (Puri and Vernon, 1960, p. 12). In some wells in central Florida it rests directly on the Avon Park.

The lower member of the Ocala is cream-colored limestone, generally harder than the upper member, and is commonly very calcitic. In contrast to the upper member, the lower member contains specimens of larger foraminifers. In western Florida where the Ocala is chiefly cream-colored chalk, Applin and Applin (1944, p. 1684) did not recognize the two members. The lower member of the Ocala, which is regarded as the equivalent of the Inglis Formation and Williston Formation of Puri, is approximately the basal 80 feet of the Ocala Limestone of Cooke (1945, p. 53). The Inglis Formation is 50 feet thick at the type locality, near Inglis, Levy County, Fla. The maximum thickness may be more than 100 feet. As described by Vernon (1951, p. 116), the Inglis is cream to tan, granular, rarely pasty, permeable, fairly hard, marine limestone containing an abundant and bizarre fauna, in part being a coquina of foraminifers, mollusks, and echinoids. The base of the bed has been dolomitized in some of the area of outcrops, but it is seldom completely dolomitized. The dolomite is tan to brown and very porous but with low permeability. Although Cole and Applin (1964, p. 1–47) found no faunal (foraminiferal) or lithologic break between the Inglis and the underlying Avon Park, Vernon reported that the base of the Inglis is generally marked by a barnacle bed and rubble of pebbles, concretions, and soil eroded from the underlying Avon Park Limestone.

The Williston Formation is almost 100 feet thick in Hillsborough and Pinellas Counties and conformably overlies the Inglis (Puri and Vernon, 1960, p. 11). It is predominantly marine limestone. Silicified limestone is common in outcrops and generally is near the contact with the Inglis. It is overlain conformably by the Crystal River Formation of Puri. Generally, the Williston thickens as the Inglis becomes thinner. In near-shore environment, deeper water facies of the Williston disappear, and shallow water facies of the Inglis appear.

The Ocala Limestone is one of the major water-bearing formations of the principal artesian aquifer in Florida and southern Georgia. Some parts of the limestone are very permeable. Circulation of water through parts of the formation has formed cavities and caverns, especially where it is at or near the surface. In these areas sinkholes are numerous. Many cylindrical holes or natural wells (figs. 8 and 9), ranging from a few feet to more than 50 feet in depth, extend downward from the surface and connect with underground passages in the limestone. Solution channels formerly occupied by water but now filled with sand and clay are exposed in some of the limestone quarries. An exposure of a small channel filled with clayey material is shown in figure 10. One of the largest channels in Marion County observed by the writer, about 12 feet wide and 6 feet high, is filled chiefly with white sand and some gray

FIGURE 8.—Exposure of a vertical section of about 120 feet of Ocala Limestone, showing vertical solution channels or natural wells in Crystal River Rock Quarry, Citrus County, Fla.

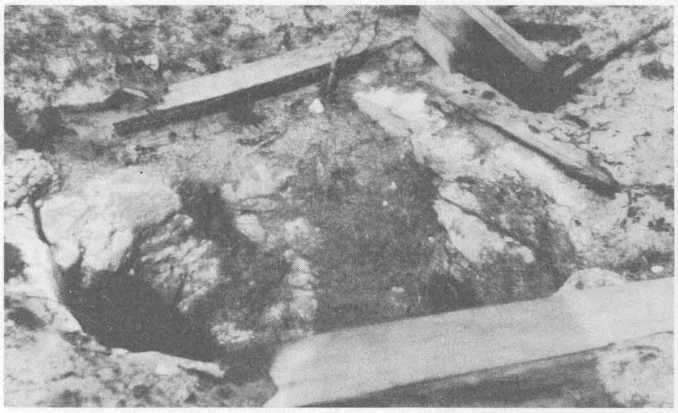

FIGURE 9.—Mouth of natural well near Brooksville, Fla. Well is about 5 feet in diameter and 50 feet or more deep.

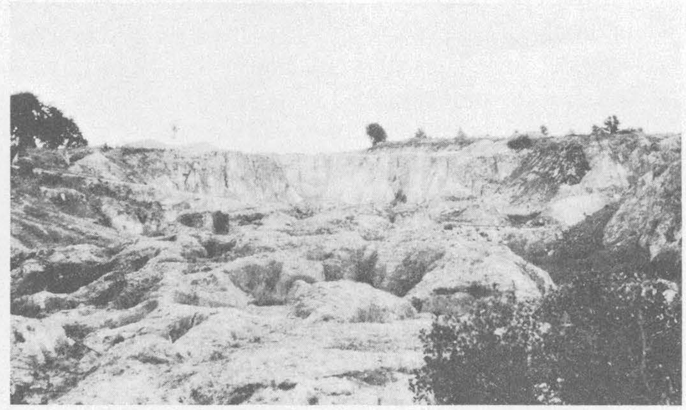

FIGURE 11.—Ocala Limestone showing old eroded surface about 5½ miles north of Ocala, Marion County, Fla.

clay. It has a fairly flat floor and an arched roof. Puri (1957, p. 32) showed an exposure of one cavern having a vertical dimension of 30 feet and stated that such caverns are common in the Ocala.

Vernon (1951, p. 152) showed pinnacles of limestone of the lower member of the Ocala Limestone extending as much as 40 feet above the floor of a quarry through the Alachua Formation in the vicinity of Floral City in southeastern Citrus County. The chert and silicified limestone are relatively impervious and do not yield water to wells, but water is commonly found beneath these rocks. An exposure of the eroded surface of the Ocala Limestone is shown in figure 11. A chalky part of the formation is shown in figure 12.

Fresh water of the Ocala Limestone enters the formation in areas where it is at or near the surface in outcrops. Also the limestone is recharged in some of the lake regions in Florida and Georgia where sinkholes filled with sand extend from the surface to the Ocala through relatively impervious beds of the Hawthorn Formation.

BREVARD COUNTY

D. W. Brown, W. E. Kenner, and Eugene Brown (1957, p. 23) described the lower member of the Ocala Limestone in Brevard County as the Inglis Formation at the bottom and the Williston Formation at the top. Rock cuttings from wells in the county show that the Inglis is a cream to white marine fossilferous granular limestone having a thickness of 50 to 100 feet. The Williston is essentially a cream-colored fossiliferous marine limestone having an average thickness of 30 feet. It is fine-grained and contains fewer echinoids than the underlying Inglis Formation.

The upper member of the Ocala Limestone (Crystal River Formation of Puri) is a white to cream

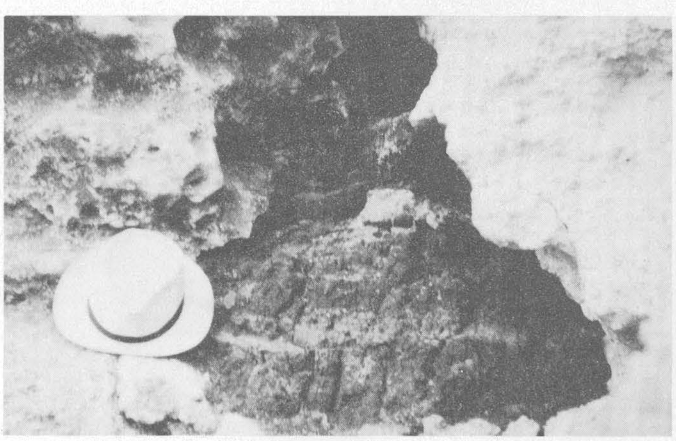

FIGURE 10.—Exposure of cavity, filled with stratified clayey material, in Ocala Limestone in a quarry south of Ocala, Marion County, Fla.

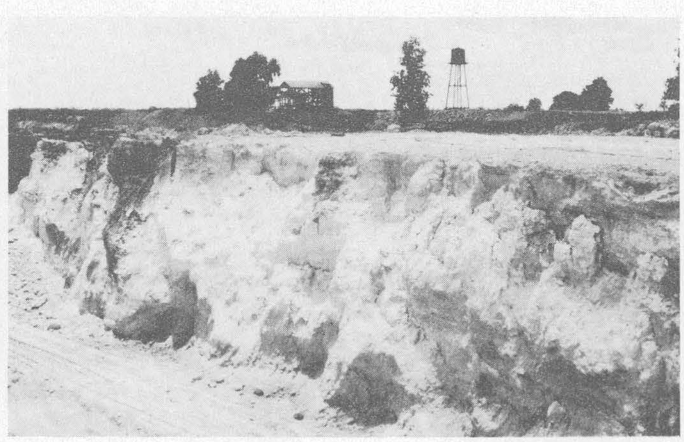

FIGURE 12.—Ocala Limestone showing chalky part of formation in a quarry about 5½ miles north of Ocala, Marion County, Fla.

soft massive friable fossiliferous limestone. The lower part of the limestone is distinguished from the underlying lower member of the Ocala on the basis of the fauna and texture. The upper member has been removed by erosion in the northern part of the county. In the southern part of the county the thickness increases southward to as much as 100 feet at the Indian River County line. A structural contour map of the top of the Ocala (D. W. Brown and others, 1957, fig. 9) shows that it ranges from about 100 feet below sea level in the western part of the county to about 300 feet below sea level in the southeastern part of the county. An east-to-west section through central Brevard County (Brown and others, 1957, fig. 10) shows a north-south fault, a short distance west of the St. Johns River, where the top of the Ocala Limestone is as much as 600 feet below sea level on the west side and about 100 feet on the east side. Brown, Kenner, Crooks, and Foster (1962, p. 73) believe the fault probably affects the direction of movement of the artesian water. The piezometric surface indicates discharge of artesian water in the northeastern part of the county which, as suggested by D. W. Brown, W. E. Kenner, and Eugene Brown (1957, p. 82), is through springs in Indian River and the Atlantic Ocean. The water-bearing properties of the different units of the Ocala, which have a total thickness of 200 or more feet in the southern part of the county, are similar and act as a hydrologic unit with the other water-bearing formations of the principal artesian aquifer. Yields of water are lowest in the fine-grained limestone in the upper part of the lower member.

HIGHLANDS COUNTY

As described by Bishop (1956, p. 20), the lower member of the Ocala Limestone consists of cream to tan-gray slightly hard to soft granular to chalky foraminiferal limestone that locally contains some crystalline calcite. The limestone is so similar to that of the upper member that the contact is not clearly defined. The lower member is about 50 to 150 feet thick. It dips south about 4 feet per mile from 500 feet below sea level in the northern part of the county to about 750 feet below sea level in the southern part. Bishop (1956, p. 22) reported that the lower member probably is not capable of producing large supplies of water but that it contributes some water to wells that penetrate it. He described the upper member as a light-gray to cream soft chalky coquina limestone composed almost entirely of large foraminifers. The thickness apparently ranges from about 150 to 250 feet, and the top of the member slopes to the south from about 250 feet below sea level in the northern part of the county to 650 feet in the southern part at an average rate of about 10 feet per mile.

The upper member does not yield as much water as the limestone below the Ocala, but in the southeastern part of the county it is capable of yielding large quantities. In the western part of the county, the Ocala is overlain unconformably by the Suwannee Limestone of Oligocene age. The Suwannee is absent in the eastern part of the county, and the Ocala is overlain unconformably by the Hawthorn Formation of Miocene age.

HILLSBOROUGH COUNTY

As described by Peek (1959b, p. 14), the Ocala Limestone is about 250 feet thick in southwestern Hillsborough County, Fla., and lies unconformably on the Avon Park Limestone. The top of the formation is about 300 feet below sea level in the northern part of the county and slopes to about 600 feet below sea level in the southern part.

The upper part of the Ocala is a creamy white to tan soft somewhat granular chalky coquinoid limestone, composed of remains of foraminifers, mollusks, echinoids, and other fossils loosely cemented in a fine granular chalky matrix. The lower part of the Ocala is more granular and less chalky than the upper part and contains fewer foraminifers. Apparently the Ocala is one of the more productive water-bearing formations of the principal artesian aquifer in Hillsborough County. However, in the coastal area the mineral content of the water generally is considerably higher in the Ocala than in the overlying limestone.

INDIAN RIVER COUNTY

Bermes (1958b, p. 13–14) reported that the lower member of the Ocala Limestone in Indian River County, Fla., probably ranges in thickness from 20 to 100 feet and presumably lies unconformably upon the Avon Park Limestone. It consists predominantly of cream-colored to tan hard to soft granular permeable limestone with calcite crystals.

The upper member of the Ocala in Indian River County consists of cream-colored to light-gray hard to soft permeable glauconitic limestone. It contains many foraminifers along with other fossils—as mollusks, echinoids, ostracods, corals, and a species of small brachiopod. The thickness ranges from 20 feet to about 380 feet, apparently the maximum reported for this part of the Ocala. The Ocala Limestone is overlain by limestone of Oligocene age in the eastern part of Indian River County. In the remainder of the county, it is overlain unconformably by the Hawthorn Formation. The Ocala is one of the most productive water-bearing formations of the principal artesian aquifer in this county.

MANATEE COUNTY

In Manatee County, Fla., the Ocala Limestone is about 300 to 325 feet thick (Peek, 1958a, p. 16). The upper part consists predominantly of cream, tan, and grayish-tan soft chalky very fossiliferous limestone. The lower part is similar to the upper part but contains beds of brown and tan hard crystalline dolomite and dolomitic limestone. Only a few wells in the county penetrate the Ocala, the top of which probably is less than 600 feet in the northeastern part of the county and more than 700 feet in the southwestern part of the county. It may be a productive source of artesian water, but the water along the coast has a relatively high mineral content.

MARTIN COUNTY

As described by (Lichtler, 1960, p. 16), the Ocala Limestone is generally less than 100 feet thick in Martin County, Fla., and the record of a well at one locality shows it is only 20 feet thick. The limestone is white to cream or slightly pink soft to medium hard and contains much calcite in some areas. Part of it is granular and in some places the limestone consists almost entirely of foraminifers. The Ocala unconformably overlies the Avon Park and is overlain unconformably by the Suwannee Limestone in Martin County.

As shown by a contour map of the top of the Ocala Limestone (Lichtler, 1960, p. 17), the depth to the top ranges from about 615 feet on a dome in the north-central part of the county to about 800 feet in the southern part.

Lichtler also reported that in the eastern part of the county the limestone is on the downthrown block of a fault with a vertical displacement of about 300 to 400 feet. The fault is approximately parallel to and about 5 miles west of the coast. Although the top of the Ocala is an erosional surface and the underlying formations do not have exactly the same shape, the major features of the structure are present in the underlying Avon Park Limestone.

The Ocala Limestone is one of the water-bearing formations of the principal artesian aquifer in this county. The contour map representing the top of the Ocala shows the depth at which the first substantial artesian flow is obtained in wells that yield water from the aquifer. West of the fault, the Ocala generally provides the first substantial flow because the overlying Tampa Limestone and Suwannee Limestone are either thin or missing. East of the fault, the Suwannee Limestone is relatively thick and will yield small quantities of artesian water. Current-meter surveys in wells west of the fault show that a large percentage of the artesian water is from the Ocala Limestone. In one well nearly 100 percent of the water is from the Ocala (Lichtler, 1960, p. 36–38). East of the fault, the water enters the wells at a more uniform rate from different parts of the aquifer than west of the fault.

PINELLAS COUNTY

Although the Ocala Limestone underlies all Pinellas County, Fla., and may be a productive water-bearing formation in that county, Heath and Smith (1954, p. 10) reported that the formation is not used because it is more than 300 feet beneath the surface and is overlain by productive water-bearing formations (Tampa and Suwannee Limestones) of the principal aquifer. Also, the water is harder and has a higher mineral content than the overlying limestone.

POLK COUNTY

H. G. Stewart (1959, p. 20) described the lower member of the Ocala Limestone in northwestern Polk County, Fla., as the Inglis and Williston Formations and the upper member as the Crystal River Formation. The Inglis is cream-colored hard granular limestone, about 25 to 50 feet thick. The Williston is cream-colored to tan generally soft granular limestone, 15 to 30 feet thick. The Crystal River Formation is described as white to cream very soft coarse-grained limestone about 100 to 150 feet thick in northwestern Polk County. It is composed chiefly of shells of large foraminifers in a fine-grained matrix of limestone. This member of the Ocala grades vertically into the underlying lower member, a condition making the contact difficult to determine. The Ocala Limestone rests unconformably on the underlying Avon Park Limestone and is overlain unconformably by the Suwannee Limestone, except in localities where the Suwannee Limestone is absent. In these areas the Tampa overlies the Ocala unconformably. A northeast-southwest section in northwestern Polk County (H. G. Stewart, 1959, p. 18) shows that the top of the Ocala Limestone ranges from about sea level to about 150 feet below sea level.

Although H. G. Stewart (1959, p. 14) recorded two solution cavities, one having a vertical dimension of 2 feet and the other of 40 feet, in the upper member of the Ocala Limestone, he reported that the yield of wells in this part of the Ocala is small, and larger yields are obtained by drilling into the underlying limestone.

PUTNAM COUNTY

Leve (1958, p. 9) described the Ocala in Putnam County, Fla., as a cream to white granular soft permeable limestone. The thickness is 110 to 135 feet in the central part of the county. It is very fossiliferous, and some zones are composed of loosely cemented shell fragments. A generalized geologic section (Leve, 1958, p. 8) shows the top of the Ocala ranges from approximately 25 feet below sea level in the western part of the county to 125 to 170 feet below sea level in the central and eastern parts. The surface of the Ocala was eroded before the younger formations were deposited on it, and the altitudes of the surface may therefore differ as much as 50 feet within a few hundred yards. The Ocala unconformably overlies the Avon Park Limestone and is overlain unconformably by Miocene or younger formations. The Ocala is the chief water-bearing formation of the principal artesian aquifer in Putnam County.

Analyses of water samples (Leve, 1958, p. 25; Black and Brown, 1951, p. 96) from artesian wells that penetrate the limestone, chiefly Ocala, show that the water having a low chloride content (less than about 20 ppm) is calcium bicarbonate water whose total hardness ranges from about 50 ppm to about 125 ppm. The samples having the lowest hardness are from wells in areas in which the limestone is recharged by water that moves from the surface to the limestone through sinkholes, most of which are now filled with permeable sand. Samples having relatively high chloride content, as much as several thousand parts per million, appear to be a mixture of fresh water in the limestone and remnants of Pleistocene sea water.

SEMINOLE COUNTY

As described by Barraclough (1962, p. 14–15), the Ocala Limestone in Seminole County, Fla., consists of white-cream to tan-gray, soft to hard, granular, permeable foraminiferal marine limestone. In most places the upper member is white to cream; parts of it are composed almost entirely of remains of large foraminifers. The lower member is harder, more granular, and contains fewer large foraminifers than the upper member.

The Ocala Limestone unconformably overlies the Avon Park Limestone and is unconformably overlain by the Hawthorn Formation. Where the Hawthorn is absent, the Ocala is overlain by younger deposits. The Ocala has been removed by erosion in the northern part and in a small area in the southwestern part of Seminole County. The thickness ranges from 0 to about 190 feet. The top of the Ocala ranges from a few feet below sea level near the town of Lake Mary to about 113 feet below sea level at the village of Lake Monroe. The Ocala Limestone is a very productive part of the principal artesian aquifer in Seminole County. It ranks next to the underlying Avon Park and yields more than 500 gpm to some wells.

VOLUSIA COUNTY

Wyrick (1960, p. 22) described the lower part of the Ocala Limestone in Volusia County, Fla., as the Inglis Formation at the bottom and the Williston Formation at the top. The Inglis is cream to white limestone. Its average thickness is 50 feet but may be as much as 120 feet in some parts of the county (Vernon, 1951, p. 117–122). The gray color is due to finely divided pyrite. The limestone is very permeable and yields a large part of the water obtained from wells in Volusia County. The Inglis has been removed from the crest of a geologic structural feature near De Land.

The Williston Formation is a soft granular limestone. It is generally finer grained and less permeable than the Inglis. It has an average thickness of about 30 feet but has been entirely eroded from the structural high near De Land and thinned by erosion throughout the remainder of the county. However, it is an important part of the principal artesian aquifer in Volusia County. Along the coast many wells yield water from this part of the Ocala. The hydrologic properties of the Inglis and Williston, which form the lower member of the Ocala, are similar but are modified locally by dolomitization. The upper member of the Ocala Limestone (Crystal River Formation of Puri) has not been recognized in Volusia County and apparently has been removed by erosion.

Ocala Limestone in Georgia

SAVANNAH AREA

In the northeastern part of the Savannah area, Georgia, Counts and Donsky (1959, p. 96; 1962, p. 24) divided the Ocala Limestone into a lower unit and an upper unit on the bases of hydrologic properties and electric-log correlations. S. M. Herrick (written commun., 1959) suggested that the same division may be made on the basis of microfaunal evidence. The lower unit is a soft sandy limestone or marl, somewhat similar to the underlying Gosport Sand, which consists of limestone, in this area. Its maximum recorded thickness is 283 feet. The upper unit is a white calcitized crystalline limestone having a maximum thickness of about 283 feet. In the southern and western part of the area, the Ocala Limestone has not been divided into upper and lower units. The maximum thickness of the undifferentiated Ocala is 575 feet. The Ocala Limestone is the major part of the principal artesian aquifer in this area. The recorded yield of wells from this aquifer is as much as 4,200 gpm.

Chemical analyses of four samples of water from the aquifer in this area (Warren, 1944, p. 138) showed that the chief constituents were silica, calcium, and bicarbonate. Its hardness ranged from 100 to 113 ppm. The silica ranged from 25 to 127 ppm. The range in bicarbonate was only from 134 to 135 ppm.

CALHOUN COUNTY

The Ocala Limestone in Calhoun County, Ga., (Wait, 1960c, p. 28) is a white to cream-colored fossiliferous limestone that ranges from about 16 feet at Morgan to about 100 feet at Leary. The limestone is at or near the land surface throughout the county. Many sinkholes in the limestone serve as areas of recharge to the Ocala.

CLAY COUNTY

The Ocala Limestone is present only in southeastern Clay County, Ga., where it consists of red sandy residual clay that contains silicified limestone boulders (Wait, 1960b, p. 96). The thickness of the residual material probably averages 40 to 50 feet.

CRISP COUNTY

The Ocala Limestone is a white to cream-colored limestone underlying Crisp County, Ga. (Wait, 1958a, p. 45). It is at or near the surface in the western part of the county in Flint River valley. It is only a few feet thick in the northwestern part of the county but thickens to as much as 130 feet in the southeast corner. Springs in the Ocala Limestone flow into the Flint River and tributary streams in the western part of the county. The Ocala Limestone is one of the more productive water-bearing formations in this county. The yield of wells increases with the increase in thickness of the limestone toward the southeastern part of the county.

DOUGHERTY COUNTY

In Dougherty County, Ga., the Ocala is a pale orange to white pure very fossiliferous recrystallized limestone, which ranges in thickness from about 70 feet in the northwestern part of the county to about 270 feet in the southeastern part (Wait, 1958b, p. 124; 1963, p. 37). It overlies the Lisbon Formation and is overlain by red to brown surficial sandy clay derived in part from weathering of the limestone. This residual material, called residuum by some geologists, has a maximum thickness of about 70 feet. Solution of the Ocala Limestone by water moving along joints and bedding planes formed many sinkholes in the county. Surface water that accumulates in these sinks recharges the Ocala.

Although the Ocala Limestone yields large supplies of water in the county, some wells, as in the Albany area, have been drilled into the underlying formations to avoid possible surface pollution of the water. The water in the Ocala is a moderately hard calcium bicarbonate type, in contrast to the soft sodium bicarbonate water in some of the underlying Cretaceous sands.

LEE AND SUMTER COUNTIES

In Lee and Sumter Counties, Ga., the Ocala Limestone is a pure to somewhat sandy limestone (Owen, 1958, p. 118) ranging in thickness from about 15 feet in the northwest corner of the county to about 150 feet in the southeast corner. It is overlain by surficial sandy clay which is as much as 60 feet thick. In valleys the Ocala is exposed at the surface. Water can be obtained from the Ocala throughout most of the county. More wells obtain water from the Ocala than any other formation in the county. The Ocala Limestone is the principal source of domestic water supplies in part of southeastern Sumter County (Owen, 1963, p. 45).

TERRELL COUNTY

The Ocala Limestone is a white to pale-yellowish orange fossiliferous pure limestone (Wait, 1960d, p. 121). It underlies much of the southern part of Terrell county, Ga., and thickens toward the southeast where the maximum is estimated at 75 feet. It is overlain by surficial sands and clays and is underlain by the Lisbon. The Ocala Limestone is an important water-bearing formation in the southeastern part of the county. Elsewhere in the county it is generally too thin to yield much water.

SOUTHWESTERN GEORGIA

In southwestern Georgia, Wait (1960a, p. 13) described the Ocala Limestone as a white to pink pure to sandy limestone. The formation contains brown dolomitic limestone in the Valdosta area. The Ocala is at or near the surface in a broad belt extending from Florida and Alabama northeast into Georgia, where it grades into the Barnwell Formation. The limestone extends southeastward under the Tifton Upland in Georgia. It is one of the principal water-bearing formations of this area and contains calcium bicarbonate water that is moderately hard to hard and slightly alkaline. The sulfate content is only a few parts per million where the limestone is at or near the surface, in contrast to the high sulfate and magnesium content in dolomitic limestone of the Ocala at depths of 350 to 400 feet at Valdosta, Lowndes County.

Ocala Limestone in Escambia County, Ala.

In Escambia County (Cagle and Floyd, 1957, p. 12), the Ocala Limestone includes only the upper part of the Jackson group (late Eocene) which consists of the Moodys Branch Formation at the bottom, Yazoo Clay in the middle, and the Ocala at the top. The Moodys Branch consists of greenish-gray fossiliferous glauconitic limestone, which is relatively impermeable but may yield small quantities of water to wells. The Yazoo Clay consists of greenish-gray clay and fine to medium glauconitic sand, which may yield small quantities of water to wells. The Ocala Limestone consists of light-gray limestone and clayey fossiliferous marl. Solution cavities in the limestone yield water to wells.

OLIGOCENE SERIES

The Oligocene is represented in south-central and southeastern Alabama by the Chickasawhay Limestone, Byram Formation, undifferentiated Marianna Limestone, and Red Bluff Clay. In Florida the Oligocene Series consists of limestone. The series thickens downdip to the maximum of about 800 feet in the Apalachicola area (Toulmin, 1952, fig. 6). In the Florida panhandle the Oligocene is represented by the Suwannee Limestone, Byram Formation, and Marianna Limestone. In peninsular Florida and in Georgia the Oligocene is represented by the Suwannee Limestone. The Flint River Formation extends from Alabama across Georgia to South Carolina. In Georgia and South Carolina the Cooper Marl is included in the Oligocene in the present report. Herrick and Vorhis (1963, p. 18) described the Cooper Marl as late Eocene in Georgia. Counts and Donsky (1963, p. 26) treated the rocks of the Oligocene Series in the Savannah area as undifferentiated. The Oligocene rocks are not exposed in the Savannah area but crop out in the southwest and central parts of Georgia and near Charleston, S.C. The writer considers the Suwannee and Flint River as part of the principal artesian aquifer in Georgia.

In Alabama, formations in the Oligocene Series are composed of limestone, marl, clay, and calcareous sand of marine origin (Cagle and Floyd, 1957, p. 12–15; Cagle and Newton, 1963, p. 26–32). The Oligocene rocks overlie the Ocala Limestone of Jackson age and are overlain by undifferentiated deposits of Miocene age. The Oligocene Series in Escambia County in southeastern Alabama includes, from bottom to top, the Marianna Limestone, with the Red Bluff Clay at its base, the Byram Formation, and the Chickasawhay Limestone. The Red Bluff Clay and the Marianna and Chickasawhay Limestones are not exposed in Escambia County. The Red Bluff Clay and Marianna Limestone undifferentiated consist of about 40 feet of light-gray fossiliferous limestone and clayey marl. Toulmin (1955, p. 226) considered the Red Bluff a faunal zone at the base of the Marianna in this area. Solution cavities in the limestone supply moderate quantities of water to domestic, industrial, municipal, and some irrigation wells.

BYRAM FORMATION

The Byram Formation in Alabama includes at the bottom the Glendon Limestone Member, a yellow to white irregularly indurated coquinoid and crystalline limestone; in the middle a gray to tan sandy glauconitic marl and marlstone member; and at the top the Bucatunna Clay Member consisting of a yellow sand and dark carbonaceous clay. In table 2 the members are undifferentiated. In Escambia County, Ala., Cagle and Floyd (1957, p. 15) described the Byram as a unit consisting generally of 80 to 90 feet of dark-gray to brown lignitic clay. It is generally not an important source of water in the county; however, sand in 40 to 50 feet of the Byram yields small supplies of water to flowing wells in Brewton. The Byram has been recognized (Puri and Vernon, 1959, p. 88) in several outcrops in Jackson County in western Florida. Farther west in Washington and Holmes Counties, Vernon (1942, p. 59) assigned all beds between the Marianna Limestone and the overlying Tampa Limestone to the Suwannee Limestone. Good exposures of the Suwannee Limestone in the panhandle of Florida include Falling Water Sink, about 72 feet deep, in Washington County (Puri and Vernon, 1959, p. 100; Vernon, 1942, p. 60–61).

CHICKASAWHAY LIMESTONE

The Chickasawhay Limestone in Alabama consists of about 70 feet of fossiliferous dolomitic greenish-gray limestone and a few beds of fine glauconitic sand. The sand and solution cavities yield small quantities of water to wells. In Escambia and Santa Rosa Counties in western Florida, Marsh (1962a, p. D59–D60) reported that the Chickasawhay Limestone underlies the entire area and that it thickens from about 30 feet to 130 feet toward the Gulf of

Mexico. The Chickasawhay consists of vesicular limestone and dolomitic limestone and some light-brown dolomite. It underlies the Tampa, which is dark to light gray to grayish white and generally is not dolomitic. The Tampa is less vesicular and contains more clay than the Chickasawhay.

The age equivalents of the Byram and Chickasawhay are not easily differentiated. However, the Bucatunna Clay Member of the Byram has been described by Marsh (1961, p. 224; 1962b, p. 243–251) in Santa Rosa and Escambia Counties, where it consists chiefly of a relatively impervious clay ranging in thickness from 45 feet in the northeast corner of Santa Rosa County to 215 feet in the area just north of Escambia Bay. It dips about 30 feet to the mile toward the southwest and separates the principal aquifer into two parts. The clay is overlain by Oligocene limestone, which Marsh (1962a, p. D60) refers to as Chickasawhay Limestone.

COOPER MARL

The Cooper Marl, a finely granular olive-drab to brown marl as much as 200 feet thick, containing glauconite and phosphatic nodules in the lower part, crops out in a broad belt extending northeastward from Allendale County on the Savannah River to the Santee River in Berkeley County. The marl is soft in fresh exposures. Cooke (1936, p. 163) assigned the marl to the Jackson Group of Eocene age and reported that in the vicinity of Charleston the Cooper Marl and the underlying Santee Limestone of late Eocene age had a thickness of about 440 feet.

Later Cooke and MacNeil (1952, p. 27) and MacNeil (in Malde, 1959, p. 19) found fossils in the formation, and they assigned the marl to the Oligocene Series. The marl is at or near the land surface in the Charleston area, where the permeability is so small that an unlined tunnel in the marl has been used for many years to conduct the municipal water supply of Charleston many miles from a surface reservoir to the city. It yields little or no water to wells and, therefore, is not important as a source of water in South Carolina and Georgia.

SUWANNEE LIMESTONE IN FLORIDA

As described by Toulmin (1955, p. 226), the Suwannee is a cream-colored granular permeable thin-bedded coquinoid limestone. The bottom part of the formation contains some thin-bedded dense hard limestone. The maximum thickness in Georgia is about 200 feet in the south-central part near Florida. As described by Applin and Applin (1944, p. 1682), at Tallahassee the thickness is 300 to 350 feet and is 450 feet in a well at Key West. The Suwannee lies unconformably on the Byram Limestone or, where that is absent, on the Ocala. It is overlain unconformably by the Tampa Limestone or by the Hawthorn Formation (Cooke, 1945, p. 88). The Suwannee is absent in southeastern Georgia and throughout the eastern and central parts of the Florida peninsula, as far south as Indian River County on the Atlantic coast. In north-central Florida, it is absent from coast to coast.

As shown by Toulmin (1952, p. 1172) and Applin and Applin (1944, p. 1682), the Suwannee is also absent in southwestern Georgia and adjacent parts of Georgia and Alabama. In the Flint River valley in southwestern Georgia, the Oligocene is represented by the Flint River Formation described by Cooke (1943, p. 77–84). The Suwannee crops out in the Suwannee River valley in Florida and in all or parts of several counties bordering the river. It also is at or near the surface in the west-central part of the peninsula, chiefly in Pasco and Hernando Counties; it extends eastward into adjacent counties and northward into Citrus County.

The Suwannee Limestone is not as extensive as the underlying Eocene formations; however, where it is present, it is one of the most productive water-bearing formations of the principal artesian aquifer. The limestone contains many cavities formed by solution. These cavities yield large quantities of water to wells. Parts of the limestone, consisting chiefly of shells of foraminifers, are very permeable. Many solution cavities in the limestone are exposed along the Suwannee River where water from the river enters the limestone during high stages of the river. During low stages large quantities of water flow from the limestone into the river. The east-west flow in the limestone, with its reversal of flow, may be observed at Falmouth Spring, 0.2 mile west of Falmouth and 3.5 miles southeast of the Suwannee River at Ellaville.

Highlands County

The Suwannee Limestone in Highlands County, Fla., (Bishop, 1956, p. 23) is predominantly cream-colored slightly permeable and soft chalky to slightly crystalline limestone. Its maximum thickness is about 80 feet. It is present only in the western part of the county where it rests unconformably on the Ocala Limestone and is unconformably overlain by the Hawthorn Formation. The top of the formation slopes from about 200 feet below sea level in the northern part of the county to about 500 feet below sea level in the southern part, an average of about

6 feet per mile. The Suwannee is not an important water-bearing formation in Highlands County although it is used for small domestic supplies.

Hillsborough County

Peek (1959b, p. 15) reported that the upper part of the Suwannee Limestone in the southwestern part of Hillsborough County, Fla., is creamy white to tan soft granular fossiliferous limestone. Some beds are crystalline, dolomitic, and partly silicified. The lower part of the Suwannee is generally a tan to brown soft to hard granular to dense limestone, which is harder, more crystalline and dolomitic, and less fossiliferous than the upper part. The Suwannee has a fairly uniform thickness of about 200 to 225 feet. As shown on a map by Peek (1959b, p. 16), the top of the limestone ranges in depth from about 75 feet below sea level in the vicinity of Tampa to 400 feet below sea level in the southwestern part of the county.

Martin County

Lichtler (1960, p. 17) reported that the Suwannee Limestone in Martin County, Fla., is cream-colored and soft. Its thickness ranges from 20 to 60 feet on the west side of a fault, which is parallel to and about 5 miles west of the coast. The thickness is 100 to 170 feet on the east (downthrown) side of the fault. These differences in thickness indicate that movement along the fault probably started during late-Oligocene or post-Oligocene time and continued when the Suwannee was exposed to erosion. The thickness of the Suwannee on the east side of the fault is greater than on the west side because the downthrown block was protected from erosion. Lichtler also suggested that some movement along the fault probably occurred during Miocene time and that the faulting, as discussed by Vernon (1951, p. 54–63), was probably associated with crustal movements which formed the Ocala uplift. The Suwannee is underlain unconformably by the Ocala Limestone and is overlain unconformably by the Tampa Limestone or by the Hawthorn Formation where the Tampa is absent. The Suwannee Limestone is part of the principal artesian aquifer, but its permeability is generally less than that of the underlying limestone. The chloride content of the water is generally larger than in the more permeable rocks because ground-water circulation has removed more salt water in the permeable rocks than in those less permeable.

Pinellas County

In Pinellas County, Fla., (Heath and Smith, 1954, p. 12) the Suwannee Limestone is predominantly white to cream colored, hard, and generally fossiliferous. A well penetrated 180 feet of the limestone north of Tarpon Springs. Although the well did not pass through the formation, Heath and Smith suggested that the limestone is not much thicker than 180 feet. In Pinellas County the Suwannee is underlain by the Ocala and is overlain by the Tampa Limestone. The Suwannee is very permeable and a good source of water in coastal areas where salt water has not entered it.

Polk County

In a report on the northwestern part of Polk County, Fla., H. G. Stewart (1959, p. 21) described the Suwannee as a light- to dark-cream granular detrital soft very pure fossiliferous limestone as much as 100 feet thick. Some parts are so fossiliferous that well drillers usually call it coquina. In some places the limestone contains extremely hard masses of dark-brown chert, commonly 1 inch to 2 feet thick, but in a few places they may be as much as 10 feet thick. The Suwannee unconformably overlies the upper member of the Ocala Limestone. In the southern part of the area, it is overlain unconformably by limestones of Miocene age, and in the northern part, by unconsolidated sand and clay, which may range in age from Oligocene to Recent. Solution cavities penetrated by a well in the Suwannee Limestone range in vertical dimensions from 2 to 5 feet. One spongy honeycomb zone has a thickness of 43 feet.

SUWANNEE LIMESTONE IN SAVANNAH AREA, GEORGIA

In the Savannah area, Counts and Donsky (1959, p. 98; 1963, p. 14) reported that undifferentiated deposits of Oligocene age consist of as much as 205 feet of loosely consolidated gray to buff limestone containing thin stringers of dense white sandy and cherty limestone. The limestone is part of the principal artesian aquifer and yields as much as 500 gpm to wells.

FLINT RIVER FORMATION

As described by Cooke (1945, p. 104–106; 1943, p. 77–84), the Flint River Formation extends from Covington County, Ala., across Georgia to Allendale County, S.C., a distance of nearly 350 miles. Its belt of outcrop is nearly 65 miles wide in southwestern Georgia, where the formation is broken into two parts by an inlier of Ocala Limestone. The Flint

River grades southward into the Suwannee Limestone and westward into the Chickasawhay Limestone. In its original condition the Flint River Formation probably consisted chiefly of sandy and pebbly limestone and calcareous sand. Solution and weathering have removed the lime from the exposed parts of the formation. Solution of the limestone was accompanied by silicification, which locally retained the original form but elsewhere produced dense vitreous chert or jasper. Some of the cavities in the chert are studded with drusy quartz crystals. The original thickness of the formation may have been more than 100 feet, but the residual products now exposed are probably less.

Southwestern Georgia

Recent reports on Calhoun, Clay, Crisp, and Terrell Counties in southwestern Georgia include brief statements on the water-bearing properties of the Flint River Formation. Wait (1960c, p. 27) reported that in Calhoun County the Flint River Formation is siliceous limestone and sandy clay. The formation occurs only in the northwest corner of the county. It may yield small amounts of water locally to dug wells. In Clay County, Wait (1960b, p. 95) described the Flint River as sandy clay and silicified limestone boulders restricted to hilltops in the southern part of the county. It is not important as an aquifer but may yield some water to dug wells. The Flint River Formation in Crisp County (Wait, 1958a, p. 44) is siliceous and sandy limestone. It is present in the eastern two-thirds of the county, where it supplies water to dug wells and shallow drilled wells. In the east half of the county, the Flint River Formation underlies the Hawthorn Formation. It is at or near the surface in a broad north-south belt 3 to 5 miles east of the Flint River. In Terrell County Wait (1960d, p. 121) reported that the Flint River consists chiefly of dark-red sandy clay intermixed with siliceous boulders. It may yield small amounts of water to dug wells.

MIOCENE SERIES

As described by Cooke (1945, p. 109), Miocene time may be divided into three parts, each of which began by an expansion of the sea upon the land. In Florida and Georgia the early Miocene is represented by the Tampa Limestone, which lies on the eroded surface of the Suwannee Limestone and the Flint River Formation of Oligocene age or upon older limestones. The Tampa seems to be contemporaneous with the Catahoula Sandstone and Paynes Hammock Sand in southeastern Alabama. In middle Miocene time, the sea may have spread out over all the Floridian Plateau, which had been partly above sea level, and covered parts of Georgia and South Carolina. However, Vernon (1951, p. 181) believed that the Miocene seas never extended across the Ocala uplift in the Florida peninsula. The Hawthorn Formation was deposited in the eastern region. In western Florida the Chipola Formation and the overlying Shoal River Formation, including the Oak Grove Sand Member, were deposited. Cooke (1945, p. 137) included the Hawthorn (east of the Apalachicola River) and the Chipola and Shoal River (west of the Apalachicola) in the Alum Bluff Group. After the Hawthorn was deposited, the sea withdrew presumably beyond the present shoreline. In late Miocene time the sea advanced and deposited the Duplin Marl.

In southeastern Florida, the late Miocene is represented by the Tamiami Formation (Parker and others, 1955, p. 84–88), which apparently is the age equivalent of the Choctawhatchee Formation of the Florida Geological Survey.

The Alachua and Bone Valley Formations described by Cooke (1945, p. 199–210) as Pliocene are regarded by Puri and Vernon (1959, p. 9, 160–174) as Miocene. In the present report, these formations are included in the Pliocene.

The Miocene is divided by Puri and Vernon (1959, p. 9) into three time-rock units as follows: Tampa stage, Alum Bluff stage, and Choctawhatchee stage. The lithostratigraphic and biostratigraphic divisions are subdivided into facies.

Tampa, Shoal River, Chipola, Hawthorn, Tamiami, Alachua, and Bone Valley are used as formation names in the present report. The Choctawhatchee is regarded (Cooke, 1945, p. 168) as part of the Shoal River, which is equivalent in age to the Tamiami. The Alum Bluff Group includes the Chipola and Shoal River Formations. The Oak Grove Sand is a basal member of the Shoal River. The Hawthorn Formation represents the Alum Bluff Group east of the Apalachicola River in Florida. The distribution of these units on the surface and in the subsurface in Florida are shown by Puri and Vernon (1959, pls. 2–7).

Goodell and Yon (1960, p. 75–113) included the Miocene formations in composite lithofacies and isopach maps of post-Eocene formations and also included lithostratigraphic cross sections of post-Eocene strata in Florida.

TAMPA LIMESTONE IN FLORIDA

As described by Cooke (1945, p. 113–114), the Tampa Limestone is commonly a fairly hard dense

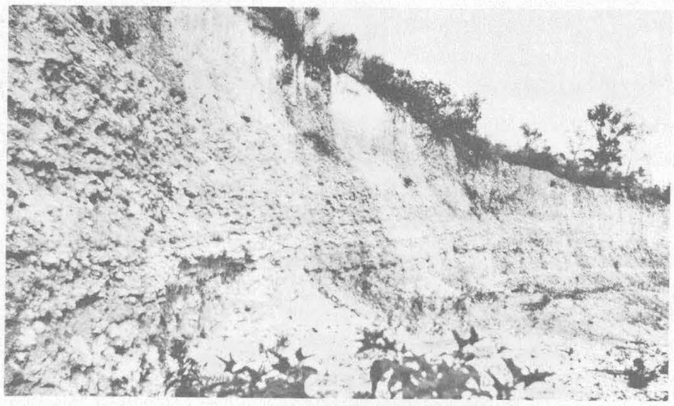

FIGURE 13.—Tampa Limestone showing bedding in portland cement quarry about 11 miles west of Brooksville, Hernando County, Fla.

light-colored to yellowish limestone in Hillsborough, Pasco, and Pinellas Counties, Fla. Its composition is much more variable than either the Suwannee or the Ocala, both of which are much purer limestone. Bedding is distinct (fig. 13), in contrast to the Ocala (fig. 12). Some weathered exposures reveal small pockets of clay, as in a quarry in Hernando County, Fla. (fig. 14).

Cooke and Mossom (1929, p. 78–79) changed the name Tampa Formation to Tampa Limestone because the formation is chiefly limestone in outcrops. They redefined it to include the Chattahoochee Formation. Vernon (1942) revived the original term Tampa Formation because the Tampa consists of sand, silt, marl, subordinate limestone, and fuller's earth downdip. In the present report the name Tampa Limestone is used.

The Tampa Limestone is at or near the surface in two general areas in Florida. One area, which includes the type locality at Tampa, is in the Florida peninsula in Hillsborough and Pasco Counties and adjacent parts of Pinellas County. The area in the panhandle extends westward from the Apalachicola River valley in western Gadsden and Liberty Counties to the west side of Holmes County. Well records indicate that the Tampa is absent in the eastern and northeastern parts of the peninsula. It extends from Florida into Georgia and is present as far north as South Carolina in the Savannah area (Counts and Donsky, 1959, p. 98; 1963, p. 28). The outcrop in Georgia, as shown on a geologic map (Cooke, 1943, pl. 1), extends as a narrow belt from southwestern Decatur County northeastward into Worth County near Sylvester. The thickest exposure reported by Cooke (1945, p. 114) is at Chattahoochee in Gadsden County, Fla., where the limestone rises from river level to 117 feet above low water level in the Apalachicola River.

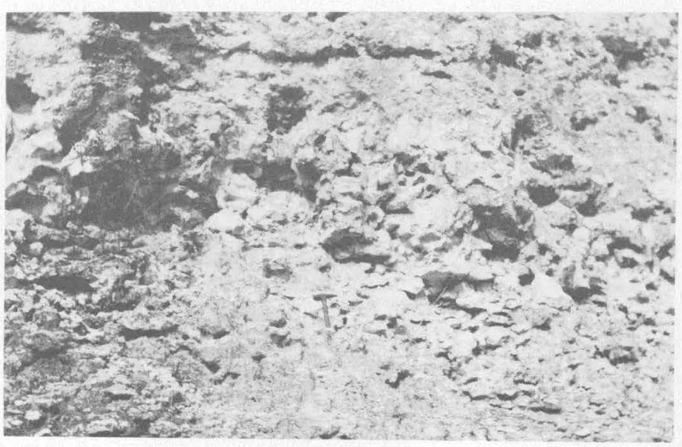

FIGURE 14.—Tampa Limestone showing weathered limestone and pockets of clay in portland cement quarry about 11 miles west of Brooksville, Hernando County, Fla.

Wells in southern Florida penetrate as much as 250 feet of the limestone. The Tampa unconformably overlies the Oligocene limestones and, according to Cook (1945, p. 115), merges upward gradually into the Hawthorn Formation with an indefinite boundary between them. However, according to Vernon (1951, p. 183) there is an unconformity between them in the west-central and southwestern parts of the peninsula. Heath and Smith (1954, p. 14) reported that the Hawthorn unconformably overlies the Tampa in Pinellas County, Fla.

In the area between Hernando and Hardee Counties in the west-central part of the Florida peninsula, Ketner and McGreevy (1959, p. 59–65) described the Tampa in three units as follows: a phosphorite unit in the northern part of the area having a maximum thickness of about 10 feet; a clay unit overlying the phosphorite unit having a maximum thickness of 25 feet; and a limestone unit in the southern part of the area having a maximum thickness of 25 feet. The phosphorite unit consists of clay, fine quartz sand, and sandy clay containing clay-sized particles of apatite. Although nonfossiliferous, the unit probably is early Miocene in age. It is underlain unconformably by the Suwannee and Ocala. It is overlain with apparent conformity by clay of early Miocene age. Rubble of Suwannee Limestone and sand- to boulder-sized concretions of apatite, known as hard-rock phosphate, are scattered in the unit. The limestone unit consists of clayey sandy limestone containing a few phosphorite nodules of sand size. Ketner and McGreevy reassigned the clay and phosphorite units from the Alachua to the Tampa because the clay contains marine invertebrate fossils, and both units are probably weathered Tampa.

In the west-central part of the Florida peninsula Carr and Alverson (1959, p. 21–32) reported that the Tampa contains both marine and fresh-water limestone. Phosphate nodules occur in the Tampa Limestone at a few localities. The formation contains lenses of limestone conglomerate, green and gray clayey sand, sandy clay, and clay-pebble conglomerate. Chert is common. In Escambia and Santa Rosa Counties in western Florida, Marsh 1962a, p. 60) reported that the Tampa Limestone is present in the south half of the area. Its maximum thickness is 270 feet. The limestone generally is not dolomitic. It resembles the underlying Chickasawhay Limestone of Oligocene age but is less vesicular and contains more clay than the Chickasawhay.

Although the Tampa as a whole is relatively impure, it contains much pure limestone. Samples range from 73 to 96 percent calcium carbonate. The quantity of heavy minerals in the Tampa is small but is much larger than in the Suwannee. Pink garnet is relatively common and may exceed 40 percent of the heavy fraction. Analyses of rock samples of the Tampa reported by Cooke (1945, p. 113) show that the formation ranges from 20 percent to about 70 percent silica (SiO_2). The silica commonly is very fine sand. In the silex bed, first described at the type locality at Tampa, silica has replaced the carbonates in the limestone or shells within it.

Highlands County

In the northern part of Highlands County, Fla., Bishop (1956, p. 25) included in the Hawthorn Formation material that may be equivalent to the sandy limestone of the Tampa.

Hillsborough County

Peek (1959b, p. 15–18) described the Tampa Limestone in the Ruskin area in Hillsborough County, Fla., as a white, gray, or tan hard dense sandy limestone. Some parts are crystalline and dolomitic. It is generally fossiliferous. The top of the Tampa ranges in depth from a little below sea level in the northern part of the area to about 250 feet below sea level in the southern part. The Tampa Limestone is a productive source of artesian water in the Ruskin area. Most of the water is from relatively thin zones of high permeability containing many interconnecting solution channels. Current-meter explorations in wells show that much of the artesian flow is from the Tampa Limestone (Peek, 1959b, p. 24).

Manatee County

The Tampa Limestone in Manatee County, Fla. (Peek, 1958a, p. 18), is white, gray, or tan hard dense sandy limestone which contains fine-grained phosphorite in some places. Part of the limestone is crystalline and dolomitic and contains thin beds of chert. The formation generally is fossiliferous. The thickness of the Tampa ranges from about 125 feet in the northeastern part of the county to about 235 feet in the southeastern part. The top of the limestone ranges from about 200 feet below sea level in the northern and northeastern parts to more than 350 feet below sea level in the southeastern part. The limestone has many solution cavities and is a productive source of artesian water.

Martin County

In Martin County, Fla. (Lichtler, 1960, p. 18), the presence of Tampa Limestone has not been definitely established, but 10 to 15 feet of sandy limestone underlying the Hawthorn Formation about 2 miles south of Stuart belongs to the Tampa.

Pinellas County

The Tampa is generally a white to tan hard sandy limestone in Pinellas County, Fla. Chert fragments are abundant in some well cuttings. A north-south geologic section through Pinellas County (Heath and Smith, 1954, fig. 4) shows that the thickness of the Tampa ranges from about 100 feet in the northern part to more than 150 feet in the southern part. A map, figure 5 of that report, shows that the surface is irregular and slopes from sea level in the northern part of the county to 120 feet below sea level in the southern part. The irregular surface in the southern part of the county is due chiefly to erosion that preceded the deposition of the Hawthorn. However, the map is too general to show the numerous pinnacles and sinkholes that might be expected on an eroded surface of limestone in which solution has taken place. Numerous solution cavities in the limestone yield large supplies of water to wells.

The chief chemical constituents of the water in the Tampa are calcium and bicarbonate, except in areas along the coast where the ground water is mixed with sea water. Away from the coastal areas the chloride of some samples is less than 10 ppm. The hardness ranges from about 150 ppm to about 250 ppm. The water from underlying formations is harder than that in the Tampa. Water samples having a chloride content ranging from 148 to 309 ppm were erroneously reported (Black and Brown, 1951, p. 93) for three wells 300 feet deep in the Cosme Odessa well field in northwestern Hillsborough

County near Pinellas County. These samples were actually from the old city wells in St. Petersburg near Tampa Bay and not from the Cosme Odessa well field.

Polk County

H. G. Stewart (1959, p. 23) described the Tampa in Polk County, Fla., as a dark-gray to white generally hard sandy limestone having black and brown granules of phosphates. The thickness ranges from less than 1 foot to about 60 feet. Although the contact with the underlying Suwannee Limestone is unconformable (Cooke, 1945, p. 109; Vernon, 1951, p. 179), it is difficult to detect and generally is regarded as the contact of the pure limestone of the Suwannee with the sandy limestone of the Tampa. In northwestern Polk County, Stewart reported that a blue-gray or blue-green and cream silty sandy clay 3 to 15 feet thick overlies the limestone. In some places this part of the Tampa is shaly and contains less sand than where it is clayey. This bed is relatively impermeable, but it yields small quantities of water to some wells. Stewart (1959, p. 14) lists solution cavities in different formations including one in the Tampa Limestone that has a vertical dimension of 5 feet.

TAMPA LIMESTONE IN GEORGIA

Savannah Area

Although the Tampa Limestone is absent in northeastern Florida and southeastern Georgia as indicated by Cooke (1945, p. 112, 115), Counts and Donsky (1963, p. 28) reported that the limestone is present in the subsurface in the Savannah area, Georgia, where it is as much as 130 feet thick. In that area it is gray sand and marl, interbedded with dolomitic limestone. It has a thin brecciated unit at the base which unconformably overlies Oligocene limestone. From place to place the Tampa ranges from broken shelly sandy limestone to hard dolomitic limestone to sandy silty limestone. In part of Hampton County in southeastern South Carolina, both the limestone of Oligocene age and the Ocala Limestone of late Eocene age are absent, and the Tampa overlies the Gosport Sand of middle Eocene age.

The Tampa is part of the principal artesian aquifer. In the Savannah area, Counts and Donsky (1959, p. 100; 1963, p. 14) reported that hydrogen sulfide is noticeable in the water from the Tampa. Commonly, this water is cased out of the well, and water is obtained from the underlying limestone. In other parts of the report area, however, the artesian water from other formations of the principal aquifer contains small quantities of hydrogen sulfide, which seem to be most abundant some distance from recharge areas.

Southwestern Georgia

A sandy facies of the Tampa in northwestern Florida, formerly called the Chattahoochee Limestone (Cooke, 1945, p. 87), extends into Decatur County in southwestern Georgia. Wait (1960a, p. 3, 15) reported a sandy facies in the Tifton Upland area which extends northeastward from Decatur and Grady Counties into east-central Georgia. The Tampa yields abundant water where it is present as part of the principal artesian aquifer, as at Valdosta.

ALUM BLUFF GROUP

As described by Cooke (1945, p. 137), the Alum Bluff Group consists predominantly of micaceous sand, sandy clay, fuller's earth, and limestone. Cooke included the Hawthorn (east of the Apalachicola River) and the Chipola and Shoal River Formations (west of the Apalachicola) in the Alum Bluff Group. The name Hawthorn Formation was first applied to rocks of Miocene age exposed in Alachua County, Fla. (Dall and Harris, 1892, p. 107). According to Cooke, at the end of Tampa time, the shoreline advanced inland beyond the shores of the Tampa sea, and the Hawthorn was deposited unconformably on the old land surface. In the area of the Tampa sea, the Hawthorn and Chipola Formations were deposited conformably on the Tampa Limestone. The Hawthorn east of the Apalachicola River in Florida and in southern Georgia represents different lithologic facies of the Chipola Formation and possibly part of the Shoal River Formation in western Florida. The contact of the Chipola with the overlying Shoal River probably is conformable. Vernon (1942, p. 75) regards the Chipola and Shoal River as contemporaneous ecologic facies. Cooke (1945, p. 138) saw some justification for this belief but considered that more probably the two formations are in chronological sequence. The Chipola is represented by unfossiliferous sand and clay west of its type locality.

Hawthorn Formation in Florida

The Hawthorn Formation is extensive, covering a large part of the area of this report. In Florida the formation consists of as much as several hundred feet of imbedded clay, sand, limestone, and sandy phosphatic limestone and marl. Lenses of fuller's earth are widely distributed in the Hawthorn. Extensive deposits in the east half of Gadsden County in western Florida have been mined for many years.

Fuller's earth is also extensively mined near Attapulgus, Decatur County, Ga. Fine sandy phosphatic limestone forms a large part of the formation in Florida and South Carolina. In Georgia phosphatic limestone is less conspicuous (Cooke, 1943, p. 90), and dolomitic limestone containing as much as 35 percent magnesium carbonate ($MgCO_3$) is near the base in the southern part of the State.

The maximum thickness reported for the Hawthorn is about 650 feet in Highlands County, Fla. (Bishop, 1956, p. 27). Cole (1944, p. 23) assigned cuttings from depths of 90 feet to almost 500 feet to the Hawthorn in Hilliard well 1, 4 miles northwest of Hilliard in northeastern Florida. In southeastern Florida, Lichtler (1960, p. 18) reported a maximum thickness of 550 feet.

A well at Quincy in western Florida penetrated the Hawthorn Formation from the surface to a depth of 210 feet where it passed into the Tampa (Cole 1944, p. 13). One of the thickest exposures described by Cooke (1945, p. 147) is in the Devils Mill Hopper, a sinkhole, about 6 miles northwest of Gainesville in Alachua County, Fla., that passed through more than 100 feet of Hawthorn to the underlying Ocala Limestone, which is not far below the water level in the sink. A description of the section at the Devils Mill Hopper by Pirkle (1956, p. 215, 216) includes 120 feet of the Hawthorn. Puri and Vernon (1959, p. 122) described a section of the Hawthorn, including Devils Mill Hopper and one 96.9 feet thick at the fuller's earth mine of the Floridin Co., Quincy, Gadsden County, Fla.

The Hawthorn grades westward into the Chipola Formation and probably includes equivalents of the Shoal River Formation. It apparently overlies the Tampa conformably but rests unconformably, in part of the area, on Ocala Limestone and older formations on which it was deposited.

Espenshade (1958, p. 208) reported that solution pipes 5 to 10 feet deep in the Ocala Limestone in a limestone quarry about 1½ miles south-southeast of Bellview in Marion County are filled with phosphatic clay of the Hawthorn.

The Hawthorn is overlain unconformably by the Duplin Marl and younger formations (Cooke, 1945, p. 143). In southeastern Florida, its contact with the overlying Tamiami Formation apparently is conformable (Lichtler, 1960, p. 18). As described by Puri and Vernon (1959, p. 119), the Hawthorn in part of Florida was deposited under continental and deltaic environments. The continental sediments are east of Marianna and north and northeast of Tallahassee in Leon County. The deltaic deposits are in Gadsden, Jefferson, and Madison Counties. Puri and Vernon concluded from exposures at Rock Bluff and at Alum Bluff 7½ miles south on the Apalachicola River in Florida that the Hawthorn Formation is contemporaneous with the Chipola and Shoal River Formations and that both the bottom and top of the Hawthorn are marked by a distinct disconformity, erosional, at least in places.

Between the Withlacoochee and Manatee Rivers in the west-central part of the Florida peninsula, Carr and Alverson (1959, p. 34–36) reported that the Hawthorn is exposed in northeastern Pasco County, in the phosphate district of Hillsborough, Polk, Hardee, and Manatee Counties, and in western Sarasota County. In southern Hillsborough and Polk Counties, the formation is about 100 feet thick, but it thickens southward to more than 300 feet near Sarasota. According to Stringfield (1933c, p. 142), the thickness ranges from about 450 to 500 feet in Sarasota County. In west-central Florida, Carr and Alverson divided the Hawthorn into lithologic units as follows: (1) A lower limestone unit, containing a fauna like that of the Oak Grove Sand Member of the Shoal River Formation in western Florida, (2) an upper limestone containing fauna similar to the Shoal River above the Oak Grove Sand Member, (3) a surficial phosphorite unit in the central and southern part of the area, and (4) a surficial gray to red sand unit in the northern part containing a few middle Miocene fossils. The surficial phosphorite and sand units are from the weathering of the underlying limestone.

Within the Hawthorn Formation are permeable water-bearing beds of sand, limestone, and marl, above and below which are less permeable beds. In some localities the water-bearing limestone contains solution channels that yield water to wells and springs. In general the lower part of the formation yields the most water, but wells usually supplied by water from the Hawthorn have only moderate yields. Where large supplies are required, the wells are drilled into the underlying limestone. If there is adequate development, however, relatively large supplies of water can be obtained from the formation. Much of the water in the Hawthorn is under artesian pressure, and the pressure in the lower part of the formation is comparable with that in the underlying limestone of the principal artesian aquifer. Under these conditions, the lower part of the Hawthorn constitutes the top of the principal artesian aquifer, and the relatively impervious clay and marl beds in the formation prevent or retard upward movement of artesian water as reported by Clark, Musgrove, Menke, and Cagle (1962, p. 68).

Fresh water enters the formation where it is exposed at or near the surface and in areas where it is overlain by permeable material. Recharge also occurs through sinkholes, some of which are filled with permeable sands. The water in general is similar to that in the underlying limestone but is softer. Water from the limestone or marl at the bottom of the formation may be of the same quality as that in the underlying limestone. Some parts of the formations which contain phosphatic material yield water that almost everywhere contains fluoride in concentrations in excess of 1.0 ppm and which may be as much as 2.5 ppm (Black and Brown, 1951, p. 15).

BREVARD COUNTY

In Brevard County, Fla. (D. W. Brown and others, 1957, p. 24–31) the Hawthorn is composed of greenish-gray calcareous clay, sandy phosphatic limestone, black and brown phosphorite, and light-green to white phosphatic radiolarian clay. The formation ranges in thickness from 10 feet in the northern part of the county to about 220 feet in the southern part. It contains many beds of relatively impervious marl and clay that prevent or retard upward movement of artesian water. The more permeable sands, shells, marls, and limestones yield water to wells and springs. The permeable beds in the lower part of the formation in contact with the underlying limestone form the top of the principal artesian aquifer.

In an east-west section through central Brevard County, D. W. Brown, W. E. Kenner, and Eugene Brown (1957, p. 29, 31) postulated that the Hawthorn is several hundred feet thick on the west side of a fault with a north-south course in the St. Johns River valley. The Hawthorn probably is less than 50 feet thick east of the fault. They believed that the fault probably affects the direction of movement of the water.

COLLIER COUNTY

In the Naples area in Collier County, Fla., Klein (1954, p. 9) described the Hawthorn as gray-green clay, silt, and fine sand interbedded with limestone and shell marl. He reported that the formation is about 400 feet thick. McCoy (1962, p. 11) stated that the Hawthorn Formation and the overlying Tamiami Formation are very difficult, if not impossible, to differentiate. However, he estimated that the thickness of the Hawthorn is from 250 to 300 feet. The top is present at depths between 40 and 50 feet below the land surface at Fort Myers. At Goodlane, south of Naples, the top of the Hawthorn is between 150 and 270 feet below the land surface. Permeable limestone and shell beds in the lower part of the formation are regarded as the uppermost part of the principal artesian aquifer. That part of the formation probably is the source of the artesian water in deep wells in Naples. The overlying clay and silt are relatively impermeable and separate the water of the principal artesian aquifer from the shallow artesian water in the Naples area.

HIGHLANDS COUNTY

As described by Bishop (1956, p. 24–28), in Highlands County, Fla., the Hawthorn consists of marine and deltaic deposits. The marine deposits consist chiefly of dark-green to white phosphatic clay and lenses of white to cream dense sandy phosphatic limestone, phosphorite pebbles, and quartz sand. The deltaic deposits consist of quartz ranging from fine sand to pebble gravel and some phosphorite, mica, and kaolinite. The marine deposits, which underlie all the county, rest unconformably on the Suwannee in the western part of the county and on the Ocala Limestone in the eastern part. In the northern part of the county, sandy limestone of the Tampa may be present.

According to Bishop the deltaic beds grade horizontally into typical marine beds and are overlain unconformably by surficial Pleistocene deposits. Bishop concluded that the Citronelle Formation (Cooke, 1945, p. 233) grades downward and laterally into the Hawthorn Formation and therefore is Miocene instead of Pliocene. In a section Bishop showed that the Tamiami Formation of Miocene age wedges out against the deltaic deposits in eastern Highlands County. The Hawthorn ranges in thickness from 300 feet in the northern part of the county to about 650 feet in the Lake Placid area in the southern part of the county.

Bishop believed that a large part of Highlands County was above the sea at the beginning of Hawthorn time. As the sea rose and covered the county, shifting currents deposited phosphatic clay having lenses of limestone, sand, and phosphorite in a small area. Before the end of Hawthorn time, a finger of a large delta moved southward across the county. The remnant of the delta is the core of the topographic ridge in Highlands County.

The unconsolidated sands which Bishop assigned to the deltaic beds of the Hawthorn are an important source of water for wells cased and finished with screens or slotted casing, at depths generally less than 200 feet. A 12-inch well near Avon Park, 180 feet deep having 120 feet of slotted casing, yields

1,800 gpm. In contrast, the limestone and sand in the lower part of the Hawthorn yield small quantities of water to wells.

In general the chief constituents of the water from the Hawthorn are calcium and bicarbonate with hardness of less than about 75 ppm, except in the limestone near the bottom of the formation, which yields water similar to that in the underlying formations. Chemical analyses of samples of water reported by Bishop (1956, p. 53) from wells in Highlands County show that most of the samples have small quantities of fluoride, ranging from 0.1 to 0.5 ppm. As the fluoride content of water in Florida is associated with phosphatic material in the Hawthorn and other deposits of Miocene age or younger, it seems that the Hawthorn yields some water to most of the wells.

HILLSBOROUGH COUNTY

As defined by Peek (1953; 1959b, p. 18) for the Ruskin area in the southwestern part of Hillsborough County, Fla., the Hawthorn includes all marine deposits of middle Eocene age. It consists chiefly of gray, blue-gray, and gray-green sandy calcareous phosphoritic clay interbedded with thin layers of gray, white, and tan sandy phosphoritic limestone and thin beds of sand and shells. The limestone is silicified and dolomitic and contains some fossils. The thickness of the formation ranges from less than 10 feet in the northern part of the area to more than 150 feet in the southern part. It is at or near the surface in several places in the Ruskin area. The top of the formation slopes to the south from about 25 feet above sea level to about 50 feet below sea level.

The Hawthorn apparently rests unconformably on the Tampa Limestone and is overlain unconformably by unconsolidated deposits, ranging in age from late Miocene to Recent. Thin beds of sand and limestone yield artesian water to some wells in the area, but generally wells are drilled into the underlying limestone for large yield. Clay beds and other relatively impervious beds prevent or retard upward movement of artesian water in the Hawthorn Formation and the underlying limestone. The temperature of water from the Hawthorn (Peek, 1959b, p. 46) generally ranges between 74° and 76°F.

Chemical analyses (Peek, 1959b, p. 57–58) of water from wells show a few samples which had a fluoride content ranging from 0.4 to 1.2 ppm. All these samples appeared to be a composite of two or more water-bearing formations. The samples containing fluoride indicate that some of the water is from the Hawthorn. A few of the composite samples had a chloride content of about 35 to 270 ppm. The others had smaller amounts of chloride. Calcium, magnesium, bicarbonate, and sulfate were the principal constituents of the samples having low chloride content. The hardness ranged from about 500 to as much as 1,000 ppm. All samples were alkaline with pH ranging from 7.3 to 8.1.

INDIAN RIVER COUNTY

Bermes (1958b, p. 15) described the Hawthorn Formation in Indian River County, Fla., as a thick section of green to brown phosphatic sandy clay and marl and interbedded lenses of hard sandy limestone, chert, and phosphorite pebbles. The limestone is most abundant in the middle and upper parts of the formation. The formation underlies the entire county and ranges in thickness from about 115 feet in the northern part of the county to about 225 feet in the central part. The Hawthorn unconformably overlies Oligocene limestones in the eastern part of the county and the Eocene Ocala Limestone in the other parts of the county.

MANATEE COUNTY

Peek (1958a, p. 21) described the Hawthorn in Manatee County, Fla., as gray, bluish-gray, and greenish-gray sandy calcareous clay interbedded with white, gray, and tan sandy limestone and thin beds of sand and shells. The clay and limestone layers contain different amounts of chert, dolomite, sand, and phosphorite grains and pebbles. The thickness of the Hawthorn ranges from about 150 feet in the northeastern part of the county to more than 350 feet in the southern part. The sand and limestone yield water to many domestic and some irrigation wells. Clay beds and other relatively impervious beds in the Hawthorn Formation prevent or retard upward movement of artesian water in the Hawthorn and the underlying limestone. The mineral content of the water generally is less than that in the underlying limestone. The quality of water is similar to that discussed under the Hawthorn in Hillsborough County, except that some of the high chloride water in Manatee County is more concentrated than sea water.

MARTIN COUNTY

The Hawthorn Formation in Martin County, Fla., is dark-green to white phosphatic clay containing thin beds of phosphatic limestone and chert, especially in the lower part (Lichtler, 1960, p. 18). Lenses of phosphatic sand and shells are common in some places. The formation underlies all the county and probably rests conformably on the Tampa Limestone where present or unconformably on the Suwannee or older limestone. Its contact with the overlying Tamiami Formation probably is conformable. The thickness of the Hawthorn ranges from 350 to 550 feet. Relatively impervious beds retard or prevent upward movement of artesian water in the Hawthorn and underlying limestones. Lichtler reported that the formation does not yield significant amounts of water to wells in Martin County.

PINELLAS COUNTY

The Hawthorn Formation is present in the Pinellas peninsula south of Clearwater, Fla. (Heath and Smith, 1954, p. 15). Its composition ranges from gray sandstone to sandy gray clay containing black and brownish phosphate grains and angular chert fragments. In some places the sandstone is calcareous. The thickness of the Hawthorn ranges from about 50 feet in the vicinity of Clearwater to 90 feet in the south end of the county. It unconformably overlies the Tampa Limestone and is overlain unconformably by surficial sands. In Pinellas County sand beds of the Hawthorn yield water to domestic wells.

POLK COUNTY

H. G. Stewart (1959, p. 23) reported that the Hawthorn in the northwestern part of Polk County, Fla., consists of light-cream to tan sandy phosphatic limestone interbedded with clay or silts. Locally the limestone is silicified. The limestone beds are generally separated by 1 to 6 feet of brown sandy gritty clay. A geologic section (Stewart, 1959, p. 18) shows the Hawthorn is absent in the northern part of the county. It has a thickness of about 100 feet in the vicinity of Lakeland. The Hawthorn unconformably overlies the Tampa Limestone and is unconformably overlain by the Bone Valley Formation. Stewart (1959, p. 15) listed records of solution cavities in the Hawthorn whose vertical dimensions ranged from 2 to 19 feet. In most places the limestone yields sufficient water for domestic supplies. Large quantities of water may be obtained from solution cavities.

Locally, artesian water in the Hawthorn Formation is separated from artesian water in the underlying Tampa Limestone by a clay bed 3 to 15 feet thick, which was assigned to the Tampa Limestone by Stewart. Clay beds in the upper part of the Hawthorn or lower part of the Bone Valley Formation prevent or retard upward movement of its artesian water. East and northeast of Lakeland in the lowland of Saddle Creek, wells ranging from 1¼ to 6 inches in diameter and only 30 to 75 feet in depth yield artesian water from limestone of the Hawthorn. The casing in the wells generally is seated in the uppermost part of the limestone. The water level in the wells in the underlying limestone of the principal artesian aquifer is 5 to 15 feet below the level in wells in the Hawthorn of that area. In parts of the area the difference in water levels is not great. The levels appear to have been approximately the same before they were affected by withdrawal of water from wells.

Chemical analyses of samples of water included by H. G. Stewart (1959, p. 43–46) show that the composition of the water from the Hawthorn Formation, in general, is similar to that in the underlying limestones which form the principal artesian aquifer. However, other analyses indicate that relatively small quantities of fluoride are present in water associated with phosphatic material in the Hawthorn and younger formations (Black and Brown, 1951, p. 15). The principal constituents of the water from the Hawthorn and the underlying limestone are calcium, magnesium, and bicarbonate. The sulfate ranged from 1.0 to 11 ppm, in contrast to the high sulfate in artesian water in the eastern and southern parts of Florida.

SEMINOLE COUNTY

Heath and Barraclough (1954, p. 14) described the Hawthorn in Seminole County, Fla., as beds of blue to gray calcareous clay, alternating with beds of sand and white to gray sandy limestone containing many grains of black to cream phosphate rock and fragments of chert. A geologic section (Heath and Barraclough, 1954, p. 29) indicates that the Hawthorn is about 75 feet thick in the southwestern part of the country. It has been removed by erosion in the St. Johns River valley in the northern and eastern part of the county. The Hawthorn is also absent in some of the sinkholes and sinkhole lakes. The Hawthorn rests unconformably on the Ocala Limestone and the Avon Park Limestone. It is overlain unconformably by younger surficial deposits, which may be as much as 100 feet thick in some areas. The limestone and sand beds in the Hawthorn Formation yield small supplies of water to wells. Clay beds and other relatively impervious beds prevent or retard upward movement of artesian water in the underlying limestone.

SOUTHEASTERN FLORIDA

Parker, Hoy, and Schroeder (in Parker and others, 1955, p. 67, 83–85) described the Hawthorn in southeastern Florida as sandy phosphatic marl, interbedded with clay, shell marl, silt, and sand. Its maximum thickness is about 500 feet. The formation includes beds of flattened well-worn quartzite and phosphate pebbles as much as half an inch in diameter. Near Clewiston on the south side of Lake Okeechobee, the zone of pebbles is 51 feet thick; its top is 76 feet below sea level. About 63 miles south of Clewiston, the zone is 52 feet thick; its top is 214 feet below sea level. This indicates a dip of 2.2 feet per mile toward the south. The Hawthorn is underlain by the Tampa Limestone and is overlain by the Tamiami Formation which has a maximum thickness of about 150 feet and includes all upper Miocene deposits in southeastern Florida.

Hawthorn Formation in Georgia

The Hawthorn extends from Florida into Georgia and South Carolina. The bulk of deposits above the principal artesian aquifer in Georgia (fig. 25) is represented by the Hawthorn Formation.

As described by Counts and Donsky (1959, p. 98; 1963, p. 14) in the Savannah area, Georgia, the Hawthorn consists of green silt and sand interbedded with clay, marl, and limestone. It has a maximum thickness of about 300 feet in the area. The formation thickens toward the south to more than 400 feet and thins toward the north in South Carolina where the maximum is about 150 feet.

Wait (1958a, p. 45) described the Hawthorn in Crisp County in southwest Georgia as pale to dark-green phosphatic sandy clay interbedded with sand and sandy limestone. It is present in the east half of the county where it supplies water to shallow and drilled wells. The Hawthorn overlies the Tampa where that formation is present. Elsewhere, the Hawthorn unconformably overlies Oligocene formations (Flint River or Suwannee) or the Ocala Limestone of Eocene age.

TAMIAMI FORMATION

As described by Parker and Cooke (1944, p. 65) in southeastern Florida, the Tamiami Formation was regarded as Pliocene in age and the equivalent of the Caloosahatchee Marl. It included permeable limestone, which is the principal source of ground water in the Miami area. However, Parker (1951, p. 821) and Hoy and Schroeder (1952, p. 283–286) assigned the Tamiami to late Miocene deposits in southern Florida having a maximum thickness of about 150 feet. The upper part includes not more than about 15 feet at the base of the shallow permeable limestone aquifer in the Miami area. The beds below this permeable limestone consist of sand, marl, and impure limestone containing relatively impervious beds similar to the underlying Hawthorn Formation. The Caloosahatchee Marl was retained in the Pliocene.

In the Miami area the upper part of the Tamiami, as revised, is an important source of water (Parker and others, 1955, p. 88). That part of the limestone and the overlying permeable limestone of Pliocene and Pleistocene age contain many solution cavities filled with permeable sands, forming one of the most productive aquifers in the area of this report.

The permeable part of the Tamiami yields fresh water except in: (1) the coastal area where sea water has entered the aquifer, and (2) in parts of the Everglades where residual salt water has not been flushed out of the formation. The less permeable part of the formation, as well as the Hawthorn Formation and the underlying artesian limestones which constitute the principal artesian aquifer, yield water having a relatively high chloride content.

Klein (1954, p. 10) reported that the Tamiami may be more than 125 feet thick in the Naples area in Collier County, Fla. The top of the formation is about 15 to 20 feet below sea level. The upper part is relatively impermeable marl below which is permeable sandy limestone containing many solution cavities filled with fresh artesian water. The limestone of the Tamiami Formation forms the principal shallow aquifer in Collier County, Fla. (McCoy, 1962, p. 13).

DUPLIN MARL AND CHOCTAWHATCHEE MARL

Cooke (1936, p. 117) recognized the Duplin Marl in South Carolina as sandy shell marl containing clay of late Miocene age. Later he assigned the upper two faunal zones (*Ecphora* and *Cancellaria* zones) of the Alum Bluff Group to the Duplin (1945, p. 181). Cooke (1945, p. 168) considered these two zones as part of the Choctawhatchee Marl. He also proposed that the *Arca* and *Yoldia* zones of the Choctawhatchee be transferred to the Shoal River. With these transfers, he considered it inadvisable to retain the name Choctawhatchee. However, Puri and Vernon (1959, p. 9) retained the name Choctawhatchee for the four zones mentioned.

Cooke (1945, p. 14) indicated that the late Miocene sea in which the Duplin was deposited, covered all Florida, except the northern part of the panhandle and the coastal areas of Georgia and South Carolina. The thickness of the beds assigned to the Duplin at Alum Bluff, Fla., is 46 feet, but the top of the formation has been eroded. In Georgia the few exposures are only 5 to 16 feet thick. The greatest thickness recorded in South Carolina is 50 feet. It thickens to the north, reaching its maximum in North Carolina. The formation lies unconformably on older beds ranging from the Late Cretaceous Black Creek Formation in the Carolinas to the middle

Miocene Hawthorn. It overlies the Hawthorn in Georgia and east of the Apalachicola River in Florida. West of the Apalachicola in Florida, it overlies the Chipola and Shoal River Formations. Locally the Duplin yields small supplies of hard water to shallow wells.

In the Savannah area, Georgia, Counts and Donsky (1959, p. 100; 1963, p. 31) recognized the Duplin only in the Savannah River valley where it is chiefly marl with some shells and sand. Locally it may be a source of small supplies of nonartesian water. The relatively impervious beds in the marl prevent or retard upward movement of artesian water in the underlying limestone. The water-bearing properties are similar to those of the Hawthorn Formation.

PLIOCENE SERIES

In a discussion of the geology of Florida, Cooke (1945, p. 197) included the following formations in the middle Pliocene: Alachua Formation, Bone Valley Formation, Buckingham Marl (of former usage), Caloosahatchee Marl, Charlton Formation, Citronelle Formation, and Tamiami Formation. Puri and Vernon (1959, p. 9) included the Citronelle Formation and the Caloosahatchee Marl in the Pleistocene Series. In the present report the Alachua and Bone Valley Formations, Caloosahatchee Marl, Charlton Formation, and Citronelle Formation are regarded as Pliocene. The Pliocene and younger formations are less than 50 feet thick or absent in a large part of the region. In small areas as in central and southeastern Florida the total thickness may be more than 150 feet (fig. 15).

ALACHUA AND BONE VALLEY FORMATIONS

The Alachua and Bone Valley Formations are present in the west-central part of the Florida peninsula. Cooke (1945, p. 199–210) described them as middle Pliocene. He stated that the fossil bones of Miocene animals attributed to the Alachua probably were buried in sinkholes during Miocene time. Puri and Vernon (1959, p. 9, 160–172) described the formations as Miocene. Vernon (1951, p. 190) believed that the Alachua may have accumulated throughout Miocene time to Pliocene.

Pirkle (1956, p. 230) cited evidence to support his conclusion that the Hawthorn Formation is the immediate source of the phosphate in the hard rock deposits of the Alachua Formation and therefore that the Alachua is post-Hawthorn in age—late Miocene or Pliocene.

Bergendahl (1956, p. 70, 83) indicated that the Bone Valley Formation is late Miocene and Pliocene in age. Also he reported that F. S. MacNeil (written commun., 1954) considered the Bone Valley Formation of marine origin and equivalent stratigraphically to the unnamed sand of late Miocene that he described in De Soto and Hardee Counties. Altschuler and Young (1960, p. 202) regard the Bone Valley as Pliocene. Also Cathcart (1963a; 1963b) considered the Bone Valley as Pliocene in Hillsborough and Polk Counties.

The Alachua consists chiefly of weathered, collapsed, and compacted residue of the Hawthorn Formation in place together with accumulations in sinkholes and ponds, some of which contain bones of Pliocene animals (Cooke, 1945, p. 200). The part of the formation to which the name was originally applied by Dall (1892, p. 127) consists chiefly of clay in sinks and ponds. Much of the formation consists of sand with some phosphate. The lower part contains phosphate rock as plates or large boulderlike masses. The formation contains a varied vertebrate fauna, ranging from middle Miocene to Pleistocene. According to Sellards and Gunter (1913, p. 30–31), the Alachua is as much as 75 to 100 feet thick in Citrus County, Fla., though it usually is thinner. The formation extends from the northern part of Gilchrist County into Hernando County. In this area the Withlacoochee River has cut through the Alachua into the Ocala Limestone. The formation is present in a few areas in the southwestern part of Lafayette County, the western part of Hamilton County, and in Alachua and Marion Counties.

The Alachua overlies an irregular eroded surface of the Ocala and older Eocene limestone, on which there are residual pieces of the Suwannee Limestone. In Gilchrist County, Puri and Vernon (1959, p. 160) reported that in some quarries the eroded surface of the Ocala Limestone has pinnacles of limestone as much as 25 feet in height. The clays and phosphatic sands deposited on such an irregular surface have an irregular thickness. This solution-pitted erosion surface probably was formed before the Hawthorn and Alachua were deposited. Pleistocene terrace sands unconformably overlie the Alachua. The Alachua Formation contains the valuable hard-rock phosphate deposits of Florida. Although the Alachua Formation probably would yield water to wells, it is not known to be an important aquifer. Clark, Musgrove, Menke, and Cagle (1962, p. 70) reported that in north-central Florida it may be a source of water for domestic supplies.

The Bone Valley Formation extends from Lake County southward to De Soto and Hardee Counties, south of the area of the Alachua Formation. As described by Cooke (1945, p. 204–205) and Matson

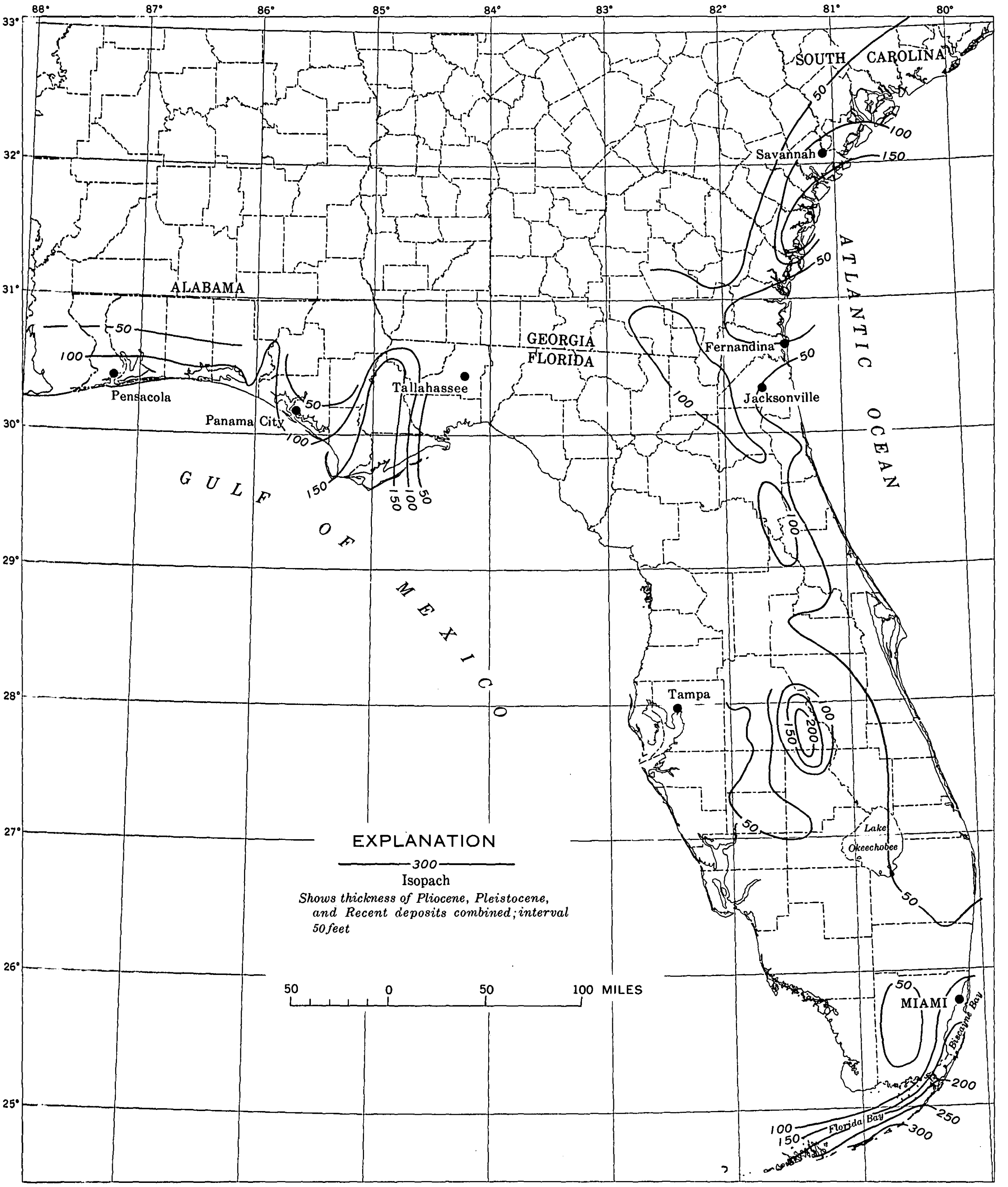

FIGURE 15.—Isopach map of Pliocene, Pleistocene, and Recent Series. (From Toulmin, 1952, fig. 8.)

(1915, p. 21) the Bone Valley consists of rounded pebbles of phosphate embedded in a matrix of sand or clay overlain by loose semi-indurated sand. The maximum thickness seems to be about 50 feet. Cooke suggested that the typical part of the Bone Valley Formation was deposited in a broad delta of a stream that flowed southward into the ocean and that some parts of the formation may be from the Hawthorn weathering in place. Locally, permeable sands of the Bone Valley may yield water to wells. It is the source of the pebble phosphate deposits in Florida.

CALOOSAHATCHEE MARL

The Caloosahatchee Marl of Pliocene age consists chiefly of sand and shells along the Caloosahatchee River in southern Florida (Cooke, 1945, p. 214). In some places the shells form most of the formation. In southeastern Florida, Parker, Hoy, and Schroeder (in Parker and others, 1955, p. 88–89) described the Caloosahatchee as a silty, sandy shell marl with interbedded layers and lenses of sand, silt, clay, and marl. In some places in the Everglades it contains carbonaceous zones of roots, stems, and other organic material. The Caloosahatchee Marl discontinuously underlies the Everglades and Big Cypress Swamp on the west side of the Everglades. It extends northward beneath Pleistocene terraces in the Kissimmee River valley. From the Caloosahatchee River and Lake Okeechobee, where the formation is at or near the surface, the Caloosahatchee Marl dips south and southeast under the Everglades and Atlantic Coastal Ridge. It is absent in many places in southeastern Florida. In the Miami area, lenses of the formation are preserved in depressions in the unconformable contact with the underlying Tamiami Formation. The maximum thickness apparently is less than 50 feet.

Stringfield (1933a, p. 7) gives a log of a well (Florida Geol. Survey No. W–20) at Belle Glade, Fla., indicating that the Caloosahatchee is present at depths of 52 feet to 175 feet and has a total thickness of 123 feet. If current correlations are used, however, the lower part probably should be assigned to the Tamiami or Hawthorn of Miocene age.

Puri and Vernon (1959, p. 178) included the Caloosahatchee in the Pleistocene Series after DuBar (1958, p. 129–155) who assigned the formation to the Pleistocene on the basis of (1) a late Pleistocene horse in the upper shell bed, (2) stratigraphic details, and (3) molluscan evolution. In his detailed study, DuBar divided the Caloosahatchee into three members. Two of these members are subdivided into several units.

Permeable sand and shell beds of the Caloosahatchee yield water to wells in the Lake Okeechobee area (Stringfield, 1933a, p. 17), but some of the water is salty. In some areas on the south side of Lake Okeechobee all the ground water, including that in the shallow formations, has a relatively high chloride content. The investigation in 1933 caused the writer to conclude that the salt water in the shallow formations is the remnant of sea water which covered the area during Pleistocene (Pamlico) time when the sea stood about 25 feet above its present level.

If the Caloosahatchee is Pleistocene as reported by DuBar (1958), the salt water could be sea water in which the formation was deposited. However, the absence of salt water in the Caloosahatchee more than 25 feet above sea level suggests that the Caloosahatchee was deposited before the Pleistocene sea stood at the 25-foot level.

CHARLTON FORMATION

As described by Cooke (1945, p. 227), the Charlton Formation consists chiefly of light-colored calcareous clay and impure limestone. Cooke and Mossom (1929, p. 129) reported a thickness of 15 feet for the Charlton and suggested that the maximum is about 20 feet. Cole (1944, p. 22–23) recommended that the name Charlton be discarded in favor of Caloosahatchee because the two formations are contemporaneous. He assigned to the Caloosahatchee 60 feet of the material penetrated in a well 4 miles northwest of Hilliard. Cooke (1945, p. 228) stated that the upper part of that unit consists of gray-green sandy clay like the Charlton but that the lower 40 feet is loosely consolidated sandstone with shell fragments similar to the Caloosahatchee. S. M. Herrick, (written commun., July 1962) doubted the presence of the Charlton in Georgia. He suggested that the deposits regarded as the Charlton may represent the Duplin Marl.

According to Cooke (1945, p. 228) exposures of the Charlton Formation in Florida are confined to the bluffs along St. Marys River in Nassau County above Orange Bluff. Eastward beyond the river it probably merges into the Caloosahatchee Marl. There are a few exposures near Satilla River in Charlton and Brantley Counties, Ga. Probably small quantities of water can be obtained from the Charlton Formation. However, information is not available on its properties as an aquifer.

CITRONELLE FORMATION

The name Citronelle Formation was applied by Matson (1916, p. 168) to sediments of Pliocene age, chiefly nonmarine, that occur near the seaward margin of the Gulf Coastal Plain, extending from western Florida to Texas. The formation as much as 400 feet thick consists of yellow and red sands and clays, locally gray where unweathered. Much of the gravel is near the landward margin and in the valleys of the principal streams. The Citronelle Formation in the area of the present report consists chiefly of sand, gravel, and clay. Much of the sand is red or orange, and the clay is stained with iron where it is mixed with the sand and gravel. It is underlain unconformably by older formations and is overlain unconformably by Pleistocene sands. It occurs as a discontinuous blanket paralleling the Fall Line across southern Alabama, northern Florida, and Georgia into South Carolina. It was mapped by Cooke (1945, p. 230) in the central ridge section in the Florida peninsula where it extends from Clay County to Highlands County.

Its thickness is as much as 140 feet in Escambia County, Ala. (Cagle and Newton, 1963, p. 37). In Escambia and Santa Rosa Counties, Fla. (adjacent to Escambia County, Ala.), Marsh (1962a, p. D61) reported that the formation probably is as much as 800 feet thick. The thickness may be more than 250 feet in southern Alabama according to Matson (1916, p. 178). In his geologic map and geologic sections of the formation in the southern part of the Atlantic Coastal Plain, Doering (1960, p. 182–200) indicated a maximum thickness of about 100 feet. The sections indicate that in some places in the Coastal Plain the Citronelle is overlain by Pleistocene terraces, showing that the Citronelle is older than the terraces. This, together with the fact that according to Matson the formation contains Pliocene flora, suggests that the Citronelle is Pliocene. However, Doering (1960, p. 199) believed that this evidence does not preclude a pre-Nebraskan Pleistocene age. After Roy (1939, p. 1553–1559) and other investigators concluded that the flora found at the type locality of the Citronelle near Citronelle, Ala., was not from the Citronelle, Stringfield and LaMoreaux (1957, p. 742–746) called attention to the locality near Red Bluff, Ala., where the flora studied by Berry (1916) is unquestionably from the Citronelle.

Miss Estella Leopold, U.S. Geological Survey, reported (written commun., June 14, 1960) that the pollen from Red Bluff is similar to that in the Pascagoula Formation of Miocene age. However, the pollen in western Florida is younger than Pliocene. As the Citronelle rests unconformably on the Miocene and is overlain unconformably by the Pleistocene, the Miocene pollen in the Citronelle in Alabama could be from reworked Miocene material. The Pleistocene pollen in the Citronelle in Florida could be from Pleistocene deposits that were reworked and mixed with Citronelle deposits.

In Highlands County, Fla., Bishop (1956, p. 26) concluded that the Citronelle red sand and gravel mapped by Cooke (1945, p. 233) as Pliocene, grade downward and laterally into the Hawthorn Formation of Miocene age. Clark, Musgrove, Menke, and Cagle (1964, p. 25) described the deposits in Clay and Bradford Counties as unnamed coarse clastics having a maximum thickness of 90 feet. Goodell and Yon (1960, p. 99) considered the sands and gravels as genetically related to the uppermost beds of similar lithology in the western panhandle of Florida and therefore probably of post-Miocene age.

Pirkle (1960) and Pirkle, Yoho, and Allen (1964) have reported that the Citronelle in the Florida peninsula overlies shell beds of late Miocene age. They concluded that the Citronelle is post-Hawthorn. The fact that the solution-pitted Hawthorn underlies the Citronelle indicates that the two formations are separated by an unconformity formed under subaerial erosion. As suggested by Pirkle, Yoho, Allen, and Edgar (1963, p. 130) and Bishop (1956), the Citronelle in the Florida peninsula is believed to be alluvial and other terrestrial materials deposited as a prograding delta built southward into Florida. However, there is not agreement on the age of the delta. Bishop reported the formation as part of the Hawthorn, but Pirkle reported it as post-Hawthorn. In Texas, Tipsword (1962, p. 22) correlated the Citronelle with the Goliad. Wilson (1962, p. 345) stated that the Goliad is Pliocene. Judging from available information, the writer finds insufficient evidence to justify assigning the Citronelle to the Pleistocene or Miocene, and in the present report it is therefore regarded as Pliocene, possibly contemporaneous with the marine Pliocene deposits.

The sand and gravel in some parts of the Citronelle are very permeable and will yield water to wells where the permeable parts of the formation are below the water table. It is a very productive aquifer in many parts of the Gulf Coastal Plain. The water has a low mineral content but in some places contains some iron.

QUATERNARY SYSTEM

PLEISTOCENE AND RECENT SERIES

Cooke (1945, p. 197–312) included the following in the Pleistocene Series in Florida: Fort Thompson Formation, Miami Oolite, Key Largo Limestone, Anastasia Formation, Lake Flirt Marl, and the sands that underlie seven marine terraces.

During the Pleistocene Epoch, the Coastal Plain remained stable relative to the continent, but the level of the sea repeatedly rose and fell in response to the alternate withdrawal from and return to the sea of large quantities of water, which formed the continental ice caps that gave the name Great Ice Age to that epoch (Cooke, p. 245). The accumulation and melting of the continental ice caps alone would account for an oscillation of sea level of about 200 or 300 feet. In addition, as suggested by Cooke, increases in the capacity of the ocean basins by a post-Pliocene sinking of the bed of the ocean in the North Atlantic, in the Indo-Pacific region, in the region off the coast of California, or at some other unstable part of the world would increase the capacity of the ocean and cause a worldwide lowering of sea level even though large parts of the continent remained stationary.

During the Pleistocene, several advances and retreats of continental ice sheets took place. The sea stood at different levels that corresponded to the advances and retreats of the glaciers. Rivers cut and scoured deeper channels during the retreats of the sea and deposited terrace materials along the sides of streams during the advances of the sea. Cooke (1939, p. 34) postulated the fluctuations of sea level as follows: an intermittent drop from 270 feet above the present to 230 or 300 feet below; a rise of 100 feet above, and an intermittent fall to 60 feet below; an intermittent rise to 25 feet above, and a drop to an undetermined low; and a rise to the present level. Later this postulate was modified as shown in his revised table of oscillation of sea level in the following section on "Marine terraces." Cooke's illustrations of the Pleistocene shorelines are shown in figures 16, 17, 18, 19, and 20. According to Cooke, the major stands of low sea level correspond to the Nebraskan, Kansan, Illinoian, and Wisconsin Glaciations.

The development of the surface and subsurface features of southern Florida was influenced by the relations of land and sea. During early Pliocene time, southern and eastern Florida were submerged. During late Pliocene time much of the Floridian Plateau emerged and was eroded. During each major stage of low sea level, in Pleistocene time the shoreline lay offshore from its present location, and subaerial erosion and subterranean solution became active. Fresh-water lakes and marshes occupied the Lake Okeechobee-Everglades depression. In Florida the major stages of low sea level are indicated by erosion surfaces, solution holes, soil zones, and fresh-water limestones and marl.

MARINE TERRACES

The marine terrace formations, consisting chiefly of sand, were named by Cooke (1945, p. 248) after the shorelines. The highest terrace is the oldest; the lowest is the youngest. Detailed maps of the terraces in local areas are given in many of the county reports on Florida. A report by Bermes, Leve, and Tarver (1963) includes a map showing the distribution of terraces in Flagler, Putnam, and St. Johns Counties, Fla.

Cooke's latest interpretation (written commun., 1963), shown in the following table, is a revision of that given in previous reports.

Marine terrace	Present altitude of shoreline (feet)	Quaternary geologic-climate classification	Oscillations of sea level
		Nebraskan	Emergence caused by the accumulation of continental ice.
Hazlehurst	270	Aftonian	Submergence to a height of 270 ft a.t. (above present tide level) caused by the melting of continental ice.
		Kansan	Emergence caused by the accumulation of continental ice, permitting the formation of sinks in rock now standing 150 ft a.t.
Coharie Sunderland Okefenokee Wicomico Penholoway Talbot	215 170 150 100 70 42	Yarmouth	Submergence to a height of 215 ft a.t. caused by the melting of continental ice, followed by intermittent emergence of at least 170 ft caused by downwarping of oceanic basins.
		Illinoian	Emergence caused by the accumulation of continental ice.
Pamlico	25	Sangamon	Submergence to a height of 25 ft a.t. caused by the melting of continental ice.
		Early Wisconsin	Emergence caused by the accumulation of continental ice.
Silver Bluff	6	Middle Wisconsin	Submergence to a height of 6 ft a.t. probably caused by the partial melting of the Wisconsin ice sheet.
		Late Wisconsin	Emergence caused by the accumulation of continental ice.
Recent	0		Submergence to the present sea level probably caused by the melting of continental ice.

As described by Cooke (1945, p. 248–312), the shoreline and terraces may be divided into groups, three of which formed during the three interglaciations (Aftonian, Yarmouth, and Sangamon). Later Cooke (written commun., 1963) revised the groups as shown in table above. The first group in his revised table consists of the Hazlehurst, the highest and oldest of the Pleistocene shorelines, formed at an elevation of about 270 feet during the Aftonian

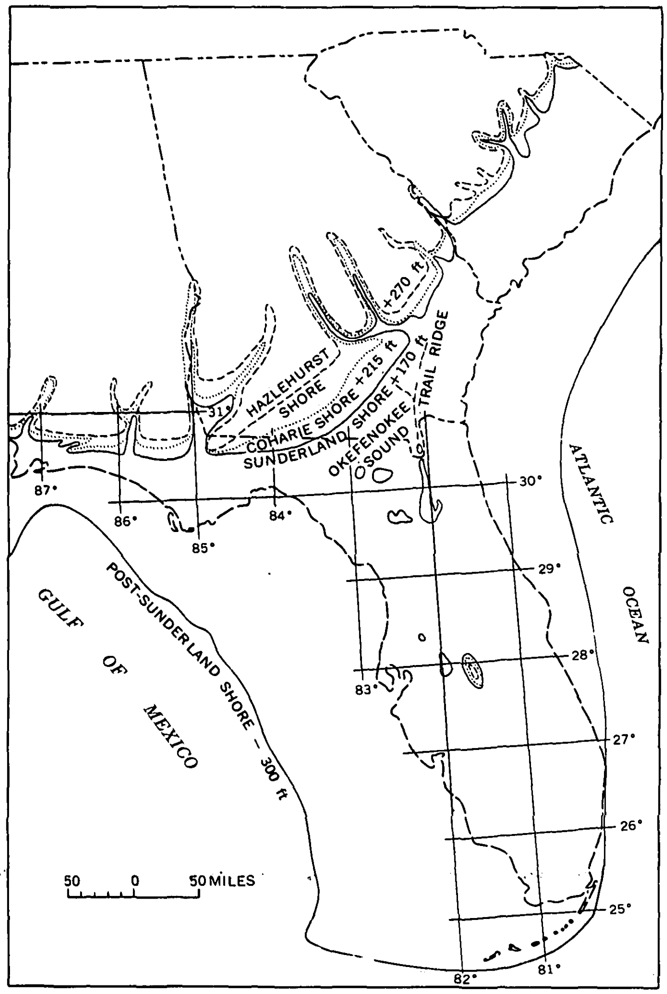

FIGURE 16.—Early Pleistocene shorelines in the Southeastern States, much generalized and in part conjectural. (After Cooke, 1939, fig. 12.)

Interglaciation after the Nebraskan Glaciation. The name Hazlehurst was proposed by Cooke (in LaForge and others, 1925, p. 29). He rejected the name in favor of Brandywine but later restored the name Hazlehurst. The second group consists of the Coharie, Sunderland, Okefenokee, Wicomico, Penholoway, and Talbot terraces at altitudes from about 215 to 42 feet, as shown in the table. These terraces formed in the Yarmouth Interglaciation after the Kansan Glaciation. Cooke included the Okefenokee shoreline at an altitude of about 150 feet above sea level. The name for this shoreline was revived by MacNeil (1950, p. 101). The third group includes the Pamlico, formed during the Sangamon Interglaciation after the Illinoian Glaciation. The fourth group includes the Silver Bluff, apparently formed during a recession in middle Wisconsin time. From studies in the Miami area, Florida, Parker and Cooke (1944, p. 22) recognized and named the Silver Bluff terrace, about 6 feet above present sea level. A terrace at about that altitude is present in other areas along the Atlantic and Gulf coasts. Cooke (1954, p. 200–202) recognized the terrace in Maryland and Virginia.

MacNeil (1950, p. 104–105, pl. 19) showed the Silver Bluff terrace along the coast of Florida and Georgia and indicated that the toe of the scarp is about 6 or 8 feet above sea level. Parker (in Parker and others, 1955, p. 146–147) described the Silver Bluff terrace and concluded that it was formed during Recent time in the interval known as climatic optimum, which is believed to have occurred about 5,000 B.C. when the sea rose to 5 and perhaps 8 feet above its present level (Brooks, 1949, p. 364). Parker, Hoy, and Schroeder (in Parker and others, 1955, p. 125) estimated that, before returning to the present level, the sea stood at the higher elevation for 2,000 to 3,000 years—long enough to cut the Silver Bluff terrace and to fill the discharge channels

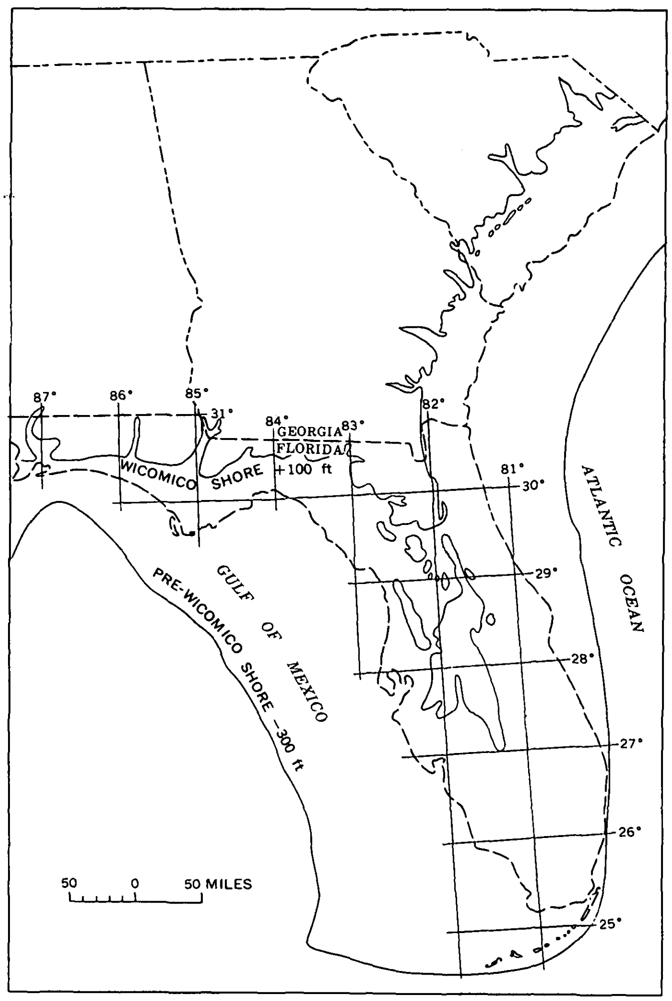

FIGURE 17.—Shoreline of the Wicomico sea in the Southeastern States. (After Cooke, 1939, fig. 13.)

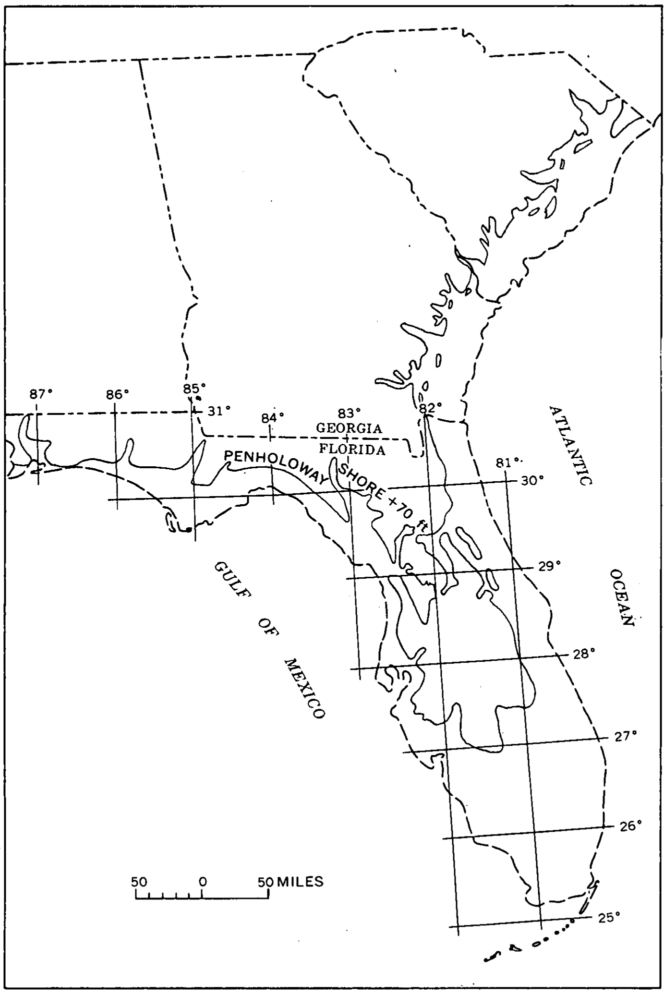

FIGURE 18.—Shoreline of the Penholoway sea in the Southeastern States. (After Cooke, 1939, fig. 14.)

with sand through the Atlantic Coastal Ridge as far south as Miami. Parker, Hoy, and Schroeder (in Parker and others, 1955, p. 109) reported that the peat and muck, as much as 8 to 10 feet thick near Lake Okeechobee in the Everglades, formed after the high level of the sea during the climatic optimum. He also reported that the age of three samples of peat, as determined by the carbon-14 method, ranged from 3800±200 to 5050±200 years. Subsequently, however, Parker (written commun., Jan. 21, 1963) concluded that the Silver Bluff terrace is late Pleistocene. Also Scholl (1963, p. 145) reported evidence that during the last 5,000 years sea level never rose above its present position.

When the Hazlehurst shoreline was at 270 feet above the present sea level, the Pleistocene sea covered a large part of the Coastal Plain in Georgia and South Carolina and the northern parts of western Florida. The Hazlehurst sea advanced from a lower level over the Citronelle and older formations. The Coharie shoreline apparently was formed in Yarmouth time when the sea rose from an undetermined lower level to a height of 215 feet above its present level (Cooke, 1945, p. 277). The Coharie deposits consist chiefly of sand and appear to have a maximum thickness of 50 feet in Florida west of the Apalachicola River, where there was an abundant source of sediments brought down to the sea by rivers. Later in the Yarmouth Interglaciation, the Sunderland shoreline was formed when the sea stood at about 170 feet above the present level. The Okefenokee shoreline was formed when the sea was about 140 to 150 feet above its present level. The Wicomico, Penholoway, and Talbot shorelines and terraces formed when the sea stood 100, 70, and 42 feet, respectively, above the present level, before the sea withdrew to a low stand during the Illinoian Glaciation. In the Sangamon Interglaciation after the Illinoian Glaciation, the sea rose to a height of 25 feet above its present level, formed the Pamlico

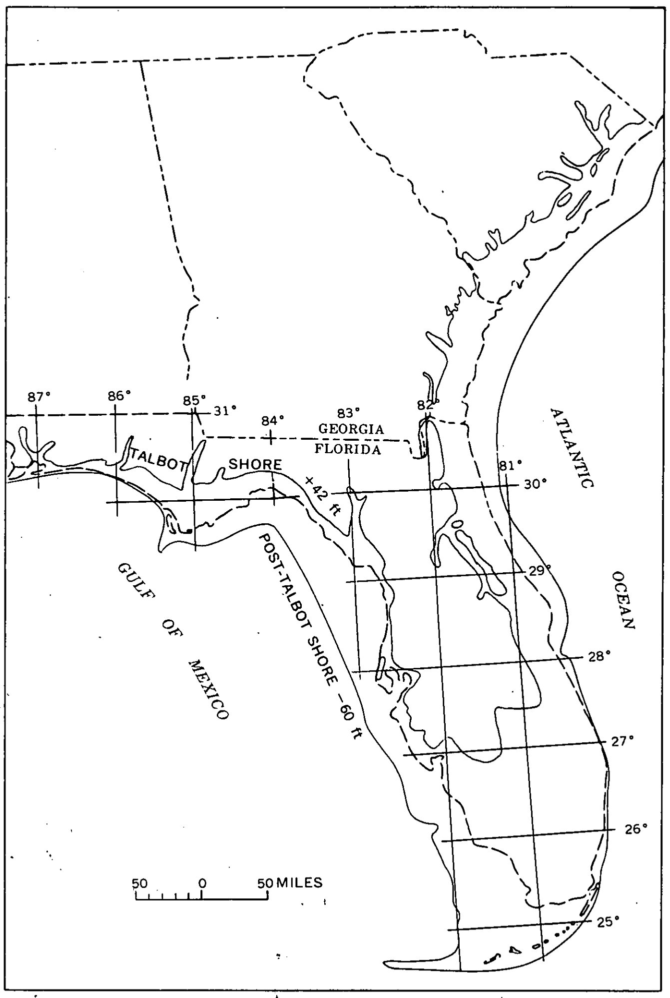

FIGURE 19.—Shoreline of the Talbot sea in the Southeastern States. (After Cooke, 1939, fig. 15.)

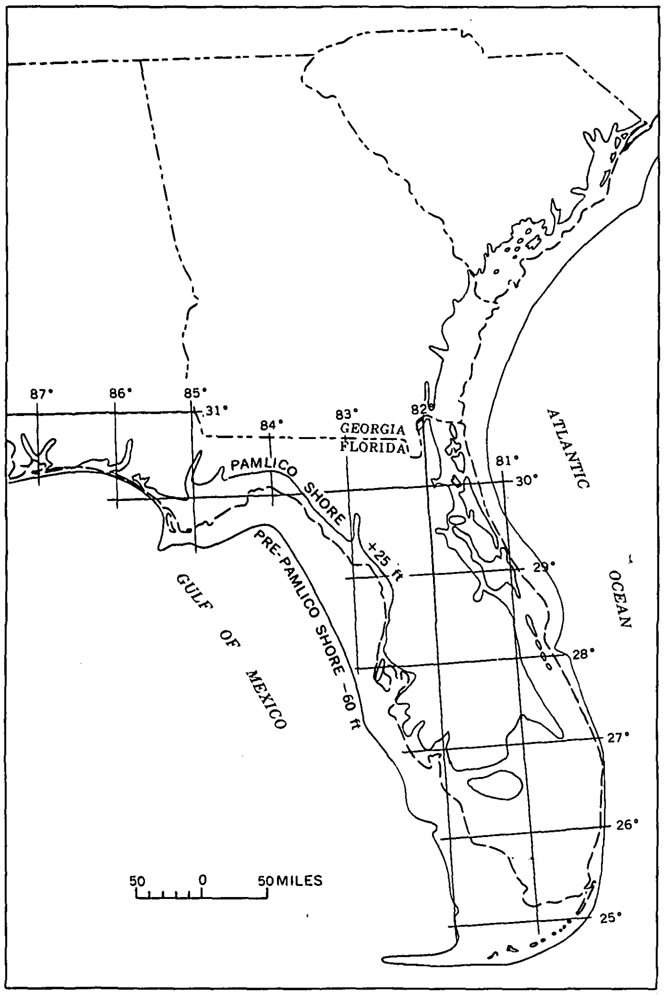

FIGURE 20.—Shoreline of the Pamlico sea in the Southeastern States. (After Cooke, 1939, fig. 16.)

shoreline, and then fell below its present level in early Wisconsin time. The sea rose to about 6 feet above the present level in middle Wisconsin time, then fell below its present level, and then rose in the late Wisconsin to its present level.

Flint (1940, p. 757–787) reviewed the reports giving results of investigations on the Atlantic Coastal Plain and expressed doubt about the marine origin of terraces that have no seaward-facing scarps. He expressed the opinion that only two scarps had been proven to be marine in the central Atlantic region but that there was a possible third and higher scarp in Georgia and Florida. Cooke (1941) called attention to the fact that seaward-facing scarps are absent from some coastlines, one of which is the present shoreline of the Atlantic coast.

The chronology and nomenclature as given in the table by Cooke are used in this report. The Pleistocene terrace formations are described by Cooke (1936, 1937, 1943, 1945) in Florida, Georgia, and South Carolina. However, in the present report, the formations are not differentiated. They consist chiefly of sands and clays having a total maximum thickness of not more than 100 feet. Locally, the thickness may be greater where the deposits fill sinkholes or stream channels. Surficial sands of Pleistocene and Recent age are present throughout most of the area and are a common source of water for domestic supply. One of the largest supplies obtained from these sands is the public supply of Pensacola, Fla. The water generally has a low mineral content, except in some places along the coast where it is exposed to salt water.

Ewing, Richards, Fray, and Craig (1962, p. 148) suggested that the maximum lowering of the Pleistocene sea in Wisconsin time was possibly as much as 450 feet below its present level. According to Donn and others (1962, p. 206–214), the lowering of sea level during Illinoian time was greater than that during Wisconsin time. In discussing the age of the fauna and the age as determined by carbon-14 tests on fossil shells from the Continental Shelf off Argentina, Richards (1963, p. 145) stated that it is more than probable that some warping or subsidence has taken place during and since Wisconsin time, thus accounting for the greater depth of a sample from 86 fathoms with a carbon-14 date of 18,700± 500 years before present time. However, Fray and Ewing (1963, p. 113) believed that the uniformity of the depth of the upper shell layer in cores in the same depth of water suggests that there has been little, if any, warping of the Argentine Continental Shelf since late Wisconsin time.

Sinkhole topography in the Flint River valley in Georgia, at altitudes of as much as 170 feet above sea level, shows evidence of having been submerged by a high stand of the Pleistocene sea after a lower stand during which the sinkholes formed. The deep buried channel of the Apalachicola River with its terraces (Hendry and Yon, 1958, p. 12–20) also indicates that the Pleistocene sea rose to a high level after a lower stand. Correlation of altitudes of the river terraces with older marine terraces indicates that the low stand of the sea during which the channel was cut was pre-Wisconsin.

ANASTASIA FORMATION

The Fort Thompson Formation, Miami Oolite, Key Largo Limestone, Anastasia Formation, and Lake Flint Marl are present in southeastern Florida. The Anastasia Formation consists of coquina, shells, sand, sandy limestone, and calcareous sandstone. As described by Parker, Hoy, and Schroeder (in Parker and others, 1955, p. 100–102) and Cooke

(1945, p. 266), the Anastasia extends along the east coast from Anastasia Island, St. Johns County, to the south boundary of Broward County where it merges with the Miami Oolite. The formation extends westward into the Lake Okeechobee-Everglades depression, where it forms the marine members of the Fort Thompson Formation. Klein (1954, p. 12) reported that the Anastasia is composed of light-gray sandy limestone and shelly sandy marl in the Naples area in Collier County. Like the Miami Oolite, it is thickest under a ridge bordering the Atlantic coast and thins to the west. The maximum thickness may exceed 100 feet. Along the Atlantic Coastal Ridge, it yields water to many wells, and in some parts of the ridge, as in Brevard County, it is a principal source of fresh water for wells. The Anastasia is the most important component of the shallow aquifer in the Pompano Beach area, Broward County (Tarver, 1964, p. 9). Parker reported that the Anastasia Formation yields potable water to wells in southern Florida. From southern Palm Beach to central St. Lucie County, it contains a considerable amount of swamp deposits, which yield only small quantities of water of poor quality.

MIAMI OOLITE

After its combination with the Anastasia Formation in Broward County, the Miami Oolite extends southward beyond Florida City. Tarver (1964, p. 9) reported that the oolite overlies the Anastasia Formation in northeastern Broward County. The Miami Oolite forms the floor of the Bay of Florida and reappears above sea level in the Florida Keys from Big Pine Key to Key West. The maximum thickness is under the Atlantic Coastal Ridge where it may be as much as 40 feet. The bottom of the formation is seldom more than 20 feet below sea level. It becomes thin in the Everglades and disappears at the east edge of the Big Cypress Swamp on the west edge of the Everglades, as described by Parker, Hoy, and Schroeder (in Parker and others, 1955, p. 102) and Cooke (1945, p. 256). The typical Miami Oolite is a soft white oolitic crossbedded to massive limestone containing as much as 95 percent calcium carbonate. Many vertical and horizontal solution channels are filled with fine to medium quartz sand (fig. 21). It yields large quantities of water to wells and forms the upper part of the shallow aquifer, the principal source for the Miami area and other parts of southeastern Florida.

FORT THOMPSON FORMATION

The Fort Thompson Formation consists of only about 6 feet of alternating fresh-water, marine, and brackish-water marls, limestones, shell beds, and sand at the type locality near LaBelle on the Caloosahatchee River (Parker and others, 1955, p. 90). Parker, Hoy, and Schroeder reported that the Fort Thompson underlies the Everglades and extends to the coast. Its thickness averages less than 10 feet in the Lake Okeechobee area; but in the Miami area the thickness averages about 80 feet, and the maximum may be about 200 feet. Parker, Hoy, and Schroeder showed that the formation merges with the Anastasia Formation at Fort Lauderdale. In the Miami area, the Fort Thompson consists chiefly of sandy limestone and calcareous sandstone containing beds and pockets of quartz sand and thin beds of dense hard fresh-water limestone. Like the overlying Miami Oolite, the Fort Thompson has many vertical and horizontal solution channels, most of which are filled with permeable sands. The Fort Thompson is one of the principal sources of fresh ground water in southeastern Florida.

KEY LARGO LIMESTONE

The Key Largo Limestone is chiefly a fossil coral reef. It interfingers with the Miami Oolite and the Fort Thompson Formation in the Miami area and underlies the Florida Keys. As described by Parker, Hoy, and Schroeder (in Parker and others, 1955, p. 99), the reef, about 90 miles long, has a maximum width of about 3 miles at sea level. It is known to be at least 60 feet thick. As reported by Cooke (1945, p. 263), the reef grew along the outer edge of the Floridian Plateau, contemporaneous with the Miami Oolite. The Key Largo Limestone is very permeable, but sea water fills the formation below the water table, except locally where there may be sufficient

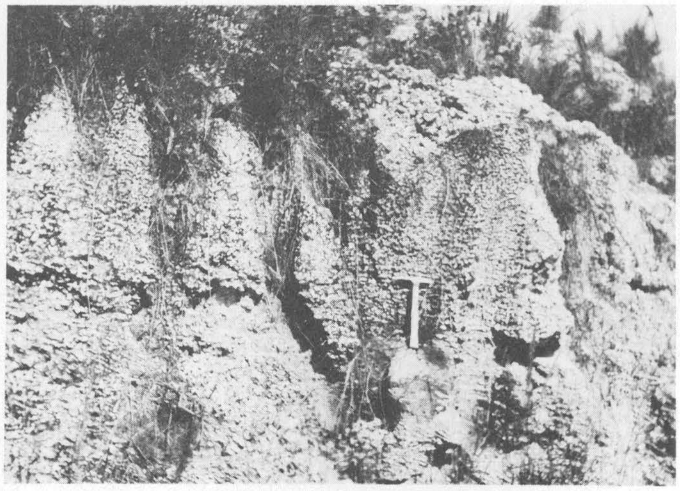

FIGURE 21.—Natural wells or solution tubes in the Miami Oolite near Miami, Fla.

fresh-water recharge to provide limited supplies of potable water.

LAKE FLIRT MARL

The Lake Flirt Marl consists chiefly of gray calcareous mud containing fresh-water shells. It is present in many parts of the Everglades. The maximum thickness of about 6 feet is in the basin of Lake Flirt on the Caloosahatchee River east of LaBelle. It generally underlies the peaty accumulations in the Everglades and overlies the Pamlico Sand, Fort Thompson Formation, and the Miami Oolite (Parker and others, 1955, p. 108). The marl is interbedded with peat or muck, suggesting that it may have been deposited in Recent time. The marl is relatively impervious and is not an aquifer. However, it prevents or retards vertical movement of the water.

GEOLOGIC STRUCTURE

MAJOR FEATURES

The regional structure is that of a wedge of sediments thickening to the southeast and south. These sediments have a gentle homoclinal dip except where modified by special structural conditions. Major structural features shown on figure 22 are: (1) Peninsular arch, (2) Ocala uplift, (3) Chattahoochee anticline, (4) Apalachicola basin, which extends into Georgia and forms the southwestern Georgia basin, (5) southern Florida basin, and (6) the southeastern Georgia basin.

The peninsular arch extending about 275 miles from southern Georgia to the vicinity of Lake Okeechobee, forms the axis of the north two-thirds of the Florida peninsula (Applin, 1951, p. 3–5). Its crest of Paleozoic sedimentary rocks lies about 60 miles west of Jacksonville (Toulmin, 1955, p. 210). The crest was above sea level in Early Cretaceous and part of Late Cretaceous time. Sediments of Austin age (Late Cretaceous) were deposited across the crest of the arch. However, throughout the remainder of the Late Cretaceous and during the early Tertiary, sedimentation in Florida was interrupted only by short periods of land emergence. During Miocene time the northern part of the peninsula was uplifted, causing the complete removal of Oligocene rocks from a broad area and the irregular erosion of the upper part of the Eocene Series.

Reports by Vernon (1951, p. 53) and Applin (1951, p. 3–5) show that the axis of the Tertiary structure, the Ocala uplift, does not coincide with the peninsular arch. Vernon believed that there is no close structural relationship between them. However, Meyer (1962, p. 22) suggested that in Columbia County the Ocala uplift is probably related to movements of the peninsular arch. Both structures have a parallel trend, but the crest of the Ocala uplift in Levy and Citrus Counties is about 60–70 miles southwest of the peninsular arch. In one of the earliest discussions of the structure of Florida, Johnson (1888, p. 230–236) described the peninsula as a broad anticline or arch with the apex in the vicinity of Gainesville. The crest of the arch was located by the sinkhole topography, which was thought to indicate the presence of Eocene limestone less than 100 feet below the surface. The dip of the limestone away from the central part of the peninsula is indicated by the presence of younger formations at the surface and by the attitude of Eocene limestones in wells at different points.

In a discussion of the structure, Matson (Matson and Sanford, 1913, p. 163–166) referred to a paper by Johnson (1888, p. 230–236) and recognized two distinct axes of the uplift which extends north-south in the Florida peninsula. He also recognized the uplift west of the Apalachicola River which Veatch and Stephenson (1911, p. 63) described as the Chattahoochee anticline. In reviewing the literature on the Chattahoochee anticline, Hendry and Yon (1958, p. 20, 21) reported that the structure has been called the Decatur arch.

This anticline extends along the Alabama-Georgia boundary into Florida. Like the peninsular arch, it was buried beneath a considerable thickness of Cretaceous sediments before the beginning of Tertiary time. East of the anticline is the southwestern Georgia basin, which forms the northern part of the Apalachicola basin. Herrick and Wait (in Thomson and others, 1956, p. 287) referred to part of the basin as the Tallahassee syncline.

In relation to oil possibilities the structure in the Tertiary rocks of the Florida peninsula was described by O. B. Hopkins (U.S. Geol. Survey, press release, Apr. 19, 1920) as an anticlinal fold which trends south-southeast and forms the axis of the Florida peninsula, which has two high areas. He called the highest part of the structure the Ocala uplift in eastern Levy County. The other high area in the vicinity of Live Oak was called the Live Oak uplift. Subsequent investigations have shown that the Ocala uplift centers around outcrops of Ocala Limestone (upper Eocene) and Avon Park Limestone (middle Eocene) in Citrus, Dixie, and Levy Counties on the west coast of Florida. On some parts of the crest, the Ocala Limestone is as much as 120 feet above sea level. The Ocala and Avon

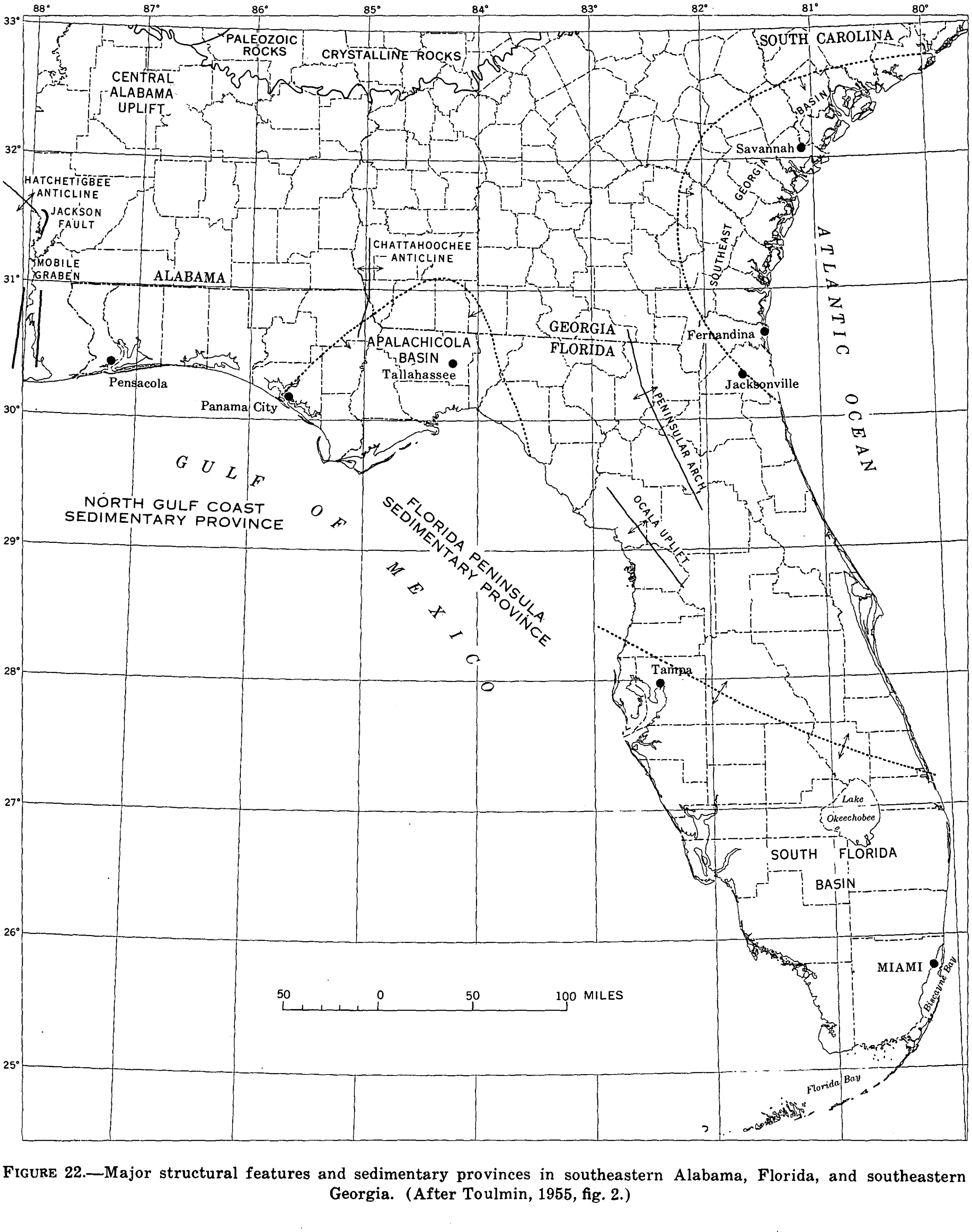

FIGURE 22.—Major structural features and sedimentary provinces in southeastern Alabama, Florida, and southeastern Georgia. (After Toulmin, 1955, fig. 2.)

Park dip under the younger formations exposed on the flanks of the fold.

The general features of the Tertiary structure in Florida are shown on a contour map by Mossom (1926, p. 256) representing the top of the Ocala Limestone. The map shows two distinct structural uplifts: one is the Ocala area and the other the Marianna-Chipley area. Mossom includes the Live Oak area as part of the Ocala uplift. The Marianna-Chipley area is part of the Chattahoochee anticline. The map also shows an arch extending from the east flank of the Ocala dome to an area on the east coast between Melbourne and St. Augustine where Mossom (1926, p. 233) reported Eocene limestone at a depth between about 100 and 200 feet below sea level. At New Smyrna the limestone is at a depth of 105 feet below the land surface, about 90 feet below sea level. Some investigators have referred to the structure as the New Smyrna arch. The limestone dips to the north and is about 500 feet below sea level at Jacksonville. It also dips to the south where it is about 1000 feet below sea level in southern Florida.

L. C. Johnson (1888, p. 230–236) recognized the New Smyrna arch and the Ocala uplift. With that information and an estimate of the dip on the northeast flank of the Ocala uplift, about 1885 he correctly estimated the depth to the top of the Ocala Limestone, the artesian aquifer at Jacksonville, Fla. Although the top of the Ocala Limestone is an eroded surface, it shows the general structural features.

Later studies of the stratigraphy and paleontology enabled the investigators to subdivide the Ocala Limestone and learn other details of the geology. A structure contour map by Vernon (1951, pl. 2) based on some of these studies shows additional details of the structure. Vernon (1951, p. 53) stated that the structural deformation of the Ocala uplift probably began during the early Miocene. Applin and Applin (1965, p. 15) described the uplift as a faulted and folded structure in the Eocene and younger rocks on the southwest flank of the older and dominant peninsular arch.

Vernon's structure map of the Ocala uplift shows that the north side is composed of two well-defined shallow folds which converge southward in Levy and Citrus Counties, Fla., where they are separated by only a few miles and their crests are extensively fractured and faulted. In Citrus County the structure includes the Bronson graben (Vernon, 1951, fig. 15) with small displacement. Yon and Puri (1962, p. 678) extended the structure northward in Gilchrist County. However, the writer believes that the topographic feature, Waacasassa Flats, in Gilchrist County is due to surface and underground solution of the limestone prior to the deposition of the Alachua Formation. On the southeast flank of the uplift in Lake, Orange, Seminole, and Osceola Counties, the map shows the Kissimmee faulted flexure, a wedge-shaped block approximately 90 miles long, 54 miles wide on the northwest border, and 17 miles wide on the southeast margin. This faulted flexure is the northwest boundary of a downfaulted triangular block which Vernon named the Osceola low, in Osceola County. The apex of the triangle formed by the fault on the northwest and east side of the block is in the northeast corner of Osceola County. The downward displacement of the block is about 300 feet at the apex with no movement on the southwest side.

East of the Kissimmee faulted structure in Seminole and Volusia Counties is a structure that Vernon named the Sanford high, which apparently is part of the New Smyrna arch.

The southern Florida basin (Pressler, 1947, p. 18–56, fig. 1) is the regional structure that extends from the south side of the Ocala uplift to the Straits of Florida just south of the Florida Keys. The southeastern Georgia basin is on the northeast flank of the uplift.

On some parts of the crest of the Ocala uplift, the principal artesian aquifer is as much as 120 feet above sea level. The aquifer and overlying formations on the flanks of the uplift dip at low angles away from the crest of the fold. The formations crop out on the floor of the Atlantic Ocean and the Gulf of Mexico some distance offshore, and some of them probably crop out on the edge of the Floridian Plateau which, as described by Cooke and Mossom (1929, p. 39) and Vaughan (1910, p. 99–185), is a peninsula that separates the deep water of the Gulf of Mexico from the deep water of the Atlantic Ocean. The plateau includes not only the State of Florida but also the parts of the adjacent ocean floor less than 50 fathoms (300 ft.) below sea level.

The outline of the plateau is shown in figure 4. Beyond a depth of 50 fathoms, the ocean floor slopes abruptly to depths of more than 400 fathoms in the Straits of Florida and the Atlantic Ocean and more than 2,000 fathoms in the Gulf of Mexico. The edge of the plateau in the gulf lies somewhat less than 75 miles to more than 100 miles west of the present coast of the Florida peninsula. Along the southern and eastern coasts of the peninsula from Key West to Palm Beach, the edge of the plateau is not more than 10 miles off the coast. In much of the area from Miami to Palm Beach, the plateau is within a few miles of the coast as shown on the Key West, Miami, and West Palm Beach quadrangle maps (scale, 1 : 250,000) by the U.S. Geological Survey.

Submarine topography of the Pourtales Terrace (G. F. Jordan, 1954, p. 1810) in the western Straits of Florida and the Tortugas Terrace (Kofoed and Jordan, 1964, p. 69–77) on the continental slope approximately 45 miles west of Dry Tortugas indicates normal block faulting in these areas. J. E. Johnston and others (1959, p. 1–7) described the general features of the emerged and submerged Atlantic Coastal Plain, including the major known structural features north of Florida. Pirkle and Yoho (1961, p. 244–276) described local folding and warping resulting from solution in north-central Florida.

JOINTS AND FRACTURES

In addition to faulting, fracture patterns in the northern part of the peninsula were first described and mapped by Vernon (1951, p. 47–48, fig. 11). The mapping of the fracture patterns was based on physiographic features and on mosaics and contact prints of aerial photographs, available for each county except Orange, Taylor, and part of Marion. Vernon checked the geology of these features in cores and records of core holes along the proposed ship-canal route across the peninsula. The core holes extend from the Gulf of Mexico along the Withlacoochee River, along the Citrus-Levy County line, and across southern Marion County to the Oklawaha River.

The regional pattern consists of two fracture systems, one trending northwest-southeast, parallel to the axis of the Ocala uplift, and the other northeast-southwest, according to Vernon (1951, p. 47). He stated that geologic sections crossing the Ocala uplift show that the fractures paralleling the axis of the uplift are faults but that sufficient data are not available to determine displacement along the transverse fractures. The two fracture systems form approximately a rectangular pattern where they intersect. Fractures trending northeastward are poorly formed along the crest of the Ocala uplift but are well formed and numerous along the northwest flank of the uplift in Jefferson, Madison, Hamilton, and Suwannee Counties, where they delineate the northwest limit of the crest. The southeast flank of the crest of the Ocala uplift is not so conspicuously marked by these systems of fractures, which Vernon states can be traced from county to county throughout the State.

Vernon (1951, p. 50) mapped two other systems of fractures, one in Union County over the crest of the peninsular arch and the other in Osceola County over the Osceola low. The pattern in Union County is radial, resembling the fracturing over structural domes. The fractures in Osceola County trend northwest-southeast and northeast-southwest similar to those on the Ocala uplift, but the northwest trend is more westerly than those on the uplift. These trends are over an area of Precambrian igneous and metamorphic rocks which are more than 6,000 feet below sea level (Applin, 1951, figs. 1, 2). As discussed by Vernon, if these fracture patterns in Union and Osceola Counties reflect the pre-Mesozoic rocks, it must be through several thousand feet of Cretaceous, Tertiary and younger sediments. Vernon suggested that adjustment of these relatively unconsolidated sediments over the stable pre-Mesozoic rocks may have formed the fractures.

As described by Vernon, the regional fracturing associated with the Ocala uplift is believed to reflect structural movement during the late Tertiary. Stream patterns and sink alinement generally parallel both the northwest and the northeast systems of fractures. The valleys of the Oklawaha, Withlacoochee, and Kissimmee Rivers are given as examples of the streams having rectangular trends northeast-southwest and northwest-southeast. In the area of Albany, Ga., Wait (1962a) reported alinement of sinkholes in two directions, one about N. 60° W. and the other about N. 10°–30°E. Moore (1955, p. 15) recognized a rectangular joint pattern on aerial photograph mosaic in Jackson County, Fla. He suggested that the angular stream pattern of the Chipola River and Dry Creek is probably caused by jointing.

SOLUTION IN LIMESTONE

Calcium carbonate, the chief constituent of pure limestone, is relatively insoluble in pure water. Only 0.014 gram of calcium carbonate is dissolved by 1 liter of distilled water at 25°C (Foster, 1949, p. 648). Calcium bicarbonate, however, formed by the reaction between calcium carbonate and water containing carbonic acid and other acids is much more soluble. The amount of calcium carbonate or magnesium carbonate taken into solution depends both on carbon dioxide content of the water and the calcium and magnesium content of the water. The carbon dioxide content of the water is from the atmosphere and oxidation of organic matter in the soil and in the geologic formations. Swinnerton (1949, p. 659) stated that under ordinary conditions when air exerts a pressure of 1 atmosphere, the partial pressure due to carbon dioxide is 0.0003 atmosphere. Under this pressure, at 16°C, about 63 ppm of calcium carbonate can be dissolved. The partial pressure of carbon dioxide required to dissolve 400 ppm is approximately 0.065 atmosphere.

The rate of solution of limestone depends upon many factors including the chemical composition, permeability of the limestone, the rate of circulation of the ground water, time, volume of solvent, area of contact, the concentration and partial pressure of carbon dioxide, and natural acids in the water. Swinnerton (1949, p. 659) reported that the temperature factor in the ordinary range of ground water is complicated but is not very significant. Above the water table, however, the variation in temperature may be large enough to be significant. Carson (1964, p. 5) observed that in Tolleys Cave, Va., the ratio of solution to deposition varies with seasons. During the winter, water entering the cavern is cold and contains a large amount of calcium carbonate in solution. As the water becomes warmer inside the cavern, carbon dioxide is released and travertine is deposited. Burdon and Papakis (1963, p. 61–62) discussed amount and rate of solution of carbonate rocks and cited results of studies by Corbel (1959, p. 117) that indicate the rate of erosion from cold rain is greater than that from warm rain.

Swinnerton (1949, p. 660) stated that the common ion effect, as that produced by calcium sulfate in solution with calcium bicarbonate in the presence of limestone, should depress the solubility of calcium carbonate. In southwestern Florida, as in Sarasota County, where the artesian water has a relatively high content of calcium sulfate, there appear to be fewer solution cavities, and the lower part of the aquifer yields very little water. This condition may be due in part to the common ion effect in addition to the depth and distance from a recharge area.

In addition to solution or chemical action, physical action or corrasion caused by running water erodes carbonate rocks. Some evidence of that action is present in some of the underground cavities and caverns. However, this action appears to be small in comparison with solution which may occur both in the zone of aeration and in the zone of saturation.

Calcareous rocks differ appreciably with respect to their strength to resist fracture and with respect to their solubility as stated by Piper (1932, p. 73). Welder and Reeves (1962, p. 36) concluded that solution channels in limestone in Uvalde County, Tex., are larger than those in dolomite because calcium carbonate dissolves more readily than the magnesium carbonate.

Fox (1941, p. 334) found that in boulders exposed in the Tennessee River for 25 years the purer limestone was more soluble than the impure limestone. Siliceous limestone was the least soluble. The purer limestone dissolved from one-fourth to three-fourths inch faster than the impure limestone. From this he estimated that limestone continually washed by the river will dissolve at a rate of approximately half an inch in 25 years.

Some of the Eocene formations of the principal aquifer contain anhydrite and gypsum which may be dissolved by water without the presence of natural acids. The water-bearing capacity of limestone, marl, dolomite, anhydrite, and gypsum depends in part on the original permeability of the formation and on the secondary permeability which is formed by fracturing, solution, and other processes after the beds have been formed. The permeability that is due to solution of limestone accounts for much of the large yield of the Tertiary and Quaternary limestones.

SOLUTION CAVITIES

Solution cavities are numerous in the aquifers and also are reported in older Eocene and Cretaceous formations penetrated by oil wells. The log of Cory well 1 of Peninsular Oil and Refining Co., Monroe County, Fla., shows cavities 18 feet high between 2,846 and 2,864 feet deep, 4 feet high between 2,959 and 2,963 feet deep, and 11 feet high between 2,986 and 2,997 feet deep (R. H. Jordan, 1950, p. 264).

The log of well W–820 of the Humble Oil Co. in Collier County, Fla., shows a cavity 40 feet high at a depth of 6,100 feet. Vernon (in Ferguson and others, 1947, p. 21) reported that cavities have been penetrated at depths of 8,000 feet in oil wells and that circulation of mud in the well has been lost at greater depths. Hughes (1944, p. 75) reported that the oil-producing horizon at depths of 11,613 to 11,626 feet in the Sunniland field in Collier County in southern Florida is cavernous limestone of Early Cretaceous age.

There may be solution by deep circulation of artesian water in areas where there are favorable structural conditions, such as recharge of the aquifers at high altitudes on the flank of an anticline or discharge from a deep basin at a lower altitude. For example, at Parris Island, S.C., fresh water and the relatively high artesian head indicate circulation at a depth of as much as 2,600 feet in water-bearing sands of the Tuscaloosa Formation of Cretaceous age. Where hydrologic and structural conditions are not, however, favorable for circulation of the ground water, deep cavities such as those in the older Eocene and Cretaceous limestone would have to form before the formations are deeply buried.

The writer found no evidence of circulation of water below the Lake City Formation of middle Eocene age in Florida in Recent time. The deep circulation of artesian water in the Lake City and the younger formations depends on (1) recharge and (2) the opportunity for discharge at submarine outcrops or through springs and upward leakage into overlying formations. The discharge at submarine outcrops is controlled by the relation of the fresh-water head and the back pressure from the salt water. In areas where the pressure of the salt water is greater than the artesian head at the submarine outcrop, no discharge occurs. Upward leakage depends on the permeability and thickness of the overlying beds and the hydrostatic head of water in the aquifer in the overlying formations.

After deposition in the sea, most of the water-bearing formations of the principal artesian aquifer were raised above sea level, and solution cavities formed in the limestone and other carbonate rocks before they were resubmerged in the sea and covered by overlying formations. Many of these solution cavities probably were filled by the overlying formations. Shallow sinkholes in the Hawthorn Formation in central Florida are filled with deposits of Bone Valley Formation (Cathcart, 1963b, p. 22). If the Bone Valley is Pliocene in age, this relationship would indicate erosion and solution in the Hawthorn began in late Tertiary time. It appears that sinkholes in the Hawthorn in some upland areas formed after the Citronelle Formation was deposited. The solution cavities which exist today in the principal artesian aquifer and younger formations apparently formed chiefly if not entirely during Pleistocene and Recent time.

Even though solution is continuous where there is circulation of artesian water as at the present time, it seems that much of the solution in the deeper water-bearing formations of the principal artesian aquifer of Tertiary age occurred during Pleistocene time when sea level was at least 300 feet below the present level. At that time, the land area extended to the edge of the Continental Shelf, and the highest areas in Florida were at least 600 feet above sea level. The solution channels in the shallow aquifer in the Miami area also formed during a low stand of the Pleistocene sea.

Although sinkholes are formed and solution cavities are enlarged above the water table, a solution cavity in the zone through which the water table or water level in the limestone fluctuates is enlarged both by water in the zone of saturation and by water in the zone of aeration. The opportunity for maximum solution, however, appears to be in the upper part of the zone of saturation where the limestone is in continuous contact with the water. Many cavities penetrated by wells in the principal aquifer at different depths appear to have formed in the upper part of the zone of saturation when that zone was at various levels in accordance with different stands of the Pleistocene sea. Records of cavities throughout the extent of the aquifer, such as those given in the following discussions, may show some correlation with the levels at which the sea stood long enough for the ground-water circulation to adjust to the new sea level. Such correlation, however, is obscured because solution occurred not only with the lowering of sea level but also during the rise.

Zones of solution cavities in the limestone exposed in channels of streams cut into the aquifer, as along the Suwannee River in Florida and the Flint River in Georgia, are examples of zonation of cavities where the opportunity for the solution of the limestone is favorable. The channel that connects Falmouth Spring with the Suwannee River is an illustration of a shallow solution channel in the aquifer. The spring is in a sinkhole formed by the local collapse of the roof of an underground stream. If there were a lowering of sea level, the base level of the streams would be lowered along with the lowering of water level in the limestone. If there were sufficient lowering of the water level, the solution channels—such as the one connecting Falmouth Spring with the Suwannee River—and the zone of cavities exposed in the river would be left above the zone of saturation in the limestone, and enlargement of the channel and cavities would occur only when surface water flowed into them.

The origin of caves or caverns in limestone, as described by Davis (1930, p. 475–628), is a two-cycle process in which the first cycle is solution in the zone of saturation which forms cavities below the water table. This cycle is related to regional peneplanation. The second cycle takes place with an uplift of the cavern opening or lowering of the zone of saturation and removal of ground water. In the second cycle, the caverns are modified by the action of water above the water table.

Bretz (1942, p. 675–811; 1956, p. 10–38) accepted almost completely the two-cycle theory of Davis and inserted another cycle that consists of cave filling with very fine red clay before the removal of ground water. Roger Baker, U.S. Geological Survey (written commun., Nov. 1962) recognized three cycles in the solution of limestone on the Edwards Plateau in Texas. Herrick and LeGrand (1964, p. 29–35) described the karst cycles of erosion in the Flint River valley in southwestern Georgia. Their study indicates that concepts of the karst cycle are useful if considered in terms of both time and space. The cycle represents a sequence of topographic features to which a corresponding sequence of time may be applied only when referring to a restricted part of a limestone terrane.

Swinnerton (1932, p. 663–693) proposed a single cycle in which the initial openings in the limestone form in the zone of saturation but the most active formation is near the water table. Vernon pointed out (in Ferguson and others, 1947, p. 19, 20) that artesian water is under pressure and any solution of the principal artesian aquifer must be in the zone of saturation.

Back (1963, p. 43) reported that water at depths of several hundred feet in the aquifer in central Florida is undersaturated with respect to calcite; therefore, solution of the deep limestone can occur. Although solution may occur at great depths, if there is circulation of artesian water, it seems that most of the solution would occur in the upper part of the zone of saturation, in the part of the aquifer where continuous circulation is the most vigorous. In recharge areas of the artesian aquifers, the piezometric surface merges with the water table, and water-table conditions are present. Solution in the aquifer may therefore occur under water-table or artesian conditions.

Piper (1932, p. 73) suggested that where ground water in limestone has a free upper surface or water table, the limestone is presumably dissolved most rapidly in the zone between the highest and lowest positions occupied by the water table in its seasonal fluctuations. In that zone the water circulates most rapidly and is most likely to contain natural acids. In a discussion of the solution cycle in limestone in south-central Tennessee, Theis (1936, p. 44) reached the conclusion that the greatest amount of solution takes place near the water table. Other conditions being the same, the large solution passages are formed near the water table. From observations of the patterns and rates of solution on the surface of small limestone blocks immersed in dilute acid, Kaye (1957, p. 45) concluded that the rate of solution is considerably affected by agitation and that the rate varies with the relative movement.

At the present time, there is movement of water through the principal artesian aquifer to springs, rivers, and lakes, such as those in the St. Johns River valley and to the Atlantic Ocean and the Gulf of Mexico. Solution is shown by the chemical composition of the water. In Citrus and Levy Counties on the gulf coast of Florida, the top of the limestone of the principal aquifer is at or near the surface, and large quantities of artesian water discharge into the Gulf of Mexico, although the gradient of the piezometric surface is small. If sea level were lowered, the opportunity for discharge into the Gulf of Mexico would be increased, and a new hydraulic gradient would be established, which eventually would be parallel to the old gradient, except for factors such as changes in the area of the cross section through which the water flows, diversion of flow, and increase in recharge. These factors would cause the new gradient to be steeper than the older one until new or enlarged solution channels formed at a lower level. As stated by Kaye (1957, p. 45), if recharge of the aquifer is not increased, the enlargement of solution channels would lower the water table and thereby expose caverns formed in the zone of saturation. This process initiates the second cycle of Davis without diastrophism, eustatic changes of sea level, or marked changed in topography; but this would not be sufficient to explain the cavernous zones at different levels. However, in the report area eustatic changes of sea level during Pleistocene time were a controlling factor in the karst cycles and the formation of solution channels at different depths in the aquifer.

Theoretically water moves in arcuate paths following lines of flow that have their origin at the top of the zone of saturation in recharge areas (Swinnerton, 1949, p. 665). The flow lines curve downward for some distance and then rise to an outlet or point of discharge. Diagrammatically these flow lines can be represented by a family of curves, the spacing of which is closest near the area of outlet and widest along the top of the zone of saturation as the distance from the outlet increases. In uniformly permeable material where geologic structure does not control the direction of movement, the water may be expected to have an arcuate pattern of flow. In the initial stages of groundwater circulation in limestone and other carbonate rocks, the lines of flow are modified. The concentration of flow lines in the discharge area, together with the greater velocities in that area, will result in an enlargement of the outlet and a consequent shallowing of the more remote arcuate paths. The more direct paths will become larger than the less direct paths and will permit progressively larger flows at the expense of other passageways.

As stated by Rhoades and Sinacori (1941, p. 794), the initial flow both at great and at shallow depths causes solution, which is quantitatively more pronounced in the upper zone because of greater circulation in that zone. Progressive concentration in the upper part of the zone of saturation produces master conduits and causes eventual diminution of flow and solution at greater depths.

In general, the solution cavities and channels form with vertical and lateral circulation of the water; however, there are exceptions as reported by Olsen (1958, p. 396–403). The main solution and flow channel of Wakulla Spring, Fla., is at a 45° slope 100 feet below the land surface (Nevin Hoy, written commun., 1962). The vertical pipes and natural wells are formed by vertical movement, chiefly above the zone of saturation. The horizontal cavities and channels are formed in the zone of saturation.

Information on solution cavities in the principal artesian aquifer and the overlying Hawthorn Formation, as reported by H. G. Stewart (1959, p. 14) in Polk County, Fla., shows that the vertical dimensions of the cavities penetrated by wells in that area range from 2 to 40 feet at depths ranging from 112 feet above sea level in the Hawthorn Formation to a depth of 805 feet, or 584 feet below sea level, in the Avon Park Limestone. The largest cavity, 40 feet in diameter, is in the Crystal River Formation, 360 feet below the land surface or about 228 feet below sea level. One "honeycomb" zone 43 feet thick, 13 feet below sea level, was penetrated in the Suwannee Limestone.

Altitudes, with reference to sea level, are given for some of the cavities. Some altitudes were estimated and therefore are approximate. However, they give information on the vertical distribution of the cavities. Seventeen of these cavities are in the Avon Park Limestone, 206 to 685 feet below sea level. Two cavities are in the Crystal River Formation, and the remainder are in the overlying Suwannee and Tampa Limestones and the Hawthorn Formation. The cavities in the Avon Park Limestone and the Crystal River Formation apparently are in zones which slope to the southwest in the same general direction as the slope of the piezometric surface at the present time. If these zones represent solution in the upper part of the zone of saturation, the hydraulic gradient of the piezometric surface was probably two to three times as large as the steepest natural gradient at the present time. The cavities in the formation above the Crystal River appear to form a zone from about 100 feet above sea level to about 25 feet below sea level. This zone appears to have a slight slope to the southwest.

In the Orlando area (Orange County) in central Florida where the surface altitude is generally about 100 feet, W. F. Lichtler (written commun., 1963) recorded cavities penetrated by wells in the limestone of the principal artesian aquifer, as follows:

Depth below mean sea level (feet)	Number of reported cavities	
	At least 1 foot in vertical dimension	At least 10 feet in vertical dimension
0–100	14	5
100–200	12	2
200–300	11	3
300–400	23	2
400–500	5	1
500–1,000	0	0
1,100–1,200	2	0
1,200–1,300	2	0
1,300–1,400	1	0

The zone, 300 to 400 feet, where most of the smaller cavities are reported consists chiefly of hard brown dolomitic layers with softer intervening layers. All cavities had a vertical dimension of at least 1 foot. Thirteen had vertical dimensions of at least 10 feet. All the cavities having dimensions of at least 10 feet were less than 400 feet below sea level except one between 400 and 500 feet. An unusual exception not given in the preceding table is a 90-foot cavern 468 to 558 feet below sea level and penetrated by a well (Primrose) drilled 885 feet deep in 1963.

The principal artesian aquifer in Florida probably has caves and solution channels comparable in size and extent to those in Mammoth Cave in Kentucky. From reports on cavities penetrated by water wells and a report by Olsen (1958, p. 396–401) on Wakulla Cave through which Wakulla Spring flows, the largest and most extensive caves are filled with water. Wakulla Cave was explored through a distance of 1,100 feet and a depth of about 250 feet below the surface and about 240 feet below sea level.

The caves above the water in the aquifer at present are not as large as those in the zone of saturation. Some of the caves in the Marianna Limestone of the principal artesian aquifer near Marianna, Fla., are above the water level in the limestone and have been explored. Those at the Florida Caverns State Park near Marianna are open to the public. Olsen (1959, p. 73) referred to two caves in Citrus County and one south of Ocala in Marion County, Fla. He stated that many of the limestone caves in the central part of the peninsula and in the panhandle of Florida have been visited by persons searching for vertebrate fossils.

Two of these in the peninsula are Iron Ladder Cave and Saber-Tooth Cave in Citrus County. Access to Iron Ladder Cave is by a metal ladder through a hole in the cave ceiling, which is 60 feet above the floor of the cave. The pile of bones beneath the opening, including one human skeleton, probably Indian, indicates this opening was a natural deathtrap similar to the exposure of natural wells, as shown in figure 9. Animals falling through the hole were killed on impact on the rocks below.

Some water wells in the areas where the aquifer is at or near the surface penetrate air-filled cavities above the water in the limestone. One of these in the De Land area in Volusia County contained air under several pounds of pressure, which apparently was caused by a rise in the water level in the limestone and in a cavity not directly connected with atmospheric pressure.

Throughout most of the areas of artesian flow many water-well drillers report cavities at different depths and increases in artesian flow immediately below relatively impervious lenses of hard silicified limestone or chert that locally may retard upward movement of artesian water in the aquifer. These relatively impervious layers apparently are not continuous over large areas except in western Florida, where the Bucatunna Clay Member of the Byram Formation of Oligocene age separates the upper part of the aquifer from the lower part. Cavities are most numerous and largest in natural recharge and discharge areas.

In the Hawthorn Formation overlying the principal artesian aquifer, relatively impervious beds may retard vertical movement of water and control to some extent the lateral movement. The vertical movement of the water in the Hawthorn Formation and the principal artesian aquifer are not, however, retarded as much as that in some of the limestones of Paleozoic age in central Tennessee and the Blue Grass region of Kentucky. In part of the Blue Grass region, solution of the limestone has occurred from the surface to a depth of about 80 feet. Underlying beds of bentonite and shale prevent downward movement of water, as described by Hamilton (1948, p. 39–52). Near Lexington, Ky., the relatively impervious beds are so effective in preventing percolation of water that a limestone mine under these beds is dry.

As stated by Piper (1932, p. 82–83) a bed of impermeable shale or other impervious material that is not readily soluble or is not jointed may prevent downward circulation, as in north-central Tennessee, where the Chattanooga Shale underlies Mississippian limestone. If the restraining bed is, however, thin and breached, channeling may take place at a lower level. The lower system of channels may drain the upper system through natural wells and pipes.

In southern Florida, solution is dominant where limestone and other calcareous deposits are at or near the surface and where the surface water contains relatively large amounts of organic acids. Solution in the shallow aquifer, which consists chiefly of cavernous limestone and marl ranging from late Miocene to Recent in the Miami area in southeastern Florida, was most active when sea level was below its present level. Solution occurs through vertical movement of the water from the land surface to the bottom of the aquifer, which overlies relatively impervious Miocene marl and clay. Thousands of vertical channels are now filled chiefly with permeable sand. They range in diameter from a fraction of a foot to several feet. Horizontal channels were formed by lateral movement of the water to the Atlantic coast. Later, when the sea covered the area, most of these cavities and vertical channels were filled with sand.

Parker and Cooke (1944, p. 29) reported that in large areas in southern Florida at least one-fourth of the total volume of limestone of the shallow aquifer, once mostly solid rock, is now occupied by solution holes, generally filled with sand. Some of the horizontal solution channels have vertical dimensions of as much as 11 feet. In some places the channels are within a few feet of the surface. The largest channel recorded at shallow depths is between 10 and 21 feet below the land surface in the Silver Bluff area in Miami. Some solution is active at the present time, although the cavities are filled with sand. If sea level were below the bottom of the aquifer for a sufficient length of time for water to remove the sand from the cavities, surface drainage would be underground, and the water table would decline to the bottom of the aquifer. Water would flow freely through the aquifer, and the zone of saturation would be temporary. At the present time, however, the cavities in the aquifer are filled with permeable sands, and sea level is near the top of the aquifer. Therefore, the water table ranges from sea level along the coast to a maximum of about 10 feet above sea level in areas several miles inland.

Although many vertical solution channels occur along joints and fractures or the intersection of joints, solution may begin in a small depression on the surface of the limestone. The water stands in the depression and dissolves the limestone until it is flushed from the depression by rain or water flowing over the surface during and after rains. Parker and Cooke (1944, p. 27) reported that on some of the limestone surfaces in southern Florida, the first effects of solution appear as small surficial pits resembling raindrops in mud. These gradually become deeper, without visible outlet along the sides and bottom. They later become tubes, which enlarge into holes of different shapes and sizes. Some of the holes observed were several feet deep.

Solution in the shallow limestone in the Miami area has been intense, but typical sinkhole or karst topography has not resulted. Soluble limestone extends to the land surface, and solution has occurred throughout the aquifer in relatively small channels instead of concentrating in large channels which would cause sinkholes. The vertical movement of the water from the surface to the aquifer is through many vertical shafts or natural wells of small diameters instead of large sinkholes.

SINKHOLES AND NATURAL WELLS

Sinkhole topography, or karst topography has formed in the area of this report where limestone is at or near the surface and the overlying Hawthorn Formation has been removed by erosion, or where sinkholes and natural wells extend through the Hawthorn to the underlying limestone.

R. H. Jordan (1950, p. 262) believed that the karst geomorphic cycle, which is typical of many regions underlain by limestone or other soluble rock, does not apply in Florida. The writer is of the opinion that both karst and cave cycles in the Tertiary limestone in the southeast are similar to those in other regions, as Mammoth Cave, Ky., except that the cycles were affected by eustatic changes of the Pleistocene sea. Von Engeln (1949, p. 563–585) discussed the karst geomorphic cycle and gave definitions of some of the foreign words used to designate features of karst topography. In a comparison of Florida limestone with the London Chalk in England, he indicated that, because of its large permeability and ability to hold water, the chalk is not cavernous; but Florida limestone is cavernous because of its small permeability and inability to hold water. Actually, Florida limestone is permeable and holds large volumes of water. Some parts of the limestone are chalky but are also permeable. The permeability of the London Chalk is small, and the water occurs chiefly in joints and fractures as indicated in the large seasonal fluctuations of water level, which may be more than 100 feet. Chalk may have a high porosity, as the Selma Chalk of Cretaceous age in Alabama, but the permeability is so small that excavations in the chalk have been used as cisterns. The permeability of the chalky part of the Cooper Marl of Oligocene age in South Carolina also is so small that an unlined tunnel in the marl is used to pipe the municipal water of Charleston, S.C., from a surface reservoir to the city. Apparently, joints and fractures that may occur in the Selma Chalk and Cooper Marl do not remain open long enough for the formation of solution channels.

Sinkholes and natural wells, or vertical shafts, are natural openings that generally extend from the land surface to a permeable or cavernous zone in the limestone. The sinkholes, in general, are caused by solution and by collapse of the roof of underground channels or caverns. Formation of a sinkhole by solution commonly originates at a vertical joint or fracture or the intersection of two joints, the crevice being enlarged by the solvent action of water that descends from land surface to a lower level or to the zone of saturation. In Tennessee, Piper (1932, p. 72) stated that at first the descending water is largely depleted in solvent power before it percolates far below the surface and, therefore, the deeper part of the joint is not likely to be enlarged appreciably. This process results in a conical depression in the limestone, the base of the cone being at the land surface and its apex pointing downward. As this depression increases in diameter and depth, the relatively insoluble soil subsides, giving the first indication of the sink. Piper reported that both cone-shaped sinks and natural wells, or vertical shafts, also form underground between solution channels at different levels in Tennessee.

Natural wells, or vertical shafts, that may be approximately cylindrical and about the same diameter at the top and bottom are formed by solution along joints above the zone of saturation in the limestone. The solution rate is approximately the same from the top to the bottom of the wells. As described by Pohl (1955, p. 10), the vertical shafts in Kentucky caves range from a few feet to more than

30 feet in diameter and 10 to 200 feet in height. Merrill (1960, p. 107) reported that the deepest shaft in central Kentucky is 240 feet. There is no uniform relation between height and diameter except that the shafts of large diameter are taller. The shafts usually have a cup-shaped base that is no larger in diameter than most of the cylinder. The top is an irregular dome. In caves, the shafts are called domes and pits, or dome pits.

One of the well-known examples of a natural well in Florida is Falling Water Sink about 4 miles south of Chipley in Washington County, which is 68 feet deep and about 20 feet in diameter (Cooke, 1945, p. 134). It penetrates the Tampa Limestone and the underlying Suwannee Limestone. A small stream from surficial sands above the Tampa flows into the cylindrical shaft and flows out through a small cavern at the bottom. Figure 9 shows the mouth of a natural well about 5 feet in diameter in the Suwannee Limestone near Brooksville, Hernando County, Fla. At a depth of 50 feet, the well was dry. The boards on the ground are remnants of a fence built to prevent persons and animals from falling into the well.

In a discussion of caves in northern Alabama, W. D. Johnston (1933, p. 53) described a feature in Madison County known as Natural Well, 186 feet deep. The sides of the well are fluted but have circular sections ranging from 25 to 40 feet in diameter. From the bottom of the well a spiral opening, sloping steeply, descends into a high narrow corridor with fluted walls. At the end of the corridor is a low crawlway which ends in a pit 30 feet deep. The total depth to which Johnston explored was 352 feet below the surface. Mohr (1964, p. 803–837) reported that a "vertical pit" in Fern Cave in northern Alabama is 426 feet deep and that the Devils Sinkhole in Texas is 407 feet deep. Lobeck (1939, p. 143) reported that some sinkholes in the karst topography in the Causses region in southern France are as much as 700 feet deep.

In Florida, sinks and natural wells are known to be as much as several hundred feet deep. H. G. Stewart (1959, p. 16) reported that the original depth of a sinkhole in Polk County may have been at least 300 feet, the surface elevation being about 230 feet above mean sea level. Meyer (1962, p. 24) indicated that Alligator Lake at Lake City occupies a large solution basin in which rocks slumped from a surface elevation of more than 100 feet above sea level to almost 100 feet below sea level. One of the deepest sinkholes reported (W. S. Wetterhall, written commun., 1961) is 480 feet deep at an elevation of 94 feet above sea level in Pasco County, Fla. The sink is filled with unconsolidated sediments.

As may be seen in caves, many of the natural wells, known as vertical shafts or dome pits in caves, terminate at the level of a lateral channel which formerly was in the zone of saturation, but a few of the wells extend to two or more levels of lateral channels. Although some of these lateral channels are now above the zone of saturation in the limestone, the writer believes that they formed in the upper part of the zone of saturation. The lowest position of the water table in the limestone is indicated by the deepest natural wells.

Where the Hawthorn Formation is present, the first cycle of solution probably was started by water in the permeable beds of the Hawthorn moving downward to the limestone below. The solution of limestone along vertical intersecting joints and fractures enlarged these vertical openings from mere tubes to large shafts. The domelike ceiling of many of the shafts in caves shows the effects of solution caused by the thin films of water which seep in from above and move along the ceiling from the center of the dome to the walls of the shaft. The downward movement of the film of water on the walls of the shaft dissolves the limestone, causing vertical fluting.

As described by Bretz (1956, p. 23) in Mammoth Cave and other caves, descending water may cling to the vertically grooved surface all the way down the vertical shaft. In some shafts, as shown by McGrain (1954, p. 29) in a cave in the Cascade Park of eastern Kentucky, a continuous underground stream of water from a solution cavity at the top of the shaft forms a waterfall that plunges down the shaft to a pool at the bottom, which may be the top of the zone of saturation in the limestone. In describing the vertical shafts which he called dome pits, Bretz (1956, p. 21–22) showed how dome pits may form by a coring mechanism. Water moves downward from a system of anastomosing horizontal solution channels at one level in the zone of aeration to large chambers at a lower level. After a vertical shaft has been formed between the upper channel and the chamber, solution enlarges the shaft along the channel until it completes the circuit and the core drops to the chamber below. Bretz (1956, p. 337) reported three vertical shafts (dome pits) in the Mystery Cave in Missouri, which appear to have been formed by a retreating waterfall underground.

Pohl (1955, p. 14) stated that the shafts in the Mammoth Cave region are exclusively the result of solution. In some shafts Pohl has found many fossil shells attached to the shaft walls by fragile pedestals showing the action of solution rather than corrasion. In a few places, such as the underground waterfall in eastern Kentucky and the waterfall in a shaft in Washington County, Fla., water flowing over the side of the shaft may remove some limestone by erosion. In the dome of the shafts, layers of the ceiling may fall as solution removes the limestone until the shaft has reached a bedding plane or unconsolidated bed that will drop into the shaft.

Pohl showed that in the Mammoth Cave area all but a few of the vertical shafts are at or near the edges of the Mammoth Cave Plateau and near the heads of the surface valley where some of the sandstone overlying the limestone has been removed. In exceptions to this rule, the shafts are related to small sinkholes or arms of larger sinkholes on the tops of the ridges or the surface of the plateau. Pohl (1955, p. 23) showed how the headward erosion of streams removes the sandstone overlying the cavernous limestone and exposes the limestone forming the Pennyroyal Plateau, which is at a lower level and is dotted with thousands of sinkholes (McFarlan, 1958, p. 46).

As part of the Hawthorn Formation was removed by erosion in Florida and Georgia, more and more of the surface drainage went underground into solution channels. After complete removal of the Hawthorn in Citrus and Levy Counties, the Ocala Limestone of the principal aquifer was exposed at the surface with sinkhole topography. There was little or no surface drainage in parts of the area. Probably the removal of the Hawthorn began at the coastline and along streams where the aquifer was nearest the surface. An escarpment, formed by the more resistant Hawthorn, retreated from the coasts and streams. For example in Leon, Wakulla, and Jefferson Counties in Florida, the Hawthorn escarpment, now at the south edge of the Tallahassee Hills, apparently retreated inland from the Gulf of Mexico. Wave action along the shoreline probably contributed to this retreat during higher stands of the sea.

In a study of Baker and Mitchell Counties in southwestern Georgia, Herrick and LeGrand (1964, p. 25) concluded that the Flint River had cut a channel through the Hawthorn Formation to the Ocala Limestone of the principal artesian aquifer. The Hawthorn escarpment which parallels the river retreated from the river to its present position some miles to the southeast. Solution at the base of the escarpment formed gullies at right angles to the scarp, which contributed to the retreat of the scarp. These gullies with vertical head and sidewalls and a nearly flat floor are called pocket valleys by Von Engeln (Engeln, 1942, p. 569). They occur chiefly along the Hawthorn escarpments in Georgia and Florida. The steepheads which Von Engeln calls pocket valleys in the Holt quadrangle in western Florida are not, however, related to the solution of limestone. The origin of these features is discussed under the section on topography of the Western Highlands physical division in western Florida.

The pocket valleys at the edge of the escarpment and shallow sinkholes filled with the Bone Valley Formation were covered and buried by a high stand of the Pleistocene sea, according to subsurface data reported by Cathcart (1963a, p. 37; 1963b, p. 1, 24) in Hillsborough County, Fla. Although an arm of this sea covered part of the Flint River valley and filled many of the sinkholes, much of the drainage is underground. However, the Flint River receives water from the limestone. In flood stages, water from the river flows into the aquifer through solution openings in the stream channel.

The erosion of the Hawthorn and the formation of solution openings in the Hawthorn and the underlying limestone are comparable to the conditions described by McFarlan (1958, p. 46–70) and Pohl (1955, p. 10) in the Mammoth Cave region of Kentucky where sandstone overlies limestone. Water moving downward from the surface through the sandstone to the zone of saturation in the limestone formed the solution cavities. The surface of the limestone, pitted with sinkholes, is exposed as the Dripping Springs escarpment of the more resistant overlying sandstone retreats. A north-south section through the vicinity of Mammoth Cave (McFarlan, 1958, p. 46) shows the Mammoth Cave Plateau where the upper part of the sandstone has been removed. Water moving from the sandstone into the underlying limestone formed the vertical solution tubes and shafts in the zone of aeration. The water moves chiefly in a lateral direction after it reaches the zone of saturation.

Karst topography (similar to that in Kentucky) developed in Florida and Georgia in areas where the Hawthorn Formation was removed, but the topography has been modified by invasions of the Pleistocene sea. In the areas where the Hawthorn is present and the top of the principal artesian aquifer is relatively high as on part of the Ocala uplift, sinkholes extend from the surface through the Hawthorn into the underlying limestone. Most of these sinks are now partly filled by unconsolidated material, some of which is relatively permeable. In the areas where the Hawthorn was overlain by unconsolidated sands, the sands slumped into the sinks and formed the sloping walls of the sink. The slope depends to a large extent on the thickness and angle of repose of the unconsolidated material. In exploring the Devils Pit, a steep-sided sinkhole in north-central Florida, Pirkle and Brooks (1959, p. 315) noted that it has a funnel shape in the surficial sands overlying the Hawthorn. This funnel shape appears to be common in sinks in areas where the Citronelle Formation or other unconsolidated sands overlie the Hawthorn. Where the sands are absent and consolidated rocks are at the surface, a new sink forms vertical walls.

In some areas, as in Orlando in Orange County, Fla., some lakes that occupy sinkholes are narrow and long, indicating that they were formed by collapse of the roof of a meander of an underground stream. Some large lake basins along the St. Johns River valley and in northern Florida resulted from solution of the limestone and collapse of solution channels.

In the upland regions of Florida, Sellards (1914, p. 156) reported that sinks have broken through as much as 100 feet of material, a large part of which, however, is calcareous and phosphatic. Some of the material may have been removed by solution and caving before the material at the surface collapsed into the underlying solution cavity.

As stated by Sellards, sinks are not known to form in areas of artesian flow. The artesian aquifer is overlain by relatively impervious beds, and the water in cavities is under artesian pressure. Along the border between the flowing and nonflowing areas, the artesian water forms artesian springs in some places where the aquifer is at or near the surface and the artesian pressure is sufficient to force water to a point of discharge at the surface. Most of these springs flow through channels and sinkholes apparently formed when the sea stood at a lower level and when the top of the zone of saturation in the limestone was at a lower level. The areas in which sinks are forming today are generally those in which (1) the limestone is near the surface, (2) the water level in the limestone is near the surface, and (3) the material overlying the limestone is too weak to prevent collapse into the underground stream. When the water level in the limestone is high, as in a rainy season, a cavity having a weak roof may be filled with water, which will give some support to the roof. During prolonged drought, however, when the water level declines, the support is withdrawn, and the roof of the underground cavity may collapse. Sometimes a similar collapse occurs because of heavy rains after a dry spell.

Some information on the depth and other features of open sinkholes has been obtained by divers in lakes and springs in sinks. Brandle (1959) and Stephens (1959) reported that divers penetrated to a depth of 210 feet in the sinkhole through which Little Salt Spring in Sarasota County, Fla., flows. They reported that stalactites and dripstones were found on protected ledges in the sink. Two ledges with stalactites are at depths of 25 to 90 feet. In nearby Warm Mineral Springs (same as Warm Salt Spring), Stephens reported that a charred log from a ledge 40 feet deep is 10,000±200 years old, according to radiocarbon dating by the Scripps Institution of Oceanography.

These results indicate that the sinkholes were formed during a low stand of the sea in Pleistocene time. The sink might have been filled later with sand during a high stand of the sea but was reopened during a later low stand. The location of the log on a ledge of the Hawthorn Formation 40 feet below present sea level suggests that the log might have entered the sink when the water in the sink stood at that level, or that the log became lodged on the ledge when surface water flowed into the sink at a lower level. If the water stood at 40 feet, it would indicate sea level probably was about 60 feet below its present level. At the present time, the head of the spring is estimated to be about 20 feet or less above sea level; if the sea were lowered about 60 feet, the water level would stand about 40 feet below present sea level in the sinkhole now occupied by the spring. The pre-Pamlico shoreline, as shown by Cooke (1939, p. 39; 1945, p. 299), was 60 feet below present sea level. However, the age of the log indicates that it entered the sink in post-Pamlico time.

The presence of partial skeletons of more than a hundred humans under a ledge 30 to 40 feet below the surface in Little Salt Spring causes W. R. Royal and others to conclude that the caves of that depth were occupied by humans when the water stood below that level in the limestone, as reported by Stephens (1959, p. 6, 7). Royal also concluded that the charred log was the remains of some prehistoric campfire in the cave where it was found. Upson, Leopold, and Meyer (1964, p. 121–132) and Scholl (1963, p. 145) reported evidence which indicates that the sea has risen from a lower level since the end of Pleistocene time. Under these conditions, the log in Warm Mineral Springs could have been carried into the cave during the last low stand of the sea.

Shumway, Dowling, Salsman, and Payne (1962, p. 271) reported a buried forest (pine stumps about 20 cm in diameter standing vertically with tops at level of sandy sea floor) on the Continental Shelf off Panama City, Fla., at a depth of 18 meters, apparently at the edge of a terrace about 60 feet below sea level. A radiocarbon age of 36,500 years was reported for a specimen of wood from one of the stumps. Another sample had a radiocarbon age of 37,500 years. A sample of peat was dated older than 40,000 years. These facts suggest that the sea stood at least 60 feet below its present level about 35 to 40 thousand years ago. Stearns (1935, p. 1955) gave evidence of submarine shorelines at 60 and 300 feet below sea level along the coast of Hawaii.

Olsen (1958, p. 402) reported mastodon bones and 600 bone spear points in Wakulla Cave several hundred feet from the entrance of the cave and about 210 feet below sea level. The spear points are similar to those found with Florida's prehistoric inhabitant, the Vero man. Although Olsen pointed out that some objects, such as crescent-shaped tusks weighing several hundred pounds, could not have been easily rolled by water down the sloping floor of the cave, he concluded that Wakulla Cavern has never been dry at this depth and thus could not have been visited by land animals and early man.

However, a study of Pleistocene chronology and submarine terraces indicates that it is entirely possible that Wakulla Cave formed during a low stand of the Pleistocene sea and that the water level in the limestone dropped below the cave during the lowest stand of the sea several hundred feet below the present level. Under these conditions, both animals and men could have entered the cave. This suggested history of the cave seems to be supported by the submarine terraces described by Logan (1965, p. 101) at approximately 96 to 120 feet, 168 feet to 190 feet, and 300 to 360 feet below sea level along the coast of Yucatan, Mexico. The Wakulla Cave could have formed when the higher submarine terraces were formed and could have been drained of water when the sea stood about 300 to 360 feet below the present level.

As the Citronelle Formation was not deposited in sinkholes in northern Florida, it seems that sinks formed in that area after the deposition of the Citronelle Formation. This fact suggests that many of the sinkholes, natural wells, solution channels, and other cavities that are open or filled with unconsolidated sand in the Tertiary limestone and younger formations in the area of this report formed during Pleistocene and Recent time. Although Bretz (1949) and Horberg (1949) believed that the caves in the Carlsbad area in New Mexico probably are older than the Ogallala Formation of Pliocene age, the consensus of Gardner (1935, p. 1270) and others is that most of the world's caverns in limestone and associated rocks formed during Pleistocene time.

Erosion and solution of the Hawthorn Formation seems to have started in late Miocene and early Pliocene in north-central Florida, where the Bone Valley Formation is deposited in shallow sinks in the Hawthorn Formation in Polk and Hillsborough Counties (Cathcart, 1963a, p. 20; 1963b, p. 22) Sinkholes were also formed after the deposition of the Bone Valley and prior to the deposition of Pleistocene sand.

Advances and recessions of the sea have affected the sinkhole topography and solution in the limestone to such an extent that it is difficult to interpret the history and the present conditions. Vernon (1942, p. 30) recognized this effect in Holmes and Washington Counties, Fla., where an embayment of the Pleistocene sea and a line of drainage appear to have affected the present distribution of the sinkholes.

Elliptical shallow depressions, called Carolina Bays, as described by Cooke (1936, p. 7, pl. 17; 1954, p. 195–207) on the Pamlico terrace and higher terraces, apparently are surficial features formed by tidal currents on the terraces when the sea stood at higher levels. LeGrand (1953, p. 263) reviewed the hypotheses given by the principal authors on the subject and concluded that the Carolina Bays resulted from solution in a shallow artesian aquifer. In some areas where the limestone is near the land surface as in the Beaufort area, South Carolina, circular depressions as shown by Siple (written commun., 1960) are believed to be circular sinkholes which were filled with sediments when the sea covered the area. After the retreat of the sea, there has been enough settling of the sediments in the sinks to form the circular depressions.

In addition to the circular lake basins, there are large solution basins formed by the collapse of the roof of underground channels and coalescing of sinkholes which formed along the courses of underground streams. Examples of these are the basins occupied by the following lakes: Lake Apopka, Lake Harris, and Lake Eustis in the Central Highlands of Florida; Lake Jessup, Lake Harney, and Lake Monroe in the St. Johns River valley; and Lake Iamonia, Lake Jackson, Lake Lafayette, and Lake Miccosukee near Tallahassee in the Tallahassee Hills in Leon and Jefferson Counties, Fla.

LAKE BASINS DUE TO SOLUTION OF LIMESTONE

Lake basins due to solution of limestone are chiefly in areas where the limestone is at or near the surface. In the upland ridge section of southern Florida, as in Polk and Highlands County, sinkholes that later became lake basins, however, formed in areas where the limestone is as much as several hundred feet below the land surface. The basins range from a few feet in diameter to several miles in diameter. Some of the basins are as much as 6 miles in length in the Tallahassee Hills. The depths range from a few feet to more than 200 feet.

Many smaller lakes occupying solution basins and some larger solution basins are more or less circular in outline, ranging from a few feet to a mile or more in diameter. These circular lakes are most common in the lake regions in the uplands in Florida and Georgia. Circular shallow depressions only a few feet deep and as much as several hundred feet in diameter are common on the Pamlico terrace and may also be present on some of the other low terraces. Although they have been called solution depressions, they apparently are surficial features that formed in tidal marshes and other shallow water along the coast during the last time the sea advanced over that area. At the present time, these circular depressions are forming on tidal marshes such as those in the salt marshes near the mouth of the St. Johns River near Mayport, Duval County, Fla., as shown by Harper (1910, pl. 17). The sediments in this area are not calcareous, and limestone of the principal artesian aquifer is as much as 500 feet below the surface.

As stated by Cooke (1945, p. 9), lakes of the Central Highlands indicate the occurrence of soluble limestone not far below the surface. Where the Ocala Limestone of the principal artesian aquifer is not too deeply buried, a lacy pattern of innumerable shallow lakes such as Lake Tsala Apopka forms. The lake region of the Central Highlands contains innumerable lakes, which range in size from mere ponds to bodies of water 9 or 10 miles wide, like Lake Apopka (Cooke, 1939, p. 102).

The largest lake basin is that occupied by Lake Okeechobee, which appears to have originated during late Pleistocene time as a slight depression on the floor of the Pamlico sea (Cooke, 1939, p. 101). The oval lake has a maximum width of about 36 miles north and south and 29 miles east and west. The water is very shallow near the shore. The bottom slopes gently to a maximum depth of about 15 feet near the center. Although this basin did not form like the large solution basins in the principal artesian aquifer, probably solution of the surface of the Pleistocene limestone and marl that forms the bottom of the lake accounts in part for the basin.

The limestone of the principal artesian aquifer under Lake Okeechobee and southeastern Florida is separated from the surficial formations by as much as 500 feet of the Hawthorn Formation, which contains relatively impervious beds. Although there are sinkholes in areas where the artesian aquifer is near the surface, there is no evidence of such sinks extending to that aquifer in southeastern Florida. In southwestern Florida, however, there was sufficient circulation and solution in the Hawthorn to form a few natural wells or sinkholes as shown by Still Lake on the sandy flatland, about 16 miles east and slightly south of Fort Myers, and Deep Lake in the Big Cypress Swamp, about 10 miles north of the Tamiami Trail and 200 yards east of Florida Route 29.

Most of the lakes are relatively shallow except those in natural wells and sinkholes which remained open. Pirkle and Brooks (1959, p. 315) reported that Devils Pit in Putnam County was explored by divers to a depth of 135 feet and 45 feet below sea level. Dismal Sink about 10 miles southeast of Tallahassee is another example of a deep sinkhole lake. As reported by R. H. Jordan (1950, p. 265), it is approximately 60 feet in diameter at the water surface, about 100 feet below the rim of the sink. The depth of the water is about 75 feet. Deep Lake in southwestern Florida is 97 feet deep and 300 feet in diameter. Still Lake is about 208 feet deep and 600 feet in diameter (Parker and Cooke, 1944, p. 30). Nevin Hoy and Robert O. Vernon (written commun., 1963) reported that Emerald Spring, a sinkhole lake, in the vicinity of Orlando, Fla., was 390 feet deep, the water level being 56 feet below land surface, July 12, 1950. The sink is about 20 feet in diameter from the surface to 20 feet below sea level where it connects with a large cavern, the bottom of which is 280 feet below sea level as reported by W. F. Lichtler (written commun., 1963).

Many of the sinkhole lakes in Florida have no surface outlets. Some lakes, however, are connected with one another and drain into surface streams. The aquifer is recharged in the area of lake basins, and the artesian head of wells in the limestone is generally below the water table in the surficial material.

Some of the large shallow lakes vary greatly in size with seasonal fluctuations; some of them are intermittent. Paynes Prairie, also called Alachua Lake, south of Gainesville in Alachua County, is an example of an intermittent lake which drains through Alachua sink into the underlying Ocala Limestone. When the sink through which it drains became clogged, the prairie was covered by a lake at least 9 miles long and 1½ miles wide (Cooke, 1939, p. 102). Lake Iamonia near Tallahassee drains intermittently through a sink in the underlying limestone as described by Gunter (1934).

A sketch by Sellards (1914, p. 156, fig. 39) shows the relation between ground-water levels in the Ocala Limestone of the principal artesian aquifer in sinks and in lake basins in central Florida, from the vicinity of Gainesville passing through Paynes Prairie and Orange Lake and following the Oklawaha to the St. Johns River. Espenshade and Spencer (1963, p. 12) contrasted the drainage systems in the areas of the Ocala with those of the Hawthorn. No surface drainage is present in the areas where the Ocala is at or near the surface in the western part of Alachua County, but streams, ponds, and lakes are present in the area north of Gainesville, where the Hawthorn has not been removed.

In a description of the origin and hydrology of lakes of north-central Florida, Pirkle and Brooks (1959, p. 302–317) included (1) a block diagram of Alachua County and vicinity, (2) section showing relationships of piezometric surface to lakes, and (3) a diagram showing the altitudes of some of the typical lakes in northeastern Alachua County and adjacent Clay County, along with logs of test borings. Their section and block diagram show the Hawthorn escarpment and its relation to the underlying Ocala Limestone. The Hawthorn Formation forms an upland surface 150 to 200 feet above sea level in the north-central and much of the northeastern parts of Alachua County. One of the large basins occupied by Santa Fe Lake is on that upland. The western part of the county, where the Ocala Limestone is at or near the surface, ranges from about 80 to 90 feet above sea level. The south-central part of the county is characterized by flat-bottomed lakes and prairies and erosional remnants of the Hawthorn Formation.

Lakes and their relation to the principal artesian aquifer in Alachua, Bradford, Clay and Union Counties, are discussed by Clark, Musgrove, Menke, and Cagle (1962). A section of Brooklyn Lake in southwestern Clay County shows a sinkhole that extends to the principal artesian aquifer (Clark and others, 1963). The sink is on the edge of the large solution basin occupied by Brooklyn Lake. The sinkhole was apparently more than 400 feet deep before it was filled with unconsolidated material. It appears to be a satellite sink such as those commonly present near large solution basins.

Pirkle and Brooks (1959, p. 309) recognized the formation of these basins through the solution of the limestone in north-central Florida but believed the solution is most rapid in the zone of aeration. The present author, however, believes that the evidence in caves in many limestone areas shows that the solution which formed the caves is chiefly in the zone of saturation. There are a few exceptions, such as Cliff Cave in St. Louis County, Mo., which Bretz (1956, p. 437) reported as having been formed almost entirely in the zone of aeration (vadose zone) and as being enlarged today by downcutting of the floor. He reported that on the walls and floor about 500 feet from the entrance of the cave is the finest showing of solution faceting and fluting which he has observed in Missouri caves. Yet, on another part of the rock floor, a cascade 3 feet high, almost a waterfall, is receiving the heaviest deposit of flowstone.

In addition to the large lake basins in north-central Florida, Sellards (1910, p. 47–76) described large lake basins in western Florida, including Lakes Iamonia, Jackson, Lafayette, and Miccosukee near Tallahassee (1917, p. 87–139). As suggested by Sellards and also by Cooke (1939, p. 103), the dendritic shorelines of these lakes suggest that they were originally surface streams which have been captured by underground drainage. Sellards showed by maps (1917, p. 134, 135) the St. Marks drainage system at the present time with Lake Miccosukee and the drainage system reconstructed as it may have existed before the drainage went underground. His map of the Wakulla drainage system, including Wakulla Spring, shows that the headwater streams are surface streams but sink underground in the limestone and reappear as a spring which forms a surface stream. White (1958, p. 67) believed that the lake basins antedated the dismemberment of the streams. Formation of this drainage system and large solution basins, however, as suggested by Sellards, seems to be in accord with the history of limestone solution as interpreted by the present writer.

During Pleistocene time, surface streams were active in removing the Hawthorn Formation in the area between the coastline and the Tallahassee Hills. As the Hawthorn escarpment retreated to its present position at the south edge of the Tallahassee Hills, the Tampa Limestone of the principal artesian aquifer was exposed. Surface streams cut deep enough into the Hawthorn Formation to permit water to pass through to the underlying limestone, thus starting the solution channels and sinkholes that formed the large lake basins. It seems entirely possible that large areas above underground channels collapsed and that smaller sinks formed adjacent to the large sink, as may be seen at the northeast edge of Lake Iamonia.

If the basins in the Tallahassee Hills were formed before surface streams cut into the Hawthorn, as suggested by White, it would seem plausible to expect an area of many circular sinkholes such as those in the southern part of Washington, Putnam, and Polk Counties and other areas where the location of many of the sinks is independent of the surface drainage. In some parts of the area in Washington County, the location of the sinks (Vernon, 1942, p. 30) appears to have been influenced by surface streams and embayments of the Pleistocene sea. Some of the sinks that formed independent of surface streams are, however, now drained by surface streams which formed after the sinks, as may be seen at the head of some tributaries of Pinelog Creek in Washington County.

ARTESIAN WATER

PRINCIPLES OF OCCURRENCE

Part of the water absorbed by the soil or surficial rocks percolates downward until it reaches a level where the rocks or soils are saturated. This saturated zone constitutes the zone of ground water that yields water to wells and springs, and its upper surface (except where that surface is formed by an impermeable body), which is at atmospheric pressure and is free to rise and fall, is known as the water table (Meinzer, 1923a, p. 22; 1923b, p. 32). The water table (the top of the zone of saturation) generally lies at a level which is the resultant of the relation between the rate at which water can drain downward and laterally and the rate at which water is added from above. Thus the water table fluctuates within a range depending on the geology, hydrology, and climate of the area. It may sink to a low level; it may rise to the land surface. The water table begins to lower as soon as recharge diminishes and to rise when local recharge exceeds the rate of discharge. Artesian aquifers are under water-table conditions in some areas where they are at the surface.

The water table, in general, is an undulating surface sloping toward nearby streams, lakes, or the ocean, where ground water discharges. Ground water moves downgradient under the influence of gravity from areas of recharge to areas of discharge, such as a spring or a well. The material in which the water occurs and moves is known as a water-bearing formation, or aquifer. The zone above the water table, not saturated with water, is known as the zone of aeration. As water from the surface percolates slowly downward to the zone of saturation, part of it is held in the zone of aeration by molecular attraction to the walls of the open spaces through which it passes. Although water in the zone of aeration is not available to wells, much of it is withdrawn by transpiration and by evaporation from the soil.

In the coastal areas where the differences in altitude of the land surface are small and surface drainage is poor, the water table is generally only a few feet below the land surface. In areas of little relief, as in the Florida Everglades and the Okefenokee Swamp in Georgia and Florida, the water table may rise to the land surface. Inland where topographic relief is greater, the water table is at various depths. In places of maximum relief in the report area, the water table may be as much as 100 feet below the surface.

Rocks that will not transmit water are said to be impermeable. In some areas, water that percolates downward reaches relatively impermeable material and, therefore, does not reach the main zone of saturation. The water table thus formed is known as a perched water table. For example, beds of clay intervening in generally permeable sand and gravel may cause a perched water table. Above the main water table there may be one or more perched water bodies. A perched body indicates a place where water is added from above faster than it can drain through or off from the perching bed.

Where artesian aquifers are at or near the surface, the water generally is under water-table conditions; the water level in wells represents the water table. In areas of recharge through sinkholes and sinkhole lakes, where the artesian aquifer is not near the surface, as in the upland lake regions of Florida and Georgia, water levels in wells in the artesian aquifer normally are below the lake level and below the water table. Generally, the water table at the lake is approximately the same as the lake level. Water tables in north-central Florida are described by Clark, Musgrove, Menke, and Cagle (1962, p. 73, 76–85; 1963, p. 15–32). Outside the recharge areas, water levels or artesian heads of wells in the artesian aquifer may be above or below the water table.

Where relatively impermeable beds restrict the vertical movement of water in a completely saturated aquifer, the water occurs under artesian conditions, and the surface described by the levels to which water will rise in wells tapping the aquifer is referred to as the piezometric surface. Artesian conditions exist when the water is under greater than atmospheric pressure or when the water will rise above the top of the aquifer when tapped. Where the piezometric surface is lower than the water table, the water may move downward from the nonartesian aquifer into the artesian aquifer. Where the water table is lower than the piezometric surface, water may move upward from the artesian aquifer into the nonartesian aquifer or to flowing wells and springs.

Artesian water is ground water that is confined between beds of low permeability and is under sufficient pressure to rise in a well above the level at which it is found. Water moving downdip under the force of gravity may eventually become confined between beds of low permeability; it is then under hydrostatic pressure. This pressure is caused by the weight of water in updip parts of the aquifer and is also affected by the degree of confinement of the overlying beds. Where ground water completely saturates an aquifer that is overlain by relatively impermeable strata and the water is under sufficient hydrostatic pressure to rise above the top of the aquifer in a well, the water is said to be under artesian pressure. The height to which water will rise in tightly cased wells in an artesian aquifer is the pressure head, often called merely head. The head is represented by water levels in nonflowing artesian wells. In flowing artesian wells, the position or the height at which the water level would stand in a well if the casing were extended may be determined by measuring the shut-in pressure. Where referred to common datum, water levels represent the pressure-indicating surface, or piezometric surface, which is the equivalent of the water table for nonartesian conditions. The position of the water table is within the nonartesian aquifer, but the piezometric surface of the artesian water is above the top of the artesian aquifer. If the artesian pressure declines and the piezometric surface falls below the top of the artesian aquifer, conditions change from artesian to nonartesian, and the water level in the aquifer will be the water table. Artesian wells will flow in areas where the piezometric surface is above the ground.

Water enters an artesian aquifer in areas of relatively high altitude where the impervious confining beds that overlie the aquifer and prevent or retard vertical movement of the artesian water are absent, where sinkholes penetrate the confining beds, and where the aquifer is at or near the land surface or is overlain by permeable material. From such intake or recharge areas, the water reaches the permeable rocks and gradually moves laterally downgradient in the aquifer under the confining beds in response to pressure produced by recharge. The hydrostatic head of the column of water extending from the water table in the recharge area through the aquifer causes the water to move to points of discharge.

The term "confined water" adapted from German usage (Tolman, 1937, p. 316) is used by some investigators instead of artesian water. Also, the terms "aquiclude" and "aquifuge" are used in some reports on artesian water. Tolman (1937, p. 36–37) defined aquiclude as a formation which, although porous and capable of absorbing water slowly, will not transmit it fast enough to furnish an appreciable supply for a well or spring. The term "aquifuge," as used by Tolman, is a rock that is impervious to water. Granite, quartzite, and completely cemented sedimentary rocks are given as examples. W. M. Davis (in Tolman, 1937, p. 37) originally suggested the term to include both aquifuge and aquiclude but approved the restricted use by Tolman. In the present report the term artesian water is used instead of confined water. The use of the terms "aquiclude" and "aquifuge" is considered unnecessary in this report.

As first adapted and used by the U.S. Geological Survey (Fuller, 1906, p. 9–15), the term "artesian" was applied to water under sufficient hydrostatic pressure to rise above the level at which it was penetrated by a well but which did not necessarily rise to or above the ground surface. Later, Meinzer (1923a, p. 39) defined artesian water as water that would rise above the zone of saturation, or water table. Tolman (1937, p. 316) and others adopted Meinzer's definition. In many artesian areas the height to which water rises in wells is not, however, directly related to the water table, which fluctuates with local recharge and discharge. In general, the position of the water table is affected by topography, being highest under hills where there is recharge and lowest in valleys and other areas where the ground water discharges to the surface. In these areas the piezometric surface may be relatively smooth and may show no relation to the ground surface. In areas of topographic relief of even only a few feet, the piezometric surface may be below the water table where the land surface is high, and it may be above the water table where the land surface is low, although there is no difference in the artesian aquifer. Because of this problem with the definition of artesian water, the Geological Survey returned to Fuller's definition which is now generally used, expressed as water that will rise above the top of the artesian aquifer in wells that penetrate it.

All aquifers are both reservoirs and conduits. However, under artesian conditions, aquifers function chiefly as conduits in which water may move literally many miles from the intake to the discharge areas. Under water-table (nonartesian) conditions, aquifers generally function chiefly as reservoirs in which the water does not move laterally many miles. There are exceptions as on the High Plains in New Mexico and Texas, where water under water-table conditions may move many miles before reaching a point of discharge. These two functions of aquifers must be recognized and differentiated in the understanding of the geology and hydrology of artesian aquifers.

Aquifers are recharged naturally by precipitation, underground percolation, and in some cases by streamflow. Discharge occurs as springs, seeps, underground leakage, evaporation, and transpiration. If the water table is near the land surface, water may be discharged by evaporation from the soils and by transpiration from plants. Although evaporation and transpiration may be as much as the precipitation in humid regions, there is generally sufficient recharge to form springs and seeps that feed the streams and maintain their flow during dry seasons. Where the artesian aquifers are deeply buried, there is no discharge from them by evaporation and transpiration.

Artesian aquifers are generally inclined. Upward leakage of the water may take place through the relatively impervious formations overlying the aquifer. A reduction of artesian pressure due to withdrawal of water may reduce the upward leakage and permit the pressing out of water from overlying beds into the permeable parts of the aquifer. Although this may be a relatively small amount for each square foot of area, the total is considerable in large areas in which the piezometric surface has been lowered such as that in the Fernandina area, Florida. Soon after pumping begins, the water table or piezometric surface around a pumped well assumes a form which is comparable to an inverted cone. Where the aquifer is homogeneous, the cone of depression will be circular if the original water table or piezometric surface had been horizontal, but elliptical if the initial water table had been sloping.

Slight differences in geology may cause significant differences in the hydrologic properties of an aquifer (Stringfield and Cooper, 1951a, p. 804). Two of these properties, the hydraulic permeability and the specific yield, are among the most important factors affecting the perennial yield. Hydraulic permeability of an aquifer is its capacity to transmit water. The quantity of water that will flow through a permeable formation is directly proportional to the cross section through which the water percolates, the hydraulic gradient, and the coefficient of permeability. The quantity is inversely proportional to the viscosity of the water. The field coefficient of permeability (Meinzer, 1936, p. 702; Wenzel, 1942, p. 7) as used by the U.S. Geological Survey represents the quantity of water in gallons per day that will flow through a cross section of the aquifer 1 mile wide and 1 foot thick, under a hydraulic gradient of 1 foot per mile, at the prevailing temperature. This unit, known as a meinzer, may be expressed as the rate of flow, in gallons per day, through a cross section of 1 square foot under a hydraulic gradient of 100 percent. The coefficients determined in the laboratory are for 60°F. Corrections for temperature must be made in comparing permeability in different areas and in laboratory tests. Wenzel (1942, p. 10) gave a conversion table for changing meinzers at 60°F to other permeability units at 60° and 68°F.

The field coefficient of permeability multiplied by the saturated thickness of the aquifer, in feet, may be defined as the coefficient of transmissibility (Wenzel, 1942, p. 10; Theis, 1935, p. 520). It represents the quantity of water, in gallons per day, that will flow through a cross section of the aquifer 1 mile wide under a hydraulic gradient of 1 foot per mile. An aquifer having a saturated thickness of 200 feet and a coefficient of permeability of 500 would have a transmissibility of 100,000. In other words, a vertical section of this aquifer 1 mile wide having a hydraulic gradient of 1 foot per mile would transmit 100,000 gpd. If the hydraulic gradient were 10 feet per mile, it would transmit 1 mgd (million gallons per day). If there were a cone of depression having a gradient of 100 feet per mile at a certain distance from the well, the aquifer having a saturated thickness of 100 feet and coefficient of permeability of 500 would transmit, through a cylindrical section 1 mile in circumference, 5 mgd (500x100x100).

A family of curves of the leaky-aquifer type was developed by H. H. Cooper, Jr., and was used by Bermes, Leve, and Tarver (1963, p. 65–67) to determine the coefficient of leakance (commonly known as coefficient of leakage), for the principal artesian aquifer in several parts of Flagler, Putnam, and St. John Counties, Fla. The curves are based upon equations that assume a permeable aquifer overlain by semipermeable confining beds through which water, under a constant head, can infiltrate to recharge the aquifer. The coefficient of leakance is defined as the number of gallons that will pass through each cubic foot of a semipermeable confining bed in 1 day under a unit hydraulic gradient. It is equal to the vertical permeability of the confining bed in meinzers divided by the thickness of the beds.

The specific yield (Meinzer, 1923b, p. 51) of an aquifer is the proportion of its volume that is occupied by water which it ultimately yields by gravity. For example, 100 cubic feet of saturated material having a specific yield of 25 percent will yield 25 cubic feet of water when drained by gravity. The term "effective porosity" has been used by ground-water investigators to mean approximately the same as specific yield. Students of agriculture prefer to use "effective porosity" in another way, and petroleum geologists use it in a more general sense. In ground-water studies, however, loose use of the term "porosity" may be misleading. A saturated clay that will yield little or no water to wells may have a higher porosity and contain more water than a productive water-bearing sand, but its effective porosity, or specific yield, is much less than that of sand. The specific yield indicates the storage capacity of nonartesian aquifers, expressed as the coefficient of storage. As used by the U.S. Geological Survey (Theis, 1940, p. 277), the coefficient of storage is the number of cubic feet of water released from storage in a saturated vertical column of the aquifer 1 foot square when the water table declines 1 foot.

Under artesian conditions, the coefficient of storage is the number of cubic feet of water released from storage in a vertical column of the aquifer 1 foot square when the piezometric surface declines 1 foot. In nonartesian aquifers the coefficient of storage is much larger than in artesian aquifers because water is drained from pores and interstices as the water table declines. Under artesian conditions, however, all pores and interstices remain saturated with water as the piezometric surface declines, and the aquifer releases water from storage only by contracting in proportion to its volumetric compressibility as the artesian pressure decreases.

A nonartesian aquifer might have a coefficient of storage or specific yield of 0.25; lowering the water table 1 foot in a cubic foot of such an aquifer would release 0.25 cubic foot of water from storage. Ferris, Knowles, Brown, and Stallman (1962, p. 76–78) gave a range of 0.05 to 0.30 for storage coefficients of water-table aquifers and a range of about 0.00001 to 0.001 for storage coefficients of artesian aquifers. Under artesian conditions, the aquifer might have a storage coefficient of 0.00025 cubic foot of water from storage in a vertical column of 1 square foot of the aquifer. This quantity may seem insignificant, but in an artesian aquifer extending over many square miles the quantity is appreciable. Available data (Meinzer and Hard, 1925, p. 90–93) on artesian water in the Dakota Sandstone led Meinzer (1936, p. 719) to the conclusion that the great quantity of water discharged by several thousand flowing wells supplied by the sandstone in the last half century was in considerable part derived from storage through compression of the aquifer, rather than from recharge or lowering of the water table in the outcrop area.

Lohman (1961, p. B47–B49), beginning with Meinzer's work, briefly reviewed the concepts of the occurrence of water in artesian aquifers; he derived an equation for determining the amount of elastic compression of artesian aquifers from known declines in artesian pressure and known hydrologic properties of the aquifers.

In a study of the coefficient of storage in a region of major subsidence caused by compaction of an aquifer system, Poland (1961, p. B52–B54) found that the stored water released by compression or compaction of clayey beds is about 50 times as great as the water released by elastic expansion of the water and elastic compression of the aquifer. The stored water yielded by clayey beds would be large only during the first decline of artesian pressure. The yield as determined from a short-term pumping test, however, would be only about one-fiftieth of the yield from storage during a period of 15 to 25 years. Poland also found that, if the pressure recovered and then was drawn down again through the same interval, the compression of the clayey beds, if mostly preconsolidated during the first drawdown phase, would be only a small fraction of that of the first phase of pressure decline, probably less than 10 percent. Meinzer stated (1928, p. 263–291; 1936, p. 718) that cones of depression produced under artesian conditions involve the transfer of much more water than would be required merely by expansion of the water as a result of its volume elasticity. The coefficient of storage is a function of the elasticity of an artesian aquifer (Ferris and others, 1962, p. 88).

The difference in the amount of water obtained from storage accounts for some of the differences between the behavior of wells in artesian aquifers and those in nonartesian aquifers. For example, under water-table conditions, the cone of depression of a producing well forms slowly because it involves the removal of much water from storage. Under artesian conditions the cone of depression forms rapidly because removal of less water from storage is involved for a given area and the transmittal of pressure effects is rapid.

In tests made by Leggette and Taylor (1934, p. 409–413) in the artesian basin of Ogden Valley, Utah, the effects of pressure changes were transmitted at different rates according to varying conditions. However, in all cases the transmission occurred at a much more rapid rate than in the elaborate tests made by Wenzel (1936, p. 37–38) under nonartesian conditions in Platte Valley, Nebr., where the rim of the cone of depression reached 500 feet from the producing well in 2 hours, 900 feet in 6 hours, and about 1,200 feet in 12 hours. In the Utah tests the opening of an artesian well affected the artesian pressure head in an observation well 2,850 feet distant in 7 minutes; the opening of another well 3,850 feet distant affected the head in the observation well in 57 minutes. In other tests, changes of pressure were transmitted a distance of 2 miles in 3 to 13 hours. The rate of progress of pressure effects in water in a permeable but perfectly rigid rock formation encased in perfectly rigid and impermeable confining beds would doubtless be very rapid although not instantaneous.

Investigations by Warren (1944, p. 24–77) on artesian water in the Tertiary limestone in the coastal area of Georgia showed that large changes in rates of withdrawal caused measurable fluctuations in artesian pressure for approximately 17 miles, and wells as much as 25 miles away appeared to be affected. In one test in the Savannah area, change in rate of pumping required about 2 days to affect the artesian pressure in a well about 6 miles distant. Warren (1944, p. 60–64) found that the pressure effects of recharge of the principal artesian aquifer in the coastal area of Georgia required several months to extend 90 miles.

The amount of water discharged naturally from an aquifer not affected by wells is equal to that entering in the recharge area, except for temporary differences due to changes in the amount stored in the aquifer. The average discharge rate for a long period is approximately equal to the average recharge rate. Withdrawal of water from wells is balanced by a decrease of water in storage, a decrease in discharge, an increase in recharge, or a combination of these changes.

Water first withdrawn from wells is largely from storage, but as withdrawal continues and the piezometric surface declines, the withdrawal consists of increasing amounts of water that would have been discharged naturally, or water that would have been rejected from recharge. Removal of water lowers the water level and creates a hydraulic gradient. The shape of the piezometric surface or water table where a hydraulic gradient has formed toward a well or group of wells is known as the cone of depression. The extent and shape of a cone of depression depends in part on the coefficient of transmissibility of the aquifer and the distance to recharge and discharge areas. When the effects of withdrawal reach the intake or recharge areas, the rate of recharge is increased if there is any rejected recharge prior to the development of wells.

When the effects of withdrawal reach an area of discharge, the rate of discharge will be decreased. As stated by Cooper (1944, p. 179), increase in recharge and decrease in natural discharge may be regarded as salvage. Water will be removed from storage and water levels will decline until the rate of salvage equals the rate of withdrawal from wells. The time required for water levels to reach equilibrium, other conditions being equal, is more or less proportional to the coefficient of storage. If the rate of withdrawal exceeds the maximum rate of salvage, the perennial yield will be exceeded, and water levels in wells in the area of withdrawal will decline persistently. Water levels and artesian head in wells are used to determine the cones of depression and other features of the piezometric surface. The fluctuations of water levels and artesian head also give essential information in determining the yield of an aquifer.

The drawdown, or lowering of water level in a pumped well, is usually limited in the development of an area. In some places, water may be withdrawn at a rate that exceeds the perennial yield, although the entire area may not be overdeveloped. The practical limits to which water levels can be lowered in wells, as stated by Cooper (1944, p. 179), may be the bottom of the aquifer, or the limit beyond which salt water might be drawn into wells. In some areas of thick deep aquifers, where water levels are deep, the practical limit is an economical one beyond which pumping of water would be too expensive to justify its use. Although the pumping costs are not generally regarded as a limiting factor in obtaining water supplies from wells in the area of this report, the economical use of the artesian water for irrigation in some areas in Florida depends on the artesian head. It is economical to use artesian wells that flow, but the cost of pumping water is not justified for some crops in some areas.

Spacing wells as far apart from one another as practicable and as near to areas of recharge or natural discharge as feasible will help keep the drawdown to a minimum. If a thick aquifer consists of relatively productive zones, a larger quantity of water for the same drawdown may be obtained by drilling through more of the productive zones, thereby increasing the amount available to wells. This method increases the yield of the wells, which generally is expressed as gallons per minute without reference to the drawdown in the well. The yield has more significance when expressed as specific capacity, which is the yield in gallons per minute per foot of drawdown.

ARTESIAN AQUIFERS IN TERTIARY LIMESTONE

Artesian aquifers in the Tertiary limestone of the southeastern States consist of many local aquifers and one principal aquifer. The principal aquifer underlies Florida, southern Georgia, and adjacent parts of South Carolina and Alabama.

Many local artesian aquifers consist of sand and limestone in the Hawthorn Formation. In some places, sand and other permeable material overlying the Hawthorn yield water under artesian pressure. All these aquifers are shallow and overlie the principal artesian aquifer of Tertiary age. Clark (1964, p. 7–12) described two shallow aquifers in the upper part of the Hawthorn Formation in the southwestern part of Sarasota County. In northwestern Polk County, Fla., two shallow artesian aquifers, one in the Hawthorn and the other in the overlying Bone Valley Formation, are described by H. G. Stewart (1959, p. 29–31).

Bermes (1958b, p. 29–32) described an artesian aquifer in the Hawthorn Formation in Indian River County, Fla. Parker (in Parker and others, 1955, p. 193) described a Pleistocene artesian aquifer 16 to 35 feet below land surface overlain by hardpan at Indiantown, Martin County, Fla. Permeable limestone in the Tamiami Formation in the Naples area in Collier County (Klein, 1954, p. 18) forms an artesian aquifer. The upper part of the Tamiami, with its top 15 to 20 feet below mean sea level, is relatively impervious and prevents or retards upward movement of artesian water from the aquifer.

These shallow artesian aquifers generally do not yield large quantities of water. When large supplies are required, wells are therefore drilled into the underlying principal artesian aquifer, except in areas where the deep artesian water is too highly mineralized to be satisfactory for use. One of the most productive aquifers is the Biscayne aquifer in southeastern Florida extending from the surface to a depth of about 100 feet or more along the coast in the Miami area. Schroeder, Klein, and Hoy (1958, p. 5) reported that the Biscayne aquifer is as much as 200 feet thick in the vicinity of Fort Lauderdale in Broward County. Tarver (1964, p. 39) reported that the aquifer extends from the surface to a depth of about 400 feet in the Pompano Beach area only a few miles north of Fort Lauderdale. A brief description of the Biscayne aquifer is given here because it is in part artesian and in part of Tertiary age. Parker (in Parker and others, 1955, p. 160–162) named the unit the Biscayne aquifer and described it as consisting of the following formations: (1) A thin layer of very permeable limestone of the Tamiami Formation of Miocene age, (2) insignificant erosional remnants of Caloosahatchee Marl of Pliocene age, (3) Fort Thompson Formation, (4) Anastasia Formation, (5) Key Largo Limestone, and (6) Pamlico Sand—the last four of Pleistocene age. The principal part of the Biscayne aquifer is the Fort Thompson Formation. This shallow aquifer consists chiefly of cavernous sandy limestone and calcareous sandstone. Most of the cavities are filled with permeable sand. Many of the vertical solution channels filled with sand extend to the land surface. Some of these areas are covered by a thin blanket of permeable sand through which the precipitation moves downward to the water table.

In 1908 the Miami public water supply was from four flowing artesian wells in the shallow aquifer. They ranged in depth from 73 to 95 feet (Parker and others, 1955, p. 585). Although there is no record of the height to which the artesian water rose, it could not have been more than a few feet above sea level. Later after the wells stopped flowing and pumps were installed, the wells were plugged at a depth of 40 to 45 feet to avoid inflow of water from the lower part of the aquifer which had become contaminated with salt water.

The capacity of the Biscayne aquifer to yield water to wells is very large. The transmissibility of the aquifer in the Miami area (Parker and others, 1955, p. 270) ranges from 4 to 15 mgd per ft. Transmissibility represents the quantity of water (gpd) that will move through a cross section of the aquifer 1 mile wide under a hydraulic gradient of 1 foot per mile. As the flow is directly proportional to the hydraulic gradient, the quantity would be twice as much under a gradient of 2 feet per mile. Where the aquifer is about 100 feet thick, the permeability would range from 40,000 to 150,000 gpd per sq ft. Results of pumping tests on wells penetrating the Biscayne aquifer in the Greater Miami area showed that the aquifer behaves as an unconfined or water-table aquifer and that the coefficient of storage is essentially equal to the specific yield.

In comparing this shallow Biscayne aquifer in the Miami area with the principal artesian aquifer (Floridan), Warren and Parker (in Parker and others, 1955, p. 270) reported that a well 18 inches in diameter penetrating less than 100 feet of the Biscayne aquifer would yield 5 mgd with a drawdown of 2 to 3 feet. A typical well of the same diameter penetrating the Floridan aquifer in the Jacksonville area would have a drawdown of about 50 feet with a yield of 5 mgd. As determined by Warren (1944, p. 103–104) the principal artesian aquifer has an average transmissibility of 250,000 gpd per ft at Savannah, Ga. At Brunswick, Ga., the transmissibility ranges from 750,000 to 1,000,000 gpd per ft. The average permeability of the aquifer where it is 500 feet thick is computed as 500 meinzers at Savannah and 1,500 to 2,000 at Brunswick.

PRINCIPAL ARTESIAN AQUIFER

The principal artesian aquifer, which is the source of nearly all the artesian water in Florida and southeastern Georgia, consists chiefly of limestone ranging in age from middle Eocene to middle Miocene. The aquifer also yields water to many wells in adjacent parts of Alabama and South Carolina. It includes the following formations or equivalents from bottom to top: Lake City Limestone, Tallahassee Limestone, and Avon Park Limestone of middle Eocene age; Ocala Limestone of late Eocene age; Marianna Limestone, Suwannee Limestone, and Flint River Formation of Oligocene age; and the Tampa Limestone and lower part of the Hawthorn Formation of Miocene age. In some places the Oldsmar Limestone or its age equivalent of early Eocene age may form part of the aquifer. Some formations in southwestern Georgia and southeastern Alabama act as separate aquifers where the Tertiary limestones merge into sandy formations. These have been designated as Paleocene and Eocene limestone-sand aquifers by Herrick (Thomson and others, 1956, p. 271). Most of the limestones grade laterally into sandy and clayey deposits in western Florida, southeastern Alabama, southwestern Georgia, east-central Georgia, and South Carolina. After the principal artesian aquifer of Tertiary age was defined (Stringfield, 1953, p. 28), Applin and Applin (1944, p. 1683–1703) divided the Ocala Limestone and older Eocene limestone into several formations on the bases of micropaleontology and named these formations Ocala, Avon Park, and Lake City. The limestones of the aquifer act as a hydrologic unit, as was demonstrated when the pressure surface of the artesian water was mapped in the Florida peninsula in 1933 (Stringfield, 1936, pl. 12).

Parker (in Parker and others, 1955, p. 189) proposed that the aquifer be named Floridan. That name is commonly used in Florida. In Georgia, Warren (1944) used the terms "the principal artesian limestone aquifer" and "the principal artesian aquifer." Counts and Donsky (1959, p. 96–102; 1963, p. 23) referred to the aquifer as the principal artesian aquifer in the Savannah area, Georgia and South Carolina. In this and some other reports, the term "principal artesian aquifer" is used because it is the principal aquifer in Florida and southeastern Georgia as defined in 1933. Where the discussion of artesian water relates chiefly to the principal artesian aquifer, in some parts of this report it is merely designated as the aquifer. In South Carolina and in parts of Georgia and Alabama, where the underlying Cretaceous formations consisting chiefly of sand are the source of artesian water locally, the principal artesian aquifer is differentiated from the Cretaceous by referring to it as the principal limestone aquifer or Tertiary artesian aquifer.

EXTENT AND THICKNESS

The principal artesian aquifer is one of the most extensive limestone aquifers in the United States. It underlies Florida, southeastern Georgia, and adjacent parts of South Carolina and Alabama. It is at or near the land surface in areas where the Tertiary limestones crop out in a broad belt extending from western Florida through southeastern Alabama, Georgia, and into southeastern South Carolina, approximately paralleling the Fall Line. The aquifer also is at or near the surface in a large area in north-central Florida, where the Tertiary limestones are exposed on the Ocala uplift. The top of the aquifer in Florida and southeastern Georgia is shown in figure 23. The extent of the aquifer in Georgia is shown in figure 24. The oldest exposed

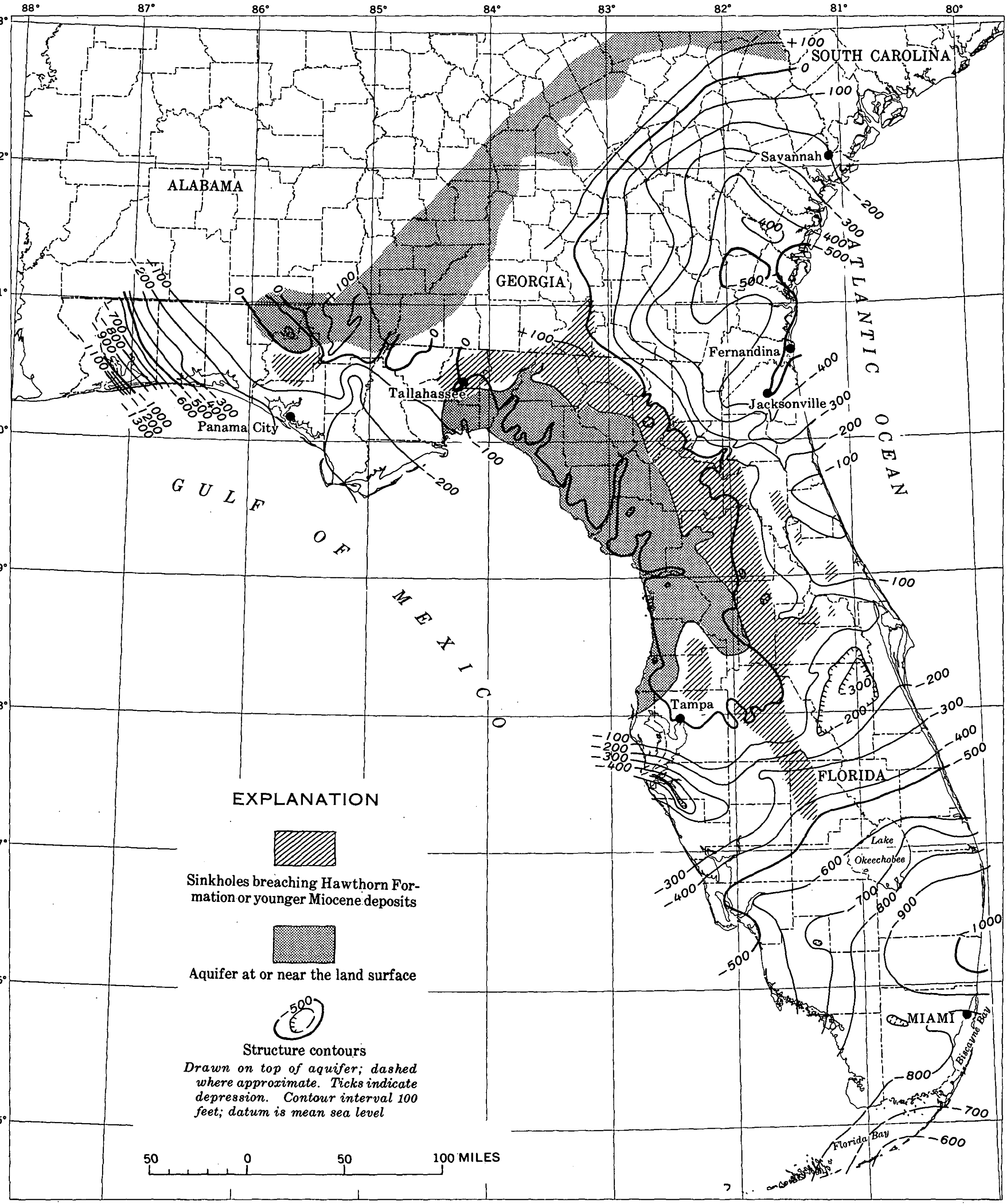

FIGURE 23.—Contour map of top of principal artesian aquifer. (Florida, from Vernon, 1955; Georgia, from Warren, 1944.)

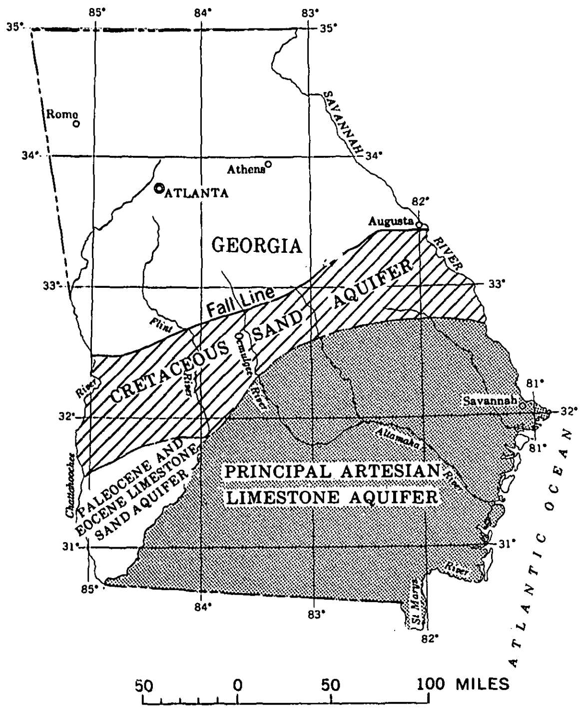

FIGURE 24.—Extent of the chief artesian aquifers in the Coastal Plain in Georgia. (From S. M. Herrick and R. L. Wait, 1956, fig. 2.)

formation of the aquifer in Florida is the Avon Park Limestone. The underlying Lake City Limestone is not exposed. Formations believed to be its equivalent in age, however, as shown in the correlation chart (table 1, p. 28), are exposed in the areas extending from Alabama to South Carolina where the Tertiary formations are at the surface. The thickness of the aquifer in a section across Florida and Georgia is shown in figure 7. Figure 25 shows several sections in Georgia.

The aquifer north and south of the Ocala uplift in Florida is as much as 1,500 feet thick. In addition to the wells in figure 7, the log of a well 1,455 feet deep reported by Bishop (1956, p. 84–86) 2 miles south of De Soto City in Highlands County, 135 feet above sea level, indicates that the top of the Oldsmar Limestone which forms the bottom of the aquifer in this area is at a depth of 1,375 feet. The depth, thickness, and correlations at De Soto City based on that record are as follows:

Formation	*Depth below land surface (feet)*	*Thickness (feet)*
Hawthorn	20–515	495
No sample	515–541	26
Suwannee Limestone	541–610	69
Ocala Limestone	610–900	290
Avon Park Limestone	900–1150	250
Lake City Limestone	1150–1375	225
Oldsmar Limestone	1375–1455	80

If we consider the Oldsmar Limestone as the bottom of the principal artesian aquifer in this area, the total thickness of the aquifer up to the Hawthorn is 860 feet. Where present, the limestone in the lower part of the Hawthorn generally is part of the aquifer. If we judge from the log, the limestone present in the Hawthorn below depths of about 400 feet may be part of the aquifer. Inclusion of the limestone from depths of 400 to 1,375 feet in the aquifer would make a total thickness of 975 feet.

In northwestern Polk County, H. G. Stewart (1959, p. 29–31) reported that the limestone of the Hawthorn is locally separated from the principal aquifer. The limestone is confined above the clay in the upper part of the Hawthorn or the lower part of the Bone Valley Formation. The deepest well reached the Avon Park at a depth of 355 feet and apparently had not passed through it at a depth of 1,200 feet. Thus the Avon Park is at least 845 feet thick. At that locality, the Avon Park is overlain by about 200 feet of the Ocala and about 75 feet of the Tampa—a total thickness of 1,120 feet for the aquifer, exclusive of the lower part of the Hawthorn.

In the Cosme-Odessa well field in the northwestern part of Hillsborough County, Fla., a well 1,200 feet deep ended in the Avon Park Limestone. A log of that well (Florida Geol. Survey W–5423) prepared by C. W. Hendry, Jr., of the Florida Geological Survey, showed the following:

Formation	*Depth below land surface (feet)*	*Thickness (feet)*
Post-Miocene	0–40	40
Tampa Limestone (Miocene)	40–110	70
Suwannee Limestone (Oligocene)	110–380	270
Ocala Limestone (Eocene)		
Upper member	380–420	40
Lower member	420–640	220
Avon Park Limestone (Eocene)	640–1200	560

Hendry refers to the Ocala Limestone as the Ocala Group, composed of the Crystal River, Williston, and Inglis Formations. The Crystal River is shown as the upper member in the preceding log. The Williston and Inglis, each 110 feet thick, are shown as the lower member. According to that log, the aquifer is at least 1,160 feet thick in the area.

In western Florida the thickness of the aquifer appears to be as much as 800 feet (Marsh, 1962b, fig. 2). In southern Florida and the coastal area south of St. Augustine, where the artesian water has a relatively high chloride content, the maximum thickness of the aquifer is not known. However, available records indicate that the thickness probably ranges from about 500 to at least 1,000 feet. The deeper water is generally more highly mineralized, and, therefore, most of the water wells are not drilled to the bottom of the aquifer. In the coastal areas from St. Augustine to South Carolina, the aquifer generally ranges from 500 to 800 feet thick. In northeastern Florida and southeastern Georgia, the bottom of the aquifer is about 1,000 feet below sea level, and the top is 450 to 550 feet below sea level. Cooper (1944, p. 171) reported that in Duval and Nassau Counties in northeastern Florida the depth to the top of the aquifer ranges from about 250 feet in southwestern Duval County to 550 feet below sea level in Nassau County. Leve (1961a, p. 9) showed the top of the Ocala Limestone (Crystal River Formation) at a depth of 570 feet in a well at Jacksonville and at a depth of 550 feet at Fernandina. The well at Jacksonville reached the top of the Lake City Limestone at a depth of 935 feet but did not pass through it. The well at Fernandina reached the Lake City at a depth of 1,280 feet and the Oldsmar at a depth of 2,130 feet.

In the Savannah area, Georgia, the top of the Ocala Limestone, the upper part of the aquifer at that locality, is about 250 feet below sea level; part of the aquifer in that area is the Gosport Sand and Lisbon (McBean) Formation of middle Eocene age. The Lisbon (McBean) Formation is the lowest part of the principal artesian aquifer in the western part of the Savannah area (Counts and Donsky, 1959, p. 99; 1963, p. 22). The formation becomes less permeable in the eastern part of the area and forms part of the relatively impervious barrier that separates the aquifer from the underlying water. The Tallahatta Formation underlying the Lisbon is the principal barrier separating the aquifer from the salt water in the Tallahatta and underlying formations in the Savannah area.

In a fence diagram, figure 25, of the artesian aquifers in the Coastal Plain in Georgia, Herrick (in Thomson and others, 1956, pl. 2) showed the relation of the principal artesian aquifer to the limestone-sand aquifers of Paleocene and Eocene ages into which it merges in southwestern Georgia and to the underlying Cretaceous aquifers. The principal artesian aquifer underlies about two-thirds of the Coastal Plain in Georgia.

RECHARGE AND DISCHARGE

Recharge of the principal artesian aquifer by surface water occurs in areas in which the aquifer is at or near the surface. Also some recharge occurs in areas in which the aquifer is overlain by relatively impervious beds of the Hawthorn Formation. Recharge through the Hawthorn in amounts sufficient to be revealed by the piezometric surface, however, occurs where sinkholes extend from the surface through the Hawthorn to the aquifer. Many sinks are now almost completely filled with relatively permeable unconsolidated sands through which water may move downward. Lakes occupy many of these sinkholes forming the upland lake regions in Florida and Georgia.

The rate of recharge through sinkholes ranges from zero in sinks filled with relatively impervious material to 100 percent in open sinks. In some areas where the sinks were covered by the Pleistocene sea, they were completely filled with relatively impervious material, but later compaction and settling in the sinks formed surface depressions that are now occupied by ponds and lakes. Probably many sinks filled with sediments on the coastal terraces are not detectable at the surface.

In a study of water-level fluctuations of ponds in depressions of old sinkholes and the water table in an area in Baker and Early Counties in southwestern Georgia, Hendricks and Goodwin (1952, p. 210) concluded that the effect of these ponds upon recharge of ground-water aquifers is minor. In other parts of southwestern Georgia and in the Valdosta area, recharge through sinks is large.

Clark, Musgrove, Menke, and Cagle (1962, p. 28, 83) reported evidence of recharge through sinkholes in part of north-central Florida, described in the present report as the Putnam County area of the piezometric surface. In discussing lakes in the northwestern part of Putnam and the southwestern part of Clay Counties, they stated that the large range in stage of the sinkhole lakes without surface outlets may be due partly to the fact that an open sinkhole is taking water when the lake level is above the piezometric surface or water table. Also, it is possible that the sinkhole is filled with very permeable material through which water moves downward to the underlying aquifer as shown in sections of Brooklyn Lake in the southwestern part of Clay County (Clark and others, 1963, figs. 13–16). Northeast of the area of sinkholes that reach the principal artesian aquifer, there is a sinkhole about 85 feet deep occupied by Kingsley Lake in western Clay County. Clark, Musgrove, Menke, and Cagle (1962, figs. 17, 18) included a section and depth contour map. As the water table and water level in the lake are about 100 feet above the piezometric surface, they concluded that if the

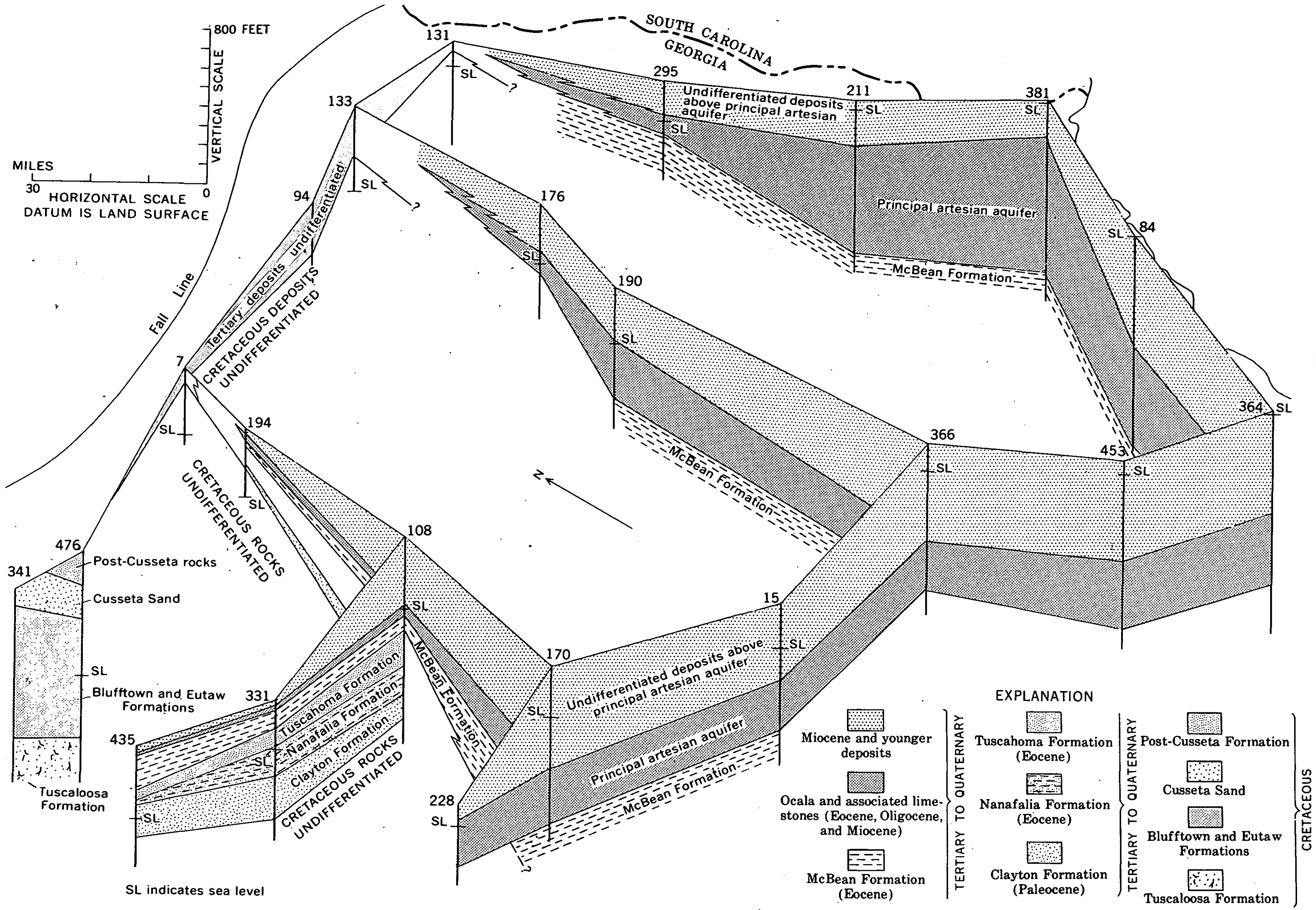

FIGURE 25.—Fence diagram showing principal artesian aquifer in southeastern Georgia (Herrick and Wait, 1956). For logs of wells see report by Herrick (1961).

bottom of the sink originally extended to the aquifer, it is now partly filled and sealed. They also concluded that if the water table were as much as 100 feet above the piezometric surface, millions of gallons of water per day probably would recharge the principal artesian aquifer by seeping downward through relatively impervious beds of the Hawthorn Formation into the aquifer. However, if such recharge occurs, it apparently is not sufficient to have a detectable effect on the piezometric surface.

In areas where the sinkholes are open or filled with permeable sand and are connected to the underlying limestone, large quantities of surface water flow directly into the aquifer. Rainfall percolates rapidly through the sand into the permeable limestone in areas in southern and western Alachua County where the Hawthorn Formation is thin or absent and the Ocala Limestone of the principal aquifer is at or near the surface. Although the amount of water entering the aquifer in that area is not known, Clark, Musgrove, Menke, and Cagle (1962, p. 84) concluded that it doubtless averages at least millions of gallons per day. This average rate of recharge probably is one of the highest, if not the highest, for this aquifer. Pride, Meyer, and Cherry (1961, p. 86–87) recognized recharge through sinkholes in the Green Swamp area in Polk and Lake Counties in central Florida.

In a study of the relation of lakes to the principal artesian aquifer in the Lake Placid area in Highlands County, Fla., Kohout and Meyer (1959, p. 64) estimated that the average downward leakage to the principal artesian aquifer caused the level of Lake Placid to decline an average of 2 to 3 inches a month from January to July 1956. This decline is equivalent to a rate of recharge to the aquifer of 6,400,000 to 9,500,000 gpd. That amount multiplied by the large number of lakes and sinkholes through which recharge occurs in the lake regions of Florida and Georgia gives some indication of the volume of recharge. However, additional studies of recharge through other lakes and sinks will be needed to give reliable estimates of the total recharge in the lake regions. Lakes that do not occupy sinkholes or solution basins in the areas underlain by the Hawthorn Formation do not recharge the principal artesian aquifer, as has been shown by Kohout (in Kohout and Meyer, 1959, p. 15–25) in a study of Lake Istokpoga east of Lake Placid, Fla.

During flood stage, water in surface streams enters the aquifer locally, as along the Flint River in Georgia and the Suwannee and Santa Fe Rivers in Florida. However, the recharge by these streams in a humid climate is not a significant source of artesian water in comparison with recharge by streams that cross the outcrops of aquifers in arid and semiarid areas, such as the Coastal Plain in Texas.

Although recharge from rivers in the area of this report returns to the surface streams, such transfer of water is of value in storing water in the aquifer during floods. Such recharge also reduces the amount of discharge from the aquifer into the rivers during floods. In the event of the development of a large water supply from the aquifer near the stream, the withdrawal of water from the stream would salvage some of the floodwater in the aquifer and reduce the discharge to the river. If the withdrawal of water reversed the hydraulic gradient between the river and the area of withdrawal, that part of the aquifer would be recharged by the river.

Although artificial recharge of the principal aquifer through wells or other methods has not been practiced to increase the supply, wells are used in some areas to drain surface water into the aquifer where the surface drainage is not adequate, as discussed under drainage wells. Such wells effectively recharge the aquifer in areas where water level in the limestone is not near the land surface. Some recharge and discharge of the aquifer may occur in the subsurface by exchange of water between the aquifer and overlying and underlying formations.

Natural discharge from the aquifer in quantities sufficient to be detected on the piezometric surface of the artesian water or by direct observation occurs as springs, where the aquifer is near the surface, and at submarine outcrops. At the submarine outcrops, discharge occurs where the artesian pressure exceeds the back pressure of the salt water. Many large springs on land and some submarine springs discharge through sinkholes and solution basins. Some sinkholes extend from the surface through several hundred feet of the Hawthorn Formation into the principal aquifer.

WATER-BEARING PROPERTIES

Water-bearing properties are discussed in the descriptions of the geologic formations of the aquifer. As a unit, the principal artesian aquifer is unusual in its great thickness and areal extent. It is the source of the large limestone springs in Florida and Georgia. Silver Springs in the north-central part of Florida near Ocala is one of the largest limestone springs in the world, having had an average discharge of 809 cfs for 26 years (U.S. Geol. Survey, 1960b, p. 69). The aquifer yields water to thousands of artesian wells that are the source of water for some of the largest ground-water supplies in the country.

Some parts of the aquifer consist chiefly of soft masses of foraminifer or coquina, which are very permeable. Part of the Ocala Limestone is soft and chalky without apparent bedding planes. Before the limestones were altered by solution, water moved through permeable parts, particularly joints and fractures. Apparently, most of these joints and fractures are now closed, except where water has enlarged them. Many of the vertical solution channels formed at intersections of two joint systems. Joints and bedding planes, differences in lithology, and original permeability of the water-bearing formations were factors in the origin of the horizontal solution channels in these formations. However, the zoning of these channels and cavities was controlled to a large extent by the position of the points of discharge with reference to sea level.

A large part of the ground water is in cavities and solution channels, many of which are filled with permeable sands. In general, the cavities are largest and most numerous in the areas where the aquifer is at or near the surface, as on the crest of the Ocala uplift in north-central Florida and in regions where sinkholes extend from the surface to the aquifer. Downdip from the Ocala uplift, as in southern Florida where there are fewer solution cavities and where the limestone contains calcite and anhydrite and gypsum, the permeability is much less. In some areas, as in Sarasota County, the lower part of the aquifer yields little or no water.

The aquifer contains, at different depths, lenses of relatively impervious chert and silicified limestone. These affect the vertical movement of the water locally, but they are not extensive enough to separate the limestone into different aquifers, except in western Florida and southwestern Georgia. Most, if not all, wells drilled into the aquifer yield water. A well drilled into the aquifer near Parrish in Manatee County, Fla., was reported to yield no water. (D. W. Dansby, oral commun., 1932). However, it is not known whether the well was deep enough to test the total thickness of the aquifer.

In some areas, as in northwestern Polk County, the lower part of the Hawthorn Formation is separated from the underlying limestone by a bed of clay (H. G. Stewart, 1959, p. 29). Locally in that area, only the lower part of the Hawthorn is an aquifer. Where the clay bed is absent, relatively impervious beds in the limestone prevent or retard upward movement of the artesian water in the principal artesian aquifer. Where the Hawthorn Formation is absent, surficial clay and other relatively impervious deposits ranging in age from Miocene to Recent may confine the water locally. Several different formations ranging from middle Eocene to late Eocene form the bottom of the aquifer.

FLORIDA

Alachua, Bradford, Clay, and Union Counties

The water-bearing properties of the principal artesian aquifer and the relation of the aquifer to surface streams and lakes in these counties were described by Clark, Musgrove, Menke, and Cagle (1962). The area is underlain by a series of limestones and dolomites to depths of several thousand feet. The limestones and dolomites are generally overlain by relatively thick beds of clay, sandy clay, and limestone of the Hawthorn Formation. A series of high terrace deposits forms most of the land surface. The water-table aquifer consists of shallow sand or clayey sand. The artesian aquifers consist of limestone layers. The source of the largest supplies is the principal artesian aquifer.

Brevard County

Reports (D. W. Brown and others, 1957, 1962) have described the geologic formations and water-bearing properties of the principal artesian aquifer. The development of adequate supplies and the prevention of flooding in the St. Johns River valley are the principal water problems in Brevard County. The mineralization of the artesian water prevents its use as a public water supply in the area east of the St. Johns River. Nonartesian water occurs in the sediments of Pleistocene and Recent age; artesian water is in the underlying limestones of Eocene age. The piezometric surface of the artesian aquifer is higher than the land surface over most of the county. Wells drilled into the aquifer overflow at the surface.

Collier County

The upper part of the principal artesian aquifer consists of the Tampa Limestone and permeable limestone and shell beds in the lower part of the overlying Hawthorn Formation (Klein, 1954, p. 22). In the Naples area the Hawthorn is about 400 feet thick with its top 170 feet below the land surface. At depths of 200 to 250 feet, limestone in the Hawthorn Formation yields artesian water that rises approximately to the land surface in wells. The artesian head in the principal aquifer was about 18 feet above land surface in 1938.

Columbia County

Meyer (1962, p. 37–38) described the geologic formations and the water-bearing properties of the principal artesian aquifer. A pumping test on a well in the Lake City area indicated a transmissibility of 270,000 gpd per ft and a coefficient of storage of 0.0008 for the upper part of the aquifer.

Duval and Nassau Counties

For the vicinity of Jacksonville, Cooper (1944, p. 178) computed that the coefficients of transmissibility of the aquifer ranged from about 50,000 to 1,000,000 gpd per ft. The smallest coefficient was obtained from a well that penetrated only 250 feet of the aquifer, and the largest was from a well that penetrated 700 feet of the aquifer. Thus, the coefficient of permeability was only about 200 gpd per sq ft for the upper 250 feet of the aquifer and about 1,430 for 700 feet. Much of the water was from cavities in the limestone. Cooper reported that, during the deepening of municipal well 22 at the McDuff pumping station at Jacksonville, the artesian flow was reported to have increased almost instantaneously from 500 to more than 1,500 gpm, when the well penetrated a cavity whose vertical dimension was 2 feet at a depth of 1,260 feet. According to a log by Leve (1961a, p. 9), the Lake City Limestone is at this depth. Because the aquifer consists of zones of permeable limestone interbedded with relatively impervious limestone or chert, the coefficient of transmissibility represents approximately that part of the aquifer that yields water to the well.

The transmissibility computed from a well that penetrated 555 feet of the aquifer at Fernandina, Nassau County, is about 150,000 gpd per ft. This value gives a permeability of about 260 gpd per sq ft, only slightly more than the upper 250 feet of the aquifer at Jacksonville. The transmissibility of the total thickness of the aquifer may be larger than that indicated for 555 feet. However, the shape of the piezometric surface of artesian water in the aquifer in local areas also shows significant differences in the transmissibility of the aquifer in different areas (Stringfield and others, 1941, p. 698–711). The shape of the piezometric surface, together with the quantity of water from wells, indicates that the transmissibility is much greater at Jacksonville than at Fernandina.

The coefficient of storage of the aquifer as determined by Cooper (1944, p. 178) by pumping tests on wells was only 0.00025 at Fernandina. Pumping tests on wells indicated coefficients of storage of 0.017 at Jacksonville and 0.021 in Duval County, 6 miles southwest of Whitehouse. A well 12 inches in diameter, drilled near Yukon, Duval County, in November 1942, flowed 6,500 gpm when first completed. The initial flow of two other wells measured by Cooper (1944, p. 174) near Yukon was 3,200 and 4,000 gpm.

In the log of a well 2,130 feet deep at Fernandina, in Nassau County, Leve (1961b, p. 8) showed the following formations:

Formation	*Depth (feet)*
Post-Hawthorn	0–40?
Hawthorn	40?–550
Ocala Limestone	
Upper member	550–840
Lower member	840–1,028
Avon Park Limestone	1,028–1,280
Lake City Limestone	1,280–1,756
Oldsmar Limestone	1,756–2,130

Leve showed the upper member of the Ocala as the Crystal River Formation from 550 to 840 feet. The lower member of the Ocala is shown as the Williston Formation from 840 to 930 feet and the Inglis Formation from 930 to 1,028 feet. The Inglis contains relatively impermeable beds of hard dense crystalline dolomite and limestone that restrict vertical movement of the water.

The lower part of the Hawthorn represents the top of the principal artesian aquifer in the Fernandina area. Although not shown by Leve, it appears that the bottom of the aquifer is at a depth of about 1,400 feet in the Lake City Limestone; below this depth are dense relatively impervious beds separating the aquifer from the relatively highly mineralized water in the lower part of the Lake City and the Oldsmar Limestones. The chloride content of water from wells more than 1,400 feet deep ranged from 50 to 1,060 ppm, and water from wells less than 1,400 feet deep ranged from 26 to 41 ppm (Leve, 1961b, p. 16–17). However, chloride content of eight samples of water collected over a period of about 3 years from one well 1,700 feet deep ranged from 52 to 38 ppm. The bottom of the well is near the unconformable contact of the Lake City Limestone and the overlying Oldsmar Limestone. A comparison of the log of a well at Fernandina with a well near Jacksonville as given by Leve (1961a, p. 9) shows significant differences in the geology, which may explain some of the differences in permeability. Apparently at Fernandina, the upper part of the Lake City Limestone which is productive at Jacksonville, Fla., was removed by erosion, and dense dolomite of the Avon Park was deposited.

Flagler, Putnam, and St. Johns Counties

A report by Bermes, Leve, and Tarver (1963) described the geology and ground-water resources of Flagler, Putnam, and St. Johns Counties and included maps showing the distribution of the members of the Ocala Limestone and the areas in which the formations contain water having a relatively high chloride content.

They computed the transmissibility, storage coefficient, and leakance coefficient for the upper part of the aquifer in several places in Flagler, Putnam, and St. Johns Counties (Bermes and others, 1963, table 5, p. 67). The transmissibility ranged from 173,000 to 360,000 gpd per ft; the storage coefficient ranged from 1.9×10^{-4} to 9.4×10^{-4}, and the leakance coefficient ranged from 1.5×10^{-3} to 1.75×10^{-2}. Judging from the thickness of the part of the aquifer penetrated by the wells tested, the average permeability ranged from about 850 to 2,500 gpd per sq ft.

Highlands County

The Lake City Limestone, consisting of crystalline dolomite and permeable limestone and dolomitic limestone, is one of the most productive formations of the aquifer in Highlands County, according to Bishop (1956, p. 18). Apparently, it forms the lower part of the aquifer in Highlands County. The overlying Avon Park Limestone consists of about 200 to 350 feet of granular to chalky limestone containing considerable secondary calcite and some dolomitic limestone. Bishop reported that it is not an important source of large water supplies in Highlands County. The Ocala Limestone, which unconformably overlies the Avon Park, consists of about 200 to 400 feet of granular to chalky foraminiferal limestone; some beds consist almost entirely of foraminifers. The yield from the Ocala apparently is not as large as that from the Lake City Limestone.

The Suwannee Limestone which unconformably overlies the Ocala is present in the western part of Highlands County. Its maximum thickness is about 80 feet. The Suwannee consists chiefly of slightly permeable soft chalky to slightly crystalline limestone. Although it is used for small domestic water supplies, the Suwannee is not an important part of the aquifer in Highlands County.

The Hawthorn Formation unconformably overlies the Suwannee Limestone and Ocala Limestone in Highlands County. In the northern part of the county, Bishop (1956, p. 25) included, in the Hawthorn, sandy limestone which may be part of the Tampa if that formation is present in this area. The sandy limestone may form the top of the principal artesian aquifer in this area. The Hawthorn ranges in thickness from about 300 feet in the northern part of Highlands County to about 650 feet in the Lake Placid area.

Hillsborough County

Peek (1959b, p. 12) stated that the Suwannee Limestone and Tampa Limestone are the chief sources of water in the aquifer in the Ruskin area of Hillsborough County, although the underlying Ocala Limestone and Avon Park Limestone may be productive. Because the beds thicken and dip to the southwest, wells of similar bottom altitude will penetrate older formations in the northeast than in the southwest. Most of the deep wells in the southwestern part of the county produce water from the Tampa and Suwannee, whereas those in the central-east and northeast produce from the Avon Park. The Tampa and Suwannee yield 1,000 gpm. The Avon Park yield exceeds 5,000 gpm in some wells.

Wetterhall (in Menke and others, 1961, p. 72) reported that the Suwannee and Tampa Limestones, partly dolomitized and having high permeability and solution channels, are more productive than the underlying Ocala and Avon Park Limestones in Hillsborough County. He stated that throughout most of the county all the limestone acts as an aquifer, but where there is large discharge from the Tampa and Suwannee Limestones, these formations act as an aquifer separate from limestones below the Ocala Limestone. Recharge to or discharge from an aquifer will cause differences in water levels at different depths within the aquifer. Therefore, differences in water levels at different depths in the same aquifer may be expected in recharge and discharge areas. The presence of solution cavities in the Oldsmar and Cedar Keys Limestones caused Wetterhall to include these formations as part of the principal artesian aquifer. In the absence of evidence that these formations are hydrologically connected with the principal artesian aquifer, the writer does not, however, regard them as part of the aquifer. Solution cavities in the Eocene and Cretaceous formations underlying the principal aquifer probably were formed before the formations of the principal aquifer were deposited. Some of the cavities remained open while the limestone was being buried by the younger formations.

The principal artesian aquifer penetrated by a well (Florida Geol. Survey W-5423) 1,200 feet deep in the northwestern part of Hillsborough County is chiefly limestone to the top of the Avon Park Limestone at a depth of 640 feet, according to the log of well W-5423 by C. W. Hendry, Jr. (written commun., 1962). The Avon Park Limestone, which was penetrated from 640 feet to the bottom of the well, consists chiefly of dolomite containing gypsum in the lower part.

In a study of the movement of water in the Tampa and Suwannee Limestones, Wetterhall (in Menke and others, 1961, p. 73–74) concluded that solution channels in the limestone formed along joints, faults, and bedding planes. In his investigation of Sulphur Springs, a sodium fluorescein dye test indicated that the water moved in a pattern similar to that of the regional joint systems mapped by Vernon (1951, p. 47–48). Wetterhall suggested that both vertical and lateral movements probably occur along faults. However, the writer is unable to find evidence to support this suggestion.

Sands and limestone in the Hawthorn Formation are the source of water for many domestic supplies and small irrigation supplies. The formation contains relatively impervious beds which retard or prevent upward movement of artesian water in the lower part of the Hawthorn and the underlying limestone of the principal aquifer. Peek (1959b, p. 23–24) reported that the artesian pressure in the Hawthorn is considerably less than that in the underlying limestone. However, a current-meter survey by Peek in part of the area seemed to indicate that the lower part of the Hawthorn is part of the principal aquifer. Results of a pumping test (Peek, 1959b, p. 54) on well 40-27-7 in the aquifer near Sun City gave a transmissibility of 114,600 gpd per ft and a storage coefficient of 0.0006.

Manatee County

The Tampa and underlying Suwannee Limestones are the chief water-bearing formations of the principal artesian aquifer in Manatee County, as described by Peek (1958a, p. 26–34). Few wells in the county penetrate the Ocala Limestone and underlying Avon Park Limestone. Current-meter surveys in wells by Peek showed that the lower part of the Suwannee Limestone below a depth of about 600 feet yielded little or no water. The most productive part of the aquifer is the Tampa Limestone. The lower part of the Hawthorn apparently forms the top of the aquifer. A survey of one well showed that permeable beds in the upper part of the Hawthorn at depths of 60 to 70 feet are under lower artesian head than that of the principal aquifer. Water from the aquifer enters the wells, moves upward, and flows into the uncased part of the Hawthorn Formation. South of Manatee County in adjoining Sarasota County, Stringfield (1933c, p. 205–214) found that the lower part of the Hawthorn Formation and the upper part of the Tampa Limestone are the chief water-bearing formations of the aquifer. No artesian flow was detected in wells below about 675 feet.

Martin County

As described by Lichtler (1960, p. 14–20, 35–36) the principal artesian aquifer in Martin County includes the Avon Park Limestone at the bottom, overlain by the Ocala Limestone and the Suwannee Limestone. About 10 to 15 feet of the Tampa Limestone may be present. A well 1,800 feet deep north of Indiantown may have penetrated the Lake City Limestone. The water was reported too salty for irrigation, and the well was sealed off at 1,100 feet before the initial depth could be checked.

The Avon Park Limestone, estimated to be about 400 feet thick, is a good source of water for irrigation where the water is not too salty. The overlying Ocala Limestone is generally permeable and is an important part of the principal artesian aquifer, although it generally is less than 100 feet thick and only 20 feet thick in one well.

A fault having a vertical displacement of 300 to 400 feet parallels the coast about 5 miles inland. The Suwannee Limestone, overlying the Ocala—20 to 60 feet thick on the west (upthrown) side of the fault and from 100 to 170 feet thick on the east (downthrown) side—yields moderate amounts of water to artesian wells. The permeability is generally lower than that of the underlying formations, and the chloride content of the water is higher. Limestone, about 10 to 15 feet thick, may represent the Tampa, about 2 miles south of Stuart. This limestone has moderate permeability and yields some water to artesian wells. The chloride content, like that in the underlying Suwannee, is higher than that from more permeable parts of the Ocala Limestone and Avon Park Limestone.

The Hawthorn Formation, 350 to 550 feet thick, is generally relatively impervious and does not yield significant amounts of water to wells in Martin County. It prevents or retards upward movement of artesian water in the underlying limestone. The top of the aquifer is about 600 to 1,000 feet below sea level. An appreciable artesian flow begins in wells drilled to about 660 to 800 feet below sea level on the west side of the fault. On the east side, wells begin to flow at depths of 800 to 1,000 feet below sea level.

Current-meter surveys (Lichtler, 1960, p. 38) in several wells show the depth at which water enters the wells. Two miles west of Palm City, in a well 773 feet deep and cased to 400 feet, the estimated flow is about 300 gpm. About 30 percent of the water enters the well between depths of 660 and 675 feet, about 25 percent between 700 and 720 feet, about 25 percent between 740 and 760 feet, and the remaining 20 percent between 760 feet and 773 feet. About 80 percent of the water is obtained from about 55 feet of the Ocala Limestone and Avon Park Limestone. Twelve miles west of Palm City, in a well 696 feet deep having an estimated flow of 190 gpm, nearly 100 percent of the water enters the well between depths of 685 and 696 feet.

East of the fault, in a well 1,315 feet deep having an estimated flow of 300 gpm, 18 percent of the water enters between depths of 960 and 970 feet, 18 percent between 1,235 and 1,245 feet, and the remainder almost uniformly between 1,245 and 1,315 feet. The limestone section through which the water moves laterally is about 355 feet thick, about three times the thickness on the west side. This increase in thickness is chiefly in the Suwannee Limestone.

The fault apparently has little or no effect on the hydraulic gradient of the artesian water or the direction of movement of the water laterally, even though the formations on the east side of the fault are 300 to 400 feet deeper than those on the west side. The faulting apparently occurred prior to the deposition of the Hawthorn Formation in Miocene time, and therefore the relatively impervious beds of the Hawthorn, which prevent or retard upward movement of the water, have not been faulted. Only the water-bearing formations of the aquifer (Suwannee, Ocala and Avon Park Limestones) have been displaced. Under these conditions relatively impervious beds which might form barriers such as those in the Hawthorn Formation have not been faulted against water-bearing formations. During the low stand of the sea in Pleistocene time there was an opportunity for solution channels to form on both sides of the fault and to cross it.

Pinellas County

The Tampa Limestone, which is cavernous in Pinellas County, forms the upper part of the artesian aquifer. It overlies the Suwannee Limestone, which is also an important water-bearing formation of the aquifer in this county (Heath and Smith, 1954, p. 12–18). The underlying Ocala Limestone is not used as much as the overlying formations because it is more than 300 feet deep and yields water that is harder than that from the overlying limestone. Along the coast some of the water has a relatively high chloride content.

The Tampa Limestone is near the surface in the northern part of Pinellas County. West of Lake Tarpon, water in the Tampa and the Suwannee is under water-table conditions. East of Lake Tarpon and south of Palm Harbor, it is under artesian conditions.

Polk County

In the Lakeland area in northwestern Polk County, the coefficient of transmissibility of the aquifer, as computed by H. G. Stewart (1959, p. 39) from a pumping test on a well 1,200 feet deep, is 1,000,000 gpd per ft. The top of the aquifer was at a depth of 180 feet; the well penetrated 1,120 feet of the aquifer. However, the well was cased to a depth of 292 feet, 908 feet being open to the aquifer. At this thickness, the average permeability of the aquifer is about 1,100, about 330 less than the highest average permeability recorded at Jacksonville, even though the aquifer appears to be more cavernous in the Lakeland area than in the Jacksonville area. This difference in permeability in the aquifer in the two areas may arise because many cavities in the Lakeland area may be filled with sand and clay that entered through sinkholes in Pleistocene time when the sea stood lower than its present level. The transmissibility is appreciably less in the upper part of the aquifer than in the lower part; it differs considerably from place to place.

In the Lakeland area, a 26-inch well, 1,200 feet deep with 292 feet of casing, yielded 6,500 gpm with a drawdown of 11.6 feet during a 6.5-hour pumping test, which gives a specific capacity of 560 gpm per ft of drawdown. The maximum specific capicity reported (Stringfield, 1936, p. 159, 173, 186) is 833, for a well 18 inches in diameter, 852 feet deep, cased to a depth of 324 feet. The yield of that well was 7,500 gpm with 9 feet of drawdown.

H. G. Stewart (1959, p. 19) reported that the Avon Park Limestone is the most productive part of the principal artesian aquifer in Polk County. Although the upper part of the overlying Ocala Limestone is soft permeable limestone containing many shells of large foraminifers, the yield to wells is reported to be small. The Suwannee Limestone above the Ocala has permeable beds of limestone containing foraminifers. Locally, at or near the top of the Suwannee, are masses of chert, commonly 1 inch to 2 feet thick, but in a few places they may be as much as 10 feet thick. The Suwannee generally supplies enough water for domestic supplies. The Tampa Limestone forms the top of the principal aquifer. Locally in northwestern Polk County, the overlying Hawthorn Formation is separated from the Tampa by a clay bed 3 to 15 feet thick which H. G. Stewart referred to the Tampa Limestone. H. G. Stewart listed many solution cavities whose vertical dimensions ranged from 2 to 43 feet at depths from 102 feet above sea level to 584 feet below sea level.

Putnam County

In Putnam County (Leve, 1958, fig. 2) the principal aquifer consists of the Lake City, Avon Park, and Ocala Limestones. It apparently is more than 700 feet thick in the western part of the county and somewhat less in the St. Johns River valley. However, only a few of the wells penetrate the Avon Park Limestone and the underlying Lake City Limestone. The Ocala, about 100 feet to 135 feet thick, is the principal source of water. The top of the Ocala is about 25 feet below sea level in the western part of the county and 125 to 170 feet below sea level in the central and eastern parts. Because of the irregular surface of the Ocala, these depths may differ as much as 50 feet within a few hundred yards. The Hawthorn Formation and younger deposits unconformably overlie the Ocala.

Discontinuous limestone beds of the Hawthorn form the upper part of the principal artesian aquifer (Leve, 1958, p. 11). Relatively impervious beds of the Hawthorn and younger formations prevent or retard upward movement of the artesian water in the underlying aquifer. In the western part of the county, sinkholes extend from the surface through the Hawthorn into the Ocala. In the southeastern part of the county in the St. Johns River valley, the Hawthorn is thin or absent, and the unconsolidated Pleistocene deposits overlie the Ocala.

Seminole County

In Seminole County, the principal artesian aquifer includes the Lake City Limestone, as shown by Heath and Barraclough (1954, fig. 2). However, few wells have been drilled into the Lake City, the top being as much as 600 feet below sea level in the southwestern part of the county. Water supplies can generally be obtained from the overlying Avon Park and Ocala Limestones.

The Lake City Limestone generally consists of alternating layers of crystalline dolomite and chalky dolomitic limestone. Where the aquifer does not contain salt water, the water in the Lake City is less highly mineralized than that in the overlying Avon Park and Ocala (Barraclough, 1962, p. 12). Heath and Barraclough (1954, p. 13) suggest that this difference may be due to the dolomitic limestone in the Lake City, which is less soluble than pure limestone. There is also the possibility that silicification of the limestone has made that part of the aquifer less soluble.

The Avon Park Limestone consists of as much as 500 feet of chalky limestone, some of which has been dolomitized since it was deposited. The limestone forms the top of the aquifer in the northeastern part of the county, where the Ocala has been removed by erosion. It is the principal water-bearing formation of the aquifer in Seminole County.

The Ocala Limestone consists of chalky limestone in the upper part and dolomitic limestone in the lower part. It is as much as 75 feet thick in the southern part of the county and thins toward the north where it has been eroded. The Ocala is one of the most productive formations of the aquifer and yields water to hundreds of irrigation and domestic wells.

The Hawthorn Formation consists of sandy limestone interbedded with clay and marl, which prevents or retards upward movements of the artesian water. It is about 75 feet thick in the southwestern part of the county but has been removed by erosion in the northern part and along the St. Johns River valley. In the northern part of the county, deposits consisting of clay in the upper part and sandy shell beds at the base (Heath and Barraclough, 1954, p. 14) overlie the Hawthorn where present and the limestones of Eocene age where the Hawthorn is absent. These deposits were assigned to the Pliocene (Caloosahatchee Marl) by Stubbs (1938, p. 30–31) and Cooke (1945, p. 225). Vernon (1951, figs. 13, 33) assigned these beds to late Miocene. Heath and Barraclough reported that the head and quality of water in the sandy shell beds is similar to that in the underlying limestone. Under these conditions, the shell beds are a part of the principal artesian aquifer—an exception to the general condition in which the lower part of the Hawthorn Formation is the youngest part of the aquifer.

A surficial blanket of deposits, as much as 50 feet thick, chiefly sand of Pleistocene and Recent age, covers the county. These deposits contain some shelly sand and thin beds of clay in the St. Johns River valley. In some places these deposits contain a layer of sand generally less than 2 feet thick, cemented with iron oxide and other cementing agents. This relatively impervious layer, known locally as hardpan, underlies most of the level lowlands at a depth of 3 to 5 feet and retards downward percolation of water, making it possible to irrigate celery and other crops through drain tile buried about 3 feet deep. In some places hardpan may retard or prevent upward movement of water in the underlying sands. Water having sufficient artesian pressure to overflow at the surface in shallow wells may be present in such areas.

Barraclough (1962, p. 18) and Wyrick (1960, p. 24) stated that the aquifer is faulted along the north edge of Seminole County and south edge of Volusia County. A downthrown block of the westward-striking fault underlies part of the St. Johns River valley and the north end of Lake Monroe. Barraclough suggested that a surface expression of this fault block is probably shown by the westerly offset of the St. Johns River along the northern part of the county.

However, the writer believes that Lake Monroe, Lake Jessup, and Lake Harney occupy large basins formed by solution of limestone of the principal aquifer. These basins formed along with the numerous sinkholes in this area. The course of the St. Johns River was controlled in part by these large lake basins and by conditions along the coast when sea level was higher than at the present time.

Volusia County

Limestone underlies Volusia County at a depth of 40 to 100 feet and extends to a depth of several thousand feet. The limestone is overlain by sand, clay, and shell sediments, which are overlain by a sand blanket to a depth of 30 to 70 feet. Beds of relatively impermeable clay of Miocene or Pliocene age overlie the artesian aquifer and confine the water in the aquifer.

As described by Wyrick (1960, p. 13–19), the Lake City Limestone is the lower part of the principal aquifer in Volusia County. The overlying Avon Park and Ocala Limestones are the middle and upper parts of the aquifer. In some places a thin layer of well-rounded phosphatic pebbles is present at the unconformity separating the Lake City from the overlying Avon Park Limestone. At one place a layer of clay and peat 6 feet thick separates the two formations.

The Lake City Limestone was not included in a report by Wyrick and Leutze (1956, p. 22), but a reexamination of the well cuttings (Wyrick, 1960, p. 16) showed that zone B of the Avon Park Limestone (Wyrick and Leutze, 1956) is the Lake City Limestone, the top of which is reached by several wells at depths of 290 to 385 feet below the land surface. The deepest of these wells, 511 feet, penetrated 126 feet of the Lake City Limestone but apparently did not pass through it.

The Avon Park Limestone is about 280 feet thick where it is overlain by the Ocala Limestone. The top of the Avon Park Limestone ranges in depth from about 580 feet below the land surface in the central part of the county to about 200 feet below along the east coast. Some of the limestone, especially near the top, is a loose coquina of foraminifers, small echinoids, and other marine shells. Wyrick reported that the Avon Park Limestone is almost everywhere dolomitized in Volusia County and that the dolomitization generally changes the permeability of the limestone. Dolomitization of the permeable loosely packed coquina generally makes it dense and less permeable. Dolomitization, however, has made other parts of the limestone more permeable. The Avon Park Limestone is the principal source of water in the artesian aquifer in the western part of the county, where the Ocala Limestone is thin or absent. The Avon Park also yields water to many of the deeper wells along the coast. The top of the Ocala ranges from about 50 feet below the land surface in the central part of the county to 100 feet below on the coast. A thickness of about 40 to 60 feet of shelly sand and clay beds of Miocene and Pliocene age overlies the Eocene limestone.

The top of the aquifer is an eroded surface, ranging from about sea level in the western part of the county to about 100 feet below sea level in the southeastern part of the county, as shown by Wyrick (1960, fig. 4). The top of the limestone is domed in the northwestern part of Volusia County near Pierson. Wyrick showed two faults—one having an east-west strike through the north end of Lake Monroe and the other striking north-south through DeLeon Springs. The top of the limestone is displaced vertically 60 to 100 feet near Lake Monroe and about 80 feet near DeLeon Springs and Lake Beresford. Wyrick believed that the east-west fault forms the north side of a graben which includes Lake Monroe. The writer believes that Lake Monroe was formed by solution of the limestone and collapse of the surface in the same way as many lakes and sinkholes formed in north-central Florida and in the

Tallahassee area in western Florida (Sellards, 1910, p. 43–76).

Wyrick (1960, p. 44) reported that movement of artesian water along the north-south fault permits salt water to move upward from the lower part of the aquifer. However, the upward leakage of artesian water in part of the St. Johns River valley, as shown on the map of the piezometric surface, is in the area where the relatively impervious beds above the aquifer are absent.

The Lake City and Avon Park Limestones contain relatively impervious layers of dense indurated limestone at different depths in Volusia County. Some of the thicker layers, such as one between 220 and 240 feet, seems to be parallel to the bedding planes. The thick layers are continuous over large areas. These layers retard vertical movement of the water in the aquifer as shown in current-meter surveys in wells (Wyrick, 1960, p. 13–15).

In well 911–104–4 in the eastern part of the county, the survey showed that the upward flow in the well was probably between 150 and 200 gpm when it was not pumped. Most of the water entered the well below a depth of 430 feet in the Lake City Limestone, moved upward and entered the Avon Park Limestone between depths of 150 to 160 feet in the upper part of the aquifer. The flow entered another well at depths of 395 to 485 feet in the Lake City Limestone when it was not being pumped. A small quantity of water probably left the well in the Avon Park Limestone between 300 and 310 feet. Most of the flow entered the Avon Park Limestone between depths of 225 and 230 feet. The remainder entered the Avon Park between depths of 165 to 180 feet. This difference in pressure apparently is caused by withdrawal of water through wells in the upper part of the aquifer in the Daytona Beach area. Wyrick reported that a current-meter survey in well 909–106–1, about 3 miles west of well 911–104–4, showed that water entered the well from the Avon Park Limestone 150 to 160 feet below the land surface, moved downward, and entered the lower part of the Avon Park and the upper part of the Lake City at depths below 225 feet.

In the Daytona Beach area pumping tests on wells (Wyrick, 1960, p. 56–62) indicated that the transmissibility of the upper part of the aquifer above the relatively impervious layer, 235 to 245 feet deep, is about 300,000 gpd per ft with a storage coefficient of about 0.0007. This represents about 150 feet of the aquifer, including the Ocala Limestone and the upper part of the underlying Avon Park. With a transmissibility of 300,000 gpd per ft and a thickness of 150 feet, the permeability is 2,000 gpd per sq ft, which is one of the highest recorded for the aquifer. Tests in other parts of the county indicate that the transmissibility may be as low as 28,000 and as high as 370,000 gpd per ft.

GEORGIA

The principal artesian aquifer yields nearly 70 percent of the ground water used in Georgia, as reported by Herrick (in Thomson and others, 1956, p. 271, 277). The aquifer underlies all the Coastal Plain in Georgia (fig. 24), except in the area of outcrop of the Cretaceous formations paralleling the Fall Line and in a small area in southwestern Georgia where some limestone formations of the aquifer grade into sand and form separate aquifers. Herrick designated these as the Paleocene and Eocene limestone-sand aquifers.

The Lisbon Formation in southwestern Georgia, the Lake City Limestone in southern Georgia and Florida, and the McBean Formation in the northeastern part of the Coastal Plain in Georgia and southeastern part of South Carolina form the bottom part of the aquifer. Herrick showed the McBean (fig. 25) as the bottom for the entire area in Georgia. In the Savannah area, Counts and Donsky (1959, p. 96; 1963, p. 22) used the name Lisbon Formation instead of McBean and reported that the Lisbon is part of the aquifer in the western part of the Savannah area. However, in the eastern part, its permeability is low, and the formation acts as a confining bed separating the water of the aquifer from that of the underlying limestone.

The top part of the aquifer is generally the lower part of the Hawthorn Formation. The top of the aquifer (fig. 23), as shown by Warren (1944, p. 17a), ranges from more than 100 feet above sea level in the area of outcrop and slopes southeastward to more than 550 feet below sea level on the coast. As described by Herrick (in Thomson and others, 1956, p. 277), the top of the aquifer is as much as 600 feet below the surface in the vicinity of Darien in McIntosh County, Ga. This depth is the maximum recorded along the coast of Georgia and northeastern Florida. The aquifer rises toward the north, south, and west from that low area. South of St. Augustine, Fla., on an arch on the east flank of the Ocala uplift, the aquifer rises to less than 100 feet below sea level. It rises from about 150 feet below sea level in the Savannah area to less than 80 feet below sea level at Parris Island and Hilton Head Island, S.C.

Pumping tests and flow-net analyses reported by Counts and Donsky (1959, p. 100; 1963, p. 41–42) show that the transmissibility of the aquifer has a wide range, averaging 220,000 gpd per ft. It is higher in the northeastern and eastern parts of the Savannah area than in the city. Pumping tests on wells by Warren (1944, p. 103–104) give an average transmissibility of about 250,000 gpd per ft. and a coefficient of storage of about 0.0003 for the aquifer in the immediate vicinity of Savannah. A test at Camp Stewart (now Fort Stewart), near Hinesville, Liberty County, 35 miles southwest of Savannah indicates the coefficient of transmissibility to be about 780,000 gpd per ft. Farther south in the Brunswick area in Glynn County the results of tests show a range of 750,000 to 1,000,000. In the St. Marys area in Camden County near the Florida State line, the tests by Warren show the transmissibility ranges from 104,000 to 177,000, averaging 140,000. Counts and Donsky (1959, p. 100; 1963, p. 44) reported that the specific capacity of wells in the Savannah area ranges from 45 to 65 gpm per foot of drawdown.

Specific capacities of 47 wells penetrating the aquifer in different parts of the coastal area of Georgia, as determined by Warren (1944, p. 83–87), ranged from 1.1 to 240 gpm per foot of drawdown. Only 50 feet of the aquifer was penetrated in the well with a capacity of 1.1. Most of the wells had penetrated more than 100 feet of the aquifer and had capacities of more than 50. These capacities, however, which correlate in a general way with the range in the transmissibility determined from pumping tests, indicate considerable differences in permeability of the aquifer. For example, one of the highest of the capacities was 206 for a well that penetrated 365 feet of the aquifer at Fort Stewart where the transmissibility was about 780,000 gpd per foot, the highest obtained in Georgia, except at Brunswick. A comparison of the specific capacity of 112 for a well that penetrates 500 feet of the aquifer at Brunswick with the results at Fort Stewart indicates that the average permeability of the aquifer is higher at Fort Stewart than at Brunswick, even though the maximum transmissibility is at Brunswick.

RATE OF MOVEMENT OF WATER

In open channels of the aquifer, as in the channel exposed at Falmouth Spring, Fla., the flow may be turbulent, and the rate of movement may be comparable to a surface stream with a similar gradient. Generally, however, ground-water flow is laminar, and the movement is much slower than that of a surface stream under a similar gradient. Laminar flow, which is proportional to the hydraulic gradient and to the permeability and effective porosity of the aquifer, may be only a few feet a year. The results of tests indicate that the permeability of the aquifer ranges from about 500 to 2,000 gpd per sq ft.

As stated by Warren (1944, p. 126), in a study of the movement of water in the artesian aquifer in the area of Savannah, Ga., having a permeability of 500 and an effective porosity of 20 percent, the average velocity with which the water would move through the aquifer for each foot of hydraulic gradient to the mile would be 0.063 foot a day, or 23 feet a year. At a permeability of 1,500 gpd per sq ft and effective porosity of 20 percent, the movement would be three times as fast but only about 70 feet a year. If the effective porosity were 10 percent, the velocity would be twice as much, or about 140 feet a year. As the velocity is proportional to the hydraulic gradient, the rate of movement would be five times as much, or 700 feet a year if the gradient were 5 feet per mile. However, the rate probably is less than that except in a few recharge and discharge areas. In cavernous limestone in a discharge area, tests (Wetterhall, 1965, p. 24) indicate a velocity of as much as 500 feet per day.

ARTESIAN HEAD AND WATER LEVELS

The artesian head, sometimes called pressure head or merely head, is the height, with reference to some datum, to which water will rise in a tightly cased well penetrating an artesian aquifer. The imaginary surface that represents the level to which water will rise in artesian wells is known as the piezometric, or pressure-indicating, surface. It is also known as the potentiometric surface. The piezometric surface may be represented by contours, or lines that pass through points where the head is at equal altitude above a given datum. The contours of equal head are known as equipotential lines (Ferris and others, 1962, p. 139).

Differences in head and artesian flow at different depths may be expected in various parts of the report area. The head in the lower part of the Hawthorn Formation generally is the same as that in the underlying limestone of the principal artesian aquifer, but it is different from that in the middle and upper parts of the Hawthorn and overlying formations, which may locally yield water under artesian pressure. In the coastal counties and in the southern part of Florida where wells in the principal artesian aquifer will overflow (fig. 28), the head in the aquifer is higher than that in the middle and lower parts of the Hawthorn and younger formations. Although the principal artesian aquifer contains relatively impervious beds that prevent or retard vertical movement of the water locally, the head generally is the same throughout the aquifer, except in recharge and discharge areas where the vertical and lateral movement of water in the aquifer may not be in equilibrium.

In some areas, increases in head and artesian flow have been observed with increased depth. According to Sellards and Gunter (1913, p. 146–147) a record of well 10 of the city water supply of Jacksonville, Duval County, showed that the artesian water had a pressure head of 27.72 feet with reference to the ground surface when the well reached a depth of 680 feet and a pressure head of 34.65 feet when it reached a depth of 900 feet. The flow was about 5 gpm from a depth of 270 feet in the Hawthorn Formation, 900 gpm from a depth of 900 feet, and 1,500 to 2,000 gpm from a depth of 980 feet. The well penetrated about 500 feet of the Hawthorn Formation and entered the Ocala Limestone at a depth of about 510 feet.

As described by Cooper (1944, p. 181), wells in Duval and Nassau Counties in northeastern Florida penetrate alternate layers of hard and soft limestone, ranging from a few feet to more than 100 feet in thickness. The hard layers are less permeable than the soft limestone and locally prevent or retard vertical movement of the water. In the Jacksonville area withdrawal of water from wells penetrating the upper part of the aquifer caused the pressure to be considerably less than that in the lower part. Cooper reported that well 7, 1,250 feet deep, of the city of Jacksonville, in the apex of the cone of depression of the piezometric surface, had a head of 55 feet above mean sea level in 1940 when the head of wells in the upper part of the aquifer was less than 40 feet. The well was apparently cased only to the top of the Ocala Limestone, as are other wells in the vicinity. Therefore the head in the wells is a composite of the aquifer. If the well had been cased to 1,250 feet, the pressure would have been more than 55 feet above sea level, possibly as much as 60 feet, which is almost as high as the original piezometric surface.

An incomplete log (Matson and Sanford, 1913, p. 396) of the well at the Ponce de Leon Hotel, at St. Augustine, Fla., reported as well 27, St. Johns County, by Stringfield (1936, p. 135), indicates that the artesian water had a pressure head of 32 feet above the land surface when the well reached a depth of 170 feet. The head was 38 feet when the well reached a depth of 350 feet, and 42 feet at a depth of 520 feet. The Ocala was penetrated at a depth of about 170 feet. The pressure of that well in 1930 (Stringfield, 1936, p. 135, 173, 187) was about 30 feet above the surface of the ground. That pressure head was about the average for wells penetrating the aquifer in the vicinity of St. Augustine. These observations indicate that where wells penetrate water-bearing beds at several horizons having different artesian pressures, there may be an equalization of pressure in the beds at different horizons in the vicinity of the wells, unless the wells are so cased that they will prevent such leakage, as discussed under "Subsurface leakage in wells."

Generally in recharge areas, as recorded by Bishop (1956, p. 47) in Highlands County, Fla., the depth of water levels below the land surface may increase with the depth of the well. In areas of artesian flow, the head may increase with increased depth as described for the wells at Jacksonville, St. Augustine, and Daytona Beach, especially if the artesian pressure has been reduced in the upper part of the aquifer by withdrawal of water from wells, natural discharge, or upward leakage.

In the local recharge area west of the Daytona Beach area in Volusia County, Wyrick (1960, p. 28) reported that a current-meter survey in a well showed that water entered the well from the upper part of the aquifer and moved downward through the well to lower parts of the aquifer.

The head in water-bearing formations below the principal artesian aquifer generally is higher than that in the aquifer. For example, a test well for oil drilled to a depth of 2,130 feet in 1920, at Cherokee Hill, 21.5 feet above sea level, 7 miles northwest of Savannah, Ga., flowed salt water from a depth of 1,980 to 2,035 feet (Warren, 1944, p. 127). Warren stated that in July 1939 the piezometric surface of the artesian water in the principal aquifer at Cherokee Hill was about 2 feet above sea level. In Dade County, Fla., a well penetrating the Cedar Keys Limestone had an artesian head equivalent to 99 feet of fresh water (Nevin Hoy, written commun., 1962).

At Parris Island, S.C., the artesian water in the Tuscaloosa Formation of Cretaceous age had a pressure of about 60 to 65 psi (pounds per square inch) at the land surface, the land being about 10 feet above sea level. This pressure is equivalent to 138 to 149.5 feet of water and is the maximum height to which water would rise above the land surface in a tightly cased well in the area covered by this report.

LOSS OF ARTESIAN HEAD AND FLOW

The loss of artesian head is a normal process that invariably accompanies withdrawal of large amounts of artesian water. In a few areas of original flow withdrawal of water has lowered the artesian head to an extent that pumps are installed on wells. After further reduction in head due to pumping, wells no longer overflow at the surface. The loss of head due to pumping is more than 100 feet in a few areas. With the lower head, loss of water formerly through uncontrolled flow of artesian wells and subsurface leakage in wells is stopped. However, loss of head not only increases the cost of pumping the water but may permit highly mineralized water to enter the aquifer in some areas.

In addition to loss of flow due to loss of head in the aquifer, loss of flow may occur because of subsurface leakage in wells and clogging of walls of wells by the accumulation of sand or other material in the well. If the wells are not adequately cased, unconsolidated material may cave into it and stop the flow completely. Sellards and Gunter (1913, p. 151) observed that although clogging of pores of the walls of wells is likely to be caused by material mechanically transported, the clogging may also be due to chemical deposition.

H. H. Cooper, Jr. (written commun., 1962) has recorded loss of flow without loss of head in wells in Duval and Nassau Counties. After underreaming the wells, the flow increased, indicating the pores in the walls of the wells were clogged. As suggested by Cooper and by Sellards and Gunter, some of this clogging appears to be due to chemical deposition from the water as its pressure is reduced when it enters the well.

FLUCTUATIONS OF ARTESIAN HEAD AND WATER LEVELS

Artesian head and water levels in wells fluctuate continuously. Fluctuations in wells that do not overflow at the land surface are determined by continuous or intermittent measurements of water levels in these wells. The fluctuations in a flowing well are determined by measuring the shut-in pressure in pounds per square inch or in feet of water. The pressure in pounds per square inch may be multiplied by 2.3 to convert to feet of water, or the height to which the water would rise in a tightly cased well. By referring these measurements to sea level or some other common datum, it is possible to determine the piezometric surface or the height to which water would rise with reference to that datum in wells.

In order that the character of the piezometric surface can be interpreted and the effects of recharge and discharge of water can be determined, the causes and amounts of these fluctuations must be determined. One of the earliest reports on the causes of fluctuations of water levels in wells is by Veatch (1906). Some of these causes are discussed in the following sections.

FACTORS AFFECTING FLUCTUATIONS OF ARTESIAN HEAD AND WATER LEVELS

Rainfall in Recharge Areas

In areas in which the aquifer is recharged, such as Marion County, Fla. (Stringfield, 1936, p. 136), the water levels in wells may rise as much as 10 feet within a period of a few weeks, and much of the rise may be attributed to rainfall that enters the aquifer. The effect of rainfall in the recharge area is transmitted to other parts of the aquifer, but this transmission is usually slow, requiring weeks or perhaps months, the time depending on the distance and the hydrologic conditions. Moreover, as distance increases, the magnitude of the effect decreases.

Between October 1941 and March 1942, Warren (1944, p. 60–66) observed the pressure effects of recharge on the artesian head in the principal aquifer in an area about 55 miles wide and 90 miles long northeast of the Valdosta recharge area in southeastern Georgia, where the aquifer is overlain by confining beds of the Hawthorn Formation. During the 6-month period, the rise in artesian head ranged from 2.5 feet a few miles from the recharge area to 0.5 foot and less at a distance of 90 miles downgradient toward Savannah, where the effects were not large enough to be measured. If there is a storage coefficient of 0.0003, as determined in the Savannah area, the amount of water going into storage when the head rises 1 foot in 1 square mile is 62,559 gallons. Using that coefficient and an average rise of 1.7 feet of head in the area 90 by 55 miles, Warren computed the amount of water required to go into storage is approximately 62,599 $\times$ 90 $\times$ 55 $\times$ 1.7 or about 526 million gallons. Warren's estimate of the recharge in the Valdosta area indicates that the recharge was sufficient to furnish that quantity of water.

Matson (Matson and Sanford, 1913, p. 238–239) pointed out that rainfall may cause some increase in the artesian head by means of the added weight that may accumulate in the formations overlying the artesian aquifer. This weight may be transmitted to the underlying aquifer and thereby cause an increase in artesian head. Increases of pressure after rains have been reported by owners of wells in Seminole County, Fla. However, these wells are in irrigation districts, and the changes in head may be caused by opening and closing artesian wells. Moreover, in Seminole County there may be local recharge of the artesian aquifer. Veatch (1906, p. 7) suggests single showers may, by transmitting pressure through the air in soil, produce instantaneous and noticeable rises in the water in wells. Robert Schneider, U.S. Geological Survey (written commun., 1963) has observed rises in water levels in wells over large areas after rains. As discussed under fluctuations caused by changes in atmospheric pressure, some of the changes after heavy rains may be due to changes in barometric pressure.

Surface Drainage Into Wells

In some parts of Florida, as in Orange and Dade Counties, and in the Valdosta area, Georgia, where the static water level in wells penetrating permeable limestone is below the land surface, water is drained into the aquifer through the wells in order to dispose of it. The wells drain into the principal artesian aquifer, except in Dade County where the wells drain into the shallow aquifer near the coast in the Miami area.

Water levels in wells near drainage wells may rise several feet during and after periods of heavy rains. The record of a continuous water-level recorder on a well near Ocoee, Orange County, shows the marked influence of drainage wells in that vicinity. Although no water entered the mouth of the recorder well, there was a rise in water levels after each rain, and the maximum rise was about 6 feet during a 3-day period (Stringfield, 1936, p. 142). At Orlando, Orange County, where there are numerous drainage wells, water levels in wells rise as much as 10 feet after periods of heavy rainfall.

Drainage wells are used to dispose of surface water in areas of poor surface drainage. The wells are effective in recharging the aquifer as described by Unklesbay and Cooper (1946, p. 299). Warren (1944, p. 64) estimated that several million gallons of water per day enter the aquifer through drainage wells in the Valdosta area. The effects of that recharge together with the natural recharge were observed over a distance of 90 miles northeast of the Valdosta area. The aquifer consisting of the Ocala Limestone and older Eocene limestones is so cavernous that the wells seldom become clogged, although some trash passing the screens (fig. 26) around the mouth of the wells enters the aquifer.

As described by Sellards (1910, p. 72) and Unklesbay and Cooper (1946, p. 305), some drainage wells spout water at intervals like a geyser. The spouting is caused by an outrush of air that has been carried into the well by surface-water drainage. The air accumulates in cavities in the aquifer and is compressed by the water until the air pressure exceeds the weight of the column of water in

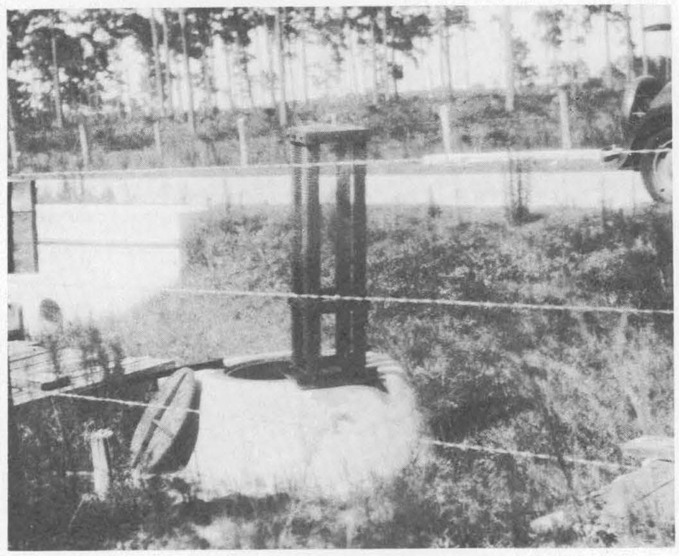

FIGURE 26.—Manhole over drainage well. Screen which fits over mouth of well is on edge of manhole.

the well, at which time the spouting occurs. One of the well-known spouting wells described by Sellards and by Unklesbay and Cooper on the south side of Lake Fairview northwest of Orlando drains water from the lake when the lake level is above the mouth of the well (fig. 27). At times the well spouts water more than 100 feet above its mouth. As the flow from the lake to the well can be controlled, spouting is produced when desired as a tourist attraction. However, spouting of a well generally is a nuisance and reduces the effectiveness of the well for draining surface water or recharging the aquifer. Also, the spouting may be a hazard to nearby structures. Consequently, some wells are equipped with devices designed to deflect the spouting or decrease its force.

FIGURE 27.—Drainage well spouting water at Lake Fairview, northeast of Orlando, Orange County, Fla.

Unklesbay and Cooper (1946, p. 305) reported that at some places in the Orlando area, air is trapped over a wide area, within which wells cased to comparatively shallow depths will contain air under pressure. They observed that the air in one well had a pressure equivalent to 54 feet of water or about 23 psi at the surface. In one area, flammable gas from citrus pulp and skins, which had been injected into a well, accumulated to such an extent that it was used locally for fuel.

Rivers

In parts of their courses some rivers flow on the aquifer where it is at or near the surface. In the northwestern part of the Florida peninsula along the Suwannee River and the lower course of the Santa Fe River and in the west-central part of the peninsula along the lower course of the Withlacoochee River changes in the stage of the rivers may affect the ground-water level in the aquifer. Ground-water levels are also affected by changes in the stage of the Flint River in Georgia.

Ground-water level near the streams is generally about the same as the water level in the rivers, but during the flood stages the rivers lose water to the formations and thereby cause the ground-water levels to rise in adjacent areas. In Florida, such fluctuations have been noted in a well at High Springs in Alachua County, in a well at Branford in Suwannee County, and in Falmouth Spring near Falmouth in Suwannee County. At Falmouth Spring, an exposed part of an underground stream in the aquifer, the movement of the water is toward the east when the river is high enough to recharge the aquifer and toward the west when the aquifer discharges into the river. During the flood stage of the river, when the spring is flowing toward the east, the spring water is the color of tea because of the colored water from the river. During the low stage of the river when the spring flows toward the west, the water is clear, indicating that either the water has lost its organic color in contact with limestone or it is ground water from a part of the aquifer that was not recharged with colored water.

Changes in Atmospheric Pressure and Wind

Variations in atmospheric pressure may cause fluctuations of head in most if not all artesian wells and some nonartesian wells, but these fluctuations may be masked by larger fluctuations due to other causes, chiefly variations in withdrawal of water. Fluctuations of head or water levels in nonartesian wells in response to changes in atmospheric pressure may occur when water in the zone of aeration is frozen, as reported by Stringfield (in Meinzer and Wenzel, 1937, p. 84), or when part of that zone above the water table is saturated with water after heavy rains. These temporarily saturated or frozen zones prevent the full effect of atmospheric pressure from being transmitted to the water table. Also, the water table responds to changes in atmospheric pressure under conditions such as that cited below in the Grand Prairie region, Arkansas.

As explained by Meinzer (1932, p. 141–142), a well will act as a barometer if it ends in an aquifer overlain by relatively impervious beds having sufficient strength to resist deformation by slight changes in pressure at the surface. The fluctuation of the water level will have about the same range as a water barometer, or 13.5 times the range in a mercury barometer because the specific gravity of mercury is 13.5 times that of fresh water. The movement of the water level in the well is in the opposite direction from that of an ordinary barometer. For example, as the atmospheric pressure transmitted through the mouth of the well increases or rises, the water level in the well is depressed. As the atmospheric pressure decreases, the water level in the well rises.

If an aquifer consists of unconsolidated sand and sandy clay overlain by clay beds that are relatively impervious but yield to slight pressure, water-level fluctuations in wells in response to changes in atmospheric pressure will be smaller than those of a water barometer. When atmospheric pressure changes are expressed in terms of a column of water, the ratio of water level changes to pressure changes expresses the barometric efficiency of an aquifer (Jacob, 1940, p. 582; Todd, 1959, p. 159). Most observations give values which range from 20 to 75 percent.

In the Grand Prairie region, near Stuttgart, in the Coastal Plain of Arkansas, D. G. Thompson (in Engler and others, 1945, p. 27) observed wells in which the water-level fluctuations due to changes in atmospheric pressure ranged from a fraction of a foot to about 1 foot. The maximum fluctuation, with a barometric efficiency of 100 percent, is in an area where the artesian pressure in the aquifer has been lowered to the extent that water-table conditions are present. Under these conditions, the atmospheric pressure on the confining beds is not transmitted to the water table because it is some distance below the bottom of the confining bed, but the atmospheric pressure is transmitted to the water through wells.

The principal artesian aquifer in the area of the present report apparently has a barometric efficiency that ranges from less than 50 to 75 percent. In Sarasota County (Stringfield, 1933c, p. 160–161), the range of water-level fluctuations due to changes in atmospheric pressure in a well in the principal artesian aquifer was about 50 to 75 percent of that of a barometer in Sarasota about 7 miles west of the well. However, the ratio was about 50 percent much of the time, and it appears that the barometric efficiency was actually about 50 percent. The higher range apparently was due to higher atmospheric pressure at the well than at the barometer in Sarasota. The record also appears to have been affected by earth tides. In Flagler, Putnam, and St. Johns Counties, Bermes, Leve, and Tarver (1963, p. 70) computed that the aquifer has a barometric efficiency of about 30 to 40 percent. Odom (1961, p. 29) showed that the water level in a well in the Savannah area, Georgia, rose more than a foot in response to the low barometric pressure caused by a tropical storm.

Changes of air pressure resulting from variation in the velocity of wind, as it blows across the top of the casing or past the structure housing the recorder, cause small fluctuations of water levels in both artesian and nonartesian wells. As gusts of wind blow over the top of the casing or past the well, the air pressure in the well is lowered, and the water level rises. Observations made at Miami (Parker and Stringfield, 1950, p. 453) showed that these fluctuations seldom exceed 0.03 foot. Such fluctuations of water levels have also been observed by Elmer Rexin, chief engineer, Nunn-Bush Shoe Co., in a well in the basement of the Nunn-Bush factory at Milwaukee, Wis. As the wind did not have access to the well, the gusts of wind apparently affected the atmospheric pressure in the building. Although such small fluctuations may not be as significant as other fluctuations of water levels in showing characteristics of an aquifer, they should be understood and recognized when studying records that have small but significant fluctuations.

Ocean Tides and Earth Tides

Ocean tides may cause fluctuations of water levels in wells in aquifers along the coasts, but earth tides (Robinson, 1939, p. 656–666) may occur in wells not only in coastal areas but in the interior. Fluctuations of head or water levels in wells caused by ocean tides may be due to (1) the result of actual transfer of water from the ocean to the aquifer and (2) alternate compression and expansion of an artesian aquifer by the added weight of water transmitted in the vicinity at high tide and removal of the weight at low tide. Transfer of water between the ocean and the aquifer may occur in the principal artesian aquifer along the gulf coast where the aquifer is at or near the surface, from Pinellas County to western Florida. It may also occur in submarine outcrops of the aquifer many miles offshore, but these effects are not known to extend to the mainland. The tidal fluctuations in wells due to transfer of water are significant in studying salt-water encroachment.

However, in most of the coastal areas of this report, conditions causing tidal fluctuations in wells in the principal artesian aquifer are similar to conditions in the vicinity of Atlantic City, N.J., where Thompson (1928, p. 27–30, 57, 113) and Barksdale, Sundstrom, and Brunstein (1936) demonstrated that the tidal fluctuations in the head of water in wells drawing from an aquifer at a depth of 800 feet are due to the alternate tidal loading and unloading in the immediate vicinity and not to transfer of water or pressure change transmitted from the submarine outcrop of the aquifer. Observations by Warren (1944, p. 72) on the rate at which pressure effects are transmitted through the artesian aquifer at Savannah indicated that days would be required for the pressure effect of the tide to be transmitted through the formation from the submarine outcrop.

The maximum fluctuation of artesian pressure that can be definitely attributed to tidal loading amounts to about 1 foot in wells near the Gulf of Mexico and 2 feet in wells near the Atlantic coast in Florida. From the nearest tidal water body, the farthest point inland at which tidal fluctuations in head were definitely observed in the principal aquifer was about 0.2 mile in Florida and more than 1 mile in Georgia. Well 7 in Effingham County, Ga., 5 miles from the nearest tidal water is reported to be affected by tides (Odom, 1961, p. 29). However, it seems entirely possible that the fluctuations attributed to ocean tide may be caused by earth tides and barometric fluctuations. At Miami, Fla., lateral transfer of pressure effect of high tides in Biscayne Bay on water levels in wells in the shallow aquifer is 6,680 feet inland (Parker and Stringfield, 1950, p. 448). Continuous records on a well on the Atlantic coast at Jacksonville Beach show a semidiurnal variation of 1 to 2 feet in the artesian head of the principal aquifer. The fluctuations on the Atlantic coast are about half the magnitude of the tides.

Warren (1944, p. 74) recorded in December 1942 a tidal fluctuation of 4.35 feet in well 328 at Fort Screven, Ga., 600 feet west of the Tybee Lighthouse, when the tidal fluctuation was 9.7 feet in the Atlantic Ocean at the Tybee Light, about 1,000 feet northeast of the well—a tidal efficiency of about 50 percent. The smallest tidal efficiency observed along the coast was about 20 percent in Glynn County.

In estimating the tidal efficiency of an aquifer along an irregular shoreline where there are tidal marshes and flats, consideration must be given to the area inundated at different stages of the tide. At the Tybee well, for example, where a larger land area is flooded during spring tide than during neap tide, the fluctuation of water level is about 7 percent larger in proportion to the range of the tide during spring and neap tides. If the area covered were always the same, it would be expected that the tidal fluctuations of water levels would be a certain percentage of the fluctuations of the tide during the spring and neap tides (Warren, 1944, p. 77).

As stated by Jacob (1940, p. 582) barometric and tidal fluctuations may be taken as an index of the elasticity of the aquifer. The barometric efficiency is a measure of the competence of the aquifer and confining beds to resist pressure changes. The tidal efficiency is a measure of the incompetence of the aquifer and confining beds to resist pressure. The tidal efficiency plus the barometric efficiency of the aquifer equals unity (Ferris and others, 1962, p. 86). Jacob (1940, p. 582–585) and Todd (1959, p. 165–168) described a method of using the barometric efficiency or tidal efficiency to compute the coefficient of storage.

Small fluctuations of water levels in artesian wells resulting from the attraction exerted on the earth's crust by the moon, and to a lesser extent by the sun, have been described (Robinson, 1939, p. 656–666; Richardson, 1956, p. 461–462; J. W. Stewart, 1961, p. 107; and Ferris and others, 1962, p. 86). Thomas Cramer of the U.S. Potash Co., working with Robinson, called attention to tidal fluctuations in a well in New Mexico (C. V. Theis, written commun., 1962). Veatch (1906, p. 69) mentioned the possibility of earth-tide fluctuations in wells but did not recognize them in wells which he described.

As stated by Todd (1959, p. 168), Robinson's observations show "(a) two daily cycles of fluctuations occur about 50 minutes later each day, as does the moon; (b) the average daily retardation of cycles agrees closely with the moon's transit; (c) the daily troughs of the water level coincide with the transits of the moon at upper and lower culmination; and (d) periods of larger fluctuations coincide with periods of new and full moon, whereas periods of small, irregular fluctuations coincide with periods of first and third quarters of the moon."

At times of new and full moon when the tide-producing forces of the moon and sun act in the same direction, the ocean tides have a range greater than average. The ocean tides are smaller than average when the moon is in the first and third quarters and the forces producing the tides act perpendicularly to one another.

Theis (1939) and Todd (1959, p. 169) suggested that the earth tides are lowest at time of the moon's transit because the overburden load on the aquifer is reduced, allowing the aquifer to expand slightly when the tidal attraction is maximum. Ferris (1962, p. 86–87) quoted the following from Theis (1939):

> As the crust of the earth in any given area rises and falls with the deformation of the earth caused by the tidal forces the crust is most probably alternately expanded and compressed laterally—expanded when the earth bulges up and compressed when it subsides. Water in an artesian aquifer making up part of the crust shares in this deformation. In localities distant from points of outflow of the water, it is in effect confined without possibility of outflow within the period of tidal fluctuations. The slight hydraulic gradient imposed by the tidal distortion is too small to cause effective release of pressure. Hence the aquifer is essentially sealed with respect to its included fluid. With the expansion of the aquifer incident to the tidal bulge the hydrostatic pressure falls and with its compression incident to tidal depression the hydrostatic pressure rises.

The records of artesian wells in the principal artesian aquifer have not been studied to determine the earth tides. However, tidal fluctuations due to earth tides are probably present in most if not all of the artesian wells in Florida and adjacent States. Careful study of the earth tides in the aquifer probably would give significant information on its water-bearing properties. Although the best known earth tides are in sedimentary artesian aquifers, J. W. Stewart (1961, p. 109) reported earth tides in three of four wells 400 feet deep in metamorphic rocks near Dawsonville, Ga.

Loads Such as Railroad Trains and Ships

Compression and expansion of artesian aquifers by addition and removal of loads, such as railroad trains, have been observed in many ground-water investigations. As the train approaches, the water levels rise in the observation wells; then the water levels decline to normal as the train passes. The record of such fluctuations in a well in the shallow aquifer in the Miami area, Florida, shows that heavy freight trains cause the largest fluctuations, which are a maximum of about 0.045 foot, and the short, light trains cause the smallest (Parker and Stringfield, 1950, p. 459).

Jacob (1939, 666–674) described the effect of the load of a train on the water level in an observation well on Long Island, N.Y. The water level reached its maximum (about 0.02 foot) when the train stopped. Within seconds the water level declined, first rapidly and then more slowly, returning to its original level. After a few seconds when the train started again, the water level declined rapidly, about 0.03 foot, and then slowly rose toward the original level. Jacob's record is also included and discussed by Todd (1959, p. 170) and Meinzer (1939, p. 212, 220).

Odom (1961, p. 28) gave a record of the effects of passing ships in the Savannah River on the water level in a well near the river. He concluded that as the ship moves through a body of water, it forces water ahead and aside in the form of a wave, thereby causing a temporary rise in the level of the river. This temporary rise causes a temporary load which is transmitted to the riverbed and to the underlying confining beds of the aquifer.

Earthquakes

Fluctuations of water levels ranging from a fraction of a foot to several feet in wells in artesian aquifers have been caused by shocks from earthquakes. The fluctuations are sudden and range above and below the water level before the shock. Apparently, the maximum fluctuation recorded was 7 feet or more on March 27, 1964, in wells in a broad belt extending southeastward from Wisconsin through Illinois and Indiana to Georgia and Florida, at the time of the Alaskan earthquake (Waller and Thomas, 1964, U.S. Geol. Survey mimeo. memo.). The maximum fluctuation in the Southeastern States was about 17 feet in a well in the principal artesian aquifer near Perry, Fla. (Waller and others, 1965, p. 123–131). The maximum fluctuation recorded in Florida prior to the Alaskan earthquake was 4.5 feet in a well at Miami, Fla., where records (Parker and Stringfield, 1950, p. 459) also show many very small fluctuations, ranging from 0.006 to 0.038 foot, not reported by regular seismological stations. Apparently, these minor shocks represent small adjustments of the earth's crust, possibly along the margin of the Floridian Plateau.

One of the most detailed records obtained is for an observation well in the basement of the Nunn-Bush shoe factory in Milwaukee, Wis. Elmer Rexin, chief engineer of the Nunn-Bush Shoe Co., designed and built the recorder with an expanded time scale which gives more detail than the conventional recorder. One of these records given by Vorhis (1955, p. 47–52) and Todd (1959, p. 170) shows the effect of an earthquake centered on the Argentina-Chile border, nearly 5,000 miles from the well. The maximum fluctuation was less than 2 inches. As stated by Todd (1959, p. 171), although the quantitative effects of earthquakes on ground water are not fully understood, the fluctuations of water levels in the response of wells to earthquakes apparently are due to compression and expansion of artesian aquifers by the earthquake waves.

Natural Artesian Flow or Pumping From Wells

The most noticeable fluctuations of head are due to withdrawal of water from wells, either by natural flow or pumping. When a well begins to discharge, the head of the water in the well immediately drops, and at the same time the head of the water in the aquifer around the well drops. The decline in head is greatest in the discharging well and decreases with increased distance from that well. The piezometric surface is nearly vertical at the well, but with increasing distance from the well the gradient gradually becomes more gentle until, generally within a few hundred or a few thousand feet, it becomes nearly horizontal. The rate of decline in head is at first rapid but becomes slower and slower until finally there may be no further apparent decline. The time required to reach the point of stability is generally at least several hours and may be several days or weeks. The conical depression in the piezometric surface is called the cone of depression.

When the discharge ceases, the head increases immediately. The rate of increase is at first rapid and then slower until, when sufficient time has passed, the water will recover its original head unless some other influence has caused the head to change. The time required to reach a stable head after discharge has ceased is approximately as long as the time required to reach a stable head during discharge. The difference between these two heads is known as the drawdown.

When water is pumped from a well, the pressure in the aquifer is decreased, and a cone of depression is established around the well. The cone of depression may be large or small, according to the amount of water removed, the rate at which it is removed, and the ability of the rock to transmit water. If large amounts of water are pumped for a long period of time, the resulting cone of depression may be extensive. When several wells discharge in a locality, their cones of depression may coalesce and form a single large irregular depression. Under artesian conditions in some areas, as at Fernandina, Fla., and Savannah, Ga., the cone of depression may extend many miles from the center of draft. R. L. Wait (1963, p. 44) stated that the cone of depression at Savannah, Ga., is more than 60 miles in diameter. The distance from the deepest part of the cone of depression to the zero contour is greater to the east than it is to the west in the Savannah area, Georgia (Counts and Donsky, 1963, p. 56). The distance is about 8 to 10 miles on the west side of Savannah, about 18 miles on the south side, and about 25 miles on the northeast side, where the cone reaches its maximum extent in the vicinity of Hilton Head, S.C.; the cone slopes more steeply on the west side than on the east side.

The maximum fluctuation in a flowing well is limited by the difference in shut-in head and the altitude of the top of the well. When a well flows, the pressure at the mouth is almost zero, so that the shut-in head is almost equal to the drawdown or loss in head resulting from discharge of water.

AREAS OF ARTESIAN FLOW

The general areas in which the artesian water is under sufficient pressure to rise to the surface and produce flowing wells in the Coastal Plain from North Carolina to Mississippi, inclusive, are shown by Stringfield (1953, p. 32). The areas in Florida, Georgia, and adjacent parts of Alabama and South Carolina are represented in figure 28. They include three principal areas: the Atlantic coast, southern Florida, and the gulf coast. The map indicates the limits of the areas of flow only approximately. More detail is shown in reports cited in the following discussion.

Within areas of flow there are relatively high districts in which wells will not flow. In some areas shown as nonflowing areas, flows may be obtained in some of the relatively low districts where the pressure is relatively high. Along the borders of areas of artesian flow where the piezometric surface is near the land surface, wells may flow intermittently in response to changes in barometric pressure, tides, and other forces which cause water-level fluctuations in wells.

In the larger river valleys, the areas of flow extend beyond the area underlain by the principal aquifer of Tertiary age into the Cretaceous area almost to the Fall Line, as shown by LeGrand (1961a) in the Macon area. The artesian water between the Fall Line and the Tertiary aquifer is from formations of Cretaceous age. The Cretaceous aquifers underlying the Tertiary are a source of artesian water in southwestern Georgia, in southeastern Alabama, and in a broad belt extending from Alabama across Georgia into South Carolina.

ATLANTIC COAST

The area of flow along the Atlantic coast extends from Savannah area, Chatham County, Ga., to the Florida Keys. The area of flow in Georgia in 1914 is shown by Stephenson and Veatch (1915, p. 123). Originally, flows could be obtained in wells in the principal aquifer in most of Chatham County and in the southern part of Effingham County and adjacent parts of South Carolina. However, in 1942, as described by Warren (1944, p. 22), withdrawal of water from wells in the Savannah area had reduced the area of artesian flow in Chatham County to approximately the southwestern quarter of the county and in Effingham County to the lowlands near Meldrim and Eden. Within the area of artesian flow in the eastern part of Bryan, Liberty, and McIntosh Counties, there are small relatively high areas in which wells would not flow in 1942. Warren reported that one area is 10 miles southeast of Richmond Hill in Bryan County, another is in the vicinity of Dorchester in Liberty County, and the third is just west of Crescent in McIntosh County. All nonflowing areas have become enlarged as a result of the increase in consumption of water and the decline of the piezometric surface. They have not been mapped recently, but a comparison of the altitude of the piezometric surface with the land surface will indicate approximately the area in which wells will flow.

In the coastal area of northern Florida, the area of flow of the principal artesian aquifer includes a large part of Nassau and Duval Counties and extends westward along the valleys of the St. Marys River into Baker County. The withdrawal of water from wells at Fernandina has lowered the pressure in the principal artesian aquifer and the overlying Hawthorn to the extent that wells no longer flow in that vicinity.

The area of flow includes the valleys of the St. Johns River and some of its tributaries, such as Black Creek and the Oklawaha and Wekiva Rivers. The area of flow along Black Creek and its tributaries extends into western Clay County. Details of the areas of flow in Clay County in 1961 are shown by J. B. Foster (1962, fig. 2). The area in which wells will flow along the Oklawaha River extends into the east-central part of Marion County almost to Silver Springs, which has the largest artesian

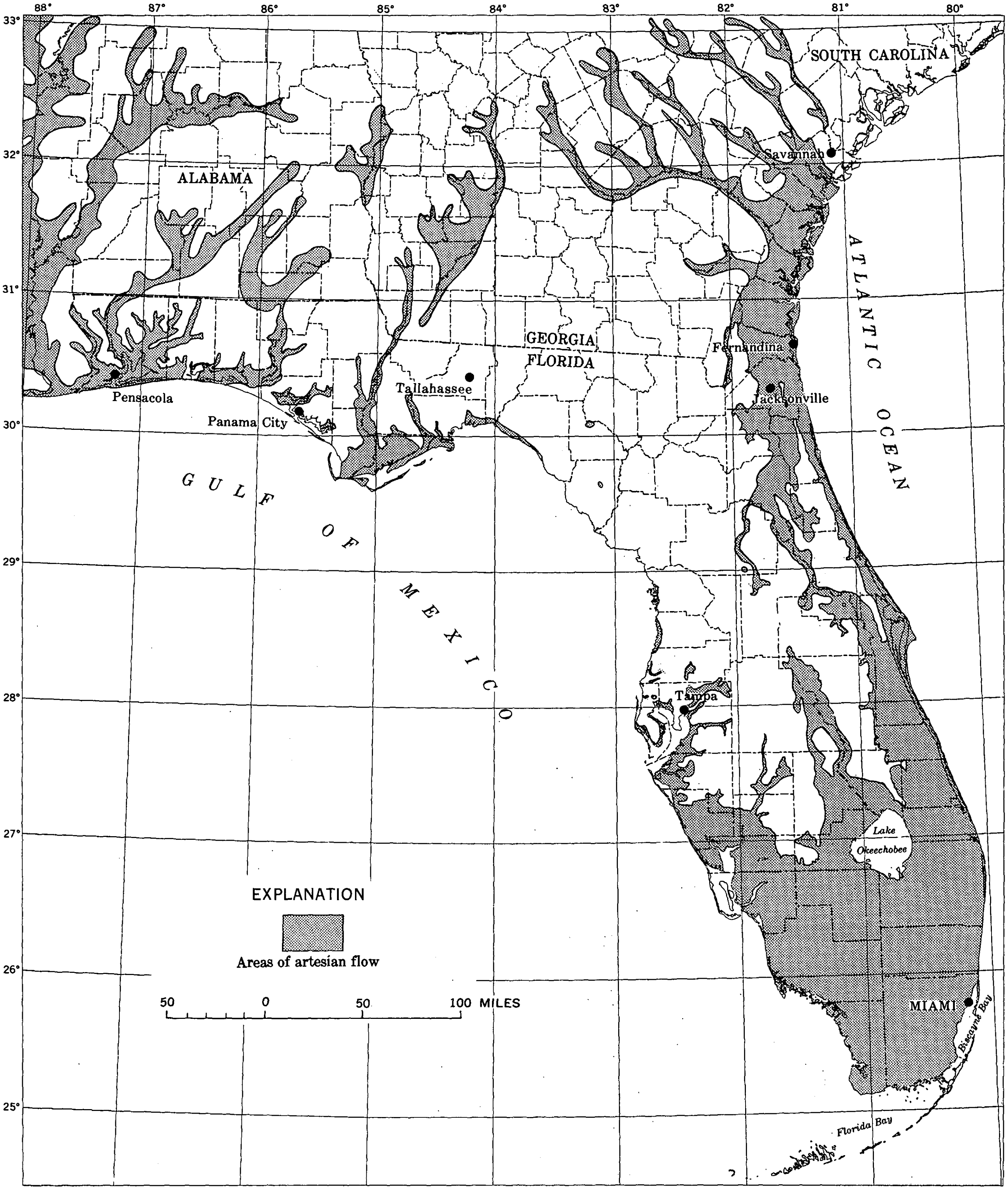

FIGURE 28.—Areas of artesian flow. (Florida, from Healy, 1961; Georgia, after Warren, 1944; Alabama, after Smith, 1907.)

flow in the area. At the headwaters of the Oklawaha River, on the borders of some of the lakes in Lake County, the artesian water levels in wells are near the surface of the ground. There are flowing wells in the lowland bordering the southeast, south, and west sides of Lake Apopka, but on the north and northeast sides of the lake, the artesian head is too low to produce flowing wells because the piezometric surface slopes to the northeast and is below the surface of the ground.

Details of the areas of flow are given by Leve (1958, p. 20) for Putnam County, Bermes (1958a, p. 7) for Flagler County, and Wyrick (1960, p. 35) for Volusia County. Bermes, Leve, and Tarver (1963) included a map showing the areas of artesian flow in Flagler, Putnam, and St. Johns Counties. Barraclough (1962) showed in detail the area of flow in Seminole County. D. W. Brown (1957, p. 81) reported that the area of flow includes all Brevard County, except the top of high areas in the coastal ridge.

SOUTHERN FLORIDA

The area of artesian flow in southern Florida merges with the Atlantic coast and gulf coast areas. It covers all the southern part of the peninsula and extends along the Kissimmee River valley into northern Osceola County and along the Peace Creek valley to the southern part of Polk County. In a relatively few high areas, such as that in northern Collier County, wells do not flow. Lichtler (1960, p. 35) reported that flowing wells may be obtained throughout Martin County, except at the tops of high sand hills in the eastern part of the county where the land surface is more than 50 feet above sea level. Wells in the principal aquifer on the Florida Keys are apparently nonflowing, although the altitude of the land surface is only a few feet above sea level.

GULF COAST

The gulf coast area of artesian flow is chiefly a narrow strip along the Gulf of Mexico. It extends inland along the valley of the Myakka River in Sarasota and Manatee Counties and the larger valleys in Manatee and Hillsborough Counties. Details of the area of artesian flow are shown by Peek (1958a, fig. 27) for Manatee County and by Heath and Smith (1954, fig. 13) for Pinellas County. In Pasco, Hernando, and Citrus Counties, flows may be expected only where the land surface is near sea level. The area of flow extends westward from Wakulla County along the coast to Alabama. From the coastal belt, the area of flow extends many miles inland along some of the larger stream valleys. It extends up the Apalachicola and Chattahoochee Rivers into Georgia and Alabama. From the Chattahoochee River it extends up the Flint River and its tributaries in Georgia. Areas of flow include the Choctawhatchee and Escambia Rivers and their tributaries in Alabama. The artesian flow north of the region underlain by the principal artesian aquifer is chiefly from the Cretaceous aquifers. Wells in shallow aquifers overlying the principal artesian aquifer will flow in the valleys of the Escambia and Perdido Rivers.

PIEZOMETRIC SURFACE OF WATER

The piezometric surface, or pressure-indicating surface, shown by means of contour lines on figure 29 represents the height to which water would rise in wells with reference to mean sea level in 1961. The piezometric surface is above sea level except in a few areas such as Panama City and Fernandina, Fla., and Savannah, Ga., where pumping has lowered the artesian head. The piezometric surface is above the land surface in areas of artesian flow. Because of fluctuations of the pressure head, the position of the piezometric surface is changing almost constantly, and the representation at any one time shows only approximately the condition at any other time. However, except in areas of heavy withdrawal of water, there has been no detectable net rise or decline of the piezometric surface, and the major features remain the same. The fluctuations in head are generally less than a foot in areas where changes caused by recharge and discharge are small or not detectable. In the areas where large quantities of water are withdrawn from the aquifers, as in the coastal counties of Georgia and northeastern Florida, the piezometric surface is based on measurements which show the effects of pumping in 1961. A comparison of the original piezometric surface prior to 1885 (fig. 30), prepared by Warren (1944, p. 26), with the piezometric surface of 1940 (fig. 31) shows the changes caused by withdrawal of water through 1940. A comparison of figures 29 and 31 shows the changes between 1940 and 1961.

Except for those areas of heavy withdrawal of water, most of the major features of the piezometric surface of 1961 are essentially the same as those mapped by Stringfield (1936, pl. 12) in the Florida peninsula, by Warren (1944, p. 18) in southeastern Georgia, and by V. T. Stringfield and F. C. Westendick in 1936 in Florida west of the Suwannee River. These maps were combined and included in reports by Warren (1944, p. 18), Stringfield (1950, p. 219), Stringfield and Cooper (1951a, p. 528), and Black, Brown, and Pearce (1953), and in many subsequent

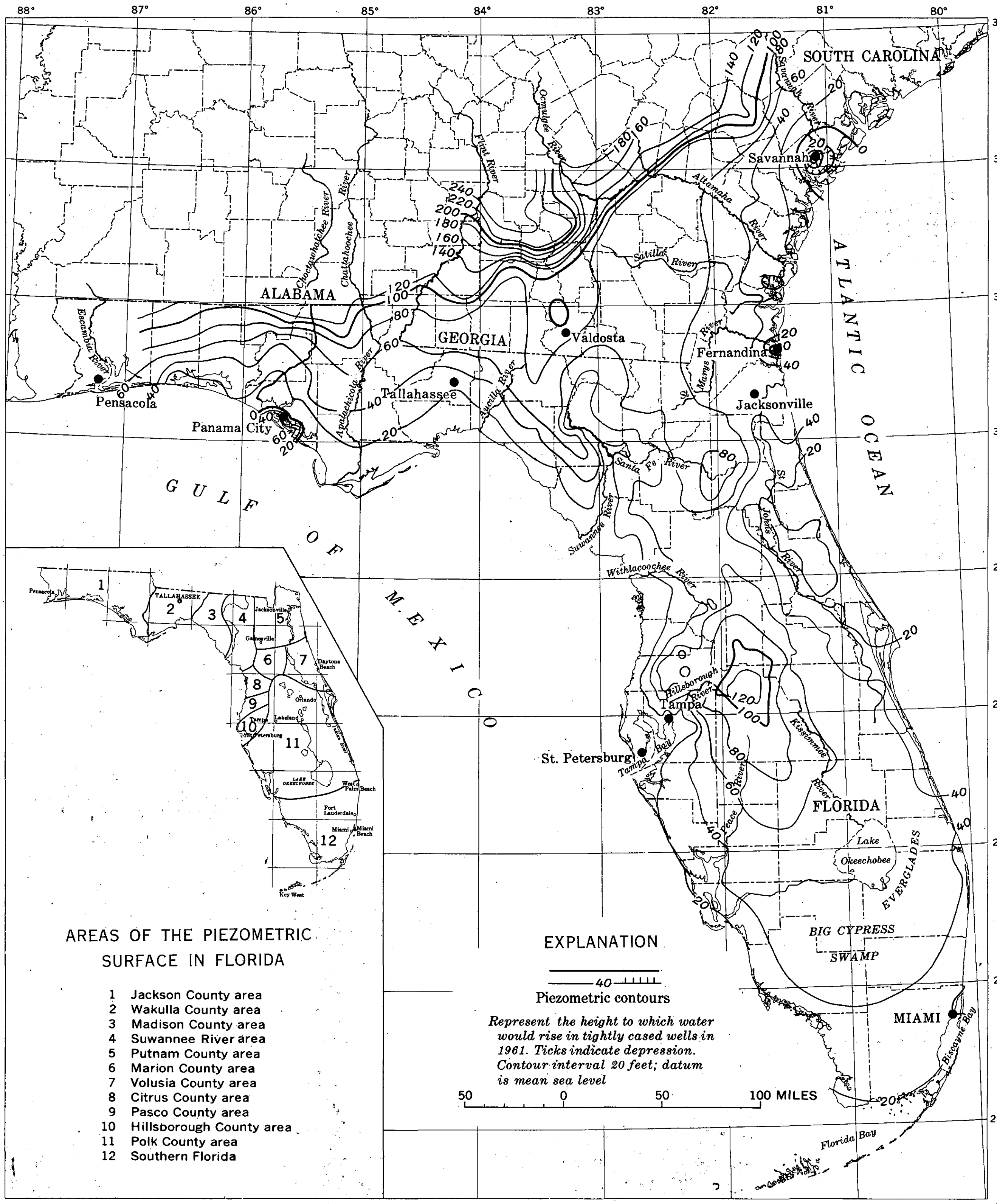

FIGURE 29.—Piezometric surface of water in the principal artesian aquifer, 1961. (From Healy, 1962; Stewart and Croft, 1960; and Warren, 1944.)

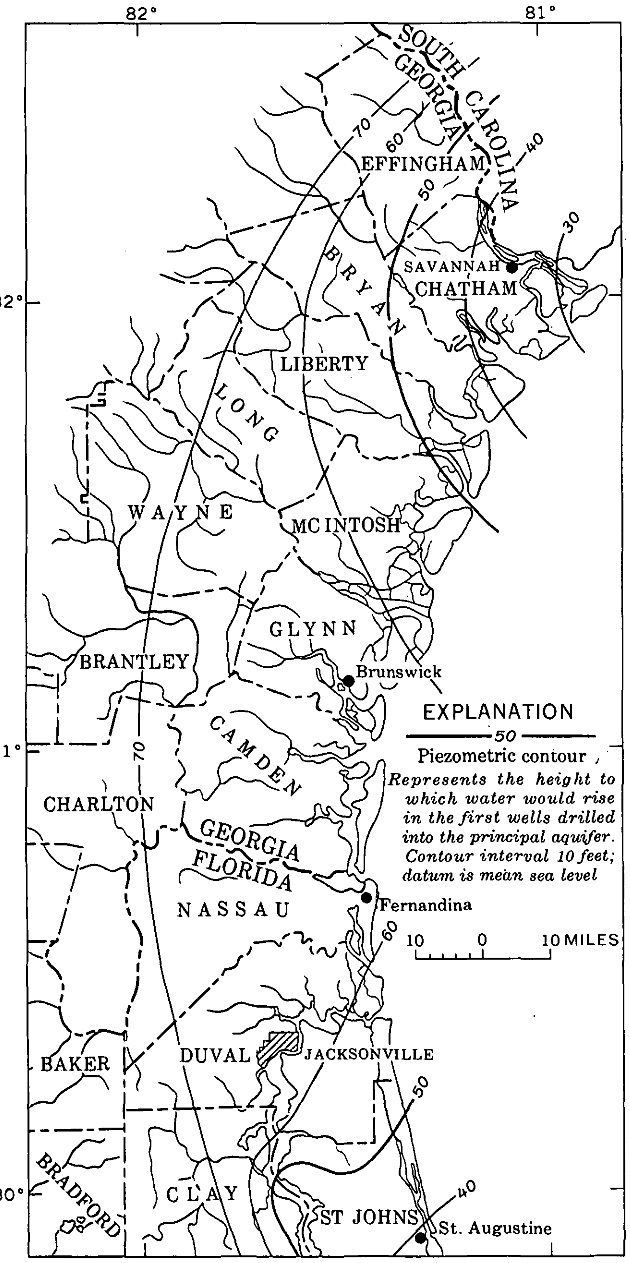

FIGURE 30.—Original piezometric surface of water in the principal artesian aquifer in the coastal area of Georgia and northeastern Florida about 1885. (By Warren in Stringfield and others, 1941, p. 706, and Warren, 1944.)

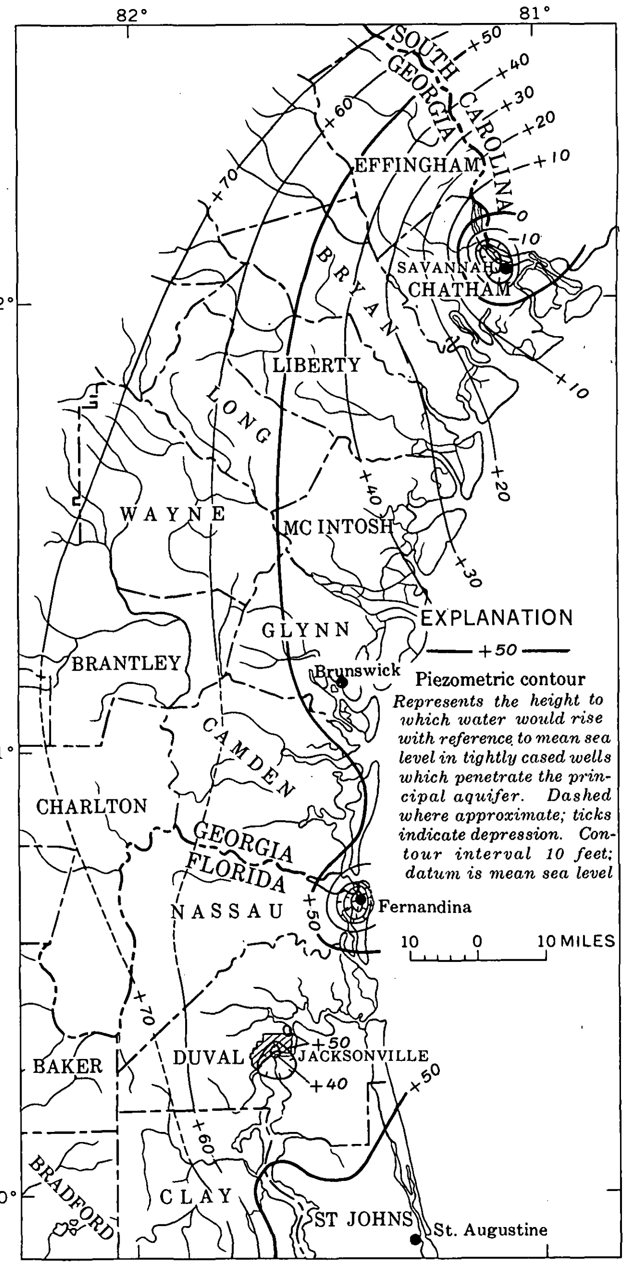

FIGURE 31.—Piezometric surface in the principal artesian aquifer in the coastal area of Georgia and northeastern Florida in 1940. (From Stringfield and others, 1941.)

reports on artesian water. Profiles of the piezometric surface across northern and north-central Florida and Marion County are shown in figures 32 and 33.

Details of the piezometric surface as mapped in local areas, in the reports cited, were used in the revised map for 1961 in the present report, figure 29, insofar as the scale would permit in Florida and Georgia. In Florida, the contours are based on a map prepared by Healy (1962a). Some features shown by the contours, as drawn by Healy, may be caused by conditions of the observation wells, such as subsurface leakage from the well, rather than being caused by natural conditions of the aquifer. For example, in southern Florida, the 50-foot contour as drawn by Healy in Okeechobee and Highlands and Glades Counties indicates a slight depression in the piezometric surface, which may be due to subsurface leakage from the observation wells measured rather than conditions in the aquifer.

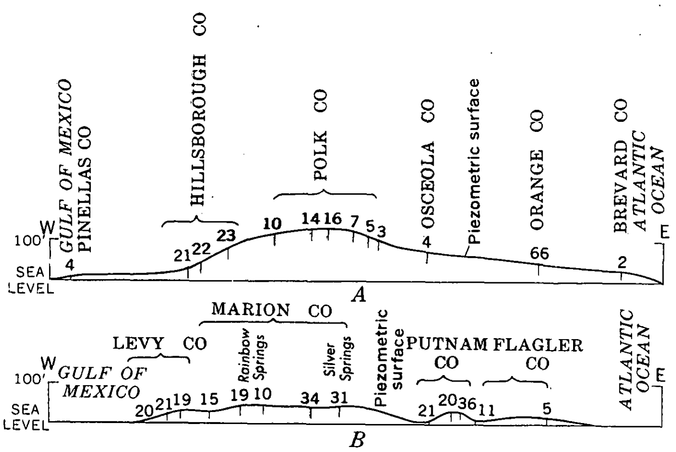

FIGURE 32.—Profiles of piezometric surfaces. *A*, Central Florida. *B*, North-central Florida. (Stringfield, 1936.)

The piezometric surface shows not only the effects of withdrawal of water from wells but also natural discharge areas, recharge areas, and the direction of the lateral movement of the water, which is from areas of recharge to areas of discharge. The high areas of the piezometric surface in general indicate recharge, and the low areas indicate discharge. However, recharge may occur in some of the areas of relatively low pressure, as the saddle in the Marion County area in the Florida peninsula.

The movement of water in the principal artesian aquifer is much more widespread than the movement in the overlying formations. Water that enters the aquifer at some places may travel more than 50 miles before it leaves the aquifer through a well or spring or by upward leakage into an overlying formation. The long distance through which artesian water may travel is generally recognized and may be responsible for the erroneous opinion (Mummey, 1943, p. 46) that water in the principal

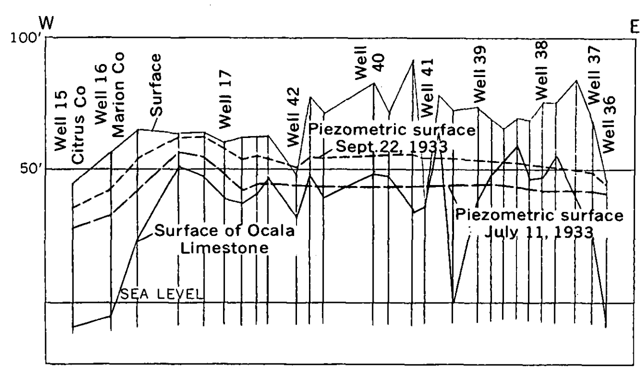

FIGURE 33.—Profile of piezometric surface in the southern part of Marion County, Fla. (Stringfield, 1936.)

artesian aquifer in Florida and Georgia comes from remote places such as the Appalachian Mountains, the Great Lakes, or the Rocky Mountains. Actually, all the fresh water in the principal artesian aquifer is from recharge within the area of this report. A small amount of the water may reach recharge areas from surface streams that rise outside the region. For convenience, the piezometric surface is discussed by areas beginning with Georgia and South Carolina. Florida is divided into 12 parts, as shown in the index map in figure 29.

GEORGIA AND SOUTH CAROLINA

In Georgia and South Carolina the piezometric surface slopes east and south from the recharge areas, where the aquifer is at or near the land surface. It extends in a broad belt from southwestern Georgia northeastward into South Carolina. The highest part of the piezometric surface is about 250 feet above sea level in a recharge area in Worth, Turner, and Wilcox Counties, Ga. As described by Warren (1944, p. 19) east of the 83d meridian, the artesian water appears to be moving chiefly toward the southeast, except in parts of Clinch and Echols Counties where some of the water may be moving southwestward to discharge areas in the Suwannee River, Ga. In the coastal counties north of Glynn County, however, the water moves east and northeast toward Savannah. This northeastward movement of water toward natural discharge areas northeast of Savannah may also be seen in the original piezometric surface (fig. 30). The movement of the water in adjacent parts of South Carolina is toward the southeast.

In Glynn and Camden Counties in southeastern Georgia, where the general movement of the water is toward the east, the original piezometric surface and subsurface information show no indication of submarine discharge areas near the coast. Therefore, the water moving to the east in these areas either discharges many miles offshore or moves northward to submarine discharge areas east of Savannah or southward to the submarine discharge area east of the Volusia County area in Florida. Part of the water may leave the aquifer by leakage into the overlying formations. A large submarine spring in this area, 2½ miles east of Crescent Beach, is one of the well-known points of submarine discharge of water from the artesian aquifer. If the relatively impervious beds of the Hawthorn Formation, which prevent or retard upward movement of the artesian water, are continuous between the coast of southeastern Georgia and the edge of the Continental Shelf (about 75 miles from the coast) and if salt water head were sufficient to prevent discharge of artesian water, there would be a flat isopiestic area of the piezometric surface between the areas of discharge to the north and to the south.

As stated by Warren (1944, p. 18), in some of the recharge areas where the aquifer is exposed in river valleys, such as the Savannah, Ogeechee, Ocmulgee, and Flint Rivers, part of the water that enters the aquifer in its area of recharge is discharged into these rivers and through springs. The piezometric surface in Screven County, Ga., indicates the discharge of water from the principal Tertiary artesian aquifer into the Savannah River.

Farther upstream in the valley of the Savannah River near the Fall Line, Siple (1960b, p. 163–166) has shown that the Cretaceous aquifer, which is recharged locally, discharges into the Savannah River in the area where clay beds have been removed. Siple showed this discharge by a map of the piezometric surface of the artesian water in the Tuscaloosa Formation of Cretaceous age. The lowest part of the piezometric surface in the area of discharge in the Savannah River valley has an oval shape, indicating upward leakage from the aquifer, as in the St. Johns River valley in the Volusia County area in Florida. In contrast, the contours of the piezometric surface in areas of discharge, as in the Savannah River valley in Screven County, Ga., have a V-shape where they cross the river. The contours point upstream, a fact indicating the aquifer is exposed, and part of the water moves laterally from the aquifer to the stream. Under these conditions, as on the Flint and Suwannee Rivers, the rivers reduce discharge of the aquifer during flood stages and receive water from the aquifer during low stages.

Blue Springs, 3.3 miles northwest of the Screven-Effingham County line at the west edge of the Savannah River valley in Screven County, Ga., is one of the places of discharge (Warren, 1944, p. 18, 19) which have a noticeable effect on the piezometric surface. The discharge through large limestone springs on both sides of the Ocmulgee River in Wilcox County and the northern part of Ben Hill County, Ga., and through large springs near the banks of the Flint River in Dougherty, Baker, and Decatur Counties is indicated locally by the relatively low areas of the piezometric surface. As stated by Warren south of Dougherty County in areas 10 to 15 miles wide bordering the Flint River, water levels in wells ending in the aquifer fluctuate through a range of 10 to 20 feet and are only slightly above river level during low stages of the river. This fluctuation indicates there is exchange of water between the aquifer and the river, as has been observed on the Suwannee River in Florida, where the direction of movement of the water in the aquifer depends on the stage of the river. At high stages, some water moves from the river to the aquifer, but at normal and low stages the movement is reversed.

A map of the piezometric surface of Dougherty County, Ga., by Wait (1963, p. 59 and pl. 2) shows two valleys in the pressure surface south of Albany and east of the Flint River. As suggested by Wait, these appear to represent cavernous zones in the limestone. The valleys appear to join a zone of underflow in the Flint River valley. Changes in stage in the Flint River are reflected by changes in ground-water levels as much as 3 miles from the river in Dougherty County (Wait, 1963, p. 62). The flow of Radium Springs about 4 miles south of Albany and a short distance east of Flint River is relatively small because the elevation of the outlet is only a few feet below the piezometric surface.

In southwestern Georgia, a map of the piezometric surface in Seminole, Decatur, and Grady Counties by C. W. Sever (1965, pl. 1) shows discharge from the aquifer to the Flint and Chattahoochee Rivers and Spring Creek. The map also shows recharge in interstream areas. The piezometric surface was more than 100 feet above sea level in the Valdosta area in Lowndes and Brooks Counties where there is local recharge through sinkholes and drainage wells, when mapped by Warren in 1942. Vorhis (1961, p. 123–129) reported that local withdrawal of water has lowered water levels in part of the area but that a large part of the artesian water moves southwestward into Florida. West of this area, the movement is southward to Florida.

The gradient of the piezometric surface southeastward between the 230-foot and 80-foot contours in Georgia is relatively steep and as much as 15 feet per mile, in comparison with relatively low gradients of less than a foot per mile between this area and the coast. The steepest gradient borders large recharge areas. H. E. LeGrand (written commun., 1963) suggested this steep gradient appears to be due in part to upward leakage into the beds overlying the principal aquifer. Some of this water is discharged into surface streams. The gradient decreases as the water moves under confining beds in the Hawthorn Formation. As stated by Warren (1944, p. 19), these low gradients probably indicate an increase in the permeability and thickness of the limestone.

Coastal Counties

The original piezometric surface in the coastal area of Georgia, southeastern South Carolina, and northeastern Florida, figure 30 (Warren, 1944, fig. 6) ranged from about 70 feet in the western part of the area to less than 30 feet in the Savannah area. In Georgia, north of Glynn County, the general direction of the movement of the water is northeastward toward a submarine discharge area east and northeast of Savannah. In southeastern South Carolina, the movement is toward the southeast to the discharge area. In St. Johns County in northeastern Florida, the movement is southeastward to a submarine discharge area.

A map of the coastal area in 1940 by Warren (1944, fig. 2) and Stringfield, Warren, and Cooper (1941, p. 704) figure 31, shows the piezometric surface was at least 70 feet above sea level in the western part of the coastal area and about 30 to 55 feet along the coast, except at Savannah and Fernandina. At Savannah, where the withdrawal of water was about 35 mgd, the piezometric surface was more than 30 feet below sea level and more than 70 feet below its original level; and at Fernandina, where the withdrawal was about 33 mgd, the piezometric surface was at or near sea level and as much as 60 feet below the original level. In contrast, at Brunswick, although the withdrawal of water was about 32 mgd, the piezometric surface was about 45 feet above sea level and only about 20 feet below its original level; and at Jacksonville, where the withdrawal of water was about 35 mgd, the piezometric surface was about 30 feet above sea level and only about 30 feet below the original artesian surface.

These differences in the effect of withdrawal on the piezometric surface show significant differences in the thickness or permeability of the aquifer, or both. Differences in permeability appear evident in comparing the Brunswick area with the Fernandina area where the thickness of the aquifer is approximately the same, as suggested in the discussion of the aquifer under Duval and Nassau Counties, Fla.

These differences in the water-bearing properties of the aquifer may also be noted in figure 29 by comparing the differences in the piezometric surface in these areas of large withdrawal in 1957 and 1958 when the withdrawal of water was 60 mgd in the Savannah area, 90 mgd in the Brunswick area, 52 mgd in the Fernandina area, and 26.6 mgd in the St. Marys area in southeastern Camden County in Georgia as reported by Stewart and Croft (1960, p. 84).

FLORIDA

For convenience in describing the piezometric surface in Florida, the State is divided into areas, each of which includes one or more major features. In the Florida peninsula, the areas are the same as those used by Stringfield (1936, pl. 12). The remainder of the State west of the Suwanee River is described as three areas. The general location of these areas is shown on the inset map (fig. 29).

Western Florida

In Florida, west of the Suwanee River, the piezometric surface slopes in general from Georgia and Alabama to the Gulf of Mexico. The contours of the piezometric surface are approximately parallel to the coast in a large part of the area. Along the Alabama State line, the piezometric surface is more than 120 feet above sea level in a recharge area in Jackson and Holmes Counties, Fla. It is as much as 130 feet above sea level in Santa Rosa County at the Alabama line, owing in part to recharge in Alabama. Along the coast west of Wakulla County, the piezometric surface rises above sea level to more than 60 feet in Santa Rosa County.

For convenience in describing the piezometric surface, the area west of the Suwannee River is divided into the Madison County area, the Wakulla County area, and the Jackson County area.

MADISON COUNTY AREA

In Madison, Taylor, and Lafayette Counties, the piezometric surface has the shape of a flat-topped ridge between the Suwannee River and Aucilla River. The piezometric surface ranges from about 80 feet above sea level at the Georgia State line to sea level along the Gulf of Mexico. The highest and widest part is adjacent to a high area of the piezometric surface in the Valdosta area, Georgia.

The aquifer is at or near the surface in most of the Madison County area. Recharge may occur throughout most of the area. Some recharge is through sinkholes. At the Georgia State line, movement of the water is southward into Florida. In Florida, the movement is from the crest of the ridge of the piezometric surface eastward into the Suwannee River and westward and southward to the Aucilla River and the Gulf of Mexico.

WAKULLA COUNTY AREA

In Wakulla and Leon and adjacent counties between the Aucilla and the Apalachicola Rivers, the piezometric surface generally ranges from 60 feet above sea level at the Georgia State line to sea level along the coast. The piezometric contours, on an unpublished map by James W. Yon, Jr., in Jefferson County and by Charles W. Hendry, Jr., in Leon County in 1961 on investigations of the Florida Geological Survey, show that the piezometric surface was a few feet higher in the northern parts of Jefferson and Leon Counties than when mapped by Stringfield in 1936. This change is probably due to seasonal fluctuations of water levels in the limestone. Hendry mapped a local area where the piezometric surface is as much as 100 feet above sea level in southwestern Leon County. There probably is recharge through sinkholes which are filled and covered with permeable sand. That feature was not discovered in the mapping in 1936 and also is not shown in a later map by Healy (1962a).

The aquifer is at or near the surface in the southern part of the Wakulla County area, but it is overlain by the Hawthorn Formation in the northern part where underground solution in the aquifer and collapse of the overlying Hawthorn Formation has formed lake basins east of the Ochlockonee River. As described by Sellards (1917, p. 118; 1910, p. 53–63), some of these basins, at times, drain into the aquifer through sinkholes when they are not clogged with silt and debris. In the area between the Ochlockonee and Apalachicola Rivers, the aquifer is overlain by the Hawthorn and younger formations of sufficient thickness to prevent sinkholes and lake basins.

A large part of the drainage in the southern part of the Wakulla County area is underground. Although there is local recharge, the discharge through the solution channels in the limestone is large. Part of the water discharges through Wakulla Spring into Wakulla River to the gulf. The discharge in the area causes a valley in the piezometric surface extending from the coast into Leon County. The cavern through which the water moves into the spring has been described by Olsen (1958, p. 396–403).

JACKSON COUNTY AREA

This area includes all Florida west of the Apalachicola River. The piezometric surface is more than 120 feet above sea level near the Georgia and Alabama State line in a recharge area in Jackson and Holmes Counties where the aquifer is at or near the land surface. The piezometric surface slopes, in general, toward the south. Along the coast it ranges from a few feet above sea level in Gulf County to at least 60 feet above sea level in Santa Rosa County, except in two areas of pumping where it is below sea level. The gradient of the piezometric surface is more uniform and steeper in the western part of the area, where some of the water-bearing formations of the aquifer grade from limestone and marl into sands and other clastic material. In the western part of the area, all the recharge appears to be in Alabama. In the eastern part of the area in Jackson and Holmes Counties, the piezometric surface shows the effects of springs and other discharge of the aquifer in the headwaters of the Chipola and Choctawhatchee Rivers where the aquifer is at or near the surface. There is recharge through sinkholes in Holmes, Washington, and northern Bay Counties. However, the discharge into Pinelog Creek, Holmes Creek, and other streams where the aquifer is near the surface forms a valley in the piezometric surface. Some of the discharge is from sinkhole lakes. The contours of the piezometric surface in Bay County suggest upward leakage of the aquifer along Bear Creek and the upper part of North Bay, even though the top of the aquifer (fig. 23) is at least 100 feet below sea level. Also, the shape of the contours in the vicinity of Choctawhatchee Bay in Walton County suggests upward leakage. It is entirely possible that a stream tributary to North Bay and Choctawhatchee Bay cut a channel in the material overlying the aquifer during a low stand of the sea in Pleistocene time. Pumping from wells has caused two cones of depression in the piezometric surface, one in the Panama City area and the other in the Fort Walton area.

Florida Peninsula

For convenience in describing the piezometric surface, the peninsula is divided into nine areas which are the same as those used in 1933 (Stringfield, 1936, p. 147–154) as shown on inset map (fig. 29). Although there may be recharge and discharge in all of the areas, those characterized chiefly by recharge are discussed first, followed by areas of large discharge.

In recharge areas in the central and northern parts of the peninsula, the piezometric surface is at least 80 feet above sea level in the northern part and more than 120 feet in the central area; but in the intervening saddle, it is only 40 to 50 feet above sea level, where there is discharge as well as recharge. The piezometric surface in the saddle area slopes to sea level on the gulf coast and to only a few feet above sea level in the St. Johns River valley. The high area of the piezometric surface in the central part slopes to a relatively flat area in southern Florida, south of Lake Okeechobee.

POLK COUNTY AREA

One of the most conspicuous features of the piezometric surface is in the central part of the peninsula, in Polk County and adjacent counties, where the surface has an elongated dome, a large part of which is 90 to 130 feet above sea level. This dome extends northward into Marion County at an altitude of about 50 feet; it extends southward into the southern part of the peninsula, where it merges about 50 feet above sea level into a relatively flat part of the piezometric surface. The total north-south extent is about 150 miles. The dome extends to the Atlantic coast on the east, where it has an altitude of 10 to 20 feet. On the west the dome merges into a relatively small saddle and dome-shaped feature in Pasco County and a valley in the Hillsborough County area. The dome extends to the Gulf of Mexico on the southwest. The total east-west extent is about 120 miles. Maps showing local details of the piezometric surface in this area are included in county reports cited on Brevard, Highlands, Hillsborough, Indian River, Manatee, Orange, Sarasota, and Seminole Counties.

The piezometric surface in the lake region of the upland indicates local recharge of the aquifer, largely in Polk, Highlands, and Lake Counties. Most of the recharge occurs in the lake region in Polk County, in the northwestern part of Highlands County, in the south-central part of Lake County, and in the lake region of Orange County. Part of the recharge at Orlando and in adjacent parts of Orange County is through drainage wells. In Highlands County, Kohout and Meyer (1959, p. 66) estimated that downward leakage from Lake Placid to the principal artesian aquifer averaged 2 to 3 inches per month during the first half of 1956. Pride and others (1961, p. 86, 87) reported evidence of recharge sinkholes in the Green Swamp area in Polk and Lake Counties.

The principal artesian aquifer is overlain by relatively impervious beds of the Hawthorn Formation in part of the Polk County recharge area. However, well records show that in parts of the area the Hawthorn is relatively thin or absent. Within the area are numerous lakes that occupy sinkholes now filled with sand that permit downward movement of the water. The log of a well at Davenport, Polk County (Stringfield, 1936, p. 148), at the edge of the depression of a filled sinkhole, indicates the presence of unconsolidated quartz sand to a depth of 110 feet. Phosphatic marl, probably representing the Hawthorn Formation, occurs in the interval between 110 and 120 feet, below which is soft limestone (Ocala) of the artesian aquifer. Under these conditions, local recharge of the Ocala Limestone may readily occur.

Artesian water moves laterally in all directions from the Polk County recharge area. It is the source of recharge to the artesian aquifer in the southern part of the peninsula and to other adjacent areas. As the water moves laterally toward the coast, some of it may leak upward into the overlying Hawthorn in the areas of artesian flow. In northeastern Brevard County, there is discharge of water to the Indian River and also to the St. Johns River north of Lake Poinsett as described by Brown, Kenner, Crooks, and Foster (1962, p. 74).

In western Manatee County, Peek (1958a, p. 45) described a low pressure area of the piezometric surface in the vicinity of Palma Sola and Palmetto that indicates upward leakage through irrigation wells and through unconsolidated material which filled valleys cut into the Hawthorn during a low stand of the Pleistocene sea.

PASCO COUNTY AREA

West of the Polk County area, in east-central Pasco County, the piezometric surface generally is at least 80 feet above sea level. The high area extends into Hernando County and slopes northward to a lower area in Citrus County. Westward on the Gulf of Mexico and southward on Tampa Bay, the piezometric surface slopes to an altitude of about 10 feet. On the east, it is bordered by a small saddle about 60 to 70 feet above sea level where it merges with the Polk County area, much higher than the saddle. A detailed map of the piezometric surface in Pasco and Hernando Counties by Wetterhall (1964) showed that the piezometric surface had an altitude of as much as 95 feet in east-central Pasco County and 100 feet at the Hernando County line in October 1960.

In most of the area, the top of the aquifer is at or near the ground surface and permits ground-water recharge. The Hawthorn Formation with relatively impervious material overlies the aquifer in east-central Pasco County and adjacent parts of Hernando County where the piezometric surface is at least 80 feet above sea level. However, within that area there are sinkholes and lakes occupying sinkholes through which recharge may take place, accounting in part for the high water levels in wells in the principal aquifer. The geology, topography, and ground-water conditions in some respects are comparable to those of Polk County area. Artesian water in the principal aquifer moves laterally in all directions from the central part of the recharge area. This recharge is the source of artesian water for the aquifer in most of Pasco County, parts of Hernando and Pinellas Counties, and the northwestern part of Hillsborough County.

Along the coast and in the Gulf of Mexico where the aquifer is at or near the floor of the gulf, the piezometric surface is less than 10 feet above sea level because of the large discharge of water into the gulf. W. S. Wetterhall (written commun., May 1961) has observed and photographed many springs in the Gulf of Mexico west of Pasco County, some of which are as much as 60 miles offshore. Photographs of these springs show that the water rises to the floor of the gulf through circular depressions, which may be submerged natural wells or sinkholes or other solution features.

A detailed map of the piezometric surface in Pinellas County (Heath and Smith, 1954, fig. 13) shows local recharge of the aquifer in Pinellas County, except in the northern part of the County where part of the recharge is from Hillsborough County. Heath and Smith reported that the rate of recharge is probably greatest in the area centered about a mile south of Coachman, where the piezometric surface has the shape of an elongated dome as much as 16 feet above sea level. Lakes in the area appear to occupy sinkholes and solution depressions. Tarpon Lake (formerly Lake Butler) occupies a large solution depression and at times discharges through an underground solution channel to Tarpon Springs and the Gulf of Mexico. Sinkholes filled with sand and other unconsolidated material may be covered by surficial sand in the Coachman area. Heath and Smith reported recharge through sinkholes in the eastern part of Dunedin.

PUTNAM COUNTY AREA

In the northwestern part of Putnam County and parts of Alachua, Clay, Columbia, Bradford, Baker, and Union Counties, the piezometric surface is about 50 to more than 90 feet above sea level. North of Putnam County, it forms a ridge 60 to 80 feet above sea level extending into Georgia. On the east, it slopes to the Atlantic Ocean to an altitude of about 20 to 40 feet. On the south, it merges with a broad saddle about 50 feet above sea level in Marion County. On the west it forms a broad area in Alachua County about 40 to 60 feet above sea level. Farther west it extends to the Suwannee River valley, where it ranges from a few feet to about 50 feet above sea level.

Clark, Musgrove, Menke, and Cagle (1962, p. 78–82) included a map and description of the piezometric surface in Alachua, Bradford, Clay, and Union Counties showing the recharge to the piezometric surface in part of the Putnam County area. Meyer (1962) included a map and description of the piezometric surface in Columbia County.

The principal artesian aquifer is not exposed where high areas of piezometric surface show local recharge, but typical sinkhole topography affords conditions favorable for recharge. Clark, Musgrove, Menke, and Cagle (1963) showed the conditions of recharge to the aquifer through sinkholes and the relation of the piezometric surface and water table to the lake levels in the southwestern part of Clay County. In the southern and western parts of the area, recharge is through sinkholes or directly to the aquifer where it is at or near the surface. In the eastern part of Baker County in the northern part of the area, although the piezometric surface of water in the principal artesian aquifer is at least 70 feet above sea level, little or no recharge takes place locally because the aquifer is overlain by relatively impervious beds of the Hawthorn Formation. However, water is supplied through a recharge area in parts of Columbia County, as well as in Baker County and in Georgia.

In the eastern part of Baker County, static water levels in wells in the middle and upper part of the Hawthorn Formation will rise higher than the level in the aquifer. However, in Duval and Nassau Counties, the pressure of the artesian water of the Hawthorn is less than that in the principal artesian aquifer except in areas, such as Fernandina, where withdrawal of water has caused the artesian levels to decline below that of the Hawthorn. Cones of depression in the piezometric surface in the Jacksonville area in Duval County and Fernandina area in Nassau County, as shown by Leve (1961a, p. 14) and in figure 31, are caused by withdrawal of water from wells.

A small local depression in the piezometric surface about 30 to 40 feet above sea level is present at Green Cove Springs and vicinity in Clay County. The withdrawal of water from wells appears to be insufficient to cause the depression. However, withdrawal of water and subsurface leakage from wells together may be sufficient to account for it. The flow of Green Cove Springs doubtless affects the head of water in the Hawthorn in the vicinity of the springs. Stringfield (1936, p. 150) was of the opinion that the spring did not directly affect the head in the principal aquifer. However, the chemical quality of the water (Ferguson and others, 1947, p. 60) is similar to that from the aquifer (Black and Brown, 1951, p. 39). Foster (1962, p. 7–8) showed large subsurface leakage from the principal aquifer to the Hawthorn and younger formations through wells. Therefore, it seems likely that some of the water of the spring is from that aquifer.

In the southern part of the Putnam County area, the water in the principal artesian aquifer moves laterally from the recharge area into Putnam, Alachua, Marion, Clay, and Bradford Counties. In the northern part of the area some of the water moves to the east into Nassau and Duval Counties and some of it moves to the west toward the Suwannee River. The hydraulic gradient in the eastern part of Nassau and Duval Counties is relatively low except in areas where the piezometric surface has been depressed by heavy withdrawal of water from wells.

MARION COUNTY AREA

In Marion County the piezometric surface forms a broad saddle about 40 to 50 feet above sea level between the Putnam County area on the north and the Polk County area on the south. In this area the top of the aquifer (the Ocala Limestone) is at or near the surface, and sinkholes afford favorable conditions for recharge. The recharge doubtless is large, and also large quantities of water move into the area from the Polk County area and the Putnam County area. There are no surface streams in part of the area where all of the drainage is underground. As the limestone is permeable and cavernous, water moves through it freely. During and after periods of large rainfall, part of the saddle area of the piezometric surface is as much as 10 feet higher than at normal times. Under such conditions, the 50-foot contour lines, instead of closing on the north and south of the saddle as mapped in figure 29, will extend along the eastern and western parts of the saddle and connect the Polk County area with the Putnam County area.

Marion County is also an area of very large discharge. It furnishes water for Silver Springs and Rainbow Springs (formerly Blue Springs), two of the largest springs in the State. The discharge of these springs having a combined maximum flow of about 2,097 cubic feet per second (1,255 mgd) and a minimum of 1,136 cfs (734 mgd) in part causes the saddle in the piezometric surface. Part of the water in the aquifer flows eastward and is discharged in the St. Johns River valley in the Volusia County area, and a large part flows westward from the saddle area to the Gulf of Mexico.

VOLUSIA COUNTY AREA

Volusia, Flagler, and parts of adjacent counties form an area of recharge and discharge of the principal artesian aquifer, although the aquifer is not exposed at the surface. Recharge through sinkholes and the lakes occupying old sinkholes was recognized and mapped in 1933 (Stringfield, 1936, p. 152). The data obtained at that time revealed a recharge area where the piezometric surface was 20 to 30 feet above sea level in a narrow district, extending from the southeastern part of Putnam County into the northwestern part of Volusia County, between St. Johns River valley and Crescent Lake. A similar area, including De Land, Orange City, and Lake Helen in Volusia County, east of the St. Johns River valley was recognized, but records were not available to map the piezometric surface. A map in 1955 (Wyrick, 1960, p. 26) showed that there are high areas of the piezometric surface, as much as 35 feet above sea level, in northwestern Volusia County. This map also shows that the piezometric surface has the shape of a broad ridge extending from Flagler County on the north through the central part of Volusia County to Seminole County. The highest part of the ridge in the piezometric surface is about 40 feet above sea level. It slopes to about 10 feet above sea level on the Atlantic coast where there is submarine discharge from the aquifer. It slopes to the south and west to about 15 feet above sea level in the St. Johns River valley, where there is upward leakage.

In the southeastern part of Putnam County, the piezometric surface has the shape of a north-south ridge between Crescent Lake and the St. Johns River. A detailed map of the county by Leve (1958, p. 16) showed that the ridge is as much as 60 feet above sea level northeast of Pomona Park. To the east, the piezometric surface slopes to about 30 feet above sea level. On the west, it slopes to less than 10 feet above sea level in the St. Johns River valley, where there is upward leakage. These features also are shown on a map of the piezometric surface (Bermes and others, 1963) in Flagler, Putnam, and St. Johns Counties.

As described by Wyrick, the high areas of the piezometric surface are in areas where there are sinkholes and sinkhole lakes through which recharge occurs. Sinkhole topography extends several miles north and south of De Land on the Penholoway terrace and also along the terrace near Pierson and Seville. Wyrick (1960, p. 9–10) showed these terraces on a map and a profile from the St. Johns River to the Atlantic Ocean, across Volusia County.

Wyrick reported that, in sinkholes, surface deposits in some places in De Land have slumped as much as 40 feet below the level of the Penholoway terrace, which is about 70 feet above sea level. It is entirely possible that east of Penholoway terrace sinkholes may have formed but were filled by sand and other material at the time the sea covered that area.

As stated by Wyrick (1960, p. 27) most, if not all, of the fresh artesian water in Volusia County is from recharge areas within the county. Areas of low pressure surround the recharge areas. This low pressure is caused in part by discharge of ground water through springs in the St. Johns River valley and submarine discharge through springs and sinkholes in the Atlantic Ocean.

A map of Flagler County by Bermes (1958a, p. 17) in 1956 showed the piezometric surface to be relatively flat, ranging from about 5 feet to more than 15 feet above sea level. The lowest point is in an area about midway between Bunnell and Crescent Lake, where relatively large quantities of water were being withdrawn for irrigation of truck crops. The contour interval of the piezometric map is too large to show it, but Bermes reported some local recharge in areas around Espanola, northwest of Bunnell, and around Favorita, southeast of Bunnell. Although he believed the recharge is due to downward leakage from the nonartesian aquifer, it seems more likely that recharge is through sinkholes which were filled and covered with unconsolidated deposits during Pleistocene time. The relatively low chloride content of the artesian water (25 ppm or less), which is surrounded by artesian water with a higher chloride content in the Espanola area, indicates that local recharge has flushed the high-chloride water from the aquifer in this area.

The piezometric surface is relatively low in an area southwest of Bunnell surrounding Haw Creek and its tributaries, indicating upward leakage into these streams. Bermes (1958a, p. 17) reported that several small springs in Haw Creek and Sweetwater Branch yield highly mineralized water from the aquifer. The part of this area in which the piezometric surface is lowest is generally the same as that in which the chloride content is 750 to more than 2,000 ppm in the upper part of the aquifer, the top of which is about 100 feet below the land surface. This fact suggests that in addition to upward leakage decreasing the head, the difference in the specific gravity between the high-chloride water and the fresh water in the aquifer may cause the water levels to stand lower than in adjacent areas.

The piezometric surface in Seminole County on the northeast side of the Polk County area merges with the Volusia County area in the St. Johns River valley. Local recharge occurs in the areas of sinkhole lakes as described by Heath and Barraclough (1954, p. 22). However, part of the artesian water of the Polk County area moves northeastward from Orange County into Seminole County. Although part of the artesian water of the principal aquifer discharges in the St. Johns River valley, there has not been sufficient discharge and time for all of the salt water in the aquifer to be flushed out. The relation of fresh artesian water to the salt water in some parts of Seminole County is similar to that in Volusia County where local recharge through sinkhole lakes has flushed out the salt water, resulting in a fresh-water area surrounded by salt water.

The piezometric surface slopes from about 60 feet above sea level in the southwest corner of Seminole County northeastward to about 15 to 20 feet above sea level in the St. Johns River valley. The details are shown on maps by Heath and Barraclough (1954) and Barraclough (1962).

HILLSBOROUGH COUNTY AREA

The piezometric surface in Hillsborough County ranges from less than 10 feet on Tampa Bay to more than 60 feet where it merges with the Pasco County area and more than 70 feet in the Polk County area. At Port Tampa, it is about 3 feet above sea level (Stringfield, 1936, p. 152). From Tampa and vicinity northeastward to Pasco County the piezometric surface has the shape of a valley that heads in a saddle in Pasco County, between the Pasco County and Polk County areas. This valley is caused in part by leakage of artesian water through springs in the outcrops of the Tampa Limestone, which is the top of the aquifer along the valley of the Hillsborough River. The largest of these springs is Sulphur Springs near Tampa. One of the best known of the smaller ones is Crystal Springs near the town of Crystal Springs. Also, the piezometric surface shows leakage of artesian water into the Alafia River and Tampa Bay.

Wetterhall (in Menke and others, 1961, p. 83–86) showed that the piezometric surface in 1958 ranged from about 100 feet above sea level in the northeastern part of Hillsborough County to a few feet above sea level on Tampa Bay. As stated by Wetterhall, the piezometric surface slopes toward Tampa Bay from the high recharge areas of the piezometric surface in Polk and Pasco Counties. In his discussion of the northwestern part of Hillsborough County, Wetterhall suggested that a major fault shown by

Vernon (1951, fig. 11) may affect the shape of the piezometric surface. However, the writer can find no evidence that the movement of the water or shape of the piezometric surface is affected by a fault.

A map of the piezometric surface by Peek (1959b, p. 52) for the Ruskin area in southwestern Hillsborough County showed that the piezometric surface ranges from sea level on Tampa Bay to more than 40 feet above sea level eastward. Along the coast from Alafia River southward to Manatee County the piezometric surface increases in altitude from sea level to about 16 feet above sea level at the Manatee County line.

CITRUS COUNTY AREA

In Citrus County and adjacent parts of Hernando, Sumter, Marion, and Levy Counties, the piezometric surface slopes from an altitude of about 40 feet in the eastern part of the area to less than 5 feet in the western part, on the gulf coast. The Ocala Limestone or Suwannee Limestone of the principal artesian aquifer is at or near the surface, and sinkholes are well formed, especially in Citrus County, facilitating local recharge. The aquifer is permeable and cavernous and thus permits fairly free movement of the water. The general direction of movement is toward the Gulf of Mexico, and most of the water discharges as springs along the coast or on the floor of the gulf. Some water from the Marion County, Polk County, and Pasco County areas moves into the Citrus County area. The alinement of some of the sinkholes in an east-west direction indicates the course of some of the underground streams. Such an alinement might be expected because the contours representing the piezometric surface show that the movement of the water is toward the west. In the northern part of Citrus County along the Withlacoochee River, the ground-water level during normal stages is about the same as the water level in the river. During flood stages, the river may lose water to the aquifer.

SUWANNEE RIVER AREA

This area is one of large discharge of artesian water into the Suwannee and Santa Fe Rivers. The piezometric surface has the shape of a valley along the Suwannee River. The ground-water level along the stream is generally about the same as the water level in the river. The piezometric surface generally slopes from 50 to 60 feet above sea level near the State line on the north to 10 feet above sea level on the Gulf of Mexico. On both sides of the valley, it rises to at least 50 feet above sea level. The gradient on the east side, however, is lower than that on the west, indicating that the aquifer is more permeable and more cavernous on the east side than on the west. Nevin Hoy (written commun., 1962) believed that the steep gradient on the west side is due to a larger volume of water moving through that section than on the east side of the river. Oligocene and Eocene limestones of the principal artesian aquifer are present at or near the surface in this area and thus receive recharge. During low stages of the Suwannee River, its flow is largely derived from ground water, but during flood stages it loses some water to the aquifer. These relations between surface water and ground water also exist along the lower course of the Santa Fe River, a tributary of the Suwannee.

In Suwannee County about 0.2 mile west of Falmouth and 3.5 miles southeast of the Suwannee River at Ellaville, a small section of the roof of an underground stream has collapsed, and the stream is exposed. This exposure is known as Falmouth Spring. During normal stages of the Suwannee River, the water level of Falmouth Spring is higher than the river, and water from the spring flows westward to the river. However, during flood stages the river is somewhat higher than the spring and contributes water to the underground stream, and the flow of Falmouth Spring is reversed. When visited by the writer in 1930, 1961, and 1963, the water appeared to be under sufficient artesian pressure so that the water level in the spring stood above the underground channel which feeds it.

SOUTHERN FLORIDA

The piezometric surface in southern Florida ranges from a few feet to about 50 feet above sea level. In the southern part of the area only a few wells penetrate the lower part of the Hawthorn Formation and the underlying rocks, and, therefore, only a few control points are available to represent the piezometric surface. When the piezometric surface was mapped in 1934 (Stringfield, 1936, p. 154), the available records indicated that the altitude of the piezometric surface was approximately sea level on the Florida Keys and about 40 feet or more at Miami and that it was about 50 feet at the south end of Lake Okeechobee.

Later investigations (Lichtler, 1960, p. 40) showed the 50-foot contour line farther south of Lake Okeechobee than on the map prepared in 1934. McCoy (1962) included a map and discussion of the piezometric surface in Collier County. The 50-foot contour line shown by Healy (1962a) suggests upward leakage from the aquifer or differences in transmissibility of the aquifer in Okeechobee, Highlands, and Glades Counties. This feature may actually be due to subsurface leakage through one or more of the observation wells. The water level or shut-in pressure on such wells is less than the pressure in a well with adequate casing which would prevent subsurface leakage.

The principal artesian aquifer is deeply buried in southern Florida, and no recharge occurs locally. Part of the water enters the aquifer through sinkholes and lakes occupying sinkholes in the Polk County area, moves southward, and spreads out toward the coast. With this increase in cross section of the aquifer through which the water moves, the gradient decreases from about 3 feet per mile to less than about 0.5 foot per mile. The gradient increases in the coastal counties. That increase may be attributed to a decrease in the thickness and permeability of the aquifer and submarine discharge of the artesian water. There seems to be submarine discharge through some outcrops of the Atlantic coast. The aquifer is not known to crop out in the Gulf of Mexico west of southern Florida, but there probably is upward leakage of artesian water.

RELATION OF STRUCTURE TO SOLUTION CAVITIES AND MOVEMENT OF WATER IN LIMESTONE

Where a water-bearing formation is overlain and underlain by relatively impervious beds, water tends to move laterally through the formation from areas of recharge to areas of discharge. If the formation is folded into anticlines or other structures, water may move approximately parallel to the dip of the overlying and underlying confining beds. Under these conditions the water may move downdip from recharge on the crest of an anticline and (or) updip in the flank of an adjacent syncline to a discharge area, if conditions of recharge and discharge are favorable as described by Reeves (1932) and Cady (1936) in the Shenandoah Valley of Virginia. In any case, the general direction would be parallel to the dip. Breathing Cave, described by Deike (1960), apparently was formed downdip; however, in his report on caverns of Virginia, McGill (1933, p. 14) found the main passages of caverns chiefly along the strike of the water-bearing limestone.

In limestone or other soluble rocks, solution cavities form in zones more or less parallel to the direction of movement of the water. Under some of the conditions given in the preceding paragraph, the zones would be approximately parallel to the dip of the water-bearing formations. In many parts of the Coastal Plain the artesian aquifer is exposed at the surface, and it dips toward the coast beneath relatively impervious beds that prevent upward movement of water. In these areas, the water moves downgradient which is also downdip. However, where there is no discharge area downdip, the water will move in the direction of a discharge area, even in a direction other than that of the dip.

Regional structures, such as the Ocala uplift in Florida, have been a factor in bringing the limestone nearer the land surface. In the areas where the Hawthorn Formation is thin or absent, solution has been most active in forming many sinkholes and natural wells. The sinkhole topography caused the early investigators to suspect a major uplift in north-central Florida. Although the major structures which extend to the surface, such as the Ocala uplift, have influenced the formation of sinkholes and solution channels in limestone of the principal artesian aquifers, the direction of movement of the artesian water is independent of the structure. For example, in the Polk County recharge area in central Florida on the south flank of the Ocala uplift, lateral movement of the water takes place in all directions from the central part of the recharge area; the geologic structure in this case has little or no effect on the movement.

Joints or fractures and bedding planes may have a pronounced effect on the solution patterns and the movement of water in limestone and other carbonate rocks. In the Tertiary limestone of the southeastern States, the joints are generally vertical, and the bedding planes are approximately horizontal or have low dips. Some of the limestone, such as the upper part of the Ocala Limestone, is chalky without bedding planes but has joints and fractures.

Most of the vertical pipes or natural wells—which are also known as vertical shafts, dome pits, and chimneys—in caves apparently form at the intersection of two sets of joints. Long narrow vertical openings may form along joint planes. Vernon (1951, p. 48) showed a fundamental regional pattern made by the regular formation of two systems of fractures trending northeast-southwest and northwest-southeast in the northern part of the Florida peninsula. These or similar joint patterns are present in the limestone in other parts of this region. Although the extent of formation of these joints with depth is not known, they probably extend through the aquifer.

Faults may affect the lateral movement of the water and the solution of the limestone, especially if water-bearing beds are faulted against relatively impervious beds that block the lateral movement. Some fault zones may serve as avenues through which water may move. Sayre and Bennett (1942, p. 19–27) concluded that the Balcones fault zone in the Coastal Plain in Texas affects the movement of the water in the Edwards Limestone. Welder and Reeves (1962, p. 41) recognized the movement of water in solution channels along faults in the Balcones fault zone in Uvalde County, Tex. DeCook (1963, p. 48, 52) reported that, in the region of the Balcones fault zone in Hays County, Tex., faults form conduits for ground-water movement at some places and in other places form barriers. He also reported some sinkholes along faults. Lobeck (1939, p. 132) showed how solution resulting in sinks may occur along a fault. If faulting occurs after solution channels have been formed, the channels may be offset vertically to an extent that affects the movement of the water. However, Theis (1936, p. 34) found that in limestone in south-central Tennessee, the influence of faults on movement of ground water appeared to be negligible. In a study of the origin of caves in folded limestone of the Appalachian region, Davies (1960) concluded that the passages are joint controlled and that faults exert very little influence. Passages rarely follow faults for any great distance.

The writer believes that faults in the thick sequences of limestone of Tertiary age in the southeastern United States generally have little or no effect on the quality and movement of the artesian water in the area of this report, although some of the investigators report areas in which they believe faults affect the quality and movement of the water.

C. W. Sever, Jr. (written commun., 1961) and Callahan (1964, p. 33) believed that the steep gradient of the piezometric surface in Georgia (fig. 28), extending from Berrien and Coffee Counties northeastward to Toombs County, is influenced by one or more faults. However, the writer believes that the change in gradient is caused by recharge and discharge relationships and by changes in permeability and thickness of the limestone.

D. W. Brown, W. E. Kenner, and Eugene Brown (1957, p. 29) showed the Hawthorn Formation in Brevard County, Fla., faulted against the water-bearing limestone of the principal artesian aquifer. They concluded that the fault affects the movement and quality of the water.

Lichtler (1960, p. 16–17, 35) reported that the principal artesian aquifer is displaced as much as 300 to 400 feet by one or more faults parallel to and about 5 miles west of the Atlantic coast in Martin County, Fla. The depth to the aquifer is greater on the downthrown block (east side of the zone of displacement) than on the upthrown (west side), but displacement does not seem to affect the piezometric surface.

Bermes (1958b, p. 10–11) showed that the artesian aquifer below the Hawthorn Formation is displaced by faulting in Indian River County. However, the writer finds no conclusive evidence that the movement of the artesian water is affected by faults.

A north-south fault reported by Bermes, Leve, and Tarver (1963, p. 34, 42) in the St. Johns River valley in southeastern Putnam County seems to have no effect on the lateral movement and quality of the water. Solution of the limestone may have been more rapid along the fault, but the available information does not seem to confirm this.

Barraclough (1962, p. 18) and Wyrick (1960, p. 11) reported faults in Seminole and Volusia Counties, Fla., respectively, that seem to be part of major fault systems described by Vernon (1951, p. 53–61, pl. 3) in north-central Florida on the Ocala uplift. However, the salt water and direction of movement of the water may result from factors other than faults.

Under some conditions, the lateral movement of the water may be influenced by bedding planes. Barr (1961, p. 12–13) reported that caves in Tennessee have at least two major patterns depending upon the inclination of the beds in which the caves are formed. In strata of low dip, the floors and ceilings of such caves are essentially horizontal. In strata that are steeply dipping or moderately inclined, the caves have floors and ceilings which are inclined with the dip and in which the major passages tend to follow the strike. In these areas, different levels of caves and channels are not superimposed as a rule but are downdip from, and usually parallel to, other levels. Barr found only one example of a cave in steeply dipping limestone along a fault zone—New River Cave in Giles County, Va. Five caves have been formed along the axes of small anticlines.

Carson (1964) reported that in Tolleys Cave, Va., on the northwest limb of a jointed and faulted syncline, the cavern passages, in general, parallel the dominant trend of the joints. A photograph of the lower entrance shows a passage approximately parallel to the strike of the beds.

In a study of caves in West Virginia, Davies (1949, p. 17) stated that in both horizontal and folded limestone, caves that have more than one level of passages commonly occur. Where vertical control is along a set of vertical joints, different levels may coincide in pattern. In thick limestones that cap the surface of the upland and have little or no dip, caves have simple patterns consisting of single or, in some cases, several parallel passages with few side passages. The vertical shafts and dome pits are abundant in the areas especially where the limestones flank higher ridges. Davies concluded that caves show no consistent relation to the dip of formations. Steeles Cave in West Virginia exhibits a trend along the dip slope, but two of its branches cross distinct anticlines and synclines. He found that the connections between levels in caves were generally by vertical shafts and crevices. Some broad passages are connected by cliffs. The steep vertical slopes of the cliffs are often modified by slabs and rocks which fall from the roof of the cave. Also, clay deposits may modify the steep slopes.

Davies found that the pattern of caves is primarily controlled by joints, the individual pattern of each cave depending on its relation to local rock structure. Also several caves along St. Clair fault in West Virginia indicate that the fault is secondary to joints in controlling the pattern. Passages follow faults for short distances, reverting to joints for the greater part of the caves.

Lobeck (1939, p. 140) showed five levels of passageways and some of the principal vertical shafts in Mammoth Cave, Ky., where the limestone dips gently westward toward Green River. The lowest level is Echo River, an underground tributary of the Green River west of the cave. Lobeck suggested that the different levels of the cave correspond approximately with the more soluble bedding planes of the limestone. Perhaps a more important factor is the difference in levels corresponding with different levels of the top of the zone of saturation. These levels changed as the elevation of points of discharge changed in Green River. The limestone on the west side of Green River does not have a cave system like Mammoth Cave on the east side because the only discharge area for water entering the limestone on the west side is into the river. Therefore, water does not move downdip into the limestone west of the river.

Although differences in the solubility of the limestone as suggested by Lobeck may affect the level at which lateral channels form, changes in the elevation of the discharge points are believed to be one of the principal controlling factors. For example, W. D. Johnston, Jr. (1933, p. 67–69, 365) showed a solution channel in Alabama Caverns in Alabama which has a channel above and below a bed of siliceous dolomite that forms a bridge at one place in the channel. Its resistance to solution is evident in some parts of the cave where most of the bed has been removed, but the resistant remnants project from the walls of the cave. Under these conditions its resistance to solution and erosion was not sufficient to control the altitude at which the channel formed.

However, where a limestone aquifer is underlain by a sufficient thickness of relatively impervious beds, the structure of the aquifer and underlying beds may affect the movement of the water. For example, in the Huntsville area in northern Alabama where cavernous limestone of Paleozoic age overlies the Chattanooga Shale, LaMoreaux, Swindle, and Lanphere (1950, p. 23) concluded that the most important structural features governing the movement of ground water in the area are extensive joints and bedding planes. Later, LaMoreaux and Powell (1960, p. 370) found that not only joints and bedding planes but also local folds and regional dips influence the direction of movement of the water under the control of gravity and in the direction of the regional dip of beds in the area where the Chattanooga Shale serves as a relatively impervious floor above which the general movement of the water is to the south and southeast. Under these conditions, the solution of the limestone was most rapid in the trough of a syncline which is parallel to the regional structure. This solution of limestone and collapse of overlying surficial material may explain the unique combination of a valley forming on a syncline.

In illustrating solution in folded and faulted limestone, Lobeck (1939, p. 132) showed surface streams parallel to and in the trough of synclines in limestone, but he showed that most of the solution openings are outside the valleys. Generally, valleys parallel to folds are expected on anticlines (as the Sequatchie anticline in eastern Tennessee and northern Alabama) where the less resistant and soluble rocks are nearer the surface than in synclines. Another example of solution occurring in the limestone where it is at or near the surface on a geologic structure may be seen on the Ocala uplift in north-central Florida where solution cavities and sinkholes are numerous.

Most of the caves and solution channels in the area of the present report are below the zone of saturation and therefore are not as accessible as those above the water table. Available records of wells and other subsurface information are not yet sufficient to give many of the details of the relation of structure to movement of water, solution channels, and cave patterns in limestone. However, the information on the geology and hydrology and caves of the area leads to the conclusion that joints in the limestone and the position of recharge and discharge areas with reference to each other and to sea level have been major factors in controlling the direction of movement of the water (both artesian and nonartesian) in the limestone and in controlling the different levels at which solution channels have formed. In a few places, movement of water and solution of the limestone may have occurred locally along faults.

As more detailed subsurface information is obtained, a better understanding of the solution patterns, both vertical and lateral, will become available. Apparently, the general direction of many of the solution channels is parallel to the movement of the water as shown by maps of the piezometric surface. Locally, the lateral channels may follow joints, but the general direction is downgradient at right angles to the contour lines.

Where streams such as the Suwannee and Flint Rivers have cut channels in the limestone, the direction of movement of the water is to or from the river in solution channels; some of the solution channels are approximately perpendicular to the river, as shown by a channel exposed at Falmouth Spring, Fla. The underground channels, approximately parallel to the direction of flow, probably are connected with a network of cross channels or by permeable limestone because most if not all wells in the limestone yield water and also because static water levels, in wells not affected by pumping, are approximately the same in a given area. The alinement of sinkholes in an east-west direction in Citrus County, Fla., indicates that the course of the underground channels is in the same general direction as movement of the water, that is, to the west. Some sinkhole basins occupied by lakes, as in the Orlando area, Florida, have shapes suggesting they formed in a meander of an underground stream.

CHEMICAL QUALITY OF ARTESIAN WATER

In Florida, reports by Collins and Howard (1928) and Black and Brown (1951) contain analyses of ground- and surface-water samples collected throughout the State. A report by Parker, Ferguson, and Love (1955) contains many analyses of ground and surface water in southeastern Florida. A report by Ferguson, Lingham, Love, and Vernon (1947) contains chemical analyses of water from many springs in Florida. Ground-water reports by counties, as cited, include many analyses. All these reports contain analyses of water from the principal artesian aquifer as well as the overlying aquifers.

In Georgia reports by Wait (1960a) and Warren (1944) and local reports by counties and areas contain analyses of water from the principal artesian aquifer. Cooke (1936) reported analyses of ground water in southeastern South Carolina. Hastings (in Carter and others, 1949, p. 244–263) included analyses of ground water in southeastern Alabama. In that report LaMoreaux discussed the quality of water in the water-bearing formations. Cagle and Floyd (1957) included analyses of samples of ground water from Escambia County, Ala.

Water falling in the form of rain or snow generally contains little or no dissolved mineral matter. Its content is usually chiefly gases of the atmosphere—especially oxygen and carbon dioxide. However, there are exceptions such as those in coastal areas where the chloride content of rainwater from storms is reported to be as much as several hundred parts per million.

Water has a solvent action on the water-bearing formations when it comes in contact with, and moves into, these formations. This solvent action is greatly increased by carbon dioxide, absorbed from the atmosphere and from the soil where it is formed by organic processes. The amount and character of the dissolved mineral matter depend upon the chemical and physical composition of the material through which the water passes, the temperature, pressure, and duration of contact, as well as the presence of sea water or other salt water in the formations.

The mineral constituents shown in the analyses are reported as parts per million, which can be converted to grains per U.S. gallon by dividing by 17.12. One part per million is equivalent to one milligram of a given constituent in one liter of water or 8.34 pounds of the constituent per million gallons of water. Many of the analyses include the following: total dissolved solids, silica, iron, calcium and magnesium, strontium, sodium and potassium, bicarbonate, sulfate, chloride, nitrate, pH, hydrogen sulfide, color, and total hardness. Three natural radioactive elements—tritium, radium, and uranium—as well as gross radioactivity are included in a few analyses.

In general ground water in the report area may be placed in the following types:

1. Calcium bicarbonate water whose hardness generally ranges from 50 ppm to several hundred parts per million. Most of the artesian water

is of this type except in southern Florida and some of the coastal areas where the fresh artesian water is mixed with remnants of sea water that has not been flushed from the aquifer. The hardness of the salt water is much higher than that of other artesian water.

2. Calcium sulfate water whose hardness is as much as 900 ppm, as reported by Black and Brown (1951, p. 77) for Manatee County, Fla. In southwestern and southern Florida the artesian water has relatively large amounts of calcium sulfate which apparently is from gypsum or anhydrite in the aquifer.
3. Sodium bicarbonate water whose hardness is less than 50 ppm. The artesian water of the principal aquifer in Okaloosa, Santa Rosa, and Escambia Counties, Fla., and adjacent parts of Alabama is of this type.
4. Sodium chloride water in which the fresh artesian water is mixed with salt water.
5. Water in surficial sand formations having total dissolved solids less than 50 ppm.

All with the exception of type 3 are represented in a general way by the analyses of samples of water from springs, as given and discussed in that part of this report.

TOTAL DISSOLVED SOLIDS

The total dissolved solids indicates approximately the amount of dissolved mineral matter in the water. As stated by Black and Brown (1951, p. 10) the total obtained by evaporating a known quantity of water to dryness and weighing the residue after it has been dried at a definite temperature includes any organic material present as well as some water of crystallization. In the case of high bicarbonate water, common in the area of this report, the total reported will be considerably less than the sum of the constituents because during the process of evaporation the bicarbonate ion is broken down with loss of water and carbon dioxide. This difference will be directly proportional to the total alkalinity of the water.

Water having less than 500 ppm of total dissolved solids is generally satisfactory for domestic and most industrial uses except for difficulties which may result from the hardness. Water having more than 1,000 ppm of dissolved solids is likely to contain enough of certain constituents to produce a noticeable taste or to make the water unsuitable in some other respects. Some water with more than 1,000 ppm of dissolved solids may be satisfactory.

The total dissolved solids in fresh ground water in the Southeastern United States ranges from a few parts per million in the surficial sands to more than 1,000 ppm in parts of the limestone. The total dissolved solids is much higher in the water mixed with sea water or other salt water.

The dissolved solids in water having a low chloride content in the principal artesian aquifer ranges from about 100 ppm in recharge areas to about 500 ppm at a considerable distance from recharge areas. The maximum reported (1,600 ppm) in water having low chloride (50 ppm) was in calcium sulfate water at Palmetto in Manatee County, Fla. (Black and Brown, 1951, p. 63, 77). Among the lowest of these were analyses of water from a group of six wells 540 to 1,055 feet deep at the U.S. bombing range near Avon Park, Highlands County, where the dissolved solids ranged from 89 to 98 ppm. Also, analyses of water from two wells 1,400 feet deep at Sebring in that county had a total dissolved-solids content of 80 ppm.

Pride, Meyer, and Cherry (1961, p. 87) reported water having low mineral content in the artesian aquifer in the Green Swamp area in Polk and Lake Counties. A sample from a well 200 feet deep had a mineral content of only 15 ppm.

Another recharge area in which the water from the principal aquifer contains less than 100 ppm of total dissolved solids is indicated by the analyses of a sample from a well 450 feet deep at Keystone Heights in Clay County and from a well 210 feet deep at Putnam Hall in Putnam County, Fla. (Black and Brown, 1951, p. 39, 96).

The wells in Highlands County are in the Polk County recharge area, and the wells in Putnam County are in the Putnam County recharge area. In these areas, relatively impervious beds of the Hawthorn Formation overlie the aquifer, but recharge occurs through sinkholes filled with permeable sands. The low mineral content of the water also suggests that the water-bearing cavities in the limestone are filled with sand. In recharge areas where the aquifer is at or near the surface, the water has more contact with the limestone, and therefore the mineral content is higher in these recharge areas than in the lake regions, such as the Polk County area and the Putnam County area.

Downgradient the mineral content of the water increases in general with the distance from the recharge areas. For example, in moving from the Polk County recharge area to Manatee and Sarasota Counties, a distance of 50 miles or more, the total dissolved solids of the water increases several hundred parts per million. Many of the samples in the recharge area had total solids of less than 200 ppm, and some had less than 100 ppm. In Sarasota and Manatee Counties, the total solids ranges from about 500 to about 1,000 ppm. The total solids is more than 1,000 ppm where the artesian water is mixed with remnants of connate water or other salt water which has not been flushed from the aquifer in coastal areas. Artesian water with similar quality is present in southern Florida and much of the area where the chloride content of the water is at least 100 ppm. Another example of an increase in total dissolved solids as the artesian water moves downgradient a distance of at least 50 miles from the recharge area is the change between the Putnam County recharge area and Duval and Nassau Counties in northeastern Florida.

The total dissolved solids is less than 100 ppm in some of the water in that recharge area of the principal artesian aquifer in Clay and Putnam Counties. Downgradient at least 50 miles from the recharge area, the total dissolved solids ranged from about 350 to 500 ppm. A few samples were more than 500 ppm, but none was as high as those in Sarasota and Manatee Counties, partly because the aquifer has more anhydrite (calcium sulfate) in Sarasota and Manatee Counties than it does in northeastern Florida. Also, the aquifer in southwestern and southern Florida contains remnants of sea water which has not been completely flushed from the water-bearing formations. In Duval and Nassau Counties in northeastern Florida, the low chloride content of artesian water shows that no remnants of sea water remain in the aquifer.

In most of the area of this report, the principal artesian aquifer has calcium bicarbonate water, which is typical of water in limestone. However, in western Florida, southeastern Alabama, and southwestern Georgia where the water-bearing formations of the aquifer grade from limestone into sands and clays, the aquifer has sodium bicarbonate water, which is common in the artesian water in sandy water-bearing formations of Tertiary and Cretaceous age in the Atlantic and Gulf Coastal Plain. The total dissolved-solids content of samples of soft sodium bicarbonate water from a well 600 feet deep at Shalimar and from two wells 834 and 880 feet deep at the Eglin Air Force Base near Crestwood in Okaloosa County, Fla., ranged from 315 to 385 ppm.

An artesian well, 1011 feet deep, at Vichy Springs, Escambia County, Fla., yielded sodium bicarbonate water having total dissolved solids of 3,697 ppm (Black and Brown, 1951, p. 52). However, a relatively high chloride content of 1691 ppm indicates that the artesian water is mixed with sea water that has not been completely flushed from the aquifer.

The shallow sand aquifers from the land surface to depths of more than 200 feet yield water with a low mineral content. For example, the total dissolved solids of water samples from four municipal wells at Pensacola 200 to 240 feet deep ranged from 27 to 43 ppm. The total dissolved solids of water samples not contaminated with sea water from many wells in the very productive, shallow limestone aquifer in southeastern Florida ranged from about 250 to about 350 ppm (Parker and others, 1955).

SILICA

Silica (SiO_2) is dissolved from nearly all rock. The quantity present in the ground water in the area of this report ranges from about 2 to 63 ppm. It is relatively unimportant except where this amount may contribute to scale formation in boilers used for the production of steam. In general, the silica content of much of the water in the surficial aquifers and some recharge areas of the artesian aquifer is less than 10 ppm. Water with the highest silica content is deep in the artesian aquifer or is some distance from recharge areas. An exception to this may be noted in Highlands County, Fla., where the silica content of water from a well 1,055 feet deep is only 6.4 ppm (Black and Brown, 1951, p. 63, 78). However, there is local recharge in this area through sinkholes filled with permeable sand. In Marion County, water from a well 1,220 feet deep at Ocala had a silica content of 63 ppm. The silica content of water from two wells, one 455 feet and the other 350 feet deep, at Ocala ranged from 7 to 27 ppm. In southeastern Georgia, silica in analyses of samples from the principal aquifer reported by Warren (1944, p. 139, 140) ranged from 33 to 56 ppm. Apparently the silica content, in general, is highest in the water which has been in contact with the aquifer for the longest period of time.

Differences in the silica content in the water-bearing formations probably affect the silica content in the water, but wells in the limestone generally are not cased except in the material overlying the aquifer. Therefore, most of the samples are composites from several formations. The samples show a range in silica content which apparently correlates with alkalinity and pH of the water and length of time in the formations. The silica content generally is highest in the water having high alkalinity and pH.

IRON

Iron (Fe), generally in the form of ferrous bicarbonate, is objectionable in water in amounts of more than 0.3 ppm because it gives the water a disagreeable irony taste and stains bathroom fixtures. Iron in excess of 0.1 ppm may separate out and settle as a reddish sediment. It remains in solution as a ferrous bicarbonate, $Fe(HCO_3)_2$, and the water is clear until it is exposed to the air which oxidizes the iron to the ferric state and precipitates it as the hydroxide, $Fe(OH)_3$, or oxide, Fe_2O_3. Iron as bicarbonate in water may be removed simply by aeration. However, where iron is combined with organic matter, additional treatment is required.

Iron in small amounts, generally not exceeding a few parts per million, is present in some places in water in the shallow surficial sands in the Southeastern States. However, iron is absent, or present in only trace amounts, in water in the principal artesian aquifer and other limestone overlying the aquifer. Some of the iron reported in analyses may be from rusty well casings or pipes through which the water flowed. The iron content of samples of the large springs in Florida, such as Silver Springs and Rainbow Springs in Marion County and Wakulla Spring in Wakulla County which receive water from the principal artesian aquifer, ranged from 0.04 to 0.15 ppm (Ferguson and others, 1947).

Bishop (1956, p. 53, 58) reported that most of the samples from the principal artesian aquifer in Highlands County, Fla., contained no iron. One sample had 0.62 ppm of iron. The others ranged from 0.1 to 0.6 ppm iron. One sample from a well 30 feet deep in the Hawthorn Formation or younger deposits had an iron content of 3.2 ppm. The other samples from shallow wells were less than 1.0 ppm, except four samples that ranged from 1.1 to 1.9 ppm. Lichtler (1960, p. 52) showed that some samples from the principal artesian aquifer in Martin County, Fla., contained no iron. The highest reported was 0.43 ppm. Wyrick (1960, p. 37–39) reported on the iron content of 24 samples from the principal artesian aquifer in Volusia County, Fla.; 13 samples had less than 1 ppm of iron, the remainder ranging from 1.0 to 3.2 ppm, except two samples which had 3.9 ppm and 6.1 ppm of iron. Apparently, some of this iron was from the well casings. Analyses reported by Black and Brown (1951) show that many of the samples from the principal artesian aquifer in Florida had no iron. Where present, the iron content in many of the samples was less than 0.5 ppm.

In southwestern Georgia, Wait (1960a) reported that some samples from the principal artesian aquifer contained no iron. The iron content in the other samples ranged from 0.01 to 0.37 ppm. Warren (1944, p. 139, 140) showed that the iron content of water in southeastern Georgia ranged from 0.01 to 0.87 ppm.

CALCIUM AND MAGNESIUM

Calcium (Ca) is dissolved in large quantities from limestone, which is essentially calcium carbonate. Some of the calcium in ground water in the Southeastern States is from anhydrite, which is anhydrous calcium sulfate ($CaSO_4$), or gypsum, which is hydrous calcium sulfate ($CaSO_4 \cdot 2H_2O$). Because dolomite and dolomitic limestone contain the double carbonate of calcium and magnesium, this limestone is the chief source of magnesium (Mg) in the fresh water.

Except in the areas where sea water has not been completely flushed from the water-bearing formations or where sea water has entered the aquifer in Recent time, calcium is highest where the aquifer contains calcium carbonate or calcium sulfate, and the magnesium is highest where the aquifer contains dolomite or dolomitic limestone. In some areas as in Sarasota County and in northeastern Florida and southeastern Georgia, the calcium content of much of the water in the principal artesian aquifer and the overlying Hawthorn Formation is about twice the magnesium content.

However, in some other areas, the calcium content is much more than twice the magnesium content in the principal aquifer. Also, limestones overlying the principal aquifer, as in the shallow productive aquifer ranging in age from late Miocene to Recent (Parker and others, 1955) in southeastern Florida, may contain very little magnesium. The concentration of magnesium is as little as one-tenth to one-twentieth that of calcium (Black and Brown, 1951, p. 11) in the water which is not mixed with sea water.

Because magnesium is one of the abundant constituents of sea water, it is present in relatively large quantities in the ground water mixed with sea water that has not been flushed from the aquifer or that has moved into the aquifer in Recent time. Where mixed with sea water, ground water may contain more magnesium than calcium.

The calcium content of the water having low chloride content in the principal artesian aquifer ranged from 16 ppm in a sample from an area of recharge through sinkholes filled with sand and other material in Highlands County to 304 ppm in Sarasota County, some distance from recharge areas. The magnesium content in these two samples was 6.6 ppm in Highlands County and 132 ppm in Sarasota County. In much of the area of this report, water having a low chloride content in the principal artesian aquifer had a calcium content of less than 50 ppm and a magnesium content of less than 25 ppm. In the soft sodium bicarbonate water in western Florida, the calcium content was as low as 4.4 ppm, and the magnesium content, 3.5 ppm (Black and Brown, 1951, p. 83).

The content of calcium is high in comparison with that of magnesium in areas where the aquifer consists chiefly of pure limestone, as at Cross City in Dixie County, Fla. Where the calcium ranged from 81 to 120 ppm, the magnesium ranged from 4.5 to 6.8 ppm, and the sulfate ranged from 1.6 to 4.5 ppm (Black and Brown, 1951, p. 47).

For Highlands County, Fla., Bishop (1956, p. 53) gave analyses in which the calcium content from the principal artesian aquifer ranged from 16 to 40 ppm. The lowest magnesium content was 1.5 ppm in a sample from the Avon Park limestone of the aquifer. The highest magnesium content was 21 ppm in the sample which also had the maximum (40 ppm) of calcium. In addition to these analyses, one sample from the Ocala Limestone of the aquifer in the southeastern part of the county had 61 ppm of calcium and 46 ppm of magnesium. However, the sample had 110 ppm chloride, indicating that the artesian water is mixed with the remnants of sea water that has not been flushed from that part of the aquifer, as was suggested by Bishop (1956, p. 64).

In Manatee County, the maximum calcium content is in calcium sulfate water. One sample reported by Black and Brown (1951, p. 77) from the principal aquifer at Palmetto in Manatee County had a calcium content of 352 ppm. The magnesium content in that sample was only 8.5 ppm, but the sulfate content was 650 ppm. The chloride content in the sample was 50 ppm, and the bicarbonate content was 154 ppm. Total dissolved solids was 1,600 ppm, and total hardness was 916 ppm as $CaCO_3$.

Peek (1958a, p. 56, 59) reported that the calcium in composite samples from the Suwannee and Tampa Limestones of the principal artesian aquifer in Manatee County, Fla., ranged from 50 to 320 ppm. Samples from the Hawthorn and younger formations had a calcium content that ranged from 36 to 204 ppm. The magnesium content of water from the Suwannee and older formations ranged from 28 to 167 ppm. Water from the overlying Tampa Limestone contained 13 to 113 ppm of magnesium, and water from the Hawthorn and younger formations contained 5.8 to 99 ppm but generally less than 50 ppm.

In Martin County, Fla., where the artesian water is mixed with remnants of sea water in the aquifer, the magnesium content is about as high as that of the calcium. In one of the samples reported by Lichtler (1960, p. 52, 58) the content of magnesium was higher than that of calcium. Because the aquifer in that area consists chiefly of limestone with little dolomite, the relatively high magnesium content apparently results from sea water in the formation.

In southeastern Georgia, the calcium content of samples of water from the principal artesian aquifer ranged from 19 ppm in Liberty County to 75 ppm in Charlton County. The magnesium content ranged from 3.8 ppm in Candler County to 39 ppm in Camden County. The calcium content in analyses of samples of water in the principal artesian aquifer of Tertiary age in southwestern Georgia ranges from about 16 ppm in the Ocala Limestone in Lee County to 102 ppm in Colquitt County (Wait, 1960a). The magnesium content ranged from a trace in several samples in different counties to 47 ppm in Colquitt County. A sample from a well in the Ocala in Mitchell County had no magnesium.

STRONTIUM

As stated by Odum (1951b, p. 20) strontium (Sr) is associated with calcium in nature, but there is only about 1 atom of strontium for every 1,000 atoms of calcium. It is chemically similar to calcium, and natural strontium is no more toxic than calcium and never approaches harmful concentrations. Skougstadt and Horr (1960, 1963) studied the strontium content of surface streams to obtain information which could be used in a study of the extent to which strontium-90, a long-lived radioactive isotope of nuclear fission, might be diluted by stable strontium in streams.

Celestite, strontium sulfate, is a common mineral in carbonate rocks. It is associated with limestone and calcite; without optical tests, it may be mistaken for calcite. Unpublished analyses in 1961 by the U.S. Geological Survey for 12 samples of water from the aquifer in Martin County, Fla., had a strontium content ranging from 10 to 49 ppm. Feulner and Hubble (1960, p. 180) reported that strontium in ground water in carbonate rocks in western Ohio in concentrations of as much as 30 ppm is principally from solution of strontium-bearing minerals such as celestite. Although such minerals have not been detected in the aquifers in the area of this report, they probably are the source of the small quantities of strontium reported by Odum (1951b, p. 20–21) and by Skougstadt and Horr (1960, p. 314) in water in Florida.

Horr (1959, p. 2–3) reported that in the deposition of carbonate rocks the strontium content and the relative solubilities of calcium and strontium in sea water cause limestone and dolomite to be deposited before celestite. When the concentration is sufficient to cause gypsum to be deposited, celestite also is deposited. Therefore, celestite deposition would be expected in the upper zone of carbonate rocks in contact with gypsum. Celestite may also be present in fossils.

F. H. Stewart (1963, p. Y40) stated that most of the strontium of marine evaporites replaces calcium in the sulfate and carbonates. He reported 0.17 to 0.69 percent SrO in anhydrite and 0.003 to 0.13 percent in SrO in gypsum. Gypsum which has replaced earlier anhydrite by hydration at ordinary temperatures cannot always retain all the strontium of anhydrite, and consequently celestite is formed.

Rankama and Sahama (1950, p. 295) reported the average strontium content of sea water as 13 ppm. However, in a statistical study of his own data and those of several others, Odum (1951a, p. 211–213) gave an average figure of 8.1 ppm, which Horr (1959, p. 3) believed was more nearly correct. Odum (1951b, p. 20-21) reported the strontium content of water from some of the springs and streams. All the samples had less than 1 ppm of strontium, except Salt Springs in Marion County, which had about 6 ppm.

Skougstadt and Horr (1963, p. 77, 80) reported that strontium content of samples of water from several streams in Florida ranged from 0.8 to 1.1 ppm. The sample having the highest strontium content was from the St. Johns River, which receives artesian water from carbonate rocks of the principal aquifer in its upper course from Putnam County to Brevard County. Ground-water circulation in the part of the aquifer that contributes water to the other streams sampled has been sufficient to remove water or most minerals which might be a source of strontium. Therefore, the low strontium content of the water from these streams might be expected. However, the aquifer in the St. Johns River valley south of Putnam County has not been completely flushed of sea water which entered the formation when the sea stood higher during Pleistocene time than at the present time. The remnants of sea water may contribute to the relatively high strontium content in the samples from the St. Johns River near Cocoa and in a sample having 6 ppm of strontium from Salt Springs, which is part of the St. Johns River system.

If sea water has a strontium content of about 8 ppm, several parts of the strontium content of 6 ppm from Salt Springs, which has total dissolved solids and chloride about one-sixth that of sea water, comes from the aquifer. A comparison of the quality of water from Salt Springs with that of Silver Springs, 22 miles southwest of Salt Springs, indicates that the aquifer has considerably more calcium sulfate (anhydrite or gypsum) at Salt Springs than at Silver Springs. The water having relatively high chloride has more calcium sulfate and strontium than can be explained by the presence of sea water. This condition suggests that strontium-bearing minerals such as celestite and possibly some salt might be present in the aquifer as part of an evaporite series. Such thin deposits would not be easily detected in test wells but could contribute to the salinity of water in the aquifer and in the salt springs such as those in the St. Johns River valley and in Marion and Sarasota Counties, Fla.

Also, Braidech and Emery (1935, p. 557) reported a strontium content of 10 ppm for the municipal supply of Jacksonville, Fla., which is from the principal artesian aquifer. Although the calcium sulfate content of the water is relatively high, all sea water has been flushed from the aquifer in that area, as indicated by the low chloride content of the water.

Additional investigations of occurrence and distribution of natural strontium might seem of little practical value. However, information on the strontium content of the ground water throughout the aquifer would be helpful in understanding the geochemistry of the ground water and the source of the water, which may be remnants of Pleistocene sea water or other sea water that has not been flushed from the aquifer.

SODIUM AND POTASSIUM

Sodium (Na) and potassium (K) are present in all natural water, but they are present in only small quantities in the ground water in the southeast, except in some coastal areas and in southern Florida where the water-bearing formations contain remnants of sea water or sea water has entered the formation along the coast. Because sea water is essentially a solution of sodium chloride (common table salt), relatively large quantities of sodium are present in the ground water mixed with sea water or in contact with salt in the water-bearing formations. Ordinarily, where the ground water is not mixed with sea water, the sodium and potassium combined ranges from a few parts per million to about 40 ppm. Many of the samples have less than 10 ppm. However, where mixed with sea water or salts in the formations, the sodium and potassium may be as much as that of sea water which has an average of 10,710 ppm of sodium and 390 ppm of potassium.

Moderate amounts of sodium and potassium have no effect on the suitability of water for all domestic and most industrial purposes. Excessive amounts of sodium obtained from food and water may adversely affect some persons. More than 100 ppm of sodium may cause foaming in steam boilers unless special precautions are taken to prevent it.

However, ground water having a sodium content of more than 100 ppm occurs only in the area where it is mixed with sea water and in a few areas in Okaloosa, Santa Rosa, and Escambia Counties in western Florida where the water in the principal aquifer has a relatively high sodium content because of natural softening of the water in which calcium and magnesium were exchanged for sodium. In water having only a few parts per million of sodium, the amount of potassium is somewhat less than that of the sodium. Generally, where the concentration of sodium and potassium increases, the concentration of sodium is much larger than that of potassium, as in some parts of coastal areas and southern Florida where the water is mixed with sea water or salts in the formation. The sodium content may be a problem in irrigation water as discussed in the section of this report on the quality of irrigation water.

BICARBONATE

Bicarbonate (HCO_3) in natural water results from the action of carbon dioxide, dissolved in the water, on carbonate rocks. The total alkalinity of water is the sum of its hydroxide (OH), carbonate (CO_3), and bicarbonate alkalinities, all expressed in terms of equivalent quantities of $CaCO_3$. Of the three, the bicarbonate is the one more commonly present in ground water in the Southeastern States. Some ground water that has not been in contact with carbonate rocks may have less than 10 ppm of bicarbonate. For example, the bicarbonate in samples of ground water for the public supply at Pensacola, Fla., as reported by Black and Brown (1951, p. 51), ranged from 2.9 to 7.3 ppm. Bicarbonate in samples of water from the principal artesian aquifer ranged from about 50 to about 350 ppm. Most of the samples had less than 300 ppm, and many had less than 200 ppm. The bicarbonate content in the shallow ground water in the Everglades of southeastern Florida is much higher than that in the principal artesian aquifer. As stated by Love (Parker and others, 1955, p. 733), ground-water samples from some parts of the Everglades had concentrations of 500 to 1,000 ppm of bicarbonate.

In Manatee County, Fla., Peek (1958a, p. 59) reported that water samples from the Suwannee and older formations of the principal artesian aquifer had a bicarbonate content of 102 to 264 ppm. Water samples from the Tampa Limestone of the principal aquifer had a bicarbonate content of 162 to 270 ppm. Samples from the overlying Hawthorn Formation had from 48 to 557 ppm of bicarbonate, but the bicarbonate generally was higher in the Hawthorn than in the principal artesian aquifer.

SULFATE

Sulfate (SO_4) is dissolved in large quantities from gypsum or anhydrite (calcium sulfate) in some of the water-bearing formations. It is also formed by the oxidation of sulfides of iron, such as pyrite, which is present in some of the limestones. Some of the sulfate in part of the ground water in the Coastal Plain of Southeastern United States is from sea water or salts in the formations. The sulfate content of ground water in this area ranges from zero to as much as 1,000 ppm. Sulfate in much of the water from the principal artesian aquifer in recharge areas is generally less than 10 ppm.

The sulfate content is highest in the deeper water and is relatively high in the Atlantic coastal area, southern Florida, and the gulf coastal areas from the Florida Keys to Tampa Bay. In most of that area, part of the sulfate apparently is from gypsum or anhydrite in the aquifer. Vernon (1951, fig. 17) showed many thin beds of anhydrite and gypsum in the principal artesian aquifer below a depth of about 250 feet below sea level in Citrus and Levy Counties, Fla. Some gypsum occurs above that depth in some of the coastal areas and in southern Florida, where the chloride content of the water is more than 100 ppm. Some of the sulfate is from sea water which has not been completely flushed from the aquifer. The highest sulfate content of the samples low in chloride was 1,132 ppm from a well in the principal artesian aquifer in Sarasota County (Black and Brown, 1951, p. 102).

Sulfates of calcium and magnesium cause noncarbonate hardness, which is more difficult to remove from the water than carbonate hardness. The sulfate in sufficient quantities may give the water a bitter taste, and magnesium sulfate has a laxative effect on persons who drink sufficient quantities of the water. Sulfate in hard water makes the scale, which forms in steam boilers, more difficult to remove.

CHLORIDE

The chloride (Cl) content of ground water in the Southeastern States may be used as an index of the extent to which the water is mixed with present or former sea water or salt in the water-bearing formations. Chloride is dissolved in small quantities from most geologic formations. It is present in large quantities in ground water mixed with sea water or with salts (sodium chloride) in the water-bearing formations. The average chloride content of sea water is about 19,350 ppm. A small quantity of chloride in some ground water is from finely divided salt spray carried with dust particles by wind and precipitated with the rain. Collins and Howard (1928, p. 183) reported that maps of "normal chlorine" for some regions indicate that the quantity of chloride from rain ranges from less than 1 ppm far inland from the coast to 5 or 6 ppm near the coast. However, along the Atlantic coast rain from storms has been reported that had a chloride content of as much as several hundred parts per million. Sewage or industrial wastes may increase the chloride content of water with which it is mixed.

Except in coastal areas and southern Florida shown in figure 36, where the ground water has a chloride content of more than 100 ppm, the chloride in the principal artesian aquifer is generally less than 50 ppm. In some recharge areas the chloride content is less than 10 ppm. Generally, below depths of about 2,000 feet, salt water may be expected. The occurrence and distribution of ground water with a relatively high chloride content is discussed in the part of this report on areas of salt water.

Chloride, like sodium with which it forms sodium chloride (common table salt), has little effect on water for ordinary use unless there is enough to give a salty taste. However, even in small amounts, salt makes the water more corrosive. Water having less than 250 ppm of chloride is acceptable for public supply if otherwise satisfactory, according to standards of the U. S. Public Health Service. Water with a chloride content of 500 ppm or more will ordinarily taste salty and is undesirable for public supply. Water having a chloride content of 2,000 ppm is not suitable for many uses, including irrigation of certain crops (Westgate, 1950, p. 116–123).

FLUORIDE

Fluoride (F) is present in small quantities in some of the ground water in the Southeastern States. Water with fluoride concentrations in excess of 1.5 ppm may cause mottling of the enamel of the teeth of children if they drink the water during the calcification, or formation, of their teeth (Cox and Ast, 1951, p. 641–648). Teeth with mottled enamel develop a dull chalky white color which in many cases changes to a dark-brown stain. However, normally formed teeth of adults have not been known to become mottled later regardless of the fluoride content of the water. Also, it is now generally recognized that water having a fluoride content of 0.7 to 1.5 ppm in public supplies results in a 50 to 63 percent reduction in dental caries or tooth decay among children using the water (Black and Brown, 1951, p. 15).

In their study of occurrence of fluoride, Black and Brown (1951, p. 15) indicated that 375 samples of water in Florida had small quantities of fluoride. Surface-water samples analyzed contained none or only traces. Water from the Hawthorn Formation of Miocene age almost invariably contained small amounts of fluoride, generally more than 1.0 ppm and in a few samples as much as 2.5 ppm. Black, Stearns, H. H. McClane, and T. K. McClane (1935, p. 21,22) reported that the largest areas in which untreated well water contained relatively high concentrations of fluorides is in a tier of nine counties (Manatee, Hardee, Sarasota, De Soto, Charlotte, Glades, Lee, Hendry, and Collier) in southwestern Florida. In other areas such as the section surrounding Jacksonville in northeastern Florida, water from wells in the Hawthorn contains significant amounts of the element. Because the Hawthorn Formation is present in all of these areas, the writer believes that most, if not all, of the water having a fluoride content of more than about 1.0 ppm is from the Hawthorn Formation or other formations of Miocene age or younger containing phosphatic deposits.

Love (Parker and others, 1955, p. 734) reported that the maximum fluoride content of samples of surface water in southeastern Florida was 0.6 ppm, and most of the samples had less than 0.3 ppm. Fluoride content in public supplies ranged from 0.0 to 0.3 ppm, except a sample having 2.4 ppm from a well 600 feet deep at La Belle in Hendry County. The fluoride content of water from this well probably is from the lower part of the Hawthorn Formation. Apparently, the well at LaBelle is the source of maximum fluoride of 2.4 ppm reported by Klein, Schroeder, and Lichtler (1964, p. 74) for Glades and Hendry Counties.

Water in the principal artesian aquifer has little or no fluoride except in areas where the lower part of the Hawthorn forms the upper part of the aquifer and in western Florida, southeastern Alabama, and southwestern Georgia where the principal artesian aquifer grades laterally into sands and clays, which yield soft sodium bicarbonate water having a fluoride content of as much as 6.5 ppm (Barraclough and Marsh, 1962, p. 24).

According to analyses of 36 samples of ground water from Highlands County, Fla., as given by Bishop (1956, p. 55), 17 contained no fluoride, and 19 contained 0.1 to 0.8 ppm. Although Bishop reported that a few of the samples containing fluoride were from Eocene limestone of the principal artesian aquifer, it seems possible that all of the fluoride is from the Hawthorn.

Lichtler (1960, p. 60) reported that in Martin County, Fla., the fluoride ranged from 0.0 to 0.4 ppm in the shallow aquifer and from 0.1 to 1.6 ppm in the artesian aquifer. The shallow aquifer extends from the surface to a depth of 150 feet and includes at its base the Tamiami Formation, which cannot be distinguished from the Hawthorn Formation except by fossils, according to Lichtler. The fluoride water in the shallow aquifer is probably from the Tamiami which was formerly considered part of the Hawthorn. The fluoride in the artesian water is probably from the Hawthorn Formation.

Wait (1960a, p. 35) stated that only small quantities of fluoride, generally less than 1 ppm, are present in ground water in the Coastal Plain in Georgia.

Hastings (Carter and others, 1949, p. 242) stated that the water in southeastern Alabama seldom contains more than 0.5 ppm of fluoride. A few wells in the Eutaw Formation of Late Cretaceous age yield water containing more than 1 ppm.

The fluoride content of water from the large springs fed by artesian water from the principal artesian aquifer, where the Hawthorn Formation is absent, ranges from 0.0 to 0.1 ppm. The highest fluoride content of spring water reported by Ferguson, Lingham, Love, and Vernon (1947, p. 145–146) is 1.6 ppm for Little Salt Spring near Murdock in Sarasota County. This fluoride content indicates that the water is from the Hawthorn Formation.

As stated by LaMoreaux (1948, p. 30–37), there are several sources of fluoride in ground water. In some areas fluoride may be traced directly to magmatic sources or to vapors in the atmosphere from a volcanic source. In the Cretaceous and Tertiary formations in the Atlantic and Gulf Coastal Plain, it appears to be from fluoride-bearing minerals such as apatite, tourmaline, topaz, vesuvianite, lepidolite, phlogopite, glauconite, and others in the water-bearing formations.

Fluoride has been correlated with the presence of volcanic ash and bentonitic material in the Catahoula Sandstone of Miocene age in the Gulf Coastal Plain in Louisiana by Maher (1939). Black and Brown (1951, p. 15) reported that water from the Hawthorn Formation, which contains phosphatic material, almost invariably contains fluoride in excess of 1.0 ppm, a few samples having as much as 2.5 ppm.

Except for the hard water in the Hawthorn Formation, the ground water having a fluoride content of more than about 1.0 ppm is a soft sodium bicarbonate water, which is common in some of the Tertiary and Cretaceous formations of the Atlantic and Gulf Coastal Plain. As suggested by Carlston (1942, p. 17–20), glauconite and other materials cause exchange of calcium and magnesium ions for sodium ions, and these minerals may be contributing fluoride to the ground water as it moves downgradient. The increase in fluoride downgradient may merely be the accretion over a long period of time as the water moves downgradient through materials which have only small quantities of fluoride-bearing minerals.

Carlston (1942, p. 19) reported that phosphate occurs in the upper part of the Eutaw Formation of Cretaceous age, which contains water having a relatively high fluoride content. According to Mansfield (1940, p. 863–879), phosphates and fluoride have an affinity for each other, and deposition of fluoride could occur in localized areas where conditions favor the accumulation of phosphates. Also, conditions are favorable for the formation of relatively stable deposits of phosphates or fluorapatite only during times of volcanic activity when large amounts of fluoride are available. He found that all major phosphatic deposits in the United States may be correlated with periods of volcanic activity.

In a study of the fluoride in water in the Hawthorn Formation, Black, Stearns, H. H. McClane, and T. K. McClane (1935, p. 22–23) indicated that the fluoride is from the phosphatic material. The phosphatic rock as mined contains approximately 4 percent fluorine. Samples of tap water stirred for varying periods of time with commercial phosphatic rock dissolved an average of 1.7 ppm of fluoride, the exact amount depending on the conditions employed. The low solubility of the phosphate as determined in that study probably accounts for the relatively small fluoride content, a maximum of only about 2.5 ppm in the Hawthorn Formation.

Gwynne (1934, p. 139–140) suggested that the breaking down by weathering processes of the less soluble fluoride minerals might be accomplished by action of sulfuric acid formed by decomposition of pyrite. As stated by LaMoreaux (1948, p. 31), pyrite occurs in many of the aquifers in Tertiary and Cretaceous formations in the Southeastern States. The presence of fluoride-bearing minerals and abundance of pyrite in some of the water-bearing formations seem to support Van Burkalow's theory (1946, p. 187–188) that fluoride in soluble form might be expected where there is an abundance of fluoride minerals and an abundance of pyrite in association with concentrated organic material, which would facilitate decomposition of the minerals and release of the fluoride.

In a table listing the principal water-bearing sands and the presence of volcanic or phosphatic material, pyrite, lignite, and glauconite, LaMoreaux (1948, p. 33) showed that water having a relatively high fluoride content correlates with these materials. The table also shows that the presence of glauconite alone is not responsible for the presence of fluoride. For example, the sands of the Nanafalia and Lisbon Formations of Eocene age are very glauconitic, but the fluoride in the ground water from these sands is generally low. LaMoreaux (1948, p. 35) observed that the fluoride content increases downgradient, indicating that the distance the water has moved and length of time in contact with the fluoride minerals are factors in the content. He suggested also that greater pressure and temperature at greater depths may catalyze the reaction.

Siple (1957a, p. 297–298) reported that water with relatively high fluoride content in the Cretaceous formations of South Carolina occurs under conditions similar to those described by Carlston in Alabama. Also, Siple concluded that the presence of glauconitic or phosphatic minerals alone is not responsible for the fluoride because some deposits of Tertiary age in South Carolina contain large quantities of the minerals but do not contain fluoride water.

NITRATE

Nitrate (NO_3) is produced by oxidation of nitrogenous material. The presence of nitrate in excess of 50 ppm may be a contributing factor in the development of cyanosis, or methemoglobinemia, in infants (Black and Brown, 1951, p. 12). However, only a few samples of water high in nitrate have been reported in the Southeastern States. Most ground water in the Southeastern States has less than 1 ppm. This small amount has no effect on the value of water for ordinary use.

HARDNESS

Hardness of water may be recognized by the lack of suds when washing with soap. It is the $CaCO_3$ equivalent of calcium, magnesium, and other cations having similar soap-consuming properties. Hardness may be of two kinds, carbonate and noncarbonate. Calcium and magnesium bicarbonate cause the carbonate hardness, which is referred to as temporary hardness. A large part of the carbonate hardness may be removed by boiling or treatment with lime. Sulfates, chlorides, and nitrates of calcium and magnesium cause noncarbonate hardness, often called permanent hardness, which is more difficult and costly to remove than the temporary hardness. Both forms of hardness may be entirely removed by passing the water through a zeolite-type softener, but water softened by this method still contains approximately the original quantities of dissolved mineral matter. The total hardness expressed as calcium carbonate is the sum of the parts per million of calcium multiplied by 2.50 and the parts per million of magnesium multiplied by 4.11. Water having a hardness of less than 60 ppm (equivalent $CaCO_3$) is generally regarded as soft, and treatment to soften such water seldom is justified for public supply. Hardness between 60 and 120 ppm is generally regarded as moderate and does not seriously interfere with the use of water for most purposes; it does, however, increase soap consumption slightly, making the removal of hardness by softening process profitable for laundries or other industries that use large quantities of soap. Hardness between 120 and 200 ppm is regarded as troublesome for many industrial and domestic uses. Such water requires treatment to prevent scale when used in steam boilers. Hardness of more than 200 ppm is regarded as very hard. However, water with hardness of 200 to 400 ppm is used by many people who obtain water supplies from privately owned wells. Although very hard water is furnished by some public supplies, there is an increasing tendency for cities to soften their supplies if the untreated water has hardness of more than 150 ppm.

The hardness of ground water in the report area, including that of the principal artesian aquifer, ranges from about 5 to about 1,000 ppm. A table of hardness of water for the larger public water supplies in Florida by Black and Brown (1951, p. 13, 15) shows that the hardness of the untreated water ranged from 4.0 to about 1,000 ppm. The hardness of water (chiefly ground water) as distributed by 96 larger public supplies ranged from 0 to 50 ppm for 3 percent of the cities, 51 to 150 ppm for 68 percent, 151 to 250 ppm for 2 percent, and more than 250 ppm for 9 percent. In general, the softest water in the principal artesian aquifer is in recharge areas, and the hardest is some distance from recharge areas. An exception to this is in Okaloosa, Santa Rosa, and Escambia Counties, Fla., where natural softening has removed the hardness as the water moved through the aquifer.

A comparison of hardness ranging from about 60 to about 100 ppm in a recharge area in Clay County with that ranging from about 200 to about 300 ppm in Duval County in northeastern Florida shows the increase in hardness with distance from recharge areas. In southwestern Florida, a comparison of the hardness of less than 70 ppm in the principal artesian aquifer in a recharge area in Highlands County with that of as much as 1,000 ppm in Sarasota County shows the increase in hardness with distance from recharge areas. In areas where sea water is mixed with the fresh artesian water, the hardness may be much more than 1,000 ppm. In recharge areas the hardness generally increases with depth of well. Water-bearing sands which are recharged locally, as at Pensacola, Fla., yield water having a low mineral content and a hardness of less than 10 ppm. The hardness of fresh ground water in the shallow aquifers in southeastern Florida ranges from about 150 to 300 ppm, as reported by Love (in Parker and others, 1955, p. 784).

The hardness of samples of water reported by Warren (1944, p. 138) from the principal artesian aquifer in southeastern Georgia ranged from 86 to 348 ppm. The highest hardness was in the southeastern part of the area. In southwestern Georgia, the hardness of samples of ground water reported by Wait (1960a, p. 42–72) ranged from 70 to 448 ppm in the principal artesian aquifer of Tertiary age. The underlying Cretaceous aquifers generally have soft sodium bicarbonate water. Also, some sandy formations of Tertiary age in southwestern Georgia, southeastern Alabama, and western Florida contain soft sodium bicarbonate water.

HYDROGEN SULFIDE

Hydrogen sulfide (H_2S) is a gas which gives the characteristic odor of rotten eggs to sulfur water. Black and Brown (1951, p. 15) suggested two possible sources of the gas in natural water—the reduction of sulfate to sulfides by organic material under anaerobic conditions in aquifers, resulting in decomposition of the metallic sulfide by free carbon dioxide and, in some cases, the anaerobic reduction of organic matter with which the water comes in contact.

In the principal artesian aquifer, the hydrogen sulfide ranges from 0 to more than 4 ppm (Black and Brown, p. 15). Wetterhall (1965, p. 14) reported that water from depths of 125 to 130 feet in an open sinkhole (Blue Sink) in Pinellas County, Fla., contained more than 37 ppm of hydrogen sulfide. Although the sink is in the principal artesian aquifer, the relatively high sulfide may represent local conditions in the sink. As little as 1 ppm gives the water a noticeable sulfur odor. Because of aeration, part of the gas is eliminated, and the remainder is rapidly oxidized by dissolved oxygen absorbed upon aeration. Special sampling and analytical methods must be used to determine the amount of the gas in the water. For this reason, relatively few values for hydrogen sulfide are reported. However, water discharging from many artesian wells has a noticeable odor of hydrogen sulfide.

HYDROGEN-ION CONCENTRATION

The hydrogen-ion concentration (pH) of water is the number of moles of ionized hydrogen per liter. Pure water contains 10^{-7} gram of hydrogen ions per liter. In order to avoid the use of exponential numbers, a system involving the so-called pH values has been developed with pH value of 7 for pure water. Water with pH of less than 7.0 is corrosive and acidic, the acidity increasing as the pH value decreases. Water with pH of more than 7 is alkaline. The alkalinity increases as the pH value increases. The pH of most natural water depends on the amount of free carbon dioxide and the amount and character of the types of alkalinity present. Free carbon dioxide readily escapes from water samples; therefore, the determination of pH should be made in the field at the time the sample is collected. Samples high in alkalinity will usually undergo only slight changes in alkalinity, but soft water high in free carbon dioxide will usually be higher in pH after the sample has been collected for some time (Black and Brown, 1951, p. 12).

Black and Brown (1951) gave the pH values of many samples of water throughout Florida. Parker, Ferguson, Love, and others (1955) gave pH values for the public water supplies in southeastern Florida. The pH of water from the principal artesian aquifer ranged from 7 to 8.75. Samples of soft water of low mineral content had a pH that ranged from 5.4 to 7.0. Most of these samples were from wells ranging from a few feet to about 250 feet deep. The deepest wells are at Pensacola, Fla.

COLOR

Color of water as shown in analyses refers to the appearance of water that is free of suspended material. Natural color in water is almost entirely from organic matter, extracted from leaves, grass, and other dead vegetation. A color of less than 20 based on a graduated standard of colored glass disks usually passes unnoticed. Some swamp water has a natural color of 200 or more. As stated by Love (Ferguson and others, 1947, p. 19) exceptionally clear water seems blue when seen through a depth of several feet. This natural blue color of clear water is caused largely by scattering of sunlight by water molecules. As most of the scattering occurs in the short wave lengths of light which are near the blue end of the visible spectrum, the water appears to be blue. Scattering of sunlight increases with depth of penetration, causing deep water to appear bluer than shallow water, as may be noticed in the artesian springs in Florida and Georgia.

Shallow aquifers recharged by surface water containing organic color yield colored water, as in the Everglades of Florida or along streams as the Suwannee River during high stages when colored water in the stream enters the cavernous limestone. Colored water may also enter the limestone aquifer through open sinkholes. However, in areas where the limestone is not near the surface, as in Highlands County, Fla., the sinkholes are filled with permeable sand. Water moving through that material probably loses most, if not all, of its color. Bishop (1956, p. 56) reported that of 36 samples analyzed, 12 were colorless, 16 had color of less than 10, and 8 had color ranging from 12 to 104. All the colorless samples were from the principal artesian aquifer. Two samples from the aquifer had a color of 7, which probably is from lignitic material in the aquifer.

Most of the large springs in Florida are clear. Two of the largest, Silver Springs and Rainbow Springs, in Marion County, are always clear. Wakulla Spring, which receives colored water through open sinkholes, has noticeable color during and after rains when colored surface water enters the aquifer. During dry times, the color is zero, as indicated in an analysis given by Ferguson, Lingham, Love, and Vernon (1947, p. 174). One analysis each shows that Silver Springs had a color of 4 and Rainbow Springs a color of 2 when sampled. Although both of these springs are in the Marion County recharge area, where the aquifer is recharged through sinkholes, the sinks are filled with permeable sands. Therefore, the water is never turbid. Also, some water in that area is from the Putnam County recharge area to the north and the Polk County recharge area to the south. As water from only a few artesian wells has noticeable color, very few color determinations have been made for this water. Although no water with noticeable color has been reported from artesian wells in the Southeastern States, water from the part of the aquifer containing large quantities of lignitic material may have noticeable amounts of organic color.

ELECTRICAL CONDUCTIVITY

The electrical conductivity of water, also known as specific conductance, is a measure of its capacity to conduct current. It is the reciprocal of specific resistance in ohms and is expressed in reciprocal ohms at 25°C (77°F). In order to avoid the use of small figures, the measured values of conductance are multiplied by 10^6 and expressed as micromhos. Some of the first measurements made in Florida were multiplied by 10^5 (Parker and others, 1955, p. 730) instead of 10^6. However, the measurements in later reports are given in micromhos. The specific conductance of water is a function of the amount and kind of the dissolved mineral matter. It varies with the concentration and also with the degree of ionization of the minerals in solution. It is an indication of the total dissolved solids, which generally is approximately equal to the conductance multiplied by a factor of 0.6 to 0.8. Specific conductance is used by the U.S. Salinity Laboratory Staff (1954, p. 60–82) in classifying the suitability of water for irrigation.

QUALITY OF WATER FOR IRRIGATION

The characteristics of water that appear to be most important in determining its quality for irrigation in the Western States are: (1) total concentration of soluble salts, (2) relative proportion of sodium to other cations, (3) concentration of boron or other elements that may be toxic, (4) and under some conditions the bicarbonate concentration as related to the concentration of calcium plus magnesium (U.S. Salinity Lab. Staff, 1954, p. 69–72). In the humid climate in the Southeastern States, where annual rainfall is as much as 60 inches, the standards set for arid and semiarid areas of the Western States are not entirely applicable but may be used in a general way.

In the Southeastern States the first two characteristics—total concentration of soluble salts and the relative amount of sodium to other cations—probably are most important in determining the quality of irrigation water. The total concentration of soluble salts (salinity hazard) may be indicated approximately as the electrical conductivity of the water.

The relative proportion of sodium to calcium and magnesium (sodium or alkali hazard) may be expressed as the sodium-adsorption-ratio (SAR) which is defined by the equation:

$$SAR = Na^{+}/\sqrt{(Ca^{++} + Mg^{++})/2}$$

where Na, Ca, and Mg are expressed in equivalents per million. If the proportion of sodium is high, the alkali hazard is high; conversely, if calcium and magnesium predominate, the hazard is low.

Classification of irrigation water according to the salinity hazard and sodium hazard as given by the U.S. Salinity Laboratory Staff (1954, p. 79–81) for the Western States is as follows:

Salinity hazard class	*Conductivity (micromhos per cm at 25°C)*
C1 (low)	100– 250
C2 (medium)	250– 750
C3 (high)	750–2,250
C4 (very high)	2,250–5,000

Sodium (alkali) hazard class	*Sodium-adsorption-ratio (SAR)*
S1 (low)	0–10
S2 (medium)	10–18
S3 (high)	18–26
S4 (very high)	26–30

Low-salinity water (C1) can be used for irrigation of most crops on most soils without developing soil alkalinity. Some leaching of soil is required but this occurs under normal irrigation except in soils of extremely low permeability. Medium-salinity water (C2) can be used if a moderate amount of leaching occurs. Plants having moderate salt tolerance can be grown in most cases without special salinity control. High-salinity water (C3) will be harmful if used on soil where drainage is restricted. Special management for salinity control may be required; plants having good tolerance for salt should be selected even though the drainage is adequate. Very high salinity water (C4) is not suitable for irrigation under ordinary conditions but may be used occasionally under special circumstances for crops that tolerate salt. The soils must be permeable, drainage must be good, and excess water is required to provide considerable leaching.

Low-sodium water (S1) can be used on almost all soils without danger of development of harmful levels of exchangeable sodium. However, sodium-sensitive crops, such as stone-fruit trees and avocados, may accumulate injurious concentrations of sodium. Medium-sodium water (S2) presents an appreciable sodium hazard in fine-textured soils of high-cation-exchange capacity, especially under low-leaching conditions, unless gypsum is present in the soil. This water may be used on coarse-textured or organic soils of high permeability. High-sodium water (S3) may produce harmful levels of exchangeable sodium in most soils and will require special soil management where there is good drainage, high leaching, and the addition of organic material. Soils containing gypsum may not develop harmful levels of exchangeable sodium, except that addition of amendments to the soil may not be feasible with water of high salinity. Very high sodium water (S4) is generally unsatisfactory for irrigation purposes except at low and perhaps medium salinity, where the solution of calcium from the soil or addition of gypsum or of other amendments makes the use of this water feasible.

In a humid area such as the Southeastern States, where leaching action from rain is greater than in arid and semiarid areas in the Western States, the above classification probably should be modified to some extent. However, Wait (1960c, p. 25–27) used the sodium-adsorption-ratio, the specific conductance classification, and salinity for samples of water from 30 wells in the Tertiary and Cretaceous formations in southwestern Georgia and found that only three samples were unsuitable for irrigation. Two samples from the Tertiary formation at Cairo and Moultrie, having calcium and sulfate as the principal constituents, had a low sodium hazard but a high salinity hazard. The other sample from the Eutaw Formation of Cretaceous age at Georgetown, having sodium and bicarbonate as the principal constituents, represents water of medium salinity hazard and a very high sodium hazard. Water represented by a sample from the Cretaceous at Fort Gaines, Ga., having sodium and bicarbonate as the principal constituents, has a medium sodium and medium salinity hazard. Of four wells in the principal artesian aquifer studied for irrigation classification in Columbia County, Fla., one of the deepest (996 feet) showed a salinity large enough to restrict its use as an irrigation supply (Meyer, 1962, p. 52). The chemical constituents of the sample consisted chiefly of calcium sulfate; the chloride content was only 12 ppm.

Although water samples from other parts of the area covered by the present report have not been classified as to suitability for irrigation, it seems that the sodium-adsorption-ratios might present a problem only in part of western Florida and southeastern Alabama where ground water may have relatively large amounts of sodium and bicarbonate and small amounts of calcium and magnesium.

The salinity hazard, however, is present in some of the coastal areas and in southern Florida where the concentration of soluble salts is relatively high in the ground water mixed with sea water. The conductivity of the water in the shallow aquifer (Hawthorn Formation) in Manatee County ranged from 418 to 2,530 micromhos, except one sample having 53,600 micromhos (Peek 1958b, p. 80). This water is more concentrated than sea water. The conductivity of samples from the principal artesian aquifer ranged from 556 to 5,260 micromhos. In a few areas, the mineralization is due chiefly to calcium sulfate from gypsum and anhydrite in the aquifer. Where some of the water is high in calcium sulfate but low in sodium chloride, as in part of Manatee County, it may have total dissolved solids of as much as 1,250 ppm and specific conductance of 1,500 micromhos. Although this kind of water would be in the high salinity class for Western States, it seems to be satisfactory for irrigation in Florida. In some of the coastal areas and in southern Florida, where the chloride content is more than 100 ppm, as shown in figure 36, the conductivity may be more than 2,250 micromhos.

Lichtler (1960, p. 52) reported that the conductivity of water samples from the principal artesian aquifer in Martin County, Fla., ranged from 1,310 micromhos to 11,300 micromhos. Lichtler noted that the total dissolved solids in Martin County can be estimated by multiplying the conductance by a factor of 0.6.

Klein, Schroeder, and Lichtler (1964, p. 70–71) showed by a graph (after Wilcox, 1948, p. 25, 26) the suitability of ground water for irrigation in Glades and Hendry Counties, Fla., where specific conductance of samples of water ranged from less than 500 to more than 3,500. The graph showed that most of the water samples from the shallow aquifers were in the range from excellent to permissible but many of the samples from the principal artesian aquifer were in the doubtful or unsuitable range.

CHANGES IN QUALITY OF WATER IN AQUIFERS

Under natural conditions, the quality of ground water is generally constant. However, in some locations, especially in recharge areas, contaminated water at the land surface may move into an aquifer under natural conditions, or through wells used to dispose of surface water or to recharge the aquifer. Under some conditions, withdrawal of water from the aquifer may cause water of poor chemical quality, such as salt water, to be drawn into the aquifer. Chemical changes may occur as the water moves through the aquifer. Some of these, such as natural softening, may improve the quality of the water. In general, however, the mineral content of the water increases as it moves through the aquifers. Water moving into and through aquifers may lose undesirable properties, such as color, turbidity, and contaminants, some of which may cause the water to be harmful or hazardous for human consumption if used without adequate treatment. The distance of travel in which these changes take place may be a few feet or many miles.

One of the factors which control these natural changes is the kind of material through which the water passes. Clean sand and gravel will serve as a filter for water moving through these materials. Water passing through permeable formations containing clay minerals or other material with ion-exchange capacity may lose some contaminants. As stated by Hem (1961, p. 21), although the water-bearing material of productive aquifers generally contains relatively little clay, there may be enough as a thin coating over sand grains and large rock particles to give considerable adsorptive capacity. Some of the geologic factors relating to ground-water contamination are described by De Buchananne and LaMoreaux (1961, p. 3–7). Some hydrologic factors pertinent to ground-water contamination are given by R. H. Brown (1961, p. 7–16).

Contamination of Ground Water

Contaminants of water may be grouped as (1) biological, including bacteria and viruses, (2) chemical, which may be organic or inorganic, and (3) radioactive.

In areas of cavernous limestone where the water may move rapidly through the limestone without natural filtering or ion exchange, contaminated water may become a serious problem. The problem of biological contamination of water has been recognized for many years. Radioactive, organic, and inorganic chemical contamination will become a problem if materials are released to the environment without adequate control. Fortunately, in the area covered by this report, problems of contamination in the limestone aquifers are confined to recharge areas in which water may enter the limestone at the surface or through open sinkholes or drainage wells. Only a few cases of such pollution are known in the region. One example of pollution through a sinkhole is reported by Meyer (1962, p. 51). Where there is recharge through sinkholes filled with permeable sand, as in some recharge areas in the lake region, biological contamination of the water in the limestone is unlikely because the water passes through the sandy fillings in the sinkholes. Some underground cavities are also filled with sand and clay.

Most, if not all, of the solution cavities, both horizontal and vertical, in the shallow limestone aquifer in southeastern Florida are filled with sand and clay. Although the surface water of relatively high organic color from the Everglades does not lose all its color in passing into the aquifer, there is no known biological pollution of wells from surface water entering the aquifers naturally. The capacity of the sand in the cavities in the limestone and permeable parts of the limestone to remove organic color and turbidity in the principal artesian aquifer is shown by the lack of color and turbidity in most of the large limestone springs.

Water from shallow wells in cavernous limestone along streams which cut the aquifer, as along the Suwannee River in Florida and the Flint River in Georgia, may yield water which enters the aquifer from the river. Because of these conditions, at Albany, Ga., deep wells were drilled through the cavernous limestone into the underlying aquifer to prevent possible pollution from the river.

Baker (1961, p. 142) observed that water of varying degrees of pollution has been discharged through drainage wells and sinkholes into the limestone in several areas in Florida. Treated municipal sewage and organic industrial wastes are being disposed of in this manner. The Florida State Board of Health has adopted a program to prevent any increase in the amount of polluted waste being discharged into the ground. Disposal of heated water into wells is permitted if the water is passed through closed cooling systems without contact with the atmosphere. Also the board issues a permit for the construction of a drainage well only if the required specifications are met. Outside the areas of recharge where relatively impervious beds overlie the limestone, there is little or no chance of the water in the limestone being contaminated by surface water, except through drainage wells or wells with defective casings.

The limestone in some of the coastal areas where the aquifer contains or is exposed to salt water at the submarine outcrop may become contaminated with salt water as discussed in the section on salt water. Contamination of the fresh-water aquifer may also occur where salt water from the formations underlying the fresh-water aquifer moves upward.

Ion Exchange and Natural Softening of Ground Water

Investigators of soil chemistry have shown that soil colloids, usually the aluminum silicate clay components, have the property of adsorbing one or more cations—as calcium, magnesium, and sodium—from solution and of releasing them again in exchange for other cations under suitable conditions. Changes in the chemical composition of ground water as it moves through water-bearing materials have been described by Renick (1925, p. 53–72). He found evidence of cation exchange in ground water at depths of less than 600 feet in two geologic formations in Rosebud County, Mont. Samples of water from wells less than 125 feet deep in the Lance Formation contained 43 to 162 ppm of calcium and magnesium, and those from wells more than 125 feet deep contained 5.2 to 18.1 ppm. Samples from wells less than 80 feet deep in the overlying Fort Union Formation contained from 99 to 212 ppm. These results show that the samples from shallow wells were relatively high in calcium and magnesium but low in sodium and those from deep wells contained little calcium and magnesium but were relatively high in sodium. Renick gave evidence that this natural softening of the water by the exchange of calcium and magnesium for sodium is due to clay minerals of the leverrierite group. However, he recognized that other hydrated aluminum silicates, such as kaolin, feldspars, and mica, are also capable of exchanging all or part of their sodium and potassium for other cations. As the exchange was accomplished within depths of 125 feet or less in the aquifer, Renick concluded that although the water may move many feet and even miles downgradient, its calcium and magnesium content was essentially removed by percolating through relatively few feet of the aquifer.

Howard (Stephenson and others, 1928, p. 42, 43) apparently reached the same conclusion in his discussion of natural softening of water in the Ripley Formation of Cretaceous age, which consists chiefly of sands and clays and some glauconite, in northern Mississippi where analyses show a change similar to that reported by Renick. Calcium and magnesium were exchanged for sodium, but the total dissolved solids apparently remained about the same. Howard included analyses of two samples from depths of 461 and 155 feet, respectively, in the same township in Tippah County, Miss. The sample from a depth of 461 feet was low in calcium and magnesium but relatively high in sodium and potassium. The sample from 155 feet was relatively high in calcium and magnesium but low in sodium. This difference at different depths in the same township was interpreted by Howard as natural softening with downward movement of the water. Although such changes similar to that of zeolite softening of water in water treatment may occur after a few feet of downward movement of water in recharge areas, probably most of the changes in water in the artesian aquifers in the Atlantic and Gulf Coastal Plain occur as the water moves downgradient and downdip in the water-bearing sand, sandstone, silt, and clay. Soft sodium bicarbonate water commonly occurs in the aquifer many miles from its recharge areas. Also, in some areas, sodium bicarbonate and other constituents, as fluoride, increase with distance from recharge areas. These aquifers contain glauconite, volcanic ash, bentonite, and other materials which may act as zeolites in natural softening of the water.

This kind of soft sodium bicarbonate water is present in the principal artesian aquifer of Tertiary age where the aquifer grades from limestone and marls to sands in Okaloosa, Santa Rosa, and Escambia Counties in western Florida and parts of southeastern Alabama and southwestern Georgia (Barraclough and Marsh, 1962). The soft sodium bicarbonate water in the aquifer along the coast in western Florida probably entered the aquifer where it is at or near the surface in Alabama. In parts of that area the aquifer consists chiefly of limestone containing relatively hard calcium bicarbonate water. In Georgia, Wait (1960a, p. 12) reported sodium calcium bicarbonate water in feldspathic sand in the lower part of the Clayton Formation. The increase in sodium is attributed to sodium feldspar in the basal sand.

As stated by Foster (1937, p. 407), the depth at which softening begins varies with the relative proportion of calcium and magnesium carbonates to the base-exchange materials through which the water passes. If the carbonates are present in amounts more than equivalent to the exchange mineral, or if the capacity of the base-exchange minerals has been exhausted in the shallower material, ground water must travel farther before being softened.

Some sodium bicarbonate water has the same bicarbonate content as the shallower calcium bicarbonate water in the same formation. However, some soft sodium bicarbonate water contains several hundred parts per million more of the bicarbonate than the calcium bicarbonate water. According to Foster (1950, p. 33–48), the water contains much more sodium bicarbonate than can be attributed to solution of calcium carbonate through the action of carbon dioxide derived from air and soil. After a study of the field data and laboratory experiments, Foster showed (1950, p. 33) that the presence of carbonaceous material, as a source of carbon dioxide, with calcium carbonate and ion-exchange minerals in a formation is sufficient to account for the high sodium bicarbonate content of the water. Foster (1950, p. 48) suggested that carbon dioxide evolved from the carbonaceous material probably would permeate the aquifer and under these conditions the water would receive the carbon dioxide without coming in contact with the carbonaceous material. Disseminated organic debris in quantities not readily detected by means of chemical and microscopic aid could also contribute carbon dioxide to the water.

In a study of the quality of ground water in the Everglades and the very productive shallow aquifer in southeastern Florida, Love (in Parker and others, 1955, p. 578, 821–822) found evidence of cation exchanges as indicated by general increases in calcium concentrations which were compensated by losses in magnesium and sodium. Because the water-bearing limestone in the shallow aquifer in the Everglades contains little or no aluminum silicate clays, except such material as that filling many cavities in the limestone, Love suggested that the cation exchange takes place largely through the medium of organic matter which colors practically all the shallow ground water in the area. He postulated that some of the mineral content of ground water in the Everglades is from remnants of Pleistocene sea water that has not been completely flushed out of the area and some of it is from cation exchange processes. He suggested that organic colloids saturated with sodium and magnesium from the sea water came in contact with fresh calcium bicarbonate water in the limestone, with the result that sodium and magnesium were exchanged for calcium. Calcium bicarbonate is readily brought into solution by carbon dioxide furnished in large part by decomposing organic material. When in contact with the material which contains the sodium and magnesium, the calcium is exchanged for the sodium and magnesium. The water then comes in contact with more limestone which dissolves to form more calcium bicarbonate. Repetition of the process increases the bicarbonate content in excess of 500 ppm and as much as 1,000 ppm.

RADIOCHEMICAL ELEMENTS

The development of nuclear energy has increased the interest in radioisotopes and radioactivity of water. Radioisotopes in water are being studied to determine the natural radioactivity and its relation to the geology and hydrology. Radioisotopes in water also are being studied to detect changes resulting from radioactivity from nuclear reactors, nuclear weapons tests, and other activities of man. Some radioisotopes are being used to good advantage in studying the movement of water on the surface and underground. A few of these are helpful in determining the movement and the relative age of water.

In connection with the present investigations, a few water samples were tested for tritium to aid in studies of recharge areas of the principal artesian aquifer. During 1960 and 1961 in another investigation of the U.S. Geological Survey to determine the natural background radioactivity of water, a few samples of water from the principal artesian aquifer were tested for uranium, radium, and gross gamma-beta radioactivity. Tests of carbon-14 in peat have been made for a few samples to determine the age of these deposits in the Florida Everglades south of Lake Okeechobee (Parker and others, 1955, p. 109). Carbon-14 content of water was recently used by Hanshaw, Back, and Rubin (1963, p. 74) to determine the age of water in the Southeastern States. Tritium is being used to determine the age of water not more than 50 years old. The use of carbon-14 content gives information on the relative age of artesian water which is too old to be tested by tritium.

Tritium

Tritium, or hydrogen-3, is the only known radioactive isotope of hydrogen found in nature. Hydrogen-4 is known only in the laboratory and has a very short half life (L. L. Thatcher, written commun., June 1962). The other isotopes of hydrogen are hydrogen-1, or protium, and hydrogen-2, or deuterium, which forms heavy water. Tritium is present in detectable quantities in nature as the product of the collision of cosmic rays with the atmosphere. It had been sought in natural water prior to discovery of its natural radioactivity (Libby, 1955, p. 301). It has a half life of 12.5 years and disintegrates to form the stable isotope of helium-3. The tritium content of water may be expressed as tritium units (TU) in which 1 TU represents 1 tritium atom for 10^{18} atoms of ordinary hydrogen atoms. The radioactivity of 3.3 TU is $10^{-8}\mu c$ per cc (microcurie per cubic centimeter), according to Kaufman (1960, p. 49). The quantity of tritium occurring naturally is so small that its presence has no effect on the use of water.

In addition to natural tritium produced by cosmic rays, tritium from nuclear weapons tests and as a fission product of nuclear reactors has been added to the environment. The nuclear weapons tests raised the tritium level in precipitation to many times the normal level. After the tests, the tritium level declined but never returned to the normal level, which L. L. Thatcher estimated was about 6 TU along the Atlantic coast. On this basis, Thatcher estimated that water with tritium content of 1.5 TU because of disintegration rate alone would be about 25 years old.

The tritium content of 11 samples of water from the principal artesian aquifer in South Carolina, Georgia, and Florida, tested in the Geological Survey tritium laboratory in Washington, D.C., ranged from less than 0.5 to 4.2 TU, as follows:

Location	*Depth of well (feet)*	*Date collected*	*Tritium units*
Hilton Head, S.C	543	11-3-60	<0.5
Beaufort, S.C	95	2-24-61	< .5
Beaufort, S.C	102	2-24-61	1.6
Savannah, Ga	557	11-14-60	1.5
Keystone Heights, Clay County, Fla	492	1-9-61	.9
Northwest of Lake Okeechobee, Fla., (sec. 28, T. 38 S., R. 34 E.)	1,300	12-8-60	1.0
Polk City, Fla	425	1-13-61	3.8
Marietta, Duval County, Fla	612	12-22-60	1.2
Silver Springs, near Ocala, Marion County, Fla	......	1-5-61	4.2
Salt Springs, 28 miles northeast of Ocala, Marion County, Fla	......	1-6-61	1.7
Radium Springs, 4 miles south of Albany, Ga	......	1-11-61	1.0

The sample containing 4.2 TU was collected from a depth of 60 feet in Silver Springs, Fla. Although there probably is local recharge of the principal aquifer within a few miles of Silver Springs, part of the water in this area is from the Putnam County area to the north and the Polk County area to the south, as indicated by the piezometric surface of the artesian water (fig. 29). The low organic color and the absence of turbidity also indicate that the water may move a considerable distance through the aquifer. The content of 3.8 TU in the sample from a well in Polk County supports other information which indicates local recharge to the principal artesian aquifer. The tritium content of the water that recharged the aquifer locally is not known. However, judging from a sample of shallow ground water collected from Nags Head, N.C., Apr. 5, 1961, containing 47 TU, the tritium content of the shallow ground water recharged to the aquifer locally was much higher than 3.8 TU. Since the time of travel from the surface to the aquifer through sinkholes filled with permeable sands should be only a few days or weeks, the low tritium value suggests that tritium in the water in the aquifer decreases with depth and the sample tested was a composite which included some old water in the lower part of the aquifer which did not contain tritium. The sample from Keystone Heights in Clay County had a tritium content of only 0.9 TU even though it is in a recharge area.

Also, a sample from a recharge area in Beaufort, S.C., had a value of only 1.6 TU. These values appear to indicate that the samples represented young water mixed with old water with little or no tritium in the aquifer. The artesian well sampled at Okeechobee in southern Florida is in an area of artesian flow about 25 miles east of the nearest known recharge area in Polk County. The sample from Marietta is from a well at the west edge of the area of artesian flow where there may be little or no local recharge, about 30 miles northeast of the nearest known recharge area in Baker and Union Counties.

The sample containing 1.6 TU from Beaufort, S.C., is in an area where the piezometric surface is relatively high and where the land surface has shallow depressions which may represent sinkholes extending to the aquifer but which were almost concealed by terrace sediments deposited when the Pleistocene sea covered this area.

In the Savannah area where the sample of water from the principal artesian aquifer had 1.5 TU, the piezometric surface was formerly as much as 40 feet above sea level, as shown in figure 30, and wells overflowed at the land surface. Large withdrawal of water from wells has lowered the piezometric surface as much as 100 feet below sea level in the center of the cone of depression. The nearest known recharge area is about 35 miles west of Savannah. If the water with 1.5 TU is about 25 years old and is from that recharge area, the rate of lateral movement would be more than a mile a year. However, as estimated by Warren (1944, p. 126) for the Savannah area and discussed in the section on the principal aquifer in the present report, the maximum rate would be 1,150 feet a year for each foot of hydraulic gradient. The average gradient between the known recharge area and Savannah is almost 3 feet per mile. Assuming a rate of movement of 1,150 feet per year for each foot of gradient, the rate would be less than a mile, only 3,450 feet per year with a gradient of 3 feet per mile. It is entirely possible that local recharge occurs through concealed sinks between the known recharge areas and the coast. If such sinks are present under tidewater in the Savannah area, they probably are filled with relatively impervious material which prevents salt water from moving downward into the aquifer.

The TU values of 1.0 at Okeechobee and 1.2 at Marietta appear to indicate some downward movement of water through the Hawthorn Formation between the area of artesian flow and the known recharge areas. Judging from the available information on the geology and hydrology of the aquifer, it probably would require more than 100 years for the artesian water to move 25 miles in these areas where the gradient of the piezometric is less than 2 feet per mile, as discussed in the part of this report on the rate of movement of water in the principal artesian aquifer. Vertical movement through the Hawthorn Formation, which is as much as 500 feet thick with relatively impervious beds, would also be very slow and under some conditions might require 25 years or more to move downward to the artesian aquifer. The result would be water with a tritium content of about 1.5 TU mixing with older water with little or no tritium in the aquifer. With this dilution, detectable amounts of tritium would not be expected. This suggests that if the laboratory tests on the tritium are correct, there are unmapped recharge areas where there is insufficient recharge to be noticeable on a generalized map of the piezometric surface but sufficient to add to the aquifer enough young water so that the mixed water has 1.5 TU. Possibly, local recharge occurs through sinkholes which were filled with unconsolidated sediments and concealed below the Pleistocene terraces.

Uranium and Radium

Uranium-238 and radium-226, radioactive isotopes of the uranium-radium series, were determined for a few samples of water from the principal artesian aquifer as part of another investigation (Scott and Barker, 1958, p. 153–157, and 1962, p. 34). This is a natural radioactive series which starts with uranium-238 and ends with the stable isotope lead. Uranium is present in small quantities in some of the phosphatic material in Miocene and younger deposits in Florida.

The Bone Valley Formation has been leached by acid ground water, forming a zone characterized by aluminum phosphate minerals. This zone generally averages 0.010 to 0.02 percent uranium (Altschuler and others, 1956, p. 503). The matrix, or calcium phosphate zone, constituting the lower phosphorite part of the Bone Valley Formation and the upper residual part of the Hawthorn, consists chiefly of equal parts of quartz sand, phosphate particles, and slime. Uranium content of the coarse material averages between 0.010 and 0.020 percent as reported by Cathcart (1956, p. 489), who believes the uranium was absorbed by phosphate particles as they formed on the sea floor. In his study of the abnormal radioactivity south of Ocala, Fla., Espenshade (1958, p. 218) concluded that much of the radioactivity probably is from leached phosphorite that is similar to rock of the leached zone of the Bone Valley Formation. Also, abnormal radioactivity at some places in the Ocala area is caused by leached, uraniferous pellet phosphorite.

In their study of the radium and uranium in ground water in the United States, Scott and Barker (1958, p. 153–154) gave the range of radium and uranium concentrations expressed as micromicrocuries per liter ($\mu\mu c$ per 1) and micrograms per liter (μg per l), respectively, in 89 samples from the Atlantic and Gulf Coastal Plain. The method of analysis used did not differentiate between radium-226 of the uranium series and radium-224 of the thorium series. The range in uranium was less than 0.1–15 μg U per l and in radium was less than 0.1–8.6 $\mu\mu c$ Ra per l. The maximum uranium reported by Scott and Barker (1962, p. 12–13) was in a sample from Miocene sand and clay containing volcanic ash in Texas. They suggested the uranium may be from the volcanic ash.

A water sample reported by Lichtler (1960, p. 52) from the principal artesian aquifer in Martin County, Fla., had 1.2 μg U per l and 11 $\mu\mu c$ Ra per l. The gross beta-gamma radioactivity was 200 $\mu\mu c$ per l. Also, a sample from Salt Spring in Marion County, Fla., which seems to be from the principal artesian aquifer, had 0.5 μg U per l and 4.7 $\mu\mu c$ Ra per l (Robert Scott, written commun., 1959).

Natural uranium in water is not known to have a harmful effect. However, radium which results from the radioactive disintegration of uranium and thorium may occur in harmful amounts. The maximum permissible concentration of radium in water for general use apparently has been set by the U.S. Public Health Service as 3.3 $\mu\mu c$ per l. Except in a few places, natural potable ground water has less than 3.3 $\mu\mu c$ Ra per l. The occurrence of 11 $\mu\mu c$ Ra per l in the principal artesian aquifer in Martin County may be from small quantities of uranium in phosphatic material in the Miocene rocks in the upper part of the aquifer. Other samples from the aquifer including one from Wakulla Spring near Tallahassee, Fla., and Silver Springs near Ocala, Fla., show low uranium and radium content as might be expected in the principal artesian aquifer where little or no phosphatic material is present.

TEMPERATURE OF ARTESIAN WATER

The temperature of shallow ground water, as indicated by Collins (1925, p. 97–104), is in general about the same as the mean annual temperature of the air. Near the ground surface the temperature of the water follows the changes in air temperature. At greater depths, the water has a higher temperature, corresponding to the increase of the earth's temperature. C. E. Van Orstrand (Collins, 1925, p. 98) computed that under normal conditions the temperature of ground water at a depth of 30 to 60 feet will generally exceed by 2° to 3°F the mean annual air temperature. At a depth of about 20 feet, the temperature of the ground water may range from 10°F above to 10°F below the mean annual temperature of the air.

A generalized map by Collins of the approximate temperature of water from nonthermal wells in the United States at depths of 30 to 60 feet shows a temperature range from 67°F in the southern part of the Coastal Plain in South Carolina to 77°F in southern Florida. In Martin County, Fla., where the mean annual temperature of the air is 75.2°F, Lichtler (1960, p. 61) reported that temperatures of 120 samples from shallow wells 10 to 100 feet deep ranged from 70° to 82°F. The average was 75.5°F, which is about the same as the air temperature. However, many samples were 2° to 3°F above the mean annual temperatures, as suggested by the study by Van Orstrand. Lichtler also observed that the temperature of the shallow ground water varied according to the season. The greatest variation was in the water nearest the land surface.

The temperature of artesian water in the principal artesian aquifer as measured at the mouths of wells ranged from about 62°F in South Carolina to 91°F in Martin County in southern Florida. The highest temperature recorded for the artesian water in the Cretaceous aquifers underlying the principal artesian aquifer of Tertiary age was 103°F from depths of 2,610 to 3,450 feet in a well at Parris Island, S.C.

The temperature of water in springs from the principal artesian aquifer ranged from 67°F in northern Florida to 86°F in Warm Salt Spring in Sarasota County in southern Florida. The highest temperature recorded by Stringfield (1933c) for artesian wells in Sarasota County was 82°F, with the exception of an oil test well 1,332 feet deep whose temperature was 87°F. It appears that a temperature of 86°F for Warm Salt Spring was affected by the air temperature. Most measurements of the temperature of spring water ranged from about 69°F in northern Florida and southern Georgia to about 70° to 74°F in central Florida. The measurements showed some variation in the temperature of the springs at different times, but this variation probably reflected in part the changes in the air temperature. Some measurements showed little or no change in the temperature, as for example, 8 of 11 measurements for Weekiwachee Spring at different times were 70°F. The other measurements were 72°, 75°, and 77°F. This wide range of three measurements may be due in part to the use of the thermometers which had not been calibrated, or perhaps to measurements in different places on the surface of the spring.

Measurements of the temperature of water at the mouths of representative wells in the principal artesian aquifer by Warren (1944, p. 138–140) in southeastern Georgia ranged from 69°F in Effingham County to 78°F in McIntosh County. In Escambia County in southeastern Alabama, Cagle and Floyd (1957, p. 24–29) reported that the temperature of water from wells ranged from 68° to 76°F.

The temperature of the water from the principal artesian aquifer in Martin County, as measured by Lichtler at the mouths of wells about 500 to 1,380 feet deep, ranged from 75° to 91°F. However, only one well had a temperature of more than 85°F. The well having the highest recorded temperature, 91°F, is 843 feet deep. Water from another well about the same depth and only 3 miles away had a temperature of 81°F. The records of the two wells indicate that the increase in the temperature with depth is 1°F for each 55 feet in one well and 1°F for each 140 feet in the other well. This difference may be due in part to the fact that the wells are not cased in the aquifer, which is as much as 500 feet thick. In one well the water may be from the upper part of the aquifer, and in the other it may be from the lower part even though the wells are about the same depth. However, in view of the fact that all but one deep well had temperatures of 85°F or less, the temperature of 91°F appears anomalous. Lichtler (1960, p. 52, 63) suggested that radioactivity may cause the higher temperature, but this explanation seems unlikely to the writer. It appears more likely to be related to some other features. F. C. Westendick (in Stringfield, 1936, p. 169) recorded a temperature of 88°F in artesian water from a well reported to be 620 feet deep in Lee County, Fla., indicating a thermal gradient of about 1°F for each 56 feet of depth. This suggests that the differences in temperature may merely be due to differences in depths at which the water enters the well.

The lowest temperature of the artesian water in Martin County is in the eastern part. Lichtler (1960, p. 63) suggested that the relatively low temperature may be due to the cooling effect of the ocean water on the submarine outcrop of the aquifer which is near the shore. Nevin Hoy (written commun., 1960) observed lower temperatures of artesian water near the coast of Dade County, Fla. Hoy suggested that the lower temperature may be due to the cooling effect of the Gulf Stream. Temperatures of about 43° to 48°F on the submarine outcrop of the aquifer are only a few miles offshore.

Other reports which contain information on the temperature of artesian water from the principal aquifer in Florida include the following. Records of temperature measurements given by Stringfield (1936, p. 165–175) in the Florida peninsula ranged from 70° to 88°F. In Brevard County, D. W. Brown, W. E. Kenner, and Eugene Brown (1957, p. 85) reported temperatures ranging from 74° to 81°F. Most of them were less than 80°F. Peek (1959a, p. 5–48) recorded temperatures that ranged from 75° to 82°F in the Ruskin area, Hillsborough County. Most of the measurements were less than 80°F. Bermes (1958b, p. 67–68) recorded temperatures that ranged from 76° to 79°F in Indian River County. The measurements in Manatee County ranged from 77° to 84°F, but most of them were less than 80°F, as reported by Peek (1959a, p. 5–48). In Flagler, Putnam, and St. Johns Counties, Fla., Bermes and others (1963, p. 75) reported that the temperature of the artesian water ranges from 72° to 75°F, which is about 1° to 3°F higher than mean annual air temperature in that area. The higher temperatures appear to be from deeper wells away from recharge areas. Artesian water is used in parts of that area to moderate air temperature to prevent freezing of young tomato plants. Also, it is used in several homes for heating and cooling.

Thermal Gradient

The temperature of ground water increases with depth as the temperature of the formations in which it occurs increases. This increase of temperature, or the thermal gradient, may differ considerably from one area to another, depending on the geologic conditions. Collins (1925, p. 98) gave an approximate average of 1°F for each 64 feet of depth reported by a committee of the British Association for Advancement of Science in 1882.

The maximum thermal gradient for a water well in the Coastal Plain of the Southeastern States as observed by G. F. Brown (1947, p. 33) was 1°F for each 53 feet of depth in an artesian well, 1,746 to 1,786 feet deep, with a maximum recorded temperature of 98.7°F at Glen Allen, Washington County, Miss. Paul Jones of the U.S. Geological Survey (written commun., 1950), recorded a temperature of 101°F for artesian water from a depth of 3,100 feet and a temperature of 98° to 99°F for water from a depth of 2,850 feet in eastern Louisiana, indicating an increase in temperature of about 1°F for each 100 feet of depth. The average of other measurements on artesian wells in that area is about 1°F for each 97 feet of increase in depth.

Incomplete data indicate that the thermal gradient may range from about 1°F for each 55 feet of depth to about 1°F for each 140 feet of depth in the area of this report. These data are based on measurement of the temperature of the water as it discharges from the wells, some of which are not completely cased. Temperature measurements at different depths in wells will be required to give a better understanding of the thermal gradient and the causes of the differences in these gradients.

SALT WATER

The potential fresh-water supply of aquifers in many areas is dependent on its relation to salt water that may be drawn into an aquifer and thus contaminate the fresh water. In the Southeastern States, this problem is most significant in the coastal areas. However, the problem is present in the upper part of the St. Johns River valley in Florida and in parts of the Florida Everglades, as on the south side of Lake Okeechobee.

In areas where salt water has encroached or may encroach in an aquifer, the fresh-water supply may not be adequate for future increases in use. However, adequate information on the geology and hydrology (Parker and others, 1955) will make it possible to maintain a fresh-water supply indefinitely if the necessary precautions are taken, as in the Miami area, Florida, where part of the aquifer was contaminated by salt water before precautions were taken. If ignored, the problem may result in contamination of the aquifer by salt water and make it necessary to develop new well fields some distance from the contaminated areas. Once an area is contaminated by salt water, it may require many years under the most favorable conditions for the salt water to be flushed out. Therefore, in proper management and planning of ground-water resources it is essential that the problem of salt water in aquifers be understood.

Salt water in fresh-water aquifers in the area of this report may come from one or more of the following sources:

1. Water from the Atlantic Ocean and the Gulf of Mexico in the coastal areas where the fresh-water head has been lowered to an extent that permits salt water to move into the aquifer. Salt-water spray along the coast contributes small amounts of salt to the ground water. Some shallow aquifers, as in the Florida Keys, are contaminated by salt water during storms.
2. Connate water or sea water that remained in the formations after deposition.
3. Sea water that entered the formations after they were deposited but before Recent time. In some areas sea water of Pleistocene age is present in the principal artesian aquifer and in the overlying aquifers.
4. Salt, as thin beds, or disseminated in geologic formations.
5. Sea water that became more concentrated by evaporation in tidal lagoons or other enclosed water bodies that received sea water during storms.

Salt domes or plugs of salt that were pushed from salt beds upward into overlying formations are sources of salt in some water in the Gulf Coastal Plain west of Florida. Deep wells drilled for oil in southern Florida have penetrated salt beds in the Cretaceous strata, but available information shows no indication of salt domes or thick salt beds in the overlying Cenozoic formations in the area of this report.

In shallow formations along the coast most, if not all, of the salt water is from sea water of Recent age. In the deeper formations, not exposed to sea water, near the coast the salt water is from connate water or sea water that entered the formation after it was deposited but before Recent time. Inland, the salt water is from connate water and sea water that entered the formation after it was deposited or from salt in the formations.

Sanford (Matson and Sanford, 1913, p. 276) reported that a city well drilled to a depth of 780 feet at Titusville, Fla., penetrated a thin bed of salt at a depth of 50 feet.

Salt water resembling sea water in composition but more than twice as concentrated as sea water was collected by Stringfield (1933c, p. 219) from an unfinished well 398 feet deep, owned by H. C. Ditmas, south of Anna Maria on Anna Maria Key, Manatee County, Fla., the only locality in the report area in which salt water more concentrated than sea water has been found at relatively shallow depths. However, Kimrey (1960, p. 14) reported ground water more concentrated than sea water, having a chloride content of as much as 42,000 ppm, at depths of less than 110 feet at the Pea Island Campground on the northern tip of Hatteras Island, Cape Hatteras, N.C. This occurrence suggests concentration of sea water by evaporation in a tidal lagoon or other enclosed water body.

CHEMICAL COMPOSITION OF SEA WATER

The chemical composition of ocean water has been determined by analyses of samples collected from many places in the world. These analyses show that concentration of dissolved mineral matter differs considerably from place to place and varies from time to time. However, as stated by Love (Parker and others, 1955, p. 572) the ratio between the more abundant constituents is almost constant (Sverdrup and others, 1942, p. 165).

The analyses commonly taken to represent the average composition of sea water are those made by Dittmar on 77 samples collected from many parts of the world by the *Challenger* Expedition in 1884. The average of these analyses is given in the following table, together with an analysis of water collected on May 23, 1941, from the Atlantic Ocean about 50 feet offshore at 41st Street, Miami Beach, Fla. The concentrations of the different constituents in the samples collected off Miami Beach in 1941 are slightly greater than those reported by Dittmar, but their ratios to chloride are almost the same.

Analyses of sea water

[From U.S. Geol. Survey Water-Supply Paper 1255, p. 572]

	Average of 77 samples		Miami Beach sample	
	Parts per million	Ratio to Cl (percent [1])	Parts per million	Ratio to Cl (percent [1])
Calcium (Ca)	419	2.17	423	2.14
Magnesium (Mg)	1,304	6.73	1,324	6.70
Sodium (Na)	10,710	55.35	10,970	55.49
Potassium (K)	390	2.02	429	2.17
Bicarbonate (HCO_3)	146	.75	147	.74
Sulfate (SO_4)	2,690	13.90	2,750	13.91
Chloride (Cl)	19,350	----	19,770	----
Bromide (Br)	70	.36	49	.21
Total dissolved solids	35,000	----	35,800	----

[1] Contents of indicated ion divided by chloride content and multipled by 100.

RELATION OF SALT WATER TO FRESH GROUND WATER

Certain general relations between salt water and fresh ground water in coastal areas have been summarized by J. S. Brown (1925, p. 16). The principle of equilibrium between salt and fresh water, as applied to the hydrology of a seacoast, is sometimes referred to as the theory of Ghyben and Herzberg because they were among the first investigators to recognize the principle. Badon Ghyben announced the theory in 1889 after an examination of water in sand dunes in Holland. Herzberg described the relation more thoroughly in a report published in 1901 after he learned, by drilling wells on the Island of Norderny, that the depth of salt water was a function of the height of the water table above mean sea level and of the density of the water of the North Sea. The results of these investigations were reviewed by Brown.

Palmer (1957, p. 181–189) reviewed the history of the principle and proposed that it be called the Herzberg principle, without its various parallels, such as the Herzberg lens. According to Palmer (1957, p. 188), Herzberg gave a far better presentation of the idea than Ghyben. Palmer included references to much of the literature on the subject.

Application of the principle, as stated by J. S. Brown (1925, p. 16) and Black, Brown, and Pearce (1953), may be expressed as follows:

Let

$H =$ total thickness of fresh water,
$h =$ depth of fresh water below sea level, and
$t =$ height of fresh water above mean sea level.

Then

$$H = h + t.$$

However, the column of fresh water (H) must be balanced by a column of salt water (h) in order to maintain equilibrium. Therefore, if g is the specific gravity of sea water and the specific gravity of fresh water is assumed to be 1, then:

$$H = h + t = hg,$$
$$t = hg - h = h(g - 1),$$
$$h = t/(g - 1),$$

in which $g - 1$ is the difference in gravity between the salt water and the fresh water. (See fig. 34.)

The specific gravity of sea water differs somewhat from one locality to another and may also be different at different depths. For example, in July and August 1913, Bigelow (1915, figs. 55, 61) found that the specific gravity of surface water in the Atlantic Ocean ranged from 1.019 near the mouth of the Chesapeake Bay to 1.025 in the Gulf of Maine. Also, at certain points opposite Chesapeake Bay, the specific gravity ranged from 1.019 at the surface to more than 1.028 below a depth of 110 fathoms (660 feet). A map by Lindenkohl (1896, p. 358) showed that the specific gravity of surface water was 1.024 near the coast, about 1.026 about 10 miles offshore, and 1.028 at a distance of nearly 100 miles. The density of water below the surface may be greater, although Lindenkohl suggests that it may actually decrease to a depth between 700 and 800 fathoms and increase below that depth. The average specific grav-

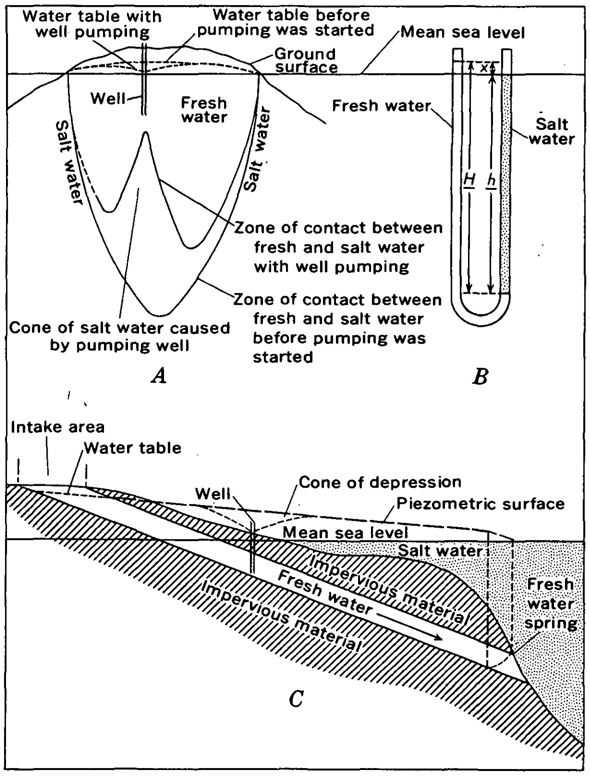

FIGURE 34.—Relation of salt water to fresh water in aquifers. (From Warren, 1944).

ity reported by Parker, Ferguson, Love, and others (1955, p. 573) from samples of water from the Atlantic Ocean at Miami, Fla., is 1.02680.

Where an aquifer is exposed in the ocean, sea water may enter it under some conditions. Under nonartesian conditions, sea water will be at such a depth that the overlying column of fresh water will balance a column of heavier sea water, according to the Ghyben-Herzberg principle. Thus, under static conditions, if the fresh ground water has a specific gravity of 1 and the sea water has a specific gravity of 1.025, the contact between the sea water and the overlying fresh water at any place is depressed 40 feet below sea level for every foot that the water table stands above sea level. Under these conditions, if the height of the water table above sea level is known, it is possible to determine with a reasonable degree of accuracy the depth to which fresh water is present. If sea level remained at a constant level and recharge from rainfall were at a uniform rate, the salt water-fresh water interface would remain in the same position, and salt water would remain motionless while the fresh water would move toward the sea in the same way as if the interface were an impermeable surface. However, the ocean tides, as well as variations in recharge and discharge, continually disturb the balance between salt water and fresh water and cause the interface to fluctuate. By this natural fluctuation as well as by diffusion of the salt water, the sharp interface is destroyed, and a considerable transition zone of brackish water may be created.

If a well is pumped and a cone of depression in the water table is developed under such conditions, salt water will rise below the well and will form an upright cone, theoretically having a height about 40 times the depth of the cone of depression in the water table. If pumping is continued at a constant rate without change in the cone of depression, the contact theoretically remains stationary and salt water remains motionless while fresh water moves from all directions toward the well. If, however, the rate of pumping is increased or because of depletion of the supply the water table is further depressed, the apex of the salt-water cone may reach the bottom of the well, salt water may be drawn into the well, and movement in the salt-water zone may begin.

Under artesian conditions, the same general principle may hold, but under modified conditions, as shown in figure 34 where artesian conditions exist, sea water has access to the aquifer at its outcrop beneath the sea where it is not covered by confining beds or at points where a fissure or other opening occurs in the confining bed. The relation between salt and fresh water under these conditions may be compared to those conditions in a U-shaped tube, one side of which is filled with salt water and the other with fresh water. One leg of the tube is comparable to the sea and the other to the aquifer, and the walls of the tube represent the confining beds.

If the confining bed is completely impervious and the head of water in the aquifer is not large enough to push the salt water back to the submarine outcrop of the aquifer, the condition is one of equilibrium between two bodies of water of different densities. On the other hand, if the head of water is sufficiently great, a hydraulic gradient will be established in the aquifer, the salt water will be pushed back to the submarine outcrop, and fresh water will escape into the sea. Under the first condition, there is no discharge of fresh water into the sea. Hence, there is no hydraulic gradient, the head of the water in the aquifer is the same at all points, and the piezometric surface becomes an even surface at some height above sea level. An area in which the head is the same at all points has been called an isopiestic area by Palmer (1927, p. 39–40). Under the first condition, the water is under artesian pressure that is due in part to the back pressure of the salt water.

Whether the active or static conditions exist depends on such factors as the artesian head and the depth of the submarine outcrop or the depth at which the sea water enters the aquifer. If the head is relatively high or the submarine outcrop is relatively near sea level, active conditions may prevail. Under these conditions, there is a hydraulic gradient; water is moving through the aquifer, and the soluble salts have generally been removed if there has been sufficient time and if the artesian water is relatively free of mineral matter. Conversely, if the head is low or the submarine outcrop is at great depth, static conditions may prevail. The aquifer is plugged by pressure of salt water, and there is no leaking out of the soluble salts, except as artesian water may escape through the overlying confining beds or through nearby submarine outcrops where the aquifer is near enough to sea level so that the fresh-water head in the aquifer at the outcrop exceeds the back pressure from the salt-water column in the ocean.

In the area of this report water-table aquifers are exposed to sea water along the coast, and in some places artesian aquifers are exposed to sea water. In these areas the problem of salt-water encroachment is present where withdrawal of water through wells or drainage of the coastal area, as in southeastern Florida (Parker and others, 1955, p. 165–166, 580–584), has lowered the water table or artesian head enough to cause the sea water to move into the aquifers.

In nearly all the coastal areas where the aquifers are exposed to sea water, the Ghyben-Herzberg principle can be used to estimate the position of the interface between the salt water and fresh water. However, the interface is deeper and nearer the coast than that indicated by the Ghyben-Herzberg principle where there are dynamic conditions in a very permeable formation and large quantities of fresh water move along the zone of diffusion at this interface and discharge over the salt water. Several investigators, including Muskat (1937, p. 289), Hubbert (1940, p. 924), Glover (1959, p. 457–459), and Henry (1959, p. 1911–1919), reported that under dynamic conditions where the fresh water flows seaward, especially with a steep water table, the position of the interface of the salt water in relation to the fresh water is governed by a dynamic equilibrium between flowing fresh water and almost static salt water.

Cooper (1959, p. 461–467) and Kohout (1960, p. 2133–2141) and others observed that during periods of heavy recharge in the shallow aquifer, the fresh water, the salt water, and the zone of diffusion move seaward in the Miami area, Florida. The shallow aquifer consists of the Tamiami Formation of Miocene age and overlying younger formations which are exposed at the surface and are exposed to salt water in Biscayne Bay. Although the gradient of the water table is very low, the aquifer is very permeable, and the flow of water through it is therefore large. Under these conditions, the diluted salt water in the zone of diffusion continues to flow seaward while the fresh water head is low, and the salt water in the lower part of the aquifer flows inland.

Kohout (1960, p. 2141) indicated that under some conditions about 20 percent of the total salt water flowing inland below the fresh water discharges seaward in the diffusion zone between the salt water and fresh water. A ground-water velocity test, using fluorescein dye as a tracer, showed that water in that zone containing 1,500 to 2,000 ppm chloride was flowing seaward at a rate greater than 70 feet per day. This cyclic flow acts as a deterrent to the encroachment of sea water, and therefore the contact between the fresh water and salt water is deeper and not as far inland as that computed by the Ghyben-Herzberg principle which holds for static conditions.

Dynamic conditions similar to those in the shallow aquifer at Miami seem to be present on the gulf coast in Citrus and Levy Counties, Fla., where Eocene limestones of the principal artesian aquifer crop out in the gulf. Large quantities of fresh water discharge through the cavernous limestone aquifer into the Gulf of Mexico. Information on the depth to salt water in north-central Florida, including Levy County, obtained in a surface electrical-resistivity survey in 1937, is given in an unpublished report ("A Geophysical Survey in North-Central Florida" by J. H. Swartz, G. R. MacCarthy, and A. C. Byers, U.S. Geol. Survey, 1937) which describes a surface resistivity survey at three selected areas along a line from Yankeetown on the gulf coast in Levy County through Dunnellon, Ocala, and Silver Springs to Welaka and Pomona east of the St. Johns River. The line from Yankeetown to Silver Springs in Marion County is approximately along the proposed route 13–B (U.S. Army, Corps of Engineers, 1933; U.S. Congress, Senate, 1936) for a ship canal across Florida. The first of these areas is along the road from Yankeetown to Dunnellon; the second is south of Ocala; and the third is east of the St. Johns River between Welaka and Pomona in the southern part of Putnam County.

Of twelve surface resistivity stations along the Yankeetown-Dunnellon highway, the first five beginning at Yankeetown recorded measurements to a depth of 1,000 feet, and the remainder, to a depth of 2,000 feet. The first station at the edge of a salt-water marsh indicated salt water to a depth of 40 feet, but there was no indication of salt water in the interval between 40 and 1,000 feet. Also, except for a shallow zone less than 100 feet deep, there was no indication of salt water at the seven stations, which were measured to a depth of 2,000 feet farther inland. This observation suggests dynamic conditions that modify the Ghyben-Herzberg principle. If there are large flows of fresh water in cavernous limestone, conditions are favorable for a thick diffusion zone and cyclic flow of salt water as in the shallow aquifer at Miami.

In the second area, which is along the road from Pedro to Bellview, about 12 miles south of Ocala, measurements at three resistivity stations, two measurements to a depth of 2,000 feet and one to 3,000 feet, showed no indication of a considerable thickness of salt water. Because the maximum freshwater head of about 50 feet above sea level in this area is not sufficient to depress salt water to a depth of more than about 2,000 feet, salt water would be expected below 2,000 feet if it is in balance with sea water according to the Ghyben-Herzberg principle.

In the third area, Welaka to Pomona, which is known to be underlain by salt water at relatively shallow depths, the depth to salt water as determined by the resistivity measurements is approximately the same as that reported in records of wells. For example, at the intersection of Chestnut and Second Streets, Welaka, where the records of the Florida Geological Survey show that a sample of water from a well at a depth of about 330 feet had a chloride content of 8,880 ppm, the resistivity survey indicates salt water at a depth of about 300 feet. The unpublished report by Swartz, MacCarthy, and Byers shows that the depth to salt water increases as the head of fresh water increases. Also, the report indicates that the Ghyben-Herzberg principle seems to apply in a general way in that area. Judging from the geologic and hydrologic conditions, however, the present occurrence and distribution of salt water in this area depends chiefly on the extent to which the aquifer has been flushed of its salt water.

A section across southern Florida (fig. 35) shows in a general way the relation of the fresh water to salt water in the aquifer. Where the flushing of the aquifer is incomplete, salt water is present, even though the application of the Ghyben-Herzberg ratio shows that the artesian head is sufficient to prevent salt-water encroachment in the aquifer. In Levy and Citrus Counties on the western coast of Florida, the large fresh-water flow through the aquifer seems to be similar to that in the shallow aquifer in the Miami area where the interface of the salt water with the fresh water is not as far inland and is deeper than that indicated by the Ghyben-Herzberg ratio. Under dynamic conditions, some of the salt water in the upper part of the zone of diffusion of the interface returns to the sea with the fresh water flowing to the submarine outcrop.

RELATION OF SALT WATER TO ARTESIAN HEAD

The principal artesian aquifer crops out in some places in the Atlantic Ocean and Gulf of Mexico. The areas of outcrop depend in part on the structure of the aquifer and the topography of the submarine floor. The depths to the sea bottom at numerous points in the Gulf of Mexico and Atlantic Ocean have been determined and charted by the U.S. Coast and Geodetic Survey and by the U.S. Hydrographic Office, as discussed by G. F. Jordan (1962).

Gulf Coast

From the western coast of the Florida peninsula, the sea bottom slopes gradually in a westerly direction to a depth of about 50 fathoms (300 feet) about 125 miles offshore and thence more steeply. Thus, the depth increases to about 100 fathoms (600 feet) beyond 125 miles offshore and about 1,500 fathoms (9,000 feet) about 180 miles offshore. The structure of the aquifer beneath the Gulf of Mexico is not known. However, if it is that inferred by Cooke and Mossom (1929, pl. 2), as shown in figure 4, the aquifer crops out offshore at a depth of more than 800 feet. The structure of the aquifer may not be as inferred, and it may actually crop out at less depth and nearer the shore. Moreover, it is possible that the salt water from the gulf may have access to the aquifer at lesser depths through permeable zones in the Hawthorn Formation or through openings in the confining beds in the Hawthorn.

In the northern part of Sarasota County, Fla., Stringfield (1933c, p. 174) found that the piezometric surface generally sloped to the west from an altitude of 40 feet above sea level along the east border of the county to 24 feet on Armand Island on the gulf coast. The hydraulic gradient, about 1 foot per mile, indicates movement of the artesian water, presumably to the outcrop of the aquifer in the Gulf of Mexico. Under such conditions the piezometric surface would continue to slope from the coast to the submarine outcrop, and the head at the outcrop would be lower than at the coast by an amount necessary to produce the movement of the water. If the outcrop were at a depth of about 800 feet and the specific gravity of the sea water were 1.025, the head created by the back pressure of the sea water would be sufficient to hold the fresh water in the aquifer at

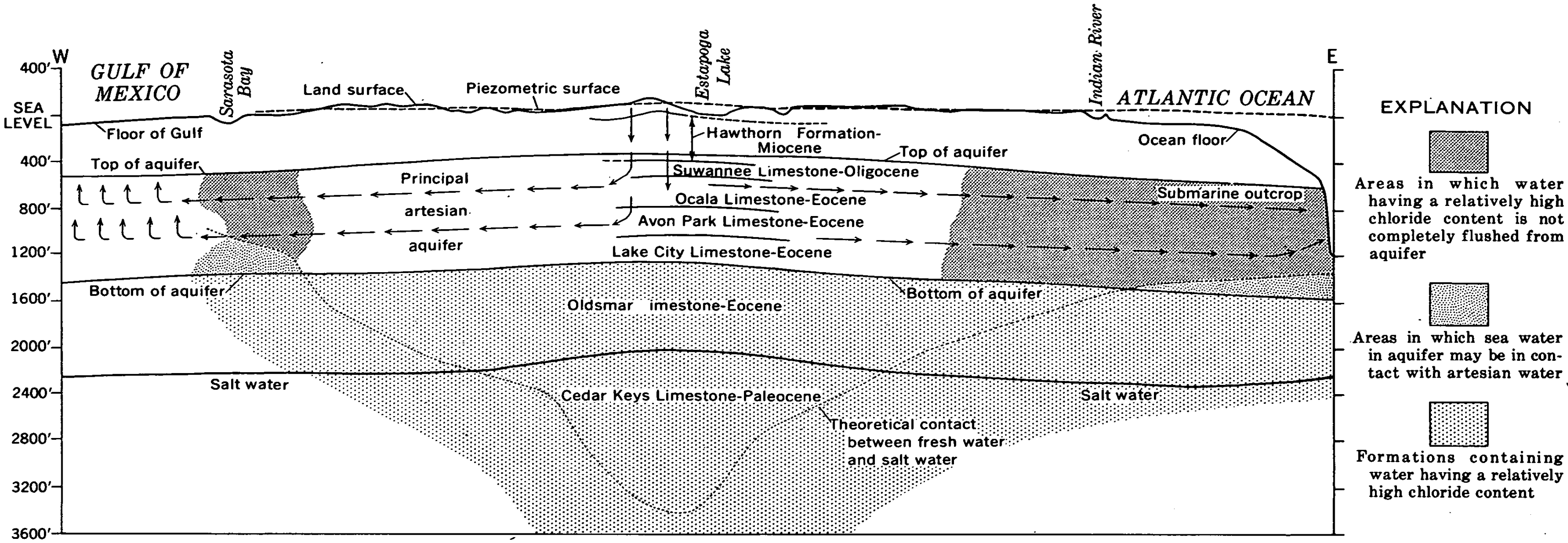

FIGURE 35.—Section across southern Florida showing relation of salt water to fresh water in the principal artesian aquifer.

a head of about 20 feet above sea level. The head at the coast would need to be greater by an amount needed to force the water to move to the submarine outcrop. The observed head of about 24 feet is apparently insufficient to provide for movement of the artesian water to a discharge point at a depth of 800 feet and more than 125 miles offshore. Therefore, it appears that the submarine outlet is at a shallower depth or nearer the coast. If an isopiestic area is present in the piezometric surface west of Sarasota County, it is possible that the artesian water offshore moves northward parallel to the coast to an area where the aquifer is present at a shallow depth. There is also the possibility that the artesian water may discharge through upward leakage into the Gulf of Mexico.

Along the gulf coast from Tampa Bay and Pinellas County to Franklin County in western Florida, the Eocene, Oligocene, and Miocene formations of the principal artesian aquifer are at or near the floor of the gulf. Closed depressions which appear to be sinkholes in a submarine valley, such as the DeSoto Canyon (Shepard, 1948, p. 125) in the Gulf of Mexico south of the Apalachicola River Delta, suggest that the limestone is near the ocean floor. Large quantities of artesian water flow directly into the gulf as indicated by the piezometric surface of artesian water and by many springs on the coast; among the largest of these springs on the coast are Homasassa and Chassahowitzka in Citrus County. A submarine spring has been recorded (Stringfield and Cooper, 1951c, p. 67) offshore from Crystal Beach in Pinellas County. W. S. Wetterhall (written commun., 1962) has observed many springs in the Gulf of Mexico west of Citrus County. Tarpon Springs in tidewater of the Anclote River near the coast of Pinellas County, as described by Heath and Smith (1954, p. 38–42), is fed by water in solution channels in the artesian aquifer. At least one of these channels is connected to Lake Tarpon, formerly known as Lake Butler.

South of Pinellas County, the principal artesian aquifer is at greater depth and does not crop out near the shore. The Hawthorn and younger formations which are confining beds for the artesian aquifer crop out, however, at or near the shore. Along the coast in western Florida, the artesian aquifer dips to the southwest to more than 1,000 feet below sea level at Pensacola. It is overlain by unconsolidated formations through which the artesian water probably leaks upward into the Gulf of Mexico.

Atlantic Coast

Available information indicates that the aquifer extends to the edge of the Continental Shelf in the Atlantic Ocean, at least offshore from Key West to West Palm Beach where the shelf is only a few miles from the coast. A map (fig. 23) of the top of the aquifer by Vernon (1955, fig. 2) and a structure contour map by Mossom (1926, pl. 1) show that the top of the aquifer ranges in depth from 600 to 1,000 feet below sea level from Key West to Palm Beach.

The top of the aquifer is 800 to 1,000 feet below sea level along the coast in Palm Beach and Broward Counties, 700 to 900 feet in Dade County, and 600 to 800 feet along the Florida Keys in Monroe County. If the specific gravity of the ocean water is 1.025, the head created by the pressure of the sea water would balance 15 feet of fresh-water head above sea level in the aquifer at a depth of 600 feet and 25 feet of head at a depth of 1,000 feet. The artesian water is brackish, however, in this area, and the amount of artesian head required to balance the column of sea water would therefore be slightly less than that for fresh water.

Along the coast from Miami to Palm Beach the artesian head is about 40 feet above sea level, which is sufficient to balance a column of salt water having a specific gravity of 1.025 to a depth of 1,600 feet. Above that depth, artesian water under that head in the aquifer would discharge into the ocean. Although the pressure will be somewhat less than 40 feet at the submarine outcrop, it should be sufficient to cause artesian discharge into the ocean. From Miami to Key Largo, the altitude of the piezometric surface ranges from 40 to 20 feet, and the top of the aquifer ranges from about 900 to 700 feet below sea level. South of Key Largo, it is about 600 feet below sea level, and the altitude of the piezometric surface ranges from 20 feet to less than 10 feet. South of Key Largo where the head is less than 15 feet above sea level and the top of the aquifer is more than 600 feet below sea level, there is no artesian discharge, and salt water has moved into the aquifer. North of that area, artesian water is discharging into the ocean.

North of Palm Beach the distance from the coast to the edge of the Continental Shelf increases. Lichtler (1960, p. 44) estimates that the aquifer crops out offshore about 25 miles east of Martin County and that the artesian head at the outcrop would be sufficient to cause artesian water to discharge into the ocean. However, he suggests that the outcrop is probably covered by relatively impermeable materials which could restrict discharge. This condition, however, appears unlikely on the steep slope at the edge of the Continental Shelf. East of the southern part of Brevard County, the edge of the shelf is about 35 miles from the coast in contrast to only a few miles at Palm Beach. At the Georgia-Florida line it is more than 75 miles east of the coast and at the Georgia-South Carolina line it is about 125 miles offshore. As shown on maps by Stringfield (1936, pl. 6) and by D. W. Brown, W. E. Kenner, and Eugene Brown (1957, fig. 28), the piezometric surface rises from 40 feet above sea level at Palm Beach to 50 feet in the southern part of Brevard County. This relatively high area of the piezometric surface suggests it might be due in part to the greater distance to the edge of the shelf and a point of discharge. Later maps (D. W. Brown and others, 1957, fig. 29, and Bermes, 1958b, fig. 7) show that the piezometric surface is less than 50 feet above sea level in the southeastern part of Brevard County. Bermes shows that the piezometric surface slopes to the east from 40 to 30 feet in a narrow strip along the coast. These general features are shown in figure 29.

In some parts of Brevard County the piezometric surface is relatively low because of withdrawal of water from wells. Bermes (1958b, p. 10, 24) believed, however, that the steep gradient along the east edge of the county probably is due to faulting along the coastal area. If the confining beds of the Hawthorn Formation were faulted, upward leakage might occur, but apparently the fault does not affect the overlying Hawthorn Formation that confines the artesian aquifer. Also, displacement of the formations which constitute the aquifer does not appear sufficient to affect the movement of water. Along the coast between southern Brevard County and St. Augustine, the piezometric surface decreases in altitude to about 10 feet above sea level in northern Brevard and Volusia Counties and increases to about 40 feet in St. Johns County north of St. Augustine (Tarver, 1958, fig. 7).

The low piezometric surface in northern Brevard and Volusia Counties is due to discharge of artesian water through submarine springs and seeps. This area is on an arch on the east flank of the Ocala uplift where the top of the aquifer is not more than about 100 feet below sea level. One of the largest of these springs is about 2½ miles east of Crescent Beach (Stringfield and Cooper, 1951c, p. 61) in St. Johns County. Matson and Sanford (1913, p. 236) described a spring offshore southeast of St. Augustine. A similar spring has been reported near Port Orange, south of Daytona. In that area the head is less than 10 feet above sea level, and because of this relatively low artesian pressure, discharge of springs may therefore not be noticed. Two large submarine springs have been reported (D. W. Brown and others, 1962, p. 77) off the coast of Brevard County; one is about 20 miles east of Eau Gallie and the other is northeast of Cape Kennedy. The spring east of Crescent Beach and probably others in this area emerge through sinkholes, which become filled with sediments from the ocean floor if there is not sufficient artesian pressure to prevent such filling.

Offshore northeast of the Savannah area, the original piezometric surface was less than 30 feet above sea level, indicating submarine discharge in an area where the top of the aquifer is not more than 150 feet below sea level. Farther north along the coast at Parris Island, S. C., the Ocala Limestone, which represents the top of the limestone aquifer, is at or near the land surface.

A map, figure 30, of the coastal area of northeastern Florida, Georgia, and southeastern South Carolina by Warren (1944, fig. 6) shows that prior to large withdrawal of artesian water, the piezometric surface along the coast was about 60 feet above sea level in northeastern Florida and southeastern Georgia. In Jacksonville (Matson and Sanford, 1913, p. 236), the original head was about 65 feet above sea level. Northward it decreased to about 30 feet above sea level in the Savannah area.

In the Jacksonville area, the edge of the Continental Shelf is about 75 miles from the coast. If the structure is that inferred by Cooke and Mossom (1929, pl. 2) as shown in figure 4, the top of the aquifer crops out at the edge of the shelf at a depth of about 1,500 feet. Unpublished information (Ed Bradley, written commun., May 10, 1965) on a test well 62 miles offshore, however, indicated that the Ocala Limestone was reached at a depth of 504 feet below sea level. The back pressure of the salt water having a specific gravity of 1.025 at a depth of about 500 feet is sufficient to balance fresh water in the aquifer, at a head of about 12.5 feet above sea level. Using a gradient (about 0.3 foot per mile) of the original piezometric surface of artesian water in northeastern Florida and southeastern Georgia, the loss of head in moving through 75 miles of the aquifer would be about 22 feet. That amount minus 60 feet of head on the coast would leave 38 feet at the submarine outcrop. Under these conditions, the artesian water would have enough head to discharge at the submarine outcrop. If less favorable conditions exist and there is not sufficient fresh-water head to cause the artesian water to discharge at the outcrop, an isopiestic area would occur, and the fresh water would move upward through the overlying confining beds or to areas to the north and south where water discharges through submarine springs and other openings.

At the present time, the withdrawal of artesian water in the coastal area of Georgia and northeastern Florida has lowered the head to an extent that there probably is not sufficient fresh-water head in the aquifer to discharge water at the edge of the Continental Shelf or northeast of Savannah where the aquifer is exposed to the sea. Warren stated that in the Savannah area (1944, p. 122–133) the cone of depression of the piezometric surface of artesian water extends to the former discharge area, which is now being recharged by ocean water.

These geologic and hydrologic conditions along the Atlantic coast indicate that artesian water is moving eastward and discharging into the ocean except in some areas of large withdrawal of water where the cones of depression of the piezometric surface extend to the coast, such as at Savannah, Brunswick, and Fernandina. The water discharges through the submarine outcrop where the edge of the Continental Shelf is near the coast from the Florida Keys to Palm Beach. North of Palm Beach and Martin Counties, the distance from the coast to the edge of the shelf increases, and it appears that the artesian pressure of the fresh water is not sufficient to force water to the outcrop. Where the artesian pressure is low along the coast, such as from Cape Kennedy (formerly Canaveral) in Brevard County to St. Augustine and in an area northeast of Savannah, Ga., the area of discharge is within a few miles of the coast. Where the artesian pressure is relatively high as on the coast east of Jacksonville, Fla., the fresh artesian water moves eastward some distance under the Atlantic Ocean and then moves upward through the overlying beds, or moves north or south approximately parallel to the coast to an area of discharge.

SALTY GROUND-WATER AREAS RELATED TO THE PRINCIPAL ARTESIAN AQUIFER

The relative amount of saltiness in water is commonly determined by the content of chloride (Cl), which is one of the two elements of sodium chloride, or common salt (NaCl), the principal constituent of sea water.

Water having a chloride content of 500 ppm will ordinarily taste salty to many people. Water having a chloride content of 750 ppm or more has a marked salty taste. Water having a chloride content of 2,000 ppm is not suitable for many uses. The average chloride content of sea water is about 19,350 ppm.

CRETACEOUS FORMATIONS

Cretaceous formations contain fresh water in a broad area between the Fall Line, where they are at or near the surface, and the coast. This area includes southeastern Alabama, Georgia, and South Carolina, except along the coast and in southeastern Georgia. The area of fresh water in the upper part of the Cretaceous may extend a short distance into western Florida from southeastern Alabama and Georgia. Fresh water extends to the coast of Parris Island, S.C.; the extent toward the coastal area of Georgia is unknown. However, the available records show no evidence of fresh ground water in the Cretaceous formations in southeastern Georgia. The chloride content of the salt water from some parts of the Cretaceous is much less than that of sea water, indicating that part of the connate water has been flushed from the aquifers.

At Parris Island, S. C., records of two wells drilled by Layne Atlantic Co. at the U.S. Marine barracks 1½ miles west of Marine Corps headquarters reveal that fresh artesian water within the Tuscaloosa Formation of Late Cretaceous age is underlain and overlain by salt water. Well 1, which is 2,830 feet deep, was drilled in 1939, and well 2, which is 3,450 feet deep, was drilled in 1940. Well 1 penetrated water of relatively high chloride to a depth of 2,500 feet. However, sample 4, from a depth of 2,600 to 2,811 feet, had a chloride content of only 82 ppm, as shown in the following table.

Analysis of water from well 1, Parris Island, S.C.

[Constituents in parts per million]

Sample	Depth (feet)	Carbonate (CO_3)	Bicarbonate (HCO_3)	Sulfate (SO_4)	Chloride (Cl)	Fluoride (F)
1	990–1149	----	----	----	8,500	----
2	1850–1900	----	----	----	925	----
3	1850–2500	----	----	----	435	----
4	2600–2811	69	1,320	1	82	7

Sample 1 was collected after the well was pumped several hours and all water-bearing formations were shut off above 990 feet. Static water level was 10 feet below land surface. Sample 2 was collected after the well was pumped 24 hours and all water-bearing formations were cased off above 1,850 feet. Sample 3 was collected after pumping 24 hours and water-bearing formations were cased off above 1,850 feet. Sample 4 was collected when strata were cased off above 2,600 feet. The artesian pressure was 49 pounds at 11 feet above sea level.

Well 2 was drilled 18 inches in diameter to a depth of 2,450 feet. It was cored 9⅝ inches in diameter from 2,450 to 3,450 feet and underreamed 18 inches in diameter to 2,610 feet and 12 inches in diameter from 2,610 to 3,450 feet. The well was finished with 12-inch casing from the land surface to 2,610 feet. The casing was grouted in with neat cement under pressure. Blank casing and screens 6 inches in diameter were set between 2,500 and 3,450 feet with No. 4 and No. 5 gravel used between the wall of the well and the screen.

The following table gives a record of the depths below the land surface at which blank casing and screens are set in well 2. All measurements are in feet. No sand or gravel of any consequence was found between 3,430 and 3,450 feet.

Depth	Screen length	Blank-casing length	Depth	Screen length	Blank-casing length
2,499.7		161.7	3,110.4	40	
2,661.4	10		3,156.4		111.3
2,671.4		80	3,261.7	20	
2,751.4	20		3,281.7		10
2,771.4		40	3,291.7	10	
2,811.4	20		3,301.7		15
2,831.4		120	3,316.7	20	
2,951.4	20		3,336.7		23.3
2,971.4		90	3,360.0	70	
3,061.4	20		3,430.0		
3,081.4		29			

Tests were made on well 2 to determine the flow of water and chloride content of samples at depths of 2,723 feet below the land surface, as shown in the following table. A packer connected by a 3-inch welded line to the end of the 4½-inch drill pipe was inserted in the 6-inch blank casing of the well at depths shown. Water below the packer flowed to the land surface through the drill pipe; water above the packer flowed to the surface through the 12-inch casing of the well. Chloride analyses were by P. H. Shuey, Savannah, Ga.

Depth to top of packer (feet)	Chloride content (ppm)		Flow (gpm)	
	Above packer	Below packer	Above packer	Below packer
2,723	88	1,328	112	174
2,784	388	1,336	150	174
2,915	92	1,368	160	174
3,033	304	1,420	160	150
3,091	654	1,415	230	140
3,222	1,144	1,024	480	25
3,285	1,128	774	480	25
3,309	1,134	696	485	10
3,346	1,128	722	480	9

Artesian water below the casing from depths of 2,610 to 3,450 feet was reported to have a pressure of 60 to 65 psi and a temperature of 103° to 109°F. The well was permanently plugged from 2,950 feet to the bottom to stop the flow of the water of relatively high chloride content. The well was then reported to have a flow of 80 to 100 gpm with a chloride content of about 42 ppm. According to analyses of a sample collected in 1954 from each well reported by Siple (1957b, table 4), well 1 had a chloride content of 10 ppm, and well 2 had a chloride content of 58 ppm.

Samples of cuttings from rotary drilling to a depth of 2,400 feet and of cores from 2,441 feet to the bottom in well 2 were studied by several geologists and paleontologists, including John B. Reeside Jr., J. A. Cushman, L. G. Henbest of the U.S. Geological Survey, R. S. Bassler of the National Museum, Miss Winnie McGlamery of the Alabama Geological Survey, and several micropaleontologists of oil companies. The log of the lower part of the well, by Miss McGlamery, is published in a paper by Munyan (1943, p. 596–607).

Log of Well 2, Parris Island, S.C.

[Prepared by John B. Reeside, Jr.; no samples, 0–100 ft]

Sample	*Depth (feet)*	*Description*
Cuttings:		
		Jackson age (Ocala Limestone)
1–3	100–140	Coquina of bryozoans and other organisms, light-gray to white.
4–11	140–300	Limestone, light-gray, fine-grained; some of it finely granular.
12–16	300–410	Limestone, light-gray, finely granular.
17–23	410–550	Limestone, light- to brownish-gray, granular; contains some fine sand.
24–26	550–610	Limestone, light-brownish-gray granular, glauconitic, sandy.
27–29	610–654	Probably limestone, light-brownish-gray, granular, glauconitic, sandy.
		Probably Claiborne and Wilcox age
30–43	654–926	Sandstone, calcareous, light-yellowish-gray, glauconitic.
44–46	926–970	Glauconite zone, in part light-gray sandy limestone; basal part, to judge by sample, a nearly pure glauconitic rock having grains up to 4 mm in diameter.
47–50	970–1030	Limestone, light-gray, calcareous, very sandy.
51–52	1030–1070	Sandstone, light-gray; apparently loosely cemented; grains average 0.2 mm.
53–57	1070–1165	Limestone, creamy-white, compact; a little glauconite and coquina.
		Midway age
58–67	1165–1325	Sandstone, light-gray, fine-grained, calcareous.
		Peedee-Black Creek age
68–125	1325–2395	Silt, medium-gray, fine; some pyrite in small masses and a little ferruginous sandstone; some flaky medium-gray shale, and some clay.
	2395–2441	No samples.

Sample	Depth (feet)	Description
Cores:		
		Eutaw age
1–8	2441–2579	Clay, olive-gray, with layers and filled borings of fine-grained soft micaceous light-colored sandstone; some layers of very hard, calcareous sandstone; some layers of fine silt; some layers glauconitic.
9–15	2599–2666	Sandstone, light-gray, fine-grained, loosely cemented, micaceous; and some clay and silt of medium-gray color, in thin layers.
		Tuscaloosa age
16–29	2672–2960	Clay, greenish-gray, waxy; contains small aggregations of pyrite and scattered quartz grains up to 2 mm in diameter. Coarse-grained (grains up to ¼ in.), subangular, largely of quartz, friable, light-greenish-gray grit. Greenish-gray and maroon micaceous silt. Red and green sandy clay. All repeated many times.
30	2966	Mudstone, medium-gray, rather hard, marine fossiliferous.
30–37	2970–3108	Like interval 2672–2960, with some maroon and purple coloring.
38–45	3123–3245	Clay, medium-gray, with small pockets of fine light-gray sand. Light-brownish-gray grit (grains up to 2 mm); coquina of molluscan fragments. Silty, fine-grained light-gray sandstone; sandy brownish-gray glauconitic limestone. These make up a marine fossiliferous zone.
46–55	3250–3454	Interval much like interval 2672–2690 with more coarse materials. Pebbles up to 30 mm in some samples.

Records of the two deep wells show that the water sample having the highest chloride content, 8,500 ppm, was collected in the interval between 990 and 1149 feet deep from formations of middle and early Eocene age. The chloride content of water samples from formations of Cretaceous age in both wells ranged from 82 to 1,420 ppm. Relatively impervious beds in the upper part of the Cretaceous retard the upward movement of artesian water and protect it from salt water in the underlying formations. The artesian pressure has been sufficient to flush connate water from the more permeable beds and to prevent sea water from moving into the beds of Cretaceous age at Parris Island. The pressure at the top of the Cretaceous is reported to be about 40 psi at the land surface about 10 feet above sea level. This pressure is equivalent to 102.4 feet of water at sea level ($40 \times 2.31 + 10$) and is sufficient to balance a column of sea water (specific gravity 1.025) to a depth of about 4,010 feet below sea level (102.4×40). The pressure in the Tuscaloosa is reported to be 60 or 65 psi.

The extent of the fresh water in the Cretaceous aquifers along the coast north and south of Parris Island is not known, but from available information it probably does not extend far in either direction. The records are not sufficient to show whether the fresh water in the Cretaceous aquifers in the interior extends as far south as northern Florida. The area of fresh water may extend from southwestern Georgia and southeastern Alabama into Florida where the Eocene formations are at or near the surface.

The extent of the fresh water in the Cretaceous aquifers east of the South Carolina and Georgia coast is not known. Although some of the Eocene formations may crop out at the edge of the Continental Shelf, the slope beyond the edge of the shelf is interrupted by the Blake Plateau, an extensive terrace more than 150 miles wide at depths of 400–500 fathoms (G. F. Jordan, 1962, p. 11). In the absence of structure which would decrease or reverse the dip, the Cretaceous formations would crop out at the east edge of the plateau. Under these conditions, the artesian head would not be sufficient to discharge water at the submarine outcrop.

An oil test well, 7 miles west of Savannah, at Cherokee Hill (Warren, 1944 p. 17, 127), 21.5 feet above sea level, was drilled to a depth of 2,130 feet in 1920 and penetrated chiefly limestone from 250 to 870 feet, limestone and chert from 870 to 950 feet, and marly limestone from 950 to 1,000 feet. Below 1,000 feet the material penetrated consists chiefly of marl and fine quartz sand from 1,980 to 2,035 feet, which was the source of the salt water. The well was cased with 24-inch casing to 27 feet, 18-inch casing to 107 feet, 15-inch casing to 250 feet, 12-inch casing to 1,426 feet, 10-inch casing to 1,630 feet, and 8-inch casing to 2,126 feet. At 2,000 feet, it penetrated a sand containing salt water under sufficient pressure to overflow at the land surface. The well was flowing about 1 to 2 gpm from the space between the 10-inch and 8-inch casings and returning to the well outside the 10-inch casing in 1939 when visited by M. A. Warren and the writer, but the casing of the well was in such poor condition that the shut-in pressure could not be determined. Later the casing at the surface was destroyed in the construction of an airport. The chloride content of the water was 2,475 ppm. The head of the principal artesian aquifer at the well was about 2 feet above sea level. The extent to which this salt water has contaminated the surficial aquifer and the principal artesian aquifer was not determined. Probably salt water underlies the Savannah area, but relatively impervious beds separate the salt water from the formations which form the principal artesian aquifer.

The ages of the formations penetrated, as indicated by the record of the Georgia Geological Survey, are as follows:

Age	*Depth (feet)*
Miocene and younger	0– 250
Oligocene and late Eocene	250– 610
Middle and early Eocene	610–1400
Paleocene	1400–1680
Cretaceous	1680–2130

Herrick (1961, p. 101–103) reported a log of a well (GGS 506) 1,088 feet deep at an altitude of 43 feet above sea level at Cherokee Hill as follows:

Age	*Depth (feet)*
Pliocene to Recent	0– 47
Miocene	223– 270
Oligocene	270– 358
Late Eocene (Ocala Limestone)	358– 730
Middle Eocene (Lisbon Formation)	730–1000
Middle Eocene (Tallahatta Formation)	1,000–1088

Wait (1960c, p. 28–29) reported that an oil test well, the J. W. West 1 in northwestern Calhoun County, reached salt water at a depth of 2,800 feet in the Upper Cretaceous rocks. On the basis of the electric log of the well, S. M. Herrick of the U.S. Geological Survey believed that salt water may have been reached at a depth of about 2,080 feet. The J. R. Sealy oil test well drilled just east of Calhoun County in southwestern Dougherty County, Ga., produced water at a depth of 1,200 feet that contained 435 ppm chloride, 586 ppm of sodium, and 820 ppm of bicarbonate. Records of a few test wells for oil in Florida give information on salt water in the Cretaceous formations.

An analysis (Parker and others, 1955, p. 65) of a sample of water from a depth of 3,000 feet in a well (S–396, Cory 1) in Dade County, Fla., shows a chloride content of 14,200 ppm and total dissolved solids of 29,460 ppm, which is somewhat less than the average for sea water. According to a log of the well by Applin and Applin (1944, p. 1750), the sample is from the Oldsmar Limestone of early Eocene age. Four samples from depths of 9,500 to 9,987 feet in Lower Cretaceous limestone under anhydrite had a chloride content which ranged from 11,200 ppm at 9,500 feet to 24,600 ppm at 9,550 feet. The samples from depths of 9,772 and 9,987 feet had chloride contents of 15,000 ppm and 17,100 ppm respectively.

The record of a well (Cooke and Mossom, 1929, p. 44) 6,180 feet deep, penetrating basement rocks at about 4,000 feet, in sec. 10, T. 16 S., R. 20 E., in Marion County, Fla., in 1928 showed no record of salt water. A geophysical probe by J. H. Swartz and G. R. McCarthy (written commun., Nov. 1937) to a depth of 3,000 feet by a surface electrical-resistivity method at the site of the well showed no evidence of salt water. However, Gunter (1949) reported that salt water was reached in 1947 at a depth of 4,637 feet in Candler well, sec. 16, T. 16 S., R. 23 E., Marion County. Salt water was reached at a depth of 2,470 feet in the Oldsmar Limestone of Eocene age in a well in Lake County. A sample from a depth of 3,419 feet in the Upper Cretaceous near the contact with the overlying Paleocene had a chloride content of 58,100 ppm.

These records show that salt water is present in most, if not all, of the Cretaceous formations in Florida, except possibly in an area in western Florida where the top of the Cretaceous is less than 2,000 feet below sea level, near the Alabama and Georgia State line, and possibly a small area in Marion County in central Florida, where the top of the Cretaceous is about 2,200 feet below sea level.

TERTIARY AND QUATERNARY FORMATIONS

The principal artesian aquifer, consisting chiefly of limestone ranging from middle Eocene to and including the lower part of the Hawthorn Formation of late Miocene age and aquifers within the Hawthorn Formation, contains water having a chloride content of 100 ppm or more in some areas (fig. 36). In Florida, the map of these areas is essentially the same as one prepared in 1934 by Stringfield (1936, pl. 16). A later map of Florida by Shampine (1964) gives more details. In the coastal areas and in southern Florida and the upper part of the St. Johns River valley south of Palatka, water having a relatively high chloride content is present in all the Tertiary formations. Hendry and Lavender (1957, p. 29–178; 1959, p. 28–29) included information on chloride in samples of water from many wells in the area of artesian flow in Florida. In the interior, salt water has been recorded in sev-

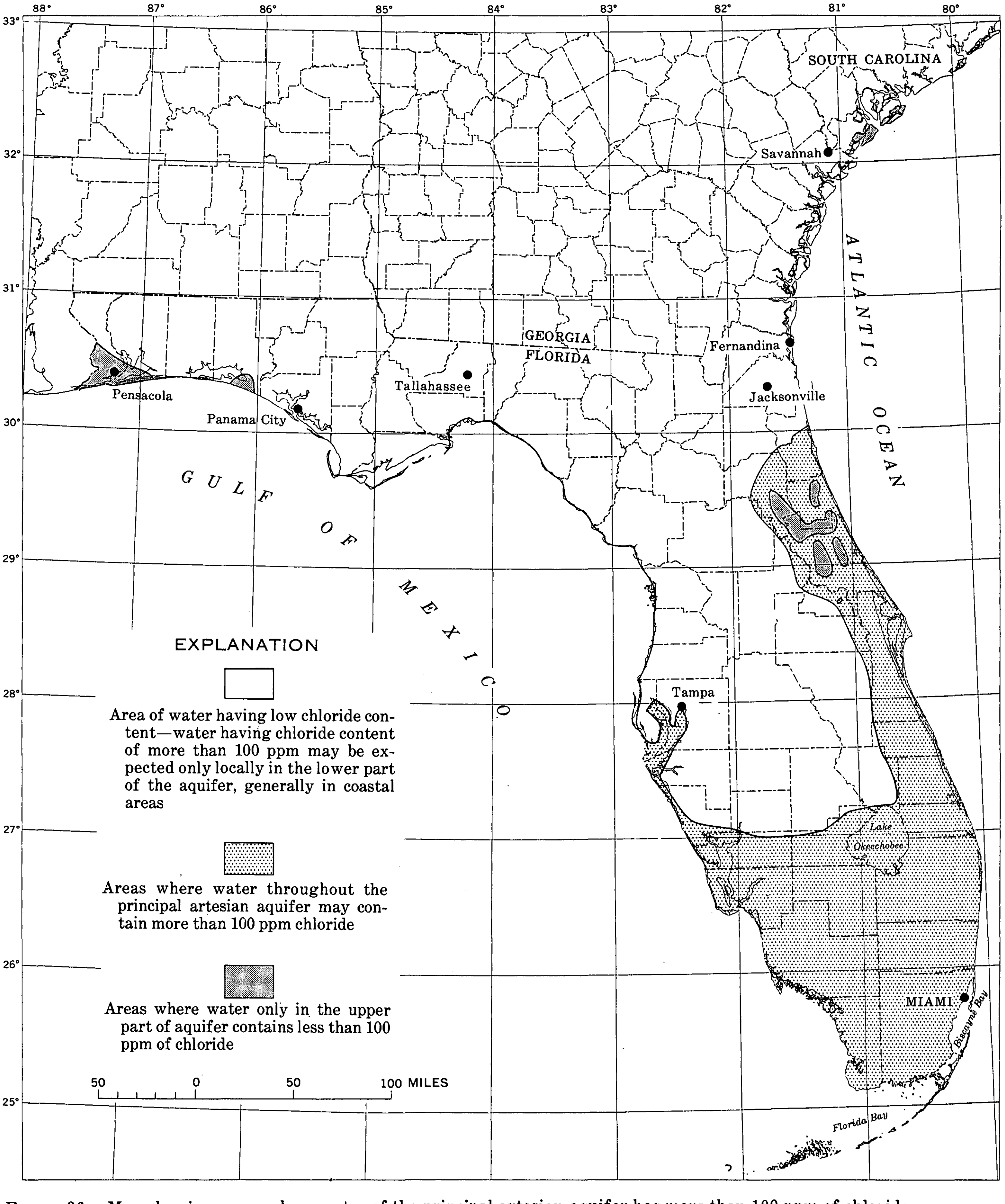

FIGURE 36.—Map showing areas where water of the principal artesian aquifer has more than 100 ppm of chloride.

eral areas including the early Eocene and Paleocene formations in Lake County, Fla., and western Florida and in middle Eocene rocks near Thomasville, Georgia.

Unpublished analyses of nine samples of water from depths of 1,408 to 3,700 feet in the South Lake well, J. Ray Arnold 1, Florida Geological Survey W-275, sec. 17, T. 24 S., R. 25 E., 12 miles south of Groveland, Lake County, give the most complete information available on the salinity of the water from the lower part of the Tertiary and upper part of the Cretaceous formations in central Florida. The well was started in February 1935 and completed in May 1937 by the Oil Development Co. of Florida. It was drilled to a depth of 6,129 feet from the surface, which was 113.66 feet above sea level. The chloride results given in the following table are in the open files of the U.S. Geological Survey in Washington, D.C., and Tallahassee, Fla., and the Florida Geological Survey in Tallahassee, Fla. The geologic correlations used in the following table are from a log of the well by Applin and Applin (1944, p. 1748):

Chloride content of water samples from South Lake well, Lake County, Fla.

[Chemical analyses by M. D. Foster, U.S. Geol. Survey]

Sample	Depth (feet)	Chloride (ppm)	Remarks
1	1,408–1,416	20	Water from artesian flow, Lake City Limestone
2	2,258	781	Sample collected after 48 hours of bailing, Oldsmar Limestone
3	2,300	6,020	Oldsmar Limestone
4	2,352	6,290	Oldsmar Limestone
5	2,470	23,020	Oldsmar Limestone near contact with Cedar Keys
6	2,590	310	Cedar Keys Limestone
7	2,593	12,000	Cedar Keys Limestone
8	3,419	58,100	Upper Cretaceous, Lawson Limestone
9	3,700	13,650	Upper Cretaceous, Lawson Limestone

NOTE.—Samples 3 to 9 inclusive were collected by drill-stem tester with bottom of tester set at depth shown, except for sample 4, which came from depth of about 2,352 feet when tester was set at 2,312.

J. L. McCord of the Oil Development Co. of Florida indicated that sample 8 was collected from oolitic limestone under anhydrite. The log by Applin and Applin (1944, p. 1748) shows oolitic limestone in the lower part of the Cedar Keys Limestone in contact with the underlying Upper Cretaceous at a depth of about 3,365 feet. This indicates that the brine represented by sample 8 is at or near the contact of the Tertiary (Paleocene) with the Cretaceous. It seems possible that the relatively low chloride content of water sample 9 from the Cretaceous and sample 6 from the Tertiary limestone in the South Lake well in Florida may have been due to inadvertent mixing with fresh water when the sample was collected. If the samples are representative of the aquifers from which they were collected, the relatively low chloride contents of the samples 6 and 9 suggest that the aquifers from which they were collected are more permeable than the underlying and overlying formations that yield water having a higher mineral content.

The fresh-water head in the artesian aquifer in the area is about 90 feet above sea level. This head is sufficient to hold the fresh-water contact with the salt water at a depth of 3,600 feet, if the fresh water were in equilibrium with the water in the Gulf of Mexico or the Atlantic Ocean. The chloride content of the water shows that the water in the principal artesian aquifer is separated from the underlying salt water by relatively impervious beds and that the Florida peninsula is not a fresh-water lens floating on salt water, as has been supposed by some investigators.

In the coastal area of South Carolina, Siple (1957b, p. 18–22) has described salt-water encroachment in Parris Island, S.C., where some of the water in the Tertiary aquifer in the area has a chloride content of more than 100 ppm.

Savannah Area, Georgia and South Carolina

Counts and Donsky (1959, p. 101) reported that the chloride content of samples of water from test wells on Hilton Head Island and Daufuskie Island, S.C., and on Cockspur Island, Ga., increased with depth and with time. The highest chloride sampled on September 30, 1957, from the Cockspur test was 40 ppm in a sample from a depth of 695 feet. A sample from that depth had 675 ppm chloride on January 6, 1959. At Hilton Island, the highest samples in June 1957 were 290 ppm at a depth of 609 feet and 1,950 ppm at 693 feet. On January 6, 1959, the water was 535 ppm at 609 feet and 2,020 ppm at 693 feet. Counts and Donsky (1959, p. 101; 1963, p. 75) concluded that the relatively high chloride content is from Pleistocene sea water or older sea water that has not been flushed out of the aquifer. Judging from the available information, this conclusion is reasonable.

At Savannah, the cone of depression in the piezometric surface of artesian water extends to the coast and has reversed the movement of the water in the aquifer. Under these conditions, salt water in the aquifer and sea water which enters the aquifer will move westward into the Savannah cone. As stated by Warren (1944, p. 122–133), any lateral movement of the salt water would be only a few feet a year and there would be time to reduce withdrawal of water and stop the encroachment before it moves far inland. Adequate observations to detect encroachment therefore should be continued in the area.

Along the coast from the Savannah area to St. Johns County, Fla., north of St. Augustine, Fla., water in the principal artesian aquifer has a chloride content of less than about 50 ppm. In much of the area, it is less than 20 ppm (Collins and Howard, 1928, p. 213, 222). Water having a relatively high chloride content, however, is present in the limestone under the aquifer. A few wells about 1,000 feet deep have penetrated water in limestone having a chloride content higher than that in the overlying aquifer. Warren (1944, p. 134) reported that a test well drilled for oil to a depth of 4,829 feet about 4 miles northwest of Hilliard in Nassau County, Fla., penetrated limestone between 412 and 3,460 feet, with salt water at a depth of about 2,100 feet in the Oldsmar Limestone of Eocene age (Applin and Applin, 1944, p. 145).

Brunswick, Ga.

At Brunswick, Ga., about 40 miles northeast of the well at Hilliard, J. W. Stewart (1960, p. 19) reported that water from an artesian well, drilled to a depth of 1,063 feet in 1939, had a chloride content of 69 ppm. A sample from a water well completed at a depth of 1,057 feet in 1942 had a chloride content of 146 ppm. After the well was plugged at a depth of 1,000 feet additional samples were collected at the overflow of a small-diameter pipe lowered to different depths in the well. At depths ranging from 743 to 943 feet, the samples showed an increase in chloride from 465 to 545 ppm. A sample from 960 feet had a chloride content of 112 ppm. Other wells 900 to 1,026 feet deep have not shown marked changes in the chloride content of the water for the period of record, 1943 to 1958. Water having a chloride content ranging from 138 to 430 ppm between beds of hard dense cherty dolomitic limestone was penetrated by a group of wells at depths between 1,014 and 1,062 feet at Brunswick (Wait, 1962a, p. 42). Another well did not, however, penetrate water having a relatively high chloride content before it reached a depth of 1,743 feet. Thus the zone at depths of 1,014 to 1,062 feet is probably limited in lateral extent.

Exploration of an oil test well drilled to a depth of 4,615 feet (Wait and McCollum, 1963) revealed that water having a relatively high chloride content is flowing upward from aquifers below about 2,000 feet into the principal aquifer between 610 and 920 feet. This probably is the source of the relatively high chloride content in some of the wells in the area. Water overflowing from the oil test well at the land surface contains as much as 7,780 ppm chloride.

Because the fresh-water head of the artesian water between Brunswick and the coast is sufficient to prevent lateral encroachment of sea water, it is concluded that the high chloride content of the water entering the wells is from remnants of connate water in the underlying formations. The concentration and distribution of this water is controlled in part by the extent to which the formation has been flushed of its salt water. The flushing depends in part on the permeability, recharge, and discharge of the water-bearing formation, and the artesian head. In general, the deeper formations have a higher artesian head than the overlying aquifers, from which salt water (connate water) has been completely flushed. The opportunity for discharge was, however, better in the overlying aquifers. The exception to this generalization is at Parris Island, S.C., where deep Cretaceous sands have been completely flushed of salt water but the overlying sands contain salt water. Investigations (J. W. Stewart, 1960, p. 40; Wait, 1962a, p. 44) are continuing in the Brunswick area to obtain more information on the occurrence, distribution, and concentration of the salt water underlying the fresh-water aquifer.

If there are only small areas of water of relatively high chloride content under low pressure, it may not be difficult to control the problem. If there are large quantities of such water under high pressure throughout the area, however, it may seriously affect the future potential of the fresh-water aquifer of the area, even though it is expected that the maximum concentration of the salt water will be less than sea water. In order to protect the aquifer, it would be necessary to limit the depths of wells and reduce the draft wells in which the chloride content of the water shows an increase above the normal for the aquifer. Special care will have to be taken because the wells generally are not cased below the top of the aquifer and one well pumping salt water may contaminate a large part of the aquifer. Wells that reach salt water will contaminate the overlying fresh water if the salty part is not properly plugged.

East Coast of Florida

The artesian water along the coast in Florida from northern St. Johns County to and including the Florida Keys and in the upper part of the St. Johns River valley has a chloride content of more than 100 ppm. Within these areas of water of relatively high chloride content, there are areas of low chloride content, as in Putnam and Volusia Counties, where the piezometric surface is relatively high and where local recharge has flushed out the salt water from the aquifer. Salt Springs in Marion County, one of the large springs in the peninsula, yields salty water. There are many small salt springs along the valley of the St. Johns River from Putnam County to Brevard County.

The area of water of relatively high chloride content extends from the east coast through the southern part of Florida and occupies a narrow belt on the west coast. There are salt springs in Sarasota County and along the coast in Citrus and Levy Counties. An area in Anna Maria Key in Manatee County is the only one in which the salt water in the Tertiary aquifer is more concentrated than sea water. This condition appears to be due to concentrations of salt by evaporation of sea water at the time the formation was deposited.

NASSAU COUNTY

At Fernandina in Nassau County, salt water underlying the aquifer has been reached by a few deep wells, indicating that the Oldsmar Limestone and possibly the lower part of the Lake City Limestone have not been completely flushed of the salt water which entered the formation prior to Recent time. Leve (1961b, p. 15) reported that the chloride content of water samples from wells less than 1,400 feet deep ranged from 26 to 41 ppm and samples from wells 1,400 to 1,826 feet deep ranged from 50 to 1,060 ppm. However, the chloride content of samples from one well, 1700 feet deep, ranged only from 38 to 52 ppm.

The chloride content of water samples from a well 2,100 feet deep (Leve, 1961b, fig. 7), collected during construction at 10-foot intervals between 1,230 feet and 1,450 feet, ranged from less than 100 ppm to more than 500 ppm, indicating a local zone of water of high chloride content in the lower part of the aquifer. As the wells are not cased in the aquifer, the water having a relatively high chloride content may have moved upward through a well. The bottom of the well is in the Lake City Limestone which contains salt water at a depth of 2,100 feet at Hilliard, Fla., as reported by Applin and Applin (1944, p. 1745).

ST. JOHNS COUNTY

A map of the distribution of the chloride water in St. Johns County (Tarver, 1958, fig. 11) shows the north limit of artesian water having a relatively high chloride content in Florida. The chloride contents of samples from most of the water wells range from about 10 ppm in the northwestern part of St. Johns County to about 3,000 ppm in the southern part of the county in the area of Crescent Beach. The minimum and maximum samples were less than 3 ppm near Switzerland and in the northwestern part of the county and 7,200 ppm 2 miles west of Crescent Beach in the southeastern part of the county. The salinity increases with depth. The wells in the principal aquifer range in depth from about 150 to 900 feet, but most of them are less than 350 feet. Water from wells less than 350 feet has a maximum chloride content of 500 ppm.

Tarver recognizes a general correlation between the piezometric surface and the chloride content of the water. The areas of relatively high chloride content correlate with those of relatively low pressure, and areas of low chloride content correlate with those of high pressure. As he suggests, the correlation may indicate one or more of the following: (1) The aquifer has been flushed less in low-pressure areas, (2) higher artesian pressure in the deep zones causes salt water to move upward, and (3) Pleistocene seas encroached farther into the aquifer where the piezometric surface is low and the flushing is less advanced downgradient. There is also the possibility that wells in low pressure areas were drilled deeper than in high pressure areas. In the Hastings area where artesian water is used for irrigation, the increase in the salinity of the water indicates that water having a chloride content of as much as 2,500 ppm is being drawn up from deeper zones in areas of greatest water use. The salinity is highest during the irrigation season when the wells are pumped.

As chloride and sulfate ions are present in the artesian water throughout St. Johns County but in different proportions in the north and south sections, Tarver (1958, p. 29) used the ratio of these ions to indicate the possible source of the chloride water. He found that the ratio of chloride to sulfate in the high chloride water in the southern part of the county was 7 to 1, which is approximately the same as sea water. In the northern part of the county, the ratio of chloride to sulfate is reversed, indicating the presence of anhydrite or gypsum in the limestone aquifer.

One area where the artesian pressure is lowest in the area of highest chloride content is where submarine discharge occurs through springs, such as the large spring 2½ miles east of Crescent Beach (Stringfield and Cooper, 1951c). Since the fresh-water head of 15 feet is sufficient to prevent lateral encroachment of sea water to a depth of about 600 feet and water of high chloride content is present at shallower depths in the aquifer, it is concluded that the salt water entered the aquifer during a high stand of the sea in Pleistocene time when the sea covered the area. At that time, the aquifer was exposed to the sea in a channel in the valley of the St. Johns River which was cut below present sea level when the Pleistocene sea stood as much as 300 feet below present sea level. The channel probably cut into the aquifer in its course from St. Johns County to Brevard County where the top of the aquifer is now less than 200 feet below sea level. There were also sinkholes and other solution depressions through which salt water could enter in that area extending east of the present coastline. Submarine springs discharge through some of these sinkholes at the present time. North of St. Johns County the aquifer was overlain by a thickness of as much as 500 feet of the Hawthorn Formation and, therefore, was not exposed to sea water during Pleistocene time. The low chloride content of water in the aquifer in some parts of north-central Florida and in some other areas where it was exposed to Pleistocene sea water shows that the connate water as well as the Pleistocene water has been flushed from some parts of the aquifer.

In the area of water of relatively high chloride content in southern Florida, the aquifer is overlain by about 500 feet of the Hawthorn Formation, which protected it from contamination from Pleistocene sea water when the Pleistocene seas covered that part of the State. The chloride probably is from salt water that entered the formation before Pleistocene time.

PUTNAM COUNTY

In Putnam County, as stated by Leve (1958, p. 24), the saline water in the aquifer appears to be due principally to sea water which entered the aquifer during Pleistocene time when the sea stood above its present level and much of the present land was inundated (Cooke, 1939, figs. 12–16). After the Pleistocene seas receded, fresh water circulated through the aquifer and flushed it of salt water, except in local areas. Leve reported that the chloride content of samples from more than 160 wells in the principal artesian aquifer ranged from less than 2 to 1,080 ppm. Although the wells range in depth from 130 to 460 feet, most of them are 180 to 300 feet deep. Leve's map (1958, fig. 10) shows that the chloride content of water in the artesian aquifer is 50 ppm or less in the northwest half of the county and in an irregular area surrounded by water of relatively high chloride content in the southeastern part of the county and northwestern part of Volusia County. A comparison of this map with the map of the piezometric surface shows that the water having a small chloride content is in and near recharge areas, thus indicating flushing has been more thorough in the recharge areas. The highest chloride (500 ppm or more) is in an area in the vicinity of Welaka, where natural discharge from springs in the St. Johns River maintains a depression in the piezometric surface. Also, the chloride is relatively high (250 to 500 ppm) in a vegetable farm area, east of Palatka, where discharge from many irrigation wells during irrigation season lowers the piezometric surface, which in turn results in sale water moving upward into the fresh-water zone. This correlation of the low chloride areas with recharge areas of Putnam, Seminole, and Volusia Counties was recognized in 1934 by Stringfield (1936, p. 162) when he mapped the piezometric surface of the artesian water and the area of water of relatively high chloride content in the Florida peninsula.

Leve (1958, p. 27) found that water from shallow wells in Miocene or Pliocene beds of mud and shells overlying the principal aquifer has a chloride content of less than 30 ppm, but a sample from one of the wells had a chloride content of 3,840 ppm. These beds probably have not been flushed as much as the more permeable limestone aquifer.

FLAGLER COUNTY

Bermes (1958a, p. 24) reported that the chloride content of the artesian water in the principal aquifer in Flagler County ranges from 15 ppm in recharge areas, as near Espanola, to more than 4,400 ppm southwest of Bunnell, where water levels are lowered by irrigation. The wells range from 55 to 555 feet in depth. His map of the chloride content of water from artesian wells shows that the chloride is lowest, 25 ppm or less, in a recharge area in the north-central part of the county between 1 and 2 miles wide and about 4 miles long, extending from the Espanola area. Around that area, the chloride is 25 to 100 ppm. That zone extends southeastward and includes all the southern part of Flagler County. The chloride water in the northeastern part of the county ranges from 100 to 750 ppm. The chloride water extends as a narrow belt to the central part of the county near Bunnell; from Bunnell it extends to the southwestern part of the county. Water in an area southwest of Bunnell has a chloride content of 2,000 or more ppm. That area is surrounded by a zone in which the chloride content of artesian water ranges from 750 to 2,000 ppm.

Bermes (1958a, p. 29) found that west of Bunnell the highest chloride content was in water from the deeper wells, but southwest of Bunnell, the highest chloride content comes from some of the shallower wells. West of Bunnell, and near Codys Corner, the chloride content is highest when the withdrawal of ground water is greatest and water levels are lowest. The chloride increased from 300 to 2,100 ppm when the water level declined 10 feet. The chloride content decreased to about 550 ppm when the water level recovered about 10 feet.

VOLUSIA COUNTY

Volusia County is one of the areas in which the correlation of the differences in salinity of the water with the piezometric surface was made in 1934 (Stringfield, 1936, p. 162). Wyrick and Leutze (1956) and Wyrick (1960) made detailed studies of the area and confirmed the conclusions reached in 1934. The wells range in depth from less than 100 to 480 feet.

A map of the county by Wyrick (1960, fig. 21) showed that in recharge areas where the piezometric surface is highest the chloride content is less than 25 ppm. In most of the county, the chloride content ranges from 25 to 250 ppm. In a narrow belt along the St. Johns River and in a few places along the coast, as at New Smyrna Beach and the southeastern part of the county, the chloride content ranges from 250 ppm to more than 1,000 ppm. A section from the St. Johns River valley across the county to the Atlantic Ocean shows the chloride content of the water to a depth of 800 feet (Wyrick, 1960, fig. 22). In the area where the piezometric surface is 60 feet above sea level, the water having a chloride content of less than 25 ppm extends to a depth of about 500 feet. The chloride ranges from 25 to about 1,000 ppm between about 500 and 700 feet. Below 700 feet, the chloride is 1,000 ppm or more. In the St. Johns River valley and on the east coast where the piezometric surface is only a few feet above sea level, artesian water having a chloride content of 1,000 ppm or more is present throughout the aquifer. In the eastern part of this section where there is no local recharge, test wells show that water having a chloride content of less than 70 ppm is present to a depth of about 500 feet about 7 miles west of the coast, but the level of the water having a higher chloride content rises to the top of the aquifer near sea level where the artesian water discharges into the ocean.

Wyrick (1960, p. 44) stated that the salt water in the St. Johns River valley moves upward along a fault. As shown by the piezometric surface of the artesian water, the upward leakage of salty artesian water in the St. Johns River, however, occurs for many miles where the top of the aquifer is near sea level and the confining beds were removed by erosion and solution. Under these conditions, there is no need to postulate a fault to explain the upward leakage of the artesian water.

SEMINOLE COUNTY

Heath and Barraclough (1954, p. 33) found that the chloride content of samples from 637 wells in Seminole County generally ranged from 5 to 5,000 ppm. Artesian wells in the county range in depth from 50 to 1,222 feet. More than 95 percent of the wells, however, are between 75 and 250 feet in depth. The lowest chloride content, 4 ppm, was for samples from wells near Paola, near the southwest shore of Lake Jessup and southeast of Lake Mary. In all hilly upland areas, where there is recharge through sinkhole lakes, the artesian water has a chloride content of less than 25 ppm. In the lowland in the valleys of the St. Johns River, Wekiva River, Little Wekiva River, and Econlockhatchee Creek and bordering Lake Harvey, Lake Jessup, and Lake Monroe, the artesian water has a chloride content of more than 25 ppm. Within this area of water of relatively high chloride content, there are two areas (the upland area of sinkhole lakes around Geneva and a small area northwest of Lake Geneva) where there is local recharge through the bottoms of the lakes and sinks which has flushed the salt water from the aquifer. Salt water entered the aquifer during Pleistocene time when the sea covered the valley of the St. Johns River. The aquifer was exposed to the salt water through the channel of the St. Johns River, sinkholes, and solution basins which were open prior to being filled with Pleistocene and Recent sediments.

Barraclough (1962, p. 71–80) recognized that the low chloride in the areas of upland lakes may be due to recharge causing more complete flushing of the aquifer than in the St. Johns River valley where there is no local recharge. Also, as suggested by Barraclough, the artesian water having a chloride content of more than about 250 ppm is in areas where the land surface is less than about 30 feet above sea level. The aquifer was exposed to the sea in those areas, while adjacent areas above sea level were being flushed of salt water to some extent. If the Pleistocene history, as discussed in this report, is correct, salt water was probably flushed from the aquifer during the time the sea stood 300 feet or more below its present level. Later, the sea rose above its present level and entered sinkholes and river valleys and other places where the aquifer was exposed. During the remainder of Pleistocene time, as the sea retreated, some flushing of the aquifer continued to take place.

During later advances, however, the sea stood about 25 feet and then 8 feet above the present level. The parts of the aquifer exposed to those invasions of the sea have had the least time to be flushed of salt water; therefore, water having the highest chloride content may be expected in the parts of the aquifers exposed. As the Avon Park Limestone of the principal artesian aquifer was exposed to the sea in the St. Johns River valley, it now contains some of the most highly mineralized water in Seminole County. This local occurrence of salt water in the Avon Park caused Stubbs (1938, p. 27) to conclude that the *Coskinolina* zone, which is part of the Avon Park, is the source of the highly mineralized water in Seminole County. Actually, in that part of St. Johns River valley, the highly mineralized water may be present in any water-bearing formation which was exposed to the sea when it stood at a higher level than at present. The difference in the mineral content of the water in these formations today is due in part to factors such as permeability and recharge which control the movement of the artesian water through the aquifers.

Heath and Barraclough (1954, p. 40) reported that a comparison of chloride analyses of artesian water made in 1937 with those made in 1954 showed that in general there was no change. An exception was in a small area southwest of Sanford where the chloride content seems to have increased as much as 100 ppm. The seasonal fluctuation in chloride is from 50 to 150 ppm in farming areas where water is used for irrigation. In the farming areas near Oviedo, the seasonal change is generally less than 50 ppm. During the period 1937 to 1954, the artesian pressure declined slightly in areas where withdrawals increased. In Seminole County, most of the water for irrigation is obtained from natural flow; therefore, the loss of head is no greater than about 20 feet, the maximum height above the land surface to which water would rise in a tightly cased well. As artesian water can be obtained at relatively shallow depths, the general practice has been to drill several shallow wells having small flows in different parts of the area to be irrigated instead of one deep well with a larger flow. This results in a much lower chloride content than would be likely from deeper wells.

BREVARD COUNTY

In Brevard County D. W. Brown and others (1957, p. 89) reported that the chloride content of samples of artesian water ranged from 32 to 14,500 ppm. Both the highest and lowest samples were from the Titusville area. Samples reported by Collins and Howard (1928, p. 209) include one with a chloride content of 14,276 ppm from a well 400 feet deep at Titusville and one from a lake 8 miles west of Titusville having a chloride content of 3,700 ppm. The chloride contents in most of the samples of artesian water tested, however, were not more than several thousand parts per million. Eight of the wells sampled had a chloride content of less than 250 ppm. These wells are in two areas north of Titusville where there may be local recharge and one area in the southeastern part of the county. The top of the aquifer is about 300 feet below sea level. The aquifer at this depth probably was not exposed directly to Pleistocene sea water. In the Titusville area and in the northwestern part of the county where the top of the aquifer is only 75 to 100 feet below sea level, Pleistocene sea water probably entered the aquifer directly in the St. Johns River valley and through sinkholes. The shape of the piezometric surface in the northeastern part of the county indicates a submarine discharge area near the shore. Such a discharge is probably through sinkholes, similar to the large submarine spring 2½ miles east of Crescent Beach.

INDIAN RIVER COUNTY

The wells of the principal aquifer reported by Bermes (1958b, p. 67–72) in Indian River County range in depth from about 500 to 1,000 feet. Wells penetrating more than about 275 to 300 feet into the aquifer probably yield water having a chloride content of more than 100 ppm. Generally, the chloride gradually increases with depth in most wells. The highest chloride samples of about 1,000 ppm were not, however, from the deepest wells. Some of the analyses show increases in chloride which may be the result of increased withdrawal of water from the aquifer in the eastern part of the county in recent years. This increase in chloride may be due to upward movement of salt water through uncased wells or through the formation. The distribution of the chloride water, as suggested by Bermes (1958b, p. 30), indicates that the salt is from connate water or sea water that entered the aquifer prior to Recent time.

Artesian water in the Hawthorn Formation above the principal aquifer and some of the nonartesian water in the Hawthorn and overlying surface formations have a chloride content of more than 100 ppm. The source of the chloride water in the Hawthorn probably is from Pleistocene sea water, except in areas where the water-bearing material is exposed to ocean water at the present time.

Southern Florida

The belt of water of relatively high chloride content along the east coast extends through St. Lucie County into an area which covers the south end of the Florida peninsula as shown in figure 36. Reports by Lichtler (1960, p. 63–79) on Martin County, Schroeder, Milliken, and Love (1954, p. 25) on Palm Beach County, Parker, Ferguson, Love, and others (1955, p. 580–682) on Dade County, and Klein (1954, p. 55–60) on Collier County give details on the occurrence and the range of the chloride content of the water. Analyses of water from two wells in the Kissimmee Valley in southeastern Highlands County (Bishop, 1956, p. 53) show that the area in which water having a chloride content of more than 100 ppm in the principal aquifer and the overlying aquifers extends north of Lake Okeechobee into the Kissimmee Valley. Reports by Black and Brown (1951) and Collins and Howard (1928) which contain analyses of water throughout the State include many analyses of samples from southern Florida.

Throughout southern Florida, the principal aquifer generally has a chloride content ranging from a few hundred to several thousand parts per million. The Hawthorn Formation and the younger formations in the Florida Everglades yield water having a chloride content of more than 100 ppm. Most of this chloride water in the Hawthorn and younger formations probably is from sea water which covered the area in Pleistocene time. Some of the water in the lower part of the Hawthorn Formation may be connate or caused by upward leakage from the underlying artesian aquifer. In parts of the areas, such as in Dade County (Schroeder and others, 1958) and in Collier County (Klein, 1954), some parts of the Hawthorn Formation and the overlying formations have been flushed of salt water. In Dade County, the very productive shallow aquifer has relatively high chloride content only along the coast and the coastal canals where sea water enters the formations. The underlying Hawthorn Formation has not, however, been completely flushed of salt water. In the Naples area in Collier County and elsewhere along the west coast, flushing has been complete in some parts of the Hawthorn Formation.

Gulf Coast of Florida

Northward on the gulf coast, the large area of water of relatively high chloride content in southern Florida becomes narrow in Sarasota County and extends as a narrow strip into Pasco County. In Citrus, Levy, Dixie, and Wakulla Counties, the large ground-water flow through the principal aquifer, which is cavernous limestone in these counties, has flushed out all the connate and Pleistocene sea water and has prevented salt-water encroachment into the aquifer. In some areas on the Florida coast west of Wakulla County, the water has a chloride content of more than 100 ppm.

SARASOTA AND MANATEE COUNTIES

Reports by Stringfield (1933c, p. 175–177, 218–220) on Sarasota County and Peek (1958a, p. 71–73) on Manatee County give information on the occurrence of salty ground water in these counties. In the southern part of Sarasota County, the chloride content of the artesian water ranges from a few hundred parts per million to several thousand parts per million. A sample from Warm Mineral Springs in sec. 25, T. 39 S., R. 20 E., about 15 miles southeast of Venice had a chloride content of 9,550 ppm. The area of water of relatively high chloride content extends eastward in De Soto County where Black and Brown (1951, p. 46) reported that a sample from a well at Carlstrom field had a chloride content of 121 ppm. North of Venice, the water having a chloride content of more than 100 ppm is confined to a narrow belt along the coast. Sarasota is on the east edge of the belt.

Maps of Manatee County by Peek (1958a, fig. 32–40) show that the coastal belt within which the chloride content of the artesian water is more than 100 ppm extends inland several miles north and south of the Manatee River. In the lower part of the principal artesian aquifer, the highest chloride content recorded was 2,400 ppm.

The maps showing the water of highest chloride content adjacent to Palma Sola and Terra Ceia Bays suggest that the aquifer was exposed to sea water in Pleistocene time in valleys which were cut into the aquifer during low stands of the sea. These valleys have been filled with Recent sediments sufficiently impervious to confine the water. The head is sufficient to prevent salt-water encroachment from the gulf. The aquifer is not, however, completely flushed of sea water.

A sample of water from a depth of 398 feet collected by Stringfield (1933c, p. 219) just south of Anna Maria on Anna Maria Key resembled sea water although it was more than twice as concentrated as sea water. Peek (1958a, p. 62) sampled the water and reported a chloride content of 44,000 ppm. He reported that the sample is from the Hawthorn Formation and attributed the high salinity to solution of mineral salts in the formation. He showed the bottom of the Hawthorn and the top of the underlying Tampa at a depth of less than 350 feet below sea level. This occurrence suggests the salt water might be in the upper part of the Tampa Limestone or at the contact between the Tampa and the Hawthorn where a brine could have formed on the eroded surface of the Tampa by evaporation, as suggested in the part of the present report on the source of salt water or salt deposits. Peek (written commun., 1960) explained that the sample containing 44,000 ppm was collected by R. B. Anders from well 31–43–2 (Peek, 1958b, p. 144) which was finished as a supply well in the Tampa Limestone. Field analyses of the chloride content of the water showed that well 29–42–1 penetrated the brine; the chloride content of the water in the Tampa Limestone was about 150 ppm below a depth of 350 feet.

Peek concurs with the writer that the brines or salt may have formed as a result of evaporation of sea water in a lagoon or an arm of the sea. As he suggests, the present occurrence of the brine may reflect the pattern of circulation of the artesian water. Leakage of water from the underlying Tampa Limestone, where the artesian pressure is considerably higher than in the Hawthorn, may have diluted or essentially replaced brines that may have existed throughout much of the area. The present occurrence of brines may be restricted to the localities where such circulation has not been possible or has been extremely poor. There is no indication of vertical or lateral movement of the brines. Poor circulation of the ground water is also indicated by the fact that the brines were not flushed from the formation when the Pleistocene sea stood below the present sea level and valleys were cut into the area. These valleys are now drowned and form the bays along the coast.

HILLSBOROUGH AND PINELLAS COUNTIES

Reports by Peek (1959b, p. 59–72) on Hillsborough County and Heath and Smith (1954, p. 34–45) and D. W. Brown (1958) on Pinellas County describe the chloride content of water in the principal aquifer in these counties. In a narrow belt along Tampa Bay and the gulf coast the ground water has a chloride content of more than 100 ppm. Some of the water of high chloride content in the lower part of the formation may be from Pleistocene sea water which has not been flushed out by the ground water. Part of the chloride water is, however, from encroachment of salt water from Tampa Bay and the gulf in areas along the coast. This is illustrated in the old well fields for the cities of Tampa and St. Petersburg, where the fresh water head was lowered by pumping to such an extent that salt water from Tampa Bay entered the aquifer.

A new well field was developed for St. Petersburg in 1930 in the Cosme-Odessa area in the northwestern part of Hillsborough County, far enough inland to be safe from lateral encroachment of sea water. The chloride content in that area is low. M. L. Brashears, of Leggette, Brashears & Graham (written commun., 1961), reported that the chloride content of water samples from a test well recently drilled 1,200 feet deep in the Cosme-Odessa well field was less than 18 ppm. Also, Brashears reported that the chloride content of samples from wells ranging from 411 to 728 feet deep in a new field near Lutz was less than 14 ppm. These records show that the salt water has been completely flushed from the principal artesian aquifer to depths of at least 728 feet in the Lutz area and 1,200 feet in the Cosme-Odessa area. The chloride content of samples of water from three wells 300 feet deep, erroneously reported in the northwestern part of Hillsborough County (Black and Brown, 1951, p. 93), was 148, 150, and 309 ppm. These wells are actually in the old well field of the city of St. Petersburg in Pinellas County, near Tampa Bay. This old well field was abandoned at the time the Cosme-Odessa well field was put into service in 1930.

Lake Tarpon, formerly known as Lake Butler, in the northern part of Pinellas County occasionally has a relatively high chloride content because it is connected by an underground channel to salt water in Spring Bayou, a tributary of Anclote River, a tidal stream at the town of Tarpon Springs. As stated by Matson (Matson and Sanford, 1913, p. 29), a spring in Tarpon Springs at the bottom of Spring Bayou, a few feet below mean tide level, is connected with Lake Tarpon by an underground channel. The flow of the spring is usually insignificant, but at times the discharge is large. Observations on the lake immediately before and after one of these outbursts of the spring show that the lake is lowered several inches while the spring flow is large. The lake occupies a large solution basin in the Tampa Limestone.

Studies by Heath and Smith (1954, p. 39–40) show that the lake discharges into a sinkhole as much as 115 feet deep just off the northwest shore of the lake. After entering the sinkhole, water moves through an underground channel or channels and emerges through an outlet in the bottom of Spring Bayou. Fluctuations of water levels in a well in the aquifer are almost identical with those in Lake Tarpon. The stage of the lake has ranged from 2.5 to 5.5 feet above mean sea level at the start of the draining of the lake and 1.2 to 3.1 feet above mean sea level after cessation of the draining. The most plausible explanation of the phenomenon seems to be that suggested by Meinzer and Stringfield and described by H. H. Cooper, Jr. (Heath and Smith, 1954, p. 39). The underground channel, with outlets in the lake and bayou, forms a crude U-tube, in which a column of the relatively dense sea water in Spring Bayou balances a higher column of fresh water in the lake. As long as the system is in balance, the contact between fresh water and sea water is in the lake outlet at a depth which depends on the lake stage, the height of the tide in the bayou, and the relative densities of the two waters. This contact is depressed as the differential in head increases with a rising stage of the lake or a falling tide. When the differential in head is large enough to depress the contact to the bottom of the U-tube, any further increase throws the system out of balance. The sea water moves out of the channel, and the lake drains to a lower stage. The lake will cease to drain when a new static balance between salt water and the fresh water is established at a lower stage of the lake. Probably the cessation of flow occurs during a rising tide in the bayou, and subsequently, near high tide, sea water moves back through the channel to the outlet in the lake to complete the cycle.

The cycles begin at different stages of the lake because of the variation of the density of the lake water and the height of the tide in the bayou. Occasionally the concentration of salts in the lake water, especially in the vicinity of the sink, may be so high as to allow the lake to drain under a considerably lower head differential than if the water were fresh. The highest stage, 5.5 feet above mean sea level, at which the lake started to drain suggests that with a ratio of 40 to 1 the depth of channel below sea level is (40×5.5) 220 feet below sea level. From the chloride content of the water in the lake at the sink, however, as reported by Heath and Smith, the ratio was less than 40 to 1, and the depth to the channel is therefore less than 220 feet. The maximum measured depth of the sinkhole through which the lake drains is 115 feet (Heath and Smith, 1954, p. 40). Thus it seems that the depth of the channel is between 115 and 220 feet.

HERNANDO TO ESCAMBIA COUNTIES

The known areas of water of relatively high chloride content are confined to the coast in this area, though a sample from a well 453 feet deep with 137 feet of casing at Jim Woodruff Dam (Apalachicola River at Georgia State line) had a chloride content of 5,330 ppm (Nevin Hoy, written commun., 1962). Matson and Sanford (1913, p. 226) reported saline water from limestones at a depth of less than 1,000 feet at Chattahoochee in Gadsden County.

From Hernando to Franklin Counties, the aquifer has been flushed of salt water. The water having high chloride content along the coast is from salt water from the Gulf of Mexico. In Citrus and Sumter Counties, however, salt water is present in the underlying limestone, according to records of two wells reported by Mossom (1926, p. 226, 230). In a well of Dundee Petroleum Co. (sec. 36, T. 20 S., R. 22 E.) 3,090 feet deep about 4 miles northeast of Bushnell, Sumter County, salt water was reported at a depth of 2,405 feet. A well 1,900 feet deep near Crystal River in Citrus County reached salt water which flowed under artesian pressure. Water of relatively high chloride content is present in the aquifer along the coast from Franklin County, Fla., to the Alabama State line, as illustrated at Panama City and Fort Walton Beach. At Pensacola, in Escambia County, the aquifer is more than 1,000 feet below sea level and contains salt water (Matson and Sanford, 1913, p. 303).

In summary, the Tertiary formations contain salt water along part of the coastal area, including southern Florida and the upper part of the St. Johns River valley. The lower Eocene and Paleocene formations contain salt water throughout most of Florida and southeastern Georgia.

SPRINGS

A classification of springs according to their average yield or discharge as proposed by Meinzer (1927, p. 3) consists of eight magnitudes. Springs of the first magnitude have an average discharge of 100 cfs (cubic feet per second) or more. One cubic foot per second equals 448.8 gpm or 646,317 gpd. Second-magnitude springs yield 10 to 100 cfs; third-magnitude springs yield 1 to 10 cfs; and fourth-magnitude springs yield 100 gpm to 1 cfs. Springs of fifth to eighth magnitudes range from 100 gpm to less than a pint a minute. All the springs of first-order magnitude and many of the smaller springs in Florida are described by Ferguson, Lingham, Love, and Vernon (1947).

The first-magnitude springs and many smaller springs shown on figure 37 are from the principal artesian aquifer. In the area where the aquifer is far below the land surface (fig. 23), as in the western, southern, and northeastern parts of Florida and the coastal area of Georgia, all the springs are small and are from the Hawthorn and younger formations overlying the principal artesian aquifer. There are 17 springs of first magnitude in Florida (Ferguson and others, 1947, p. 37). Measurements of the largest spring in Georgia, Radium Springs (formerly Blue Spring), 4 miles south of Albany, range from 26.4 to 135 cfs (Stephenson and Veatch, 1915, p. 240). However, the minimum recorded in 1954 was less than 18 cfs (R. L. Wait, written commun., 1962; Callahan, 1964, p. 30). Many springs are along streams, as the Suwannee River and its tributaries in Florida and the Flint River in Georgia, where the rivers are flowing on Oligocene and Eocene limestones of the principal aquifer. Also, there are submarine springs in coastal areas where the aquifer is at or near the ocean floor. Many springs along the rivers discharge at or below the water level in the rivers. Falmouth Spring in Florida is a sinkhole formed by collapse of part of the roof of a solution channel which connects with the Suwannee River. A submarine spring east of Crescent Beach, Fla., appears to be of first magnitude at the ocean surface, but Brooks (1961) estimated a flow of 40 cfs.

Vernon (in Ferguson and others, 1947, fig. 6) showed the locations of the springs on the Suwannee River, the bed of which is marked by an almost continuous line of springs. Large quantities of water flow into the bed of the river from the aquifer, in addition to the springs and streams tributary to the Suwannee. As reported by Vernon (p. 18), the minimum flow of the Suwannee River above White Springs is 4.8 cfs, whereas at Ellaville the minimum discharge is 1,000 cfs. The total discharge from tributary springs and streams is less than 400 cfs, which leaves more than 600 cfs that must be discharged directly into the river. Although the water from many of the springs on or near rivers is probably from the upper part of the aquifer, some of them receive a large part of the water from greater depths, such as Radium Springs on the Flint River near Albany, Ga.

Most, if not all, of the springs of first magnitude (100 cfs or more) and some of the smaller springs from the principal aquifer are artesian and rise from considerable depths through vertical solution channels which appear to be sinkholes or natural wells. Some of the springs, such as Silver Springs, emerge below the water surface from a series of outlets which may be along a large solution channel. Wakulla Spring south of Tallahassee is one of a series of outlets for a large underground stream system, as described by Sellards (1917, p. 136). At the present time, Wakulla Spring forms the head of Wakulla River.

The Hawthorn Formation is the source of a few of the second-magnitude springs, such as Rock Springs in Orange County and numerous smaller springs. Rock Springs is one of the few large springs, in the area of this report, that has an outlet of the underground stream in part above the water level.

The remarkable depth of some of the springs is illustrated by Bugg Spring, about half a mile northwest of Okahumpka in Lake County, Fla., which is 176 feet deep. As shown on a contour map (Ferguson and others, 1947, p. 97), the spring is less than 50 feet in diameter at the bottom and about 400 feet at the surface—the typical shape of sinkholes in this part of Florida, where the Hawthorn Formation is overlain by unconsolidated material which tends to slump into the sinks. Except on the northwest side, the walls of Bugg Spring are essentially vertical below a depth of about 60 feet. The head of the spring is an elliptical cavity approximately 200 by 100 feet submerged in a nearly circular pool about 400 feet in diameter. The outline of the bottom of the spring suggests that it was formed by one sinkhole around which one or more small sinks or vertical shafts formed and later coalesced with the central sink.

One of the deepest pools of the first-magnitude springs is that of Weekiwachee Spring near Brooksville in Hernando County which, according to measurements made by sounding line by D. G. Thompson and the writer (Stringfield, 1936, p. 157), has a depth of about 145 feet.

Warm Mineral Springs and Little Salt Spring near Murdock in Sarasota County appear to be circular sinkholes about 250 feet in diameter. The depth of Warm Mineral Springs, as reported by Lingham (in Ferguson and others, 1947, p. 145–148) is 167 feet. William M. Stephens in an article, "Early Cave Man in Florida Springs," in "All Florida Magazine," (Dec. 27, 1959), and Lowell Brandle in an article, "Exciting Fossil Find Made in 210-foot Deep Florida Spring," in the Tallahassee Democrat (May 14, 1959) reported that divers penetrated to a depth of 210 feet in Little Salt Spring.

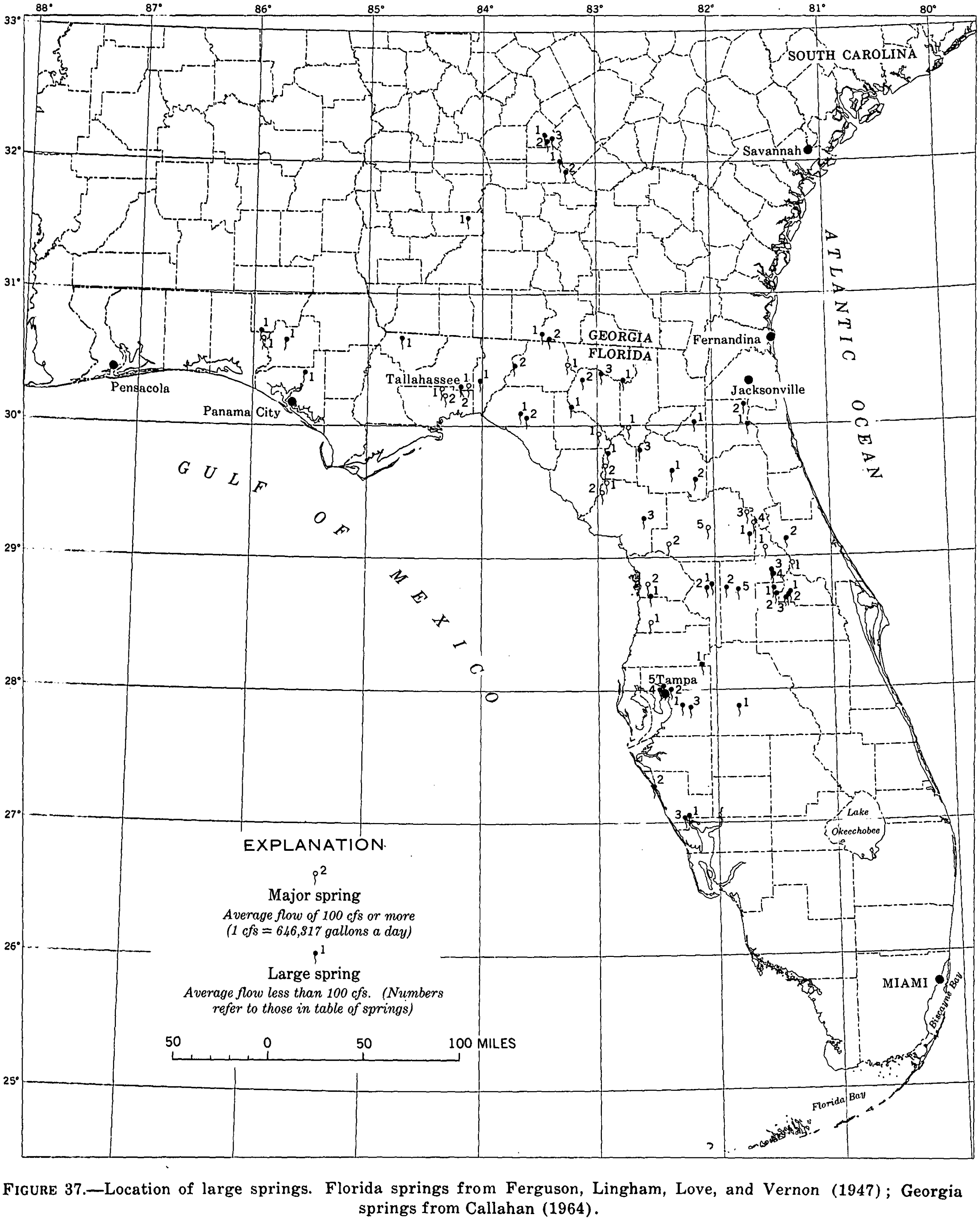

FIGURE 37.—Location of large springs. Florida springs from Ferguson, Lingham, Love, and Vernon (1947); Georgia springs from Callahan (1964).

S. J. Olsen (1958, p. 401) reported that Wakulla Spring extends to a depth of 100 feet where the bottom slopes sharply downward to 180 feet before it levels off and the sand floor gives way to limestone rubble. Three hundred feet farther along on the floor the depth reaches 225 feet where one side of the wall of the cave opens into a depression, the bottom of which is 240 feet below the surface and about 230 feet below sea level. This depression seems to be a sinkhole in the cave floor. Layers of clay exposed at the edge of the sink indicate that the sink was originally filled with clay. At a distance of 1,100 feet from the spring and at the depth of 250 feet, the floor of the cavern slopes down out of sight.

The depth of the submarine spring east of Crescent Beach, Fla., is only about 75 feet below the ocean floor. Zans (1951, p. 267–279) reported a circular submarine basin in the Bay of Bueno, Jamaica, having a depth of 840 feet, where fresh water issues in such a quantity that the sea water on the surface is nearly fresh.

The flow of the springs varies with the artesian head in the principal artesian aquifer, as is shown by the comparison of the discharge of Silver Springs in Marion County with the head of an artesian well about 4 miles southeast of the spring. A rating curve based on the artesian head in the well and the discharge of the spring showed that with a range of artesian pressure from about 3 feet to 11 feet (with reference to the measuring point at the well) the discharge ranged from about 600 to 1,150 cfs (Stringfield, 1938, p. 52–54).

A comparison of discharge of Silver Springs to the artesian pressure at Sharpes Ferry shows a good correlation between the two, except following rains when surface-water runoff increases the discharge of Silver Springs more than does the artesian pressure.

The flow of the artesian springs also varies with the relation of artesian head to the altitude of the outlet of the spring. For example, Bugg Spring yields water from the principal artesian aquifer, but the yield was only about 17 cfs when measured in 1943 and 1946 (Ferguson and others, 1947, p. 98). Although the artesian head is much higher at Bugg Spring in Lake County than at Silver Springs, as shown on the map of the piezometric surface, figure 29, the outlet for Bugg Spring is approximately as high as the artesian head in the area. If the head were lowered or the outlet raised sufficiently there would be no flow. Although the measurement made in 1943 was reported to be at the lowest stage remembered by old residents (Ferguson and others, p. 96), the writer visited the spring in 1932 when the artesian head at Sharpes Ferry and the discharge of Silver Springs were lowest during the 1931–46 period. Apparently there was little or no discharge from Bugg Spring, and according to reports at that time, the flow of the spring would reverse at different times. The water level in the spring is probably affected in the same way as that of an artesian well in which the water level declines with an increase of barometric pressure and rises with a decrease in barometric pressure. Under these conditions, with a low flow, the barometric pressure may depress the water level in the spring to such an extent that the flow of the spring would stop and the water in the discharge stream would flow into the spring.

The discharge of the springs from the principal artesian aquifer ranges from a few gallons a minute to more than 1,000 cfs. Two of the largest springs are Silver Springs near Ocala and Rainbow Springs near Dunnellon in Marion County, Fla., with a combined maximum flow of 2,310 cfs. As reported by Ferguson, Lingham, Love, and Vernon (1947, p. 117), the maximum discharge measured for Rainbow Springs (formerly Blue Springs) before 1947 was 927 cfs (599 mgd), November 9, 1935, and the minimum was 487 cfs (315 mgd), October 3, 1932. However, the discharge on September 28, 1950, was 1,060 cfs. The maximum discharge measured for Silver Springs before 1947 was 1,170 cfs (756 mgd) on August 4, 1930, and the minimum was 649 cfs (419 mgd) on June 22, 1945. Later measurements showed a maximum of 1,290 cfs on September 28, 1960, and a minimum of 539 cfs on May 3, 1957. Ichatucknee Springs in Columbia County ranks third in average flow. The combined average discharge of the springs has been estimated to be 3,700 mgd (U.S. Congress, Senate Select Committee on National Water Resources, 1960, p. 40–45). The estimated total use of water, both surface and ground water, in 1956 in Florida was 3,799 mgd.

The following list of springs by counties gives maximum and minimum discharge measurements where more than two measurements are available. The records for Florida are from Ferguson, Lingham, Love, and Vernon (1947) who included detailed descriptions of the springs and their location with discharge records and other records, as temperature measurements and chemical analyses of the water. In that report Vernon gave a table of Tertiary and Quaternary formations in Florida indicating the aquifers of selected springs. Reports by McCallie (1908) and Stephenson and Veatch (1915) contain descriptions and records of springs in Georgia. Calla-

FIGURE 38.—Silver Springs, Marion County, Fla., looking toward head of springs.

FIGURE 39.—Rainbow Springs, Marion County, Fla. View looking downstream from head of springs.

han (1964) lists 55 springs flowing from the principal artesian aquifer in Florida and Georgia. Of these, 22 are in Georgia. However, except for Radium Springs, the maximum flow recorded in Georgia is less than 50 cfs. The largest of the Georgia springs are on the Flint River in Dougherty County, the Withlacoochee River in Brooks County, and the Ocmulgee in Wilcox County, where the aquifer is near the surface.

Twenty-seven of the largest springs in the Florida peninsula, listed by Stringfield (1936, p. 155–156) approximately in order of discharge, include all but four of the springs of first magnitude in the following list. Three springs—Silver Springs, Rainbow Springs, and Weekiwachee Spring—are shown in figures 38, 39, and 40.

FIGURE 40.—Weekiwachee Spring, Hernando County, Fla. View looking downstream from head of spring.

Springs shown on map (fig. 37)

Discharge and temperature: Records for Florida (Ferguson and others, 1947; U.S. Geological Survey, 1960b); records for Georgia (Callahan, 1964; Wait, 1963).
Discharge: Maximum (max) and minimum (min) given where there are several discharge records.

Temperature measurements: By many persons in different places in the springs with different thermometers, some of which were not calibrated.
Aquifer: 1, principal artesian aquifer; 2, Hawthorn and younger Miocene formations; 3, post-Miocene formations; C, indicates chemical analyses published in reference.

Spring		Discharge		Aquifer	Temperature	
No.	Location and name	Cfs	Date		°F	Date
	Florida					
	Alachua County:					
1	Glen Springs near Gainesville	0.32 .33	Dec. 10, 1941 Apr. 16, 1946	3,C	72	Apr. 16, 1946
2	Magnesia Spring near Hawthorn	1.8	Dec. 10, 1941	2,C	75	Apr. 16, 1946
3	Poe Springs near High Springs	31.2 (min) 86.5 (max)	Mar. 14, 1932 Feb. 19, 1917	1,C	73	July 22, 1946
	Bay County:					
1	Blue Springs near Bennett:					
	Spring 1	4.7	May 22, 1942	1	71	May 22, 1942
	2					
	3	44.5	Nov. 14, 1941	1		
	Bradford County:					
1	Heilbronn Spring near Starke	.56 (max) .08 (min)	1913 May 8, 1946	2,C	70	May 8, 1946

See footnotes at end of table.

Springs shown on map (fig. 37)—Continued

Spring		Discharge		Aquifer	Temperature	
No.	Location and name	Cfs	Date		°F	Date
	Florida—Continued					
	Citrus County:					
1	Chassahowitzka Springs near Homosassa Springs	101 (max)	Oct. 9, 1930	1,C	74	Feb. 14, 1933
		54.6 (min)	Nov. 8 1935		75	July 25, 1946
2	Homosassa Springs at Homosassa Springs	141 (min)	Feb. 14, 1933	1,C	75	Apr. 3, 1946
		222 (max)	Mar. 7, 1936			
	Clay County:					
1	Green Cove Spring at Green Cove Spring	5.4 (max)	Feb. 12, 1929	2,C	70	Feb. 16, 1924
		4.4 (min)	Apr. 18, 1946		77	Apr. 18, 1946
2	Wadesboro Spring at Orange Park	1.4	Apr. 18, 1946	2,3,C		
	Columbia County:					
1	Ichatucknee Springs near Hildreth	578 (max)	Apr. 29, 1948	1,C	71–72	May 17, 1946
		241 (min)	Jan. 28, 1956			
	Gadsden County:					
1	Glen Julia Springs at Mount Pleasant	.78	May 16, 1946	3,C	69	May 16, 1946
	Gilchrist County:					
1	Hart Spring near Wilcox	63.1	May 12, 1932	1,C	73	July 24, 1946
		58.6	July 24, 1946			
2	Rock Bluff Springs near Bell	42.1	Dec. 8, 1942	1		
	Hamilton County:					
1	White Springs at White Springs	72 (max)	Feb. 13, 1907	1,C	72	Sept. 3, 1923
		36.2 (min)	Nov. 4, 1931		70	May 6, 1946
	Hernando County:					
1	Weekiwachee Spring near Brookville	231 (max)	May 6, 1931	1	[1] 74	Sept. 9, 1944
		106 (min)	Feb. 14, 1933			
	Hillsborough County:					
1	Buckhorn Spring near Riverview	11	May 1, 1946	2	76	May 1, 1946
2	Eureka Springs near Tampa	3.9	May 1, 1946	2	74	May 1, 1946
3	Lithia Springs near Lithia	39.2 (min)	Apr. 13, 1943	1,C	70	July 19, 1923
		64.2 (max)	Apr. 30, 1946		76	Apr. 30, 1946
4	Purity Spring at Tampa	1+	------------	2,C	70	July 20, 1923
4	Sulphur Springs at Sulphur Springs	12.9 (min)	Feb. 12, 1934	2,C	70	July 1923
		163 (max)	Aug. 3, 1945		78	Apr. 6, 1931
	Holmes County:					
1	Ponce de Leon Springs at Ponce de Leon	20.7	May 20, 1942	1,C	68	May 20, 1942
		18.1	Dec. 9, 1946			
	Jackson County:					
1	Blue Springs near Marianna	86.4 (min)	Oct. 14, 1941	1,C	70	May 20, 1942
		277 (max)	Apr. 11, 1946			
	Jefferson County:					
1	Wacissa Springs at Wacissa	120+	July 16, 1942	1,C		
	Lafayette County:					
1	Troy Spring near Branford [2]	55.2	May 15, 1927	1		
		149	July 17, 1942			
	Lake County:					
1	Alexander Springs near Astor	117 (avg)	1931–46	1,C	74	Apr. 2, 1946
2	Bugg Spring near Okahumpka	17.3	Mar. 16, 1943	1,C	74	Apr. 19, 1946
		17.6	Apr. 19, 1946			
3	Messant Spring near Sorrento	18.4	May 10, 1946	1, 2	79	May 10, 1946
4	Seminole Springs near Sorrento	27.1	Feb. 5, 1931	1, 2	80	Feb. 5, 1931
		10.2 (min)	Mar. 8, 1932		76	------------
		35.8 max)	Feb. 10, 1933		74	Feb. 10, 1933
5	Spring at Echo Glen at Yalaha	4.6	Apr. 19, 1946	2		
	Leon County:					
1	Natural Bridge Spring at Natural Bridge south of Tallahassee	115	May 19, 1942	1,C	68	May 19, 1942
		132	May 14, 1946		69	May 14, 1946
2	Rhodes Spring south of Tallahassee	70+	May 19, 1942	1	69	May 19, 1942
	Levy County:					
1	Fanning Spring near Wilcox	79 (min)	Mar. 14, 1932	1,C	72	Mar. 14, 1942
		137 (max)	Dec. 17, 1942			

See footnotes at end of table.

Springs shown on map (fig. 37)—Continued

Spring		Discharge		Aquifer	Temperature	
No.	Location and name	Cfs	Date		°F	Date
	Florida—Continued					
	Levy County—Continued					
2	Manatee Spring near Chiefland	149 (max)	Mar. 14, 1932	1,C	72	Mar. 14, 1932
		137 (min)	July 24, 1946		73	July 24, 1946
3	Wekiva Springs near Gulf Hammock	100 (max)	Feb. 1, 1929	1	78	Feb. 9, 1931
		55 (min)	Mar. 16, 1932		74	July 25, 1946
	Madison County:					
1	Blue Spring near Madison	145	July 23, 1946	1,C	70	Mar. 16, 1932
					71	July 23, 1946
2	Pettis Spring near Greenville	.16	May 16, 1946	1,C	68	May 16, 1946
	Marion County:					
1	Juniper Springs near Ocala	12.8	Feb. 11, 1929–	1,C	72	Apr. 4, 1946
		(avg of 11)	Apr. 4, 1946			
2	Rainbow Springs near Dunnellon	487 (min)	Oct. 3, 1932	1,C	72	Feb. 9, 1931
		1020 (max)	Sept. 28, 1950		76	June 18, 1946
3	Salt Springs at Lake Kerr	105 (max)	May 5, 1931	1,C	75	Apr. 4, 1946
		54 (min)	Oct. 15, 1935			
4	Silver Glen Springs near Astor	89.9 (min)	Feb. 7, 1933	1,C	73	Apr. 1, 1946
		129 (max)	Apr. 12, 1935			
5	Silver Springs near Ocala	526 (min)	June 6, 1932	1,C	74	Mar. 2, 1945
		1240 (max)	Sept. 9, 1933		72	Aug. 31, 1946
	Orange County:					
1	Rock Springs near Apopka	51.9 (min)	Mar. 8, 1932	2,C	74	May 20, 1933
		62.8 (max)	Jan. 30, 1935		75	May 9, 1946
2	Wekiwa Springs near Apopka	63.9 (min)	Mar. 8, 1932	2	75	May 9, 1946
		72.5 (max)	Nov. 7, 1935			
	Pasco County:					
1	Crystal Springs near Zephyrhills	147 (max)	July 19, 1941	1	74	Feb. 17, 1933
		20.3 (min)	July 1, 1946		75	Dec. 27, 1946
	Polk County:					
1	Kissengen Springs near Bartow	43.6 (max)	Oct. 11, 1933	1,C	72	Aug. 24, 1923
		0 (min)	Feb. 1950		77	Mar. 10, 1932
	Sarasota County:					
1	Little Salt Spring near Murdock	1.49 (max)	Apr. 29, 1946	2,C	77	Apr. 29, 1946
		.17 (min)	Jan. 1943		82	May 29, 1946
2	Pinehurst Spring near Sarasota	.11 (max)				
		.006 (min)	Apr. 1946	2,C	73	Apr. 30, 1946
3	Warm Salt Spring near Murdock	11.0 (max)	Oct. 1, 1942	2,C	86	Apr. 29, 1946
		10.8 (min)	Apr. 29, 1942			
	Seminole County:					
1	Palm Springs near Longwood	9.7	Nov. 12, 1941	2,C		
2	Sanlando Springs near Longwood	22.4	Nov. 12, 1941	2,C	74	Apr. 23, 1946
		21.7	Apr. 23, 1946			
3	Sheppard Spring near Longwood	16.7	July 25, 1944	2,C	74	July 25, 1944
	Sumter County:					
1	Fenney Springs near Coleman	21.6	July 26, 1946	1	76	July 26, 1946
2	Panasoffkee River (formerly Branch Mill Springs) group. Includes Fenney and other springs	8.6 (min)	Feb. 17, 1933	1	74	Feb. 17, 1933
		40.2 (max)	July 26, 1946		76	July 26, 1946
	Suwannee County:					
1	Charles Springs near Luraville	9.4 (min)	Dec. 12, 1941	1	69	May 29, 1942
		36.8 (max)	May 29, 1942			
2	Falmouth Spring at Falmouth. The flow on Feb. 10, 1933, was from the Suwannee River	365	Feb. 10, 1933	1,C	71	July 22, 1946
		59.6	Dec. 9, 1942			
		157.0	July 22, 1946			
3	Suwannee Springs near Live Oak	44	May 17, 1906	1,C	70	Mar. 16, 1932
		6.1	Mar. 16, 1932			Dec. 27, 1945
		37.9	May 16, 1946			May 16, 1946
	Taylor County:					
1	Hampton Springs near Perry	.15 (min)	June 25, 1959	1,C	70	Nov. 21, 1923
		.58 (max)	May 21, 1923		73	July 23, 1946
2	Waldo Springs near Perry	26.5 (max)	1913			
		3.3 (min)	July 24, 1946	1	71	July 24, 1946
	Volusia County:					
1	Blue Spring near Orange City	188 (max)	Dec. 5, 1932	1,C	73	Mar. 7, 1932
		62.7 (min)	Nov. 6, 1935		74	Jan. 3, 1947
2	Ponce de Leon Springs near De Land	20.4 (min)	Mar. 7, 1932	1,C	79	Oct. 26, 1923
		41.8 (max)	Apr. 23, 1946		73	Nov. 27, 1946

Springs shown on map (fig. 37)—Continued

Spring		Discharge		Aquifer	Temperature	
No.	Location and name	Cfs	Date		°F	Date
	Florida—Continued					
	Wakulla County:					
1	River Sink in River Sink Precinct south of Tallahassee	178	May 19, 1942	1	72	Oct. 14, 1941
2	Wakulla Spring near Crawfordville	283 (avg)	1941–47	1,C	77	Apr. 22, 1931
					74	Sept. 15, 1931
					73	June 18, 1946
	Walton County:					
1	Morrison Spring near Ponce de Leon	121	May 27, 1942	1	69	May 23, 1942
		89	Dec. 9, 1946		67	Dec. 9, 1946
	Washington County:					
1	Beckton Springs near Vernon	49.0	May 26, 1942	1	67–73	
2	Blue Springs near Redhead	31.6	May 26, 1942	1	71	May 22, 1942
		52.5	Dec. 10, 1946			
3	Cypress Spring near Vernon	84.9	May 26, 1942	1		
	St. Johns County:					
1	Submarine Spring 2½ miles east of Crescent Beach. Temperature taken at a depth of 121 ft by U.S. Coast and Geodetic Survey			1	71¼	1925
	Georgia					
	Brooks County:					
1	Blue or Wade Spring	18.9	Apr. 22, 1937	1		
		23.21				
2	McIntyre Spring	46.42		1		
	Dougherty County:					
1	Radium Springs, formerly Blue Spring, near Albany	135 (max)	Apr. 19, 1904	1	69	Not recorded
		18 (min)	Feb. 7, 1954			
		[3] 4.09	Oct. 19, 1954			
	Pulaski County:					
1	Mock Spring	6.47	Oct. 20, 1943	1	68	Sept. 17, 1954
		9.28				
		5.57	Sept. 17, 1959			
2	Blue Spring	4.64		1	67	Oct. 23, 1962
		1.66	Oct. 23, 1962			
	Wilcox County:					
1	Poor Robin Spring	2.75	Sept. 16, 1954	1	68	Sept. 16, 1954
		.62				
		4.52	Oct. 25, 1962			
2	Osewichee Spring	18.57		1	67	Oct. 24, 1962
		1½ to 2	Oct. 24. 1962			

[1] Eight of eleven measurements at different dates are 74°F, the others are 72°, 75°, and 77°F.
[2] According to reports, no flow visible during extremely low stage of Suwannee River.
[3] Leakage through weir; not entire flow at spring outlet.

Springs of first order of magnitude (an average discharge of 100 cfs or more) are indicated with open circles and those with smaller average discharge are shown with closed circles in figure 37. The submarine spring east of Crescent Beach, Fla., is discharging through a sinkhole similar to many of the large springs on land (Stringfield and Cooper, 1951c, p. 67–72). This spring evidently is the same as that reported by Matson and Sanford (1913, p. 207, 213, 397).

As shown on U.S. Coast and Geodetic Survey Chart 3258 (Florida inside route, St. Augustine to Titusville, 1931), the ocean floor at the submarine spring about 2½ miles east of Crescent Beach is about 55 feet below sea level. The bottom of the spring, as described by A. M. Sobieralski (in Rude, 1925, p. 85–91), is as much as 125 feet below sea level. The spring has sufficient pressure and discharge to be noticeable at the surface of the ocean as shown in figure 41 at the time it was visited by Florida State Geologist Herman Gunter, F. C. Westendick, and the writer in 1934. The water, like much of the artesian water in Florida, contains hydrogen sulfide, as could be detected by the odor at the surface of the spring.

Underwater investigations of the geology and hydrology of the spring in 1959 and 1960 are described by H. K. Brooks (1961, p. 122–134). The maximum

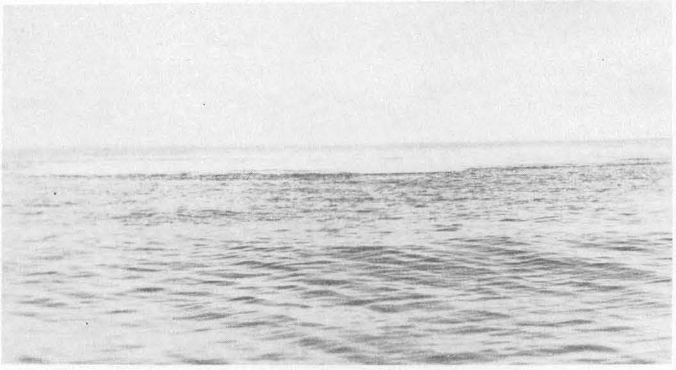

FIGURE 41.—Submarine Spring, 2½ miles east of coast at Crescent Beach, Fla. Spring forms smooth surface in background.

depth recorded by him in diving is 132 feet. As described by Brooks, the floor of the spring, about 126 feet below sea level, is pitted with conical depressions as much as 12 feet in diameter and 6 feet deep. Water rises through loose, coarse, granular pebbly material irregularly distributed over the bottom. No outcrop of limestone was seen. Two samples of water from spring discharge at the bottom had chloride contents of 7,680 and 8,720 ppm, which are comparable to the chloride contents of some of the artesian water from wells on that part of the coast. A sample of water at the bottom near the outer edge of a point of discharge had a chloride content of 16,560 ppm, as compared with 20,100 ppm for coastal water and 19,800 ppm at the surface of the spring.

Brooks estimated the discharge on the floor of the spring is 40 cfs. The boils of the spring about 75 feet in diameter at the surface of the ocean give the impression that the discharge is tremendous. However, he stated that the large boils on the surface of the ocean are not due to the swift current jetted upward but are due to the upward rising of large masses of relatively fresh artesian water of lower density than sea water. The temperature of the spring water also has an effect on the buoyancy because it is warmer than that of the sea water. Brooks suggests the temperature of the spring water may be as much as 80°F but is more likely 74° to 76°F. The sea water was 71°F November 3 and 72°F June 16 at the time of the investigation. The measurement made by the Coast and Geodetic Survey at a depth of 121 feet in the spring was 71¼°F, as shown in the table of springs.

The general direction of movement of water through the principal artesian aquifer from recharge areas to the springs is indicated by the piezometric surface of the artesian water as shown in figure 29. Aquifers which are the source of the springs are given in the list of springs. The course of the water from the Putnam County recharge area eastward to the submarine spring 2½ miles east of Crescent Beach, St. Johns County, is described by Stringfield and Cooper (1951c, p. 61–72) and shown in figure 42.

The movement of water in the principal artesian aquifer from a recharge area in Polk County to Kissengen Springs is indicated in figure 43, as shown in a section by Peek (1951, p. 78). These sections (figs. 42 and 43) show deep circulation through sinkholes and solution channels. The low tritium content of water from Silver Springs near Ocala, Fla., and Radium Springs near Albany, Ga., also indicates deep circulation.

As described by Wait (1963, p. 58), Radium Springs, about 4 miles south of Albany and 200 yards east of the Flint River, emerges from an opening about 3 feet in diameter in the bottom of a 15-foot depression in the Ocala Limestone. Below the opening is a cavern 300 feet wide, 150 feet long, and 80 feet deep. Changes in the stage of the river affect the discharge of the spring. As the stage of the river rises, discharge from the limestone to the river decreases, and the water level rises.

Although the discharge of the springs listed is many millions of gallons daily, that discharge represents only part of the water which moves through the principal artesian aquifer. For example, in addition to the visible springs on land and diffused discharge into streams, there is large discharge into the gulf through submarine outcrops along the western coast of Florida from Pinellas County to Franklin County. The range in the discharge varies with the season, depending on rainfall and recharge to the aquifer.

Kissengen Springs with a maximum recorded flow of 43.6 cfs is the only known large spring of the principal artesian aquifer which has stopped flowing be-

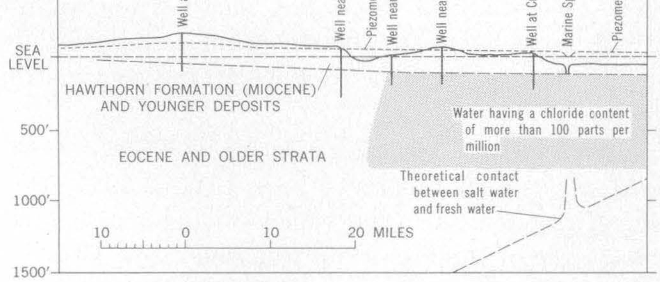

FIGURE 42.—Section across Putnam and St. Johns Counties, Fla., showing submarine spring east of coast at Crescent Beach.

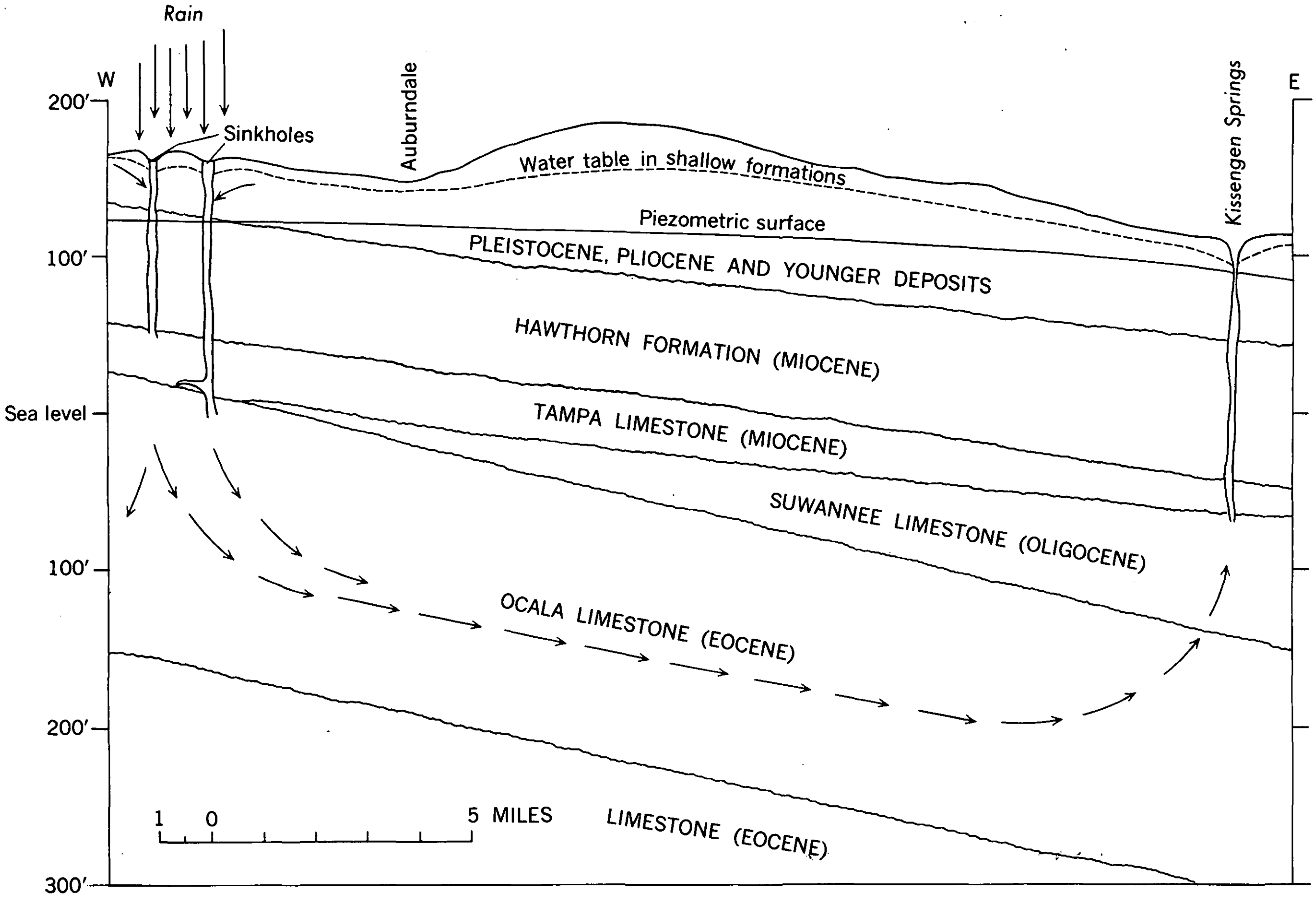

FIGURE 43.—Section through Kissengen Springs, Polk County, Fla. (From Peek, 1951, p. 78.)

cause of withdrawal of water from wells. Peek (1951, p. 77, 81) pointed out that after 1936 the flow declined progressively until in February 1950 it ceased to flow when the withdrawal of ground water from wells in southwestern Polk County reached approximately 110 mgd, of which about 75 mgd was used by phosphate companies. Peek estimated that about 20 mgd of the total was from the capture of the flow of Kissengen Springs and 90 mgd is partly from other natural discharge, partly from an increase in recharge, and partly from a slight reduction in storage in the aquifer where the piezometric surface is lowered.

Notes by P. R. Speer dated February 5, 1929 (Peek, 1951, p. 80; Ferguson and others, 1947, p. 141) show that Kissengen Springs stopped flowing once before, during the drilling of an oil test well a few hundred feet northwest of the spring in 1927. Speer stated that at a depth of 220 feet the well tapped the spring flow, practically draining it. The well was then cased and continued to 4,700 feet, striking a strong sulfur flow the entire way. Speer reported also that the casing was set so that the flow from the well flowed back into the spring cavity and apparently increased the flow of the spring. A comparison of analyses of samples of water (Ferguson and others, 1947, p. 143) collected from the spring in 1923 and 1946 shows that the calcium sulfate content was higher in 1923 than in 1946, indicating some of the water was from the lower part of the aquifer. The low chloride content of 7.6 ppm in both samples suggests, however, that none of the water was from formations below the principal artesian aquifer.

Chemical analyses of samples of water from several springs are given in the following list to indicate the composition of four of the five types of water as discussed in the section on quality of water. No spring yields soft sodium bicarbonate type water such as that from deep wells in the aquifer in western Florida.

Chemical analyses of water from seven springs

[From Ferguson and others, 1947; results in parts per million except as indicated]

Name and location	Date sampled (1946)	Silica (SiO_2)	Iron (Fe)	Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Potassium (K)	Bicarbonate (HCO_3)	Sulfate (SO_4)	Chloride (Cl)	Fluoride (F)	Nitrate (NO_3)	Dissolved solids	Total hardness as $CaCO_3$	Carbon dioxide (CO_2)	Color (Hazen units)	pH
Silver Springs, Marion County	Oct. 21	9.2	0.04	68	9.6	4.0	1.1	201	34	7.8	0.1	1.3	237	209	5	4	7.8
Rainbow Springs, Marion County	June 18,	7.7	.08	21	4.0	2.9	.4	78	4.7	3.5	.0	.8	81	69	2	2	7.9
Salt Springs, Marion County	Apr. 4	11.0	.10	240	167	1540	38	87	613	2800	.0	......	5850	1290	......	0	7.1
Little Salt Spring, Sarasota County	May 29	17	.05	194	136	758	24	171	534	1430	1.6	1.8	3480	1040	......	12	7.3
Rock Springs, Orange County	May 9	9.6	.07	29	8.4	4.3	.6	105	17	6.1	.1	.3	128	107	8	4	7.3
Hampton Springs, Taylor County	July 23	10.0	.13	189	85	7.0	2.0	288	557	8.8	.7	.0	1080	821	......	30	6.9
Glen Julia Springs, Gadsden County	May 16	4.6	.08	.5	.4	1.9	.5	3.0	.2	3.1	.1	.7	15	2.9	14	10	5.7

The analyses of water from Silver Springs and Rainbow Springs represent the calcium bicarbonate type of water low in chloride and sulfate. This type of water is characteristic of most of the artesian water in the limestone and dolomite of the principal artesian aquifer, except in southern Florida and some of the coastal areas. The water from Rainbow Springs in central Florida is softer than that from Silver Springs. Its mineral content is less than that of Silver Springs, indicating that a large part of its flow is from local recharge. Judging from the chemical analyses of the water and discharge from Silver Springs, Ferguson, Lingham, Love, and Vernon (1947, p. 127) estimated that a ton of dissolved mineral matter, consisting chiefly of calcium and bicarbonate and a moderate amount of sulfate, issues from the spring every 3 minutes.

Little Salt Spring in Sarasota County and Salt Springs in Marion County represent calcium bicarbonate water mixed with remnants of sea water or salt in the aquifer. Only the springs in the St. Johns River valley and some flowing from the principal artesian aquifer in coastal areas have a relatively high chloride content. Little Salt Spring and Warm Mineral Springs in Sarasota County are in an area where the water in the Hawthorn Formation and the underlying principal artesian aquifer has a relatively high sulfate content from anhydrite in the water-bearing formations.

Water from Hampton Springs has a higher content of calcium, magnesium, and sulfate than that of the other springs having a low chloride content but not as high as some of the water from wells in the principal artesian aquifer, as in Sarasota County, Fla. The sample from Rock Springs is typical of water from some parts of the Hawthorn which may be similar to that in the underlying artesian aquifer. The soft water having a low mineral content from Glen Julia Springs in Gadsden County is typical of the ground water in unconsolidated sands.

The approximate temperature of the water ranges from about 67° to 86°F. Some of this difference may be due to approximate measuring with uncalibrated thermometers. Most of the measurements ranged from about 69°F in northern Florida and southern Georgia to about 70° to 74°F in central Florida.

WELLS

EARLY EXPLORATION

A summary of the history of drilling of artesian wells and shafts by Tolman (1937, p. 316), based on a review of the history of development of artesian wells by Keilhack (1935), shows that 2,000 years before Christ, oases in Egypt were watered by numberless shafts as much as 300 feet deep. The word "artesian" originated from Artois, a province in northern France, where wells that overflowed at the land surface under natural pressure were bored in the 12th century. The first of these wells was completed in 1126.

The first artesian well in the United States (Carlston, 1943, p. 119–136) was constructed in

1820 in Charleston, S. C., by sinking an iron pipe through clay. Auger boring for artesian water was used in Charleston in 1823; however, the first successful auger-bored well was not completed in the city until after 1825. The drilling methods and tools were copied from a description of a well bored in London, England. Auger boring of artesian wells in the Cretaceous chalk belt in the Coastal Plain in Alabama and Mississippi began about 1820 at Cahaba. At that time Cahaba was the capital of Alabama.

After the construction of the early artesian wells in South Carolina, Alabama, and Mississippi in the first half of the 19th century, there was no discovery of artesian areas in other States until the latter part of the century when jetting and cable-tool methods were introduced in the Southeast. In 1854, before discovery wells were drilled in the other Southeastern States, Wailes (1854, p. 260, 265) estimated that there were about 100 flowing wells in Mississippi and more than 500 in Alabama.

The standard cable-tool drilling rig in the United States was developed in drilling salt wells in West Virginia, Ohio, and Pennsylvania (Carlston, 1943, p. 119). The first successful well was drilled near Charleston, W. Va., in 1808. By using this method, it was possible to drill through hard rock; later the rotary method (Bowman, 1911, p. 70) was developed and used for drilling in both soft and hard rock. However, the cable-tool method was not used successfully for water-well drilling in the southeast until the first flowing well in Florida (Stringfield, 1953) was drilled at St. Augustine between 1880 and 1882 by a driller from the Pennsylvania oil fields. The discovery well for artesian water supply at Jacksonville, Fla., was completed about 1885. For many years, Jacksonville had the largest municipal supply derived entirely from natural flow of artesian wells. Although water for the public supply is now obtained by pumping artesian wells, the piezometric surface was 25 or more feet above sea level outside the deepest part of the cone of depression in 1962 (Leve, 1965, fig. 12).

Although at least six attempts had been made between 1840 and 1850 (Wait, 1957, p. 143), the first flowing well in Georgia (McCallie, 1898, p. 63–64) was completed in 1881 on a plantation 20 miles west of Albany. The second successful flowing well in Georgia was drilled in Savannah in 1885 (McCallie, 1908, p. 72). Artesian wells were drilled for the public supply of Savannah in 1887. In 1888 artesian wells completely replaced the city supply from the Savannah River. Wait reported that the failures prior to 1881 probably were due to improper construction.

Much of the early drilling for artesian water, like the early drilling for oil, was without adequate geologic advice. A few notable exceptions in which geologic information was used, as at Jacksonville, Fla., have been recorded. For example, after the first flowing well was drilled at St. Augustine, R. N. Ellis, city engineer at Jacksonville, without an understanding of the geologic structure, assumed that artesian water could be reached at about the same depth at Jacksonville as at St. Augustine. The test well at Jacksonville was unsuccessful because it was not deep enough to tap the artesian aquifer, the top of which is about 500 feet below sea level at Jacksonville, although it is only about 200 feet below sea level at St. Augustine. The hope of obtaining flowing wells at Jacksonville was, therefore, abandoned until L. C. Johnson, a geologist of the U.S. Geological Survey, on a ground-water reconnaissance in Florida, was informed of the effort to obtain water. From his information on the geologic structure of Florida, Johnson estimated correctly that a flow of artesian water could be reached at a depth of about 500 feet. This discovery started the development of the large artesian system in the northeastern part of Florida. Thousands of artesian wells are now in use in the Coastal Plain of the Southeastern States.

RECORDS AND YIELD OF WELLS

Records of representative artesian wells in different parts of the Florida peninsula, on which the first map of the piezometric surface of water in the principal artesian aquifer was based, are included in a report by Stringfield (1936). The wells and measurements used for the first draft of the piezometric map for western Florida are recorded in an unpublished report by V. T. Stringfield and F. C. Westendick on artesian water west of the Suwannee River. A report by Warren (1944) gives records and measurements of wells used in mapping southern Georgia. Records of many additional wells and measurements have been published in later reports and have been used in preparing more detailed piezometric maps.

The areas in which the artesian wells will flow under natural pressure are shown in figure 28, and the height to which water would rise in tightly cased wells in 1961 is shown in figure 29. Artesian wells range from about 50 to 1,000 feet in depth, depending on the local conditions within the area in which they are constructed, and from about 2 to 12 inches

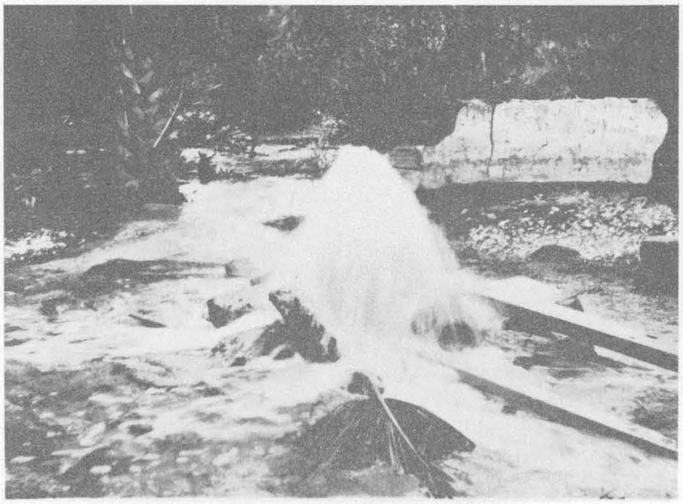

FIGURE 44.—Artesian well near Belle Glade, Palm Beach County, Fla. Well is finished with valve to control artesian flow. Casing at surface is enclosed in concrete.

in diameter. Some of them are as much as 24 inches in diameter. Except in western Florida where part of the principal artesian aquifer consists of unconsolidated formations, few of the wells are entirely cased. The casing generally ends in the top of the first limestone penetrated. Some wells, as much as 1,000 feet deep, may have only about 100 feet of casing.

Wells in areas of artesian flow are commonly finished with valves to shut off the flow when the water is not needed (fig. 44). However, some wells flow continuously because the casings are corroded or the valves are broken or corroded (fig. 45). Hendry and Lavender (1957, p. 29–177) included records of 967 wells which were flowing continuously in 22 counties in Florida. They reported that the total flow from these wells was 37,762 gpm.

Four methods used in casing wells, described by J. B. Foster (1962) for eastern Clay County, Fla., and illustrated in figure 46, are used in many parts of the region underlain by the principal artesian aquifer. The general direction of movement of water in the wells is shown by arrows.

In well *A*, the casing is seated on a hard layer of rock, and the well is drilled to the top of the aquifer. A liner of smaller diameter is lowered into the well and seated near the top of the aquifer. The liner is sealed at the land surface to prevent flow of water through the opening between the casing and liner. Then an open hole is drilled into the aquifer to complete the well. This method is one used to prevent subsurface leakage from one permeable bed to another through wells.

The construction of well *B* is similar to that of well *A* except that, instead of running the liner to the land surface and sealing it to the casing, the liner ends below the top of the casing and is not sealed to it. Under these conditions water may move from the aquifer to the top of the liner and then downward between the casing and the liner into permeable beds below the casing and above the aquifer. Subsurface leakage in wells of this type could be eliminated by sealing the liner to the casing with a packer.

Well *C* illustrates the method commonly used. The well is cased to the first hard layer of rock. Well *D* is similar to well *C*, except that a short liner is set in the open hole to prevent sand and other unconsolidated material from caving into the well.

Although the principal artesian aquifer is tapped by wells throughout its extent, wells are most numerous within areas in which the wells flow. The greatest concentrations are in irrigation districts as in Indian River, Seminole, Manatee, and Sarasota Counties, Fla. In Seminole County, several thousand wells have been drilled for irrigation of celery and other truck crops. Bermes (1958b, p. 40) reported that more than 2,000 wells yield water from the principal artesian aquifer in Indian River County. In parts of Seminole County, there is an average of one or more wells for each acre of land irrigated. Some artesian wells are not more than about 50 feet deep in areas where the principal artesian aquifer is near the land surface. Artesian wells are also numerous in Jacksonville, Savannah, and in other large cities and industrial areas.

FIGURE 45.—Artesian well in Flagler County, Fla., flowing about 750 gpm without valve to control flow.

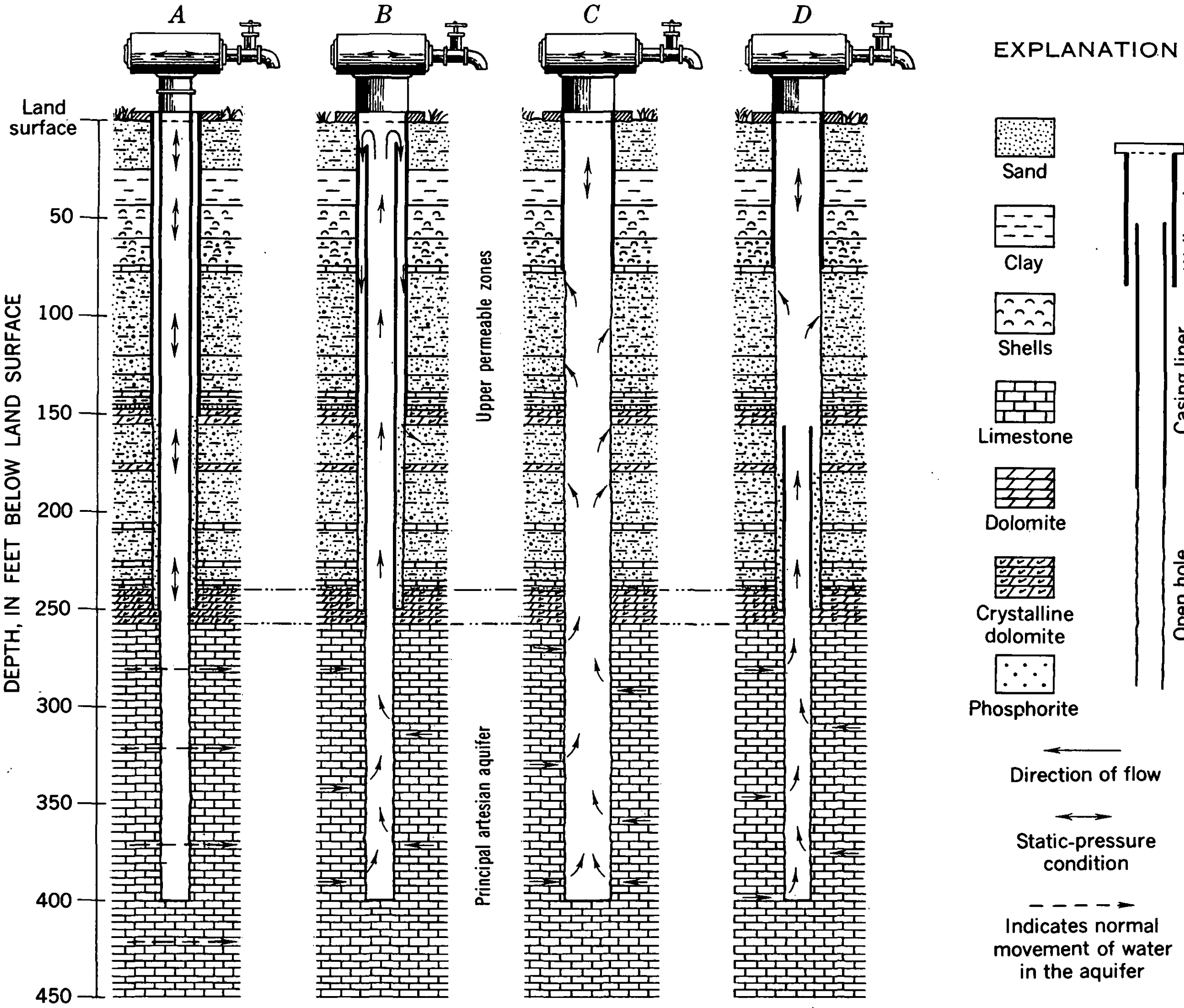

FIGURE 46.—Diagram of four methods used in casing wells. (From J. B. Foster, 1962.)

Some nonflowing wells are used to drain surface water into the aquifer. The largest concentration of these is in the Orlando area in Orange County, Fla., as described by Unklesbay (1944) and Unklesbay and Cooper (1946). A few wells used for drainage in the Miami area, Florida, are in the shallow aquifer, the chief source of ground water in southeastern Florida. Wells for drainage and many wells for water supply are finished in the shallow aquifer without screens. The principal artesian aquifer is as much as 1,000 feet deep in southeastern Florida; the wells that tap it will flow. Therefore, wells are not used to drain water into the artesian aquifer in that area. However, farther north in the coastal area, the artesian flow from wells is used to drain lowlands by means of a venturi tube on the discharge pipe of the well. Bermes (1958b, p. 39) reported the use of this method to drain lowlands near the Sebastian River in Indian River County, Fla. Flowing wells used for drainage are called siphon wells. Westendick (Stringfield and Westendick, 1935, p. 15) reported the use of this method in Brevard County. As stated by Bermes, in some installations the venturi tube is submerged so that the surface water enters the tube directly. In others, the venturi tube is above the surface water, which is drawn into the tube by a pipe extended to the water.

In a few areas as in Black Hammock, Seminole County, Fla., where the artesian aquifer is overlain by relatively thin confining beds, a shallow artesian well may be drilled to relieve the pressure and prevent sand boils during construction of drainage canals, as illustrated by Ferris, Knowles, Brown, and Stallman (1962, fig. 20, p. 81).

The yield of the artesian wells depends on the hydrologic conditions and the construction of the wells. In general, the wells having the smallest capacities are in the southern part of Florida. The yield of flowing artesian wells under natural flow ranges from a few to several thousand gallons per minute. The largest yields by natural flow are in the coastal area and in southern Florida where the artesian pressure is relatively large and the surface of the ground is relatively low. One of the largest recorded yields by natural flow (Cooper, 1944, p. 173) was 6,500 gpm from a well 12 inches in diameter near Yukon, Duval County, Fla., in November, 1942, when the well was first completed. The initial flows of two other wells measured by Cooper were 3,200 and 4,100 gpm. The yield of each of two wells drilled in 1964 near Palatka, Fla., exceeds those at Yukon (M. L. Brashears, written commun., 1964).

Among the largest yields recorded from nonflowing wells in the principal artesian aquifer is 7,500 gpm from a well 18 inches in diameter and 852 feet deep in Polk County, measured in 1926 by the American Agricultural Chemical Co. (Stringfield, 1936, p. 159, 183). In southeastern Florida, nonflowing wells in the shallow aquifer yield large quantities of water (Parker and others, 1955, p. 919, 940). Wells 12 to 14 inches in diameter have been reported to yield as much as 5,000 gpm with a drawdown of only about 5 feet.

When wells are flowing under natural artesian pressure, the pressure at the mouth of the well is almost zero, so that the drawdown or loss in head resulting from discharge of water is almost equal to the head with reference to the outlet of the well. When nonflowing wells are pumped, the drawdown is the difference between the static water level and the water level when the well is pumped. Where the well is pumped by suction lift, the drawdown may be determined by the vacuum created on the suction line of the pumped well. The maximum loss of head in a flowing well is limited to the shut-in head. This temporary loss in head for flowing wells in the principal artesian aquifer in different parts of the area of artesian flow ranges from a fraction of a foot to about 45 feet. The loss of head in a flowing well, or the drawdown, may be expressed in terms of specific capacity, which is the number of gallons discharged per unit loss of head.

The specific capacity is significant for comparison of yield of different wells and for determining the loss of head that will result if the yield of the well is increased by pumping. Data regarding the specific capacities of wells for which calculations could be made in Brevard, Clay, Flagler, Hendry, Polk, and Palm Beach Counties, Fla., in 1934, are included by Stringfield in a table (1936, p. 159). Data for wells, including specific capacities in southeastern Georgia, are given in a table by Warren (1944, p. 83–87). Many later reports on ground water include information on the specific capacity of wells.

Some wells in the shallow aquifer in the Miami area, Florida, have larger specific capacities than those of the principal artesian aquifer. Some of them are as much as 2,600 gpm per foot of drawdown. Although Parker, Ferguson, Love, and others (1955, p. 197–290) do not give specific capacities of wells, they give detailed information on the water-bearing capacity of the shallow aquifer, which is very large. The highest specific capacity—833 gpm for each foot of drawdown—in the principal artesian aquifer is reported for a well in Polk County, Fla., by Stringfield (1936, p. 159–160). The specific capacity of flowing wells recorded in Florida ranged from about 1 to 248 gpm. The maximum recorded by Warren (1944, p. 86) for flowing wells in Georgia was 206 gpm for a 16-inch well, 816 feet deep, at Camp Stewart in Liberty County.

SUBSURFACE LEAKAGE IN WELLS

Few artesian wells in the principal artesian aquifer are completely cased and finished with screens, except in areas of western Florida where unconsolidated water-bearing materials will collapse into wells if they are not cased and finished with screens. Where the aquifer consists chiefly of limestone, the casing may reach only to the first limestone, and the uncased part may extend through the aquifer, which in some places consists of several formations. Under these conditions, water entering the wells from formations of relatively high pressure may escape into formations of lower pressure instead of rising to the surface or remaining confined in the well.

The artesian pressure of the water in the middle and upper parts of the Hawthorn Formation in different localities may be higher or lower than that in the underlying part of the Hawthorn and other formations of the principal artesian aquifer. In Baker County, Fla., and other areas west of the areas of artesian flow in northeastern Florida and southeastern Georgia, the artesian head of the middle and upper parts of the Hawthorn is higher than that in the lower part and in other parts of the principal artesian aquifer. A well drilled into the principal aquifer, therefore, will drain water from the Hawthorn to the principal aquifer if it is not cased to the top of the principal aquifer. Within the area of artesian flow in the coastal counties and in southern Florida, the pressure in the Hawthorn is less than that in the principal aquifer, and water will flow through the well from the aquifer into the Hawthorn if the casing does not extend from the surface through the Hawthorn to the top of the aquifer.

Within the principal artesian aquifer, the water level or artesian pressures will be essentially the same at different depths except in recharge and discharge areas. The water levels or artesian pressures in general decrease with depth as the water moves downward into the aquifer. The water levels or artesian pressures increase with depth as the water moves upward to a discharge area. Also, the head in the upper part of the aquifer may become less than that in the lower part of the aquifer in areas in which water is withdrawn from the upper part of the aquifer through wells. Current-meter surveys in wells in two areas in Volusia County, Fla., as reported by Wyrick (1960, p. 14–15) showed that in an area of recharge the water moves downward from one part of the aquifer to a lower part through uncased wells. In a discharge area the direction of movement of the water in the well was upward into the aquifer.

In Manatee County, Fla., Peek (1958a, p. 28–33) reported that current-meter surveys in wells show that the Suwannee Limestone, which is the deepest part of the principal aquifer penetrated by the wells, yields no water below a depth of 605 feet. All the artesian water that entered one well, 4 miles west of Bradenton, flowed into the upper part of the Hawthorn at depths of 60 to 70 feet where there was no casing. The well was cased above and below that interval. In Sarasota County, Fla., Stringfield (1933c, p. 199–216) found no evidence of leakage into the Hawthorn. However, it is entirely possible that some leakage had taken place, but the pressure in the Hawthorn and the underlying principal artesian aquifer were in equilibrium at the time the tests were made. The current-meter survey in wells in Sarasota County showed that little or no water was coming from the lower part of the principal aquifer.

On the coast of Manatee County, wells that flow were reported to have been nonflowing during construction before their upper parts were cased. Near Sun City, in the southwestern part of Hillsborough County, Fla., a well 340 feet deep was reported (Stringfield, 1936, p. 161) to be nonflowing until a well at Sun City, 550 feet deep with only 42 feet of casing was constructed. This report thus indicates that part of the water from the formations penetrated by the 550-foot Sun City well enters the formations penetrated by the 340-foot well.

A well in the town of Green Cove Spring in eastern Clay County is reported to have had a pressure head of about 21 feet above the ground in 1927 when it was constructed. In 1934 the well had a reported pressure head of 1.5 feet above the ground surface. The loss of head in that well may have been caused by leakage through defective casing. Although the loss of head may be attributed to other causes, the inference of underground leakage is substantiated to some extent by reports that the water level in this well is influenced by fluctuations in Green Cove Spring a few hundred yards to the east. The water from Green Cove Spring apparently comes from the Hawthorn Formation and should not influence the water level in a well cased to a depth of 400 feet unless there is some defect in the casing or the method used in casing the well does not prevent subsurface leakage. The piezometric surface of the artesian water in the principal artesian aquifer in that area indicates continuous discharge from the aquifer, and the quality of the spring water is similar to that in the principal aquifer.

In eastern Clay County, J. B. Foster (1962) reported that 14 of 69 examined wells leaked underground. He estimated the loss of water from leaky wells to be about 1,000 gpm. Foster assumed that 5 percent of the existing wells were inventoried, and it seems probable that the same percentage of leaky wells would be found among all the wells in the area. If these assumptions are correct, the total loss would be about 20,000 gpm or about 30 mgd.

J. B. Foster (1962) reported that a comparison of the piezometric surface of the principal artesian aquifer in 1934 with that in 1960 showed a decline of 5 to 10 feet in the vicinity of Green Cove Spring and 15 to 20 feet in the northeastern part of the county in the vicinity of Orange Park. Although part of this decline may be caused by withdrawal of water from wells in the vicinity of Jacksonville northeast of Clay County, part of the decline is the result of subsurface leakage.

Even though the subsurface leakage recharges the permeable beds of the Hawthorn and other aquifers overlying the principal aquifer, the water is considered lost from the standpoint of recovery because water in the shallow aquifers is not used in that area. Subsurface leakage through wells may also be harmful if water of poor quality enters an aquifer that contains water of good quality.

SURFACE DRAINAGE INTO WELLS

In some parts of the lake region and other localities in Florida and Georgia where the surface drainage is poorly developed and where ground water stands several feet below the surface in wells that penetrate permeable aquifers, surface water is drained into wells constructed for that purpose. These drainage wells are constructed in sinkholes or other depressions along margins of lakes or in ditches (figs. 26 and 27).

The greatest concentration of drainage wells is probably in and near Orlando, Orange County, Fla., where more than 180 wells penetrating the Ocala Limestone and older formations of the principal artesian aquifer are used for drainage. Lichtler, Anderson, and Joyner (1964, p. 39) reported more than 300 drainage wells in Orange County. The Orange County Highway Department owns and operates 40 drainage wells. The Orlando Air Force Base has 12 drainage wells, 40 are privately owned, and the city of Orlando owns 90. Nearly all the runoff from rainfall in the city is disposed of through drainage wells. Before a sewage disposal plant was built east of Orlando, the city sewage, as septic tank effluent, also was drained into wells which are called sanitary wells. Drainage wells described by Unklesbay (1944, p. 31) are as much as 1,000 feet deep, and some sanitary wells are more than 850 feet deep. The casings ranged from 5 to 18 inches in diameter and 67 to 400 feet in depth. Current-meter explorations indicated that water from the wells entered the surrounding formations at depths ranging from 70 to 400 feet; in the deeper wells it may enter at greater depths.

In different parts of Orange County, the static water levels representing the piezometric surface of water in the lower part of the Hawthorn Formation, the Ocala Limestone, and older formations of the principal aquifer, as measured in wells (Stringfield, 1936, p. 162), range from a few feet to as much as 60 feet below the surface of the ground. The estimated drainage capacities of the wells range from less than 100 gpm to several thousand gallons per minute. The maximum capacity reported was 9,500 gpm for well 50 (county well 16), about 4 miles northeast of Orlovista.

The effects of drainage wells on recharge of the principal aquifer in the Orlando area, Florida, and the Valdosta area, Georgia, has been discussed in regard to water-level fluctuations caused by surface drainage into wells. Where the water level in the drainage well is at or near the level of the surface water to be drained, the well is not effective for drainage. In some areas, as at Lake Greenwood and Lake Davis at Orlando, where the aquifer is under artesian pressure and the water levels in the drainage wells fluctuate several feet from season to season, drainage wells may overflow instead of receiving water after rains during wet seasons.

In the Miami area, Florida, the shallow aquifer is very permeable, and drainage wells may be effective even though the water level in the wells stands near the land surface. In order not to contaminate the potable water supply in that aquifer, the drainage wells in the Miami area are constructed along the coast where the ground water is salty.

USE OF WATER AND ITS EFFECT ON THE PRINCIPAL ARTESIAN AQUIFER

The principal artesian aquifer is the chief source of water for municipal, industrial, and irrigation supplies in the area of this report. Although the aquifer yields water to the large limestone springs, nearly all the water consumed is from wells, both artesian and nonartesian, in the aquifer. A report by Ferguson, Lingham, Love, and Vernon (1947) discussed the utilization of springs in Florida. Many springs are used for recreation. A few small springs are used for water supply. A few mineral springs are used at health resorts, such as the Safety Harbor Spa near the head of Tampa Bay. One large spring, Weekiwachee Spring, in Hernando County, Fla., has been considered as a source of water for the city of St. Petersburg if additional water is needed to supplement the public supply from wells.

The flow of the Withlacoochee River, fed chiefly by Rainbow Springs, 4 miles northeast of Dunnellon in Marion County, is used to operate a hydroelectric plant. Hillsborough River, which is sustained by springs during dry seasons, is the source of water for the public supply of the city of Tampa.

A few of the artesian wells in areas of artesian flow have been used to generate electricity, and a few are used to lift surface water to drain low areas. In some areas where the water levels in the wells are below the adjacent land surface, water is drained into the aquifer through wells.

A preliminary estimate by MacKichan and Kammerer (1961, 1962) of ground water used in southeastern river basins was 710 mgd in 1960. Although the region includes parts of the Piedmont province and the Cretaceous area, it does not include the Florida peninsula where large quantities of water from the principal artesian aquifer are used for irrigation, public, and private supplies.

Estimates of the average consumption of water in Florida alone in 1960 reported by M. I. Rorabaugh (written commun., 1961) are as follows:

	Gallons per day
Public supplies	502,800,000
Private supplies for industrial and commercial use	657,400,000

Large quantities of ground water are used for irrigation of truck crops and citrus crops in the Florida peninsula. The average quantity used is difficult to estimate because of the difference in rainfall from one growing season to another. The largest quantities are used for truck crops such as celery in Seminole, Sarasota, and Manatee Counties and potatoes in Volusia County. During dry seasons many artesian wells are used to irrigate citrus crops.

Most of the public water supplies, including those of Savannah, Jacksonville, St. Petersburg, and Tallahassee, are from the principal artesian aquifer. The public supply of Tampa, Fla., was from wells near Tampa Bay. After salt water from Tampa Bay contaminated these wells, a supply was obtained from the Hillsborough River, which is fed during dry times by springs and ground water from the aquifer. However, ground-water supplies can be obtained from wells drilled into the aquifer at a safe distance inland from coastal areas of salt-water encroachment. The supply for Miami is from a very productive shallow limestone aquifer. The supply for Pensacola is from a shallow, but very productive, aquifer consisting chiefly of sand. The principal artesian aquifer in both of these areas is deeply buried and contains water having a relatively high chloride content.

In Georgia, Stewart and Croft (1960, fig. 3) estimated that the total annual withdrawal of artesian water in the 10 coastal counties was 279 mgd. Of that amount 197 mgd was for industrial use (fig. 47), 31 mgd for public supplies, 21 mgd for domestic supplies, and 30 mgd flowed continuously from wells for domestic use, stock, and game preserves. A large part of that water was not used. This unused water amounts to about 11 percent of the average daily discharge or about the same as that used for municipal supplies in 1957. Callahan (1960, p. 22) estimated there were 377 uncontrolled flowing wells. In the Savannah area, the withdrawal of water has reduced the area of flow and thereby reduced the loss of water by uncontrolled flow of artesian water from wells. Large quantities flow to waste in the areas of artesian flow in Florida, where Hendry and Lavender (1957) reported a total flow of about 54 mgd from 967 wells.

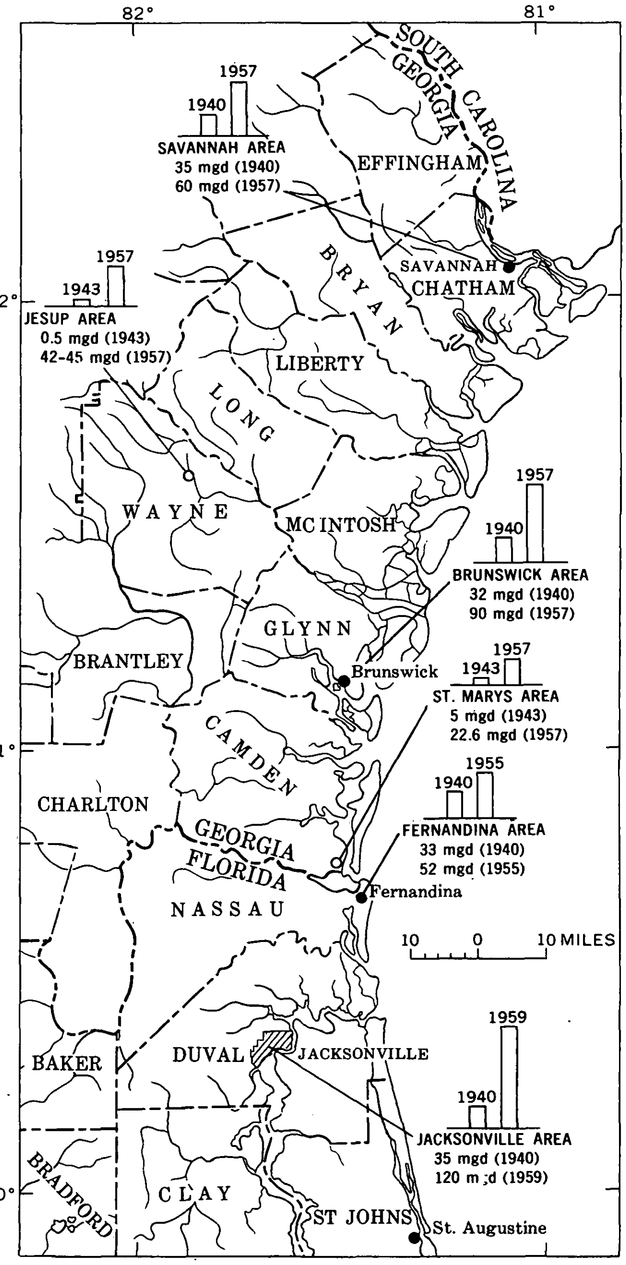

FIGURE 47.—Map showing consumption of artesian water in the principal industrial areas in coastal counties of Georgia and northeastern Florida.

The principal localities of large withdrawal in 1957 were the Brunswick area with 90 mgd and Savannah area with 60 mgd. The total estimates of Stewart and Croft for 1957 are valid for 1962 (H. B. Counts, written commun., 1962). The quantity of water used for irrigation in the coastal counties in Georgia is only a fraction of 1 percent of the total discharge.

Although these large quantities of water withdrawn from the principal artesian aquifer are remarkable, they are only part of the many hundreds of millions of gallons of water discharged naturally each day. The discharges of the larger limestone springs, which rank among the largest in the world, show the large capacity of the principal artesian aquifer. Among the largest of these springs is the Silver Springs group having an average flow in excess of the consumption of ground water for public supplies in Florida. The combined flow of the springs has been estimated (U.S. Congress, Senate Select Committee on National Water Resources, 1960, p. 40) to be 3,700 mgd and the total use of water from both ground and surface sources was 3,799 mgd in 1956. Much of the large quantities of ground water discharging naturally can be salvaged and used when needed.

Proposals for a ship canal that would cut into the principal artesian aquifer across the Florida peninsula have been considered in the past and may be reconsidered in the future. A barge canal, which will cut the aquifer is under construction (1965). Therefore, a brief discussion of possible effects of these projects on the artesian water follows. A sea-level ship canal, the proposed route 13–B (U.S. Army, Corps of Engineers, 1933; U.S. Congress, Senate, 1936) from the Gulf of Mexico across Marion County, Fla., a few miles south of Silver Springs and Rainbow Springs to the Oklawaha and St. Johns Rivers and to the Atlantic Ocean by the St. Johns River, at an estimated cost of about $240,000,000, would have cut the principal artesian aquifer in Marion County. Discharge of artesian water into the canal would have lowered water levels in the aquifer from their present levels 40 to 50 feet above sea level to approximately sea level along the canal route in Marion County. Large discharge into the canal would have resulted. Lowered water levels would have caused salt-water encroachment in the aquifer. Discharge of Silver Springs and Rainbow Springs would have been captured by underground flow. Water levels in the pools of the springs would have been lowered to a point near sea level.

These possible effects on water levels and quality of water have been discussed by Paige (1936, p. 537–570); J. S. Brown (1937, p. 589–599); Thompson, Meinzer, and Stringfield (1938, p. 87–107); Hubbert (1940, p. 785–944). The extent to which this lowering of water levels would affect the water in the aquifer some distance from the canal would depend on the following: (1) The amount by which the area of cross section through which the water flows is reduced, (2) the quantity of water which is diverted and discharged into the canal, and (3) additional recharge resulting from the lowering of water levels in the limestone.

If the cross section of limestone through which the water moves were to remain constant and if there were no diversion of water or additional recharge, the effects on the water levels in the limestone would extend to the highest parts of the piezometric surface south of the canal in Polk County and north of the canal in Putnam County. The new hydraulic gradient of the water would be parallel to the old gradient north and south of the canal and would be 40 to 50 feet below the old one. The highest part of the piezometric surface in Polk and Putnam Counties would be lowered by that amount.

However, the new gradient would actually be steeper than the old one, and the lowering of water levels in the Polk County and Putnam County recharge areas would be less than that indicated by a new gradient parallel to the old one. The new gradient would be steeper than the old one because the area of cross section through which the water is moving would be reduced by 40 to 50 feet, the amount to which the water levels are lowered along the canal. If it is assumed that the thickness through which flow occurs in that area is about 500 feet, the cross section of flow would be reduced about 8 to 10 percent and would increase the gradient by that amount. Lowering of the water levels along the canal would cause an increase in gradient of water moving to the canal from the north and south. Some of the water that normally flows in other directions would be diverted toward the canal with the lowering of water levels in the limestone. Some of the sinkholes which are now partially filled with unconsolidated material would be opened, permitting additional recharge. Some of the lakes which occupy basins in filled sinks would drain into the aquifer, increasing the recharge. All these factors would make the new gradient steeper than the old gradient. However, the available information is not adequate to make detailed estimates of the amount of lowering of the water levels some distance from the canal. In any case, the proposed canal would have no effect on the shallow aquifers at considerable distances from the canal, such as in the Miami area in southern Florida where the principal artesian aquifer is deeply buried.

The barge canal being constructed along route 13–B has locks to hold the water levels in the canal at approximately the same level as the adjacent water level in the principal artesian aquifer in Marion County (Vernon, 1961, p. 1–7). Water will be pumped from streams fed by Silver Springs and

Rainbow Springs into the summit level of the canal to replace water lost in operating the locks and leakage around locks. This use of water from the springs is to maintain the water level in the limestone at its natural level adjacent to the canal. As salt water is present in surface streams at each end of the section with locks, salt water eventually will be brought up to the summit level as water in the locks is raised to that level. If the natural fresh-water head in the aquifer is maintained, the salt-water and fresh-water balance in the aquifer will not be disturbed.

Except in a few areas of heavy withdrawal of water, the present use of water has had little or no effect on the aquifer. Outside these local areas many additional water supplies can be obtained in most of the region of this report without depleting the aquifer or creating problems of salt-water encroachment. The problem of salt-water encroachment is confined to a few places along the coastal areas and to a few places away from the coast where salt water is in the lower part of the principal artesian aquifer or in formations underlying the aquifer. Areas where water has more than 100 ppm chloride are shown in figure 36. As more information becomes available, a better understanding of the distribution of this water of poor quality and its relation to the overlying fresh water will be obtained. The large use of water from the principal artesian aquifer in the Southeastern States for industrial, municipal, domestic, and irrigation supplies emphasizes the fact that this water is one of the most valuable of the mineral resources of the region.

SUMMARY AND CONCLUSIONS

This report is based on many previous investigations and reports, including some by the writer. References to the literature are cited in the various chapters of the report. The area of this report includes Florida, most of the Coastal Plain in Georgia, and adjacent parts of Alabama and South Carolina.

The surface, in general, is characterized by a plain that slopes to the sea and extends beneath the sea as the Continental Shelf. Pleistocene marine terraces record oscillations of sea level. Coastal terraces along the Atlantic Ocean and Gulf of Mexico ranging from sea level to as much as 270 feet above sea level cover much of the report area. The landward limit of each terrace is defined by the shoreline at which the sea stood when the terrace was under water. Some of the higher terraces are dissected forming hilly topography. Some uplands above the terraces also are hilly; others are relatively level plateaus. The region has been uplifted sufficiently to cause downcutting of major streams. Valleys are cut as much as 100 feet below some of the uplands. In some areas the lower terraces have been only slightly modified by erosion. In areas where limestone is at or near the surface, solution of the limestone has resulted in sinkhole or karst topography. Many lakes in the uplands and on some of the terraces occupy sinkholes formed by solution of the underlying limestone. Some of the sinkhole lakes are more than 100 feet deep. Lake Okeechobee, which covers about 730 square miles in Florida, is less than 20 feet deep. The lake basin may have originated as a depression in the sea bottom.

Some of the principal streams that drain the area, such as the Savannah River, rise in the Piedmont province and flow across the Coastal Plain to the sea. A few of the streams that rise in the Coastal Plain, such as the St. Johns River on the east coast of Florida, were formed as parts of coastal lagoons and are approximately parallel to the coast.

On the Coastal Terraces there are many areas of poor drainage, especially in the swamps and low grassy plains. There are many swamps along the flood plains of streams. In southern Florida the Everglades cover an area about 40 miles wide, which slopes from 15 feet above sea level at the south side of Lake Okeechobee to sea level at the tip of the peninsula, a distance of more than 100 miles. The Okefenokee Swamp on one of the higher terraces in southern Georgia and northern Florida covers an area of about 660 square miles. The swamp slopes from about 120 feet above sea level to about 100 feet. Most of the water drains westward into the Gulf of Mexico; part of it drains southward to the Atlantic Ocean.

The climate of the area ranges from temperate in the northern part of the report area to subtropical in southern Florida. The annual rainfall ranges from about 50 to 60 inches in a large part of the region. However, rainfall decreases to a minimum of 38 inches at Key West. The average annual temperature ranges from about 65°F in the northern part of the area to about 76°F on the Florida Keys. Evaporation losses from water surfaces appear to average 40 to 45 inches a year. Experiments indicate evaporation and transpiration losses combined may range from 50 to more than 100 inches a year in the Everglades.

GEOLOGIC FORMATIONS

The geologic formations that crop out in this area range from Late Cretaceous to Recent in age. Igneous and metamorphic rocks which underlie the Piedmont province also underlie the sedimentary rocks in some places in the Coastal Plain. The Cretaceous formations consist chiefly of sand, gravel, and clay in the areas where they are at or near the surface. The overlying Tertiary formations consist chiefly of limestone, dolomite, and marl, with some anhydrite and gypsum. Some formations grade into sands and other clastic material in western Florida, southeastern Alabama, the northwestern part of the Coastal Plain in Georgia, and adjacent parts of South Carolina.

Pleistocene and Recent deposits of sand, gravel, clay, and shells generally are less than 100 feet thick. In southeastern Florida, the Pleistocene formations include 100 feet or more of limestone, marl, sand, and shell beds.

The Tertiary formations are at or near the surface in belts approximately parallel to the Cretaceous outcrops and the Fall Line in Georgia and adjacent parts of Alabama and South Carolina. The Tertiary formations also are at or near the surface on geologic structures, such as the Ocala uplift in north-central Florida and in the Jackson County area in western Florida and adjacent parts of Alabama and Georgia. Except where affected by local structure, the formations dip gently toward the coast at right angles to the belts of outcrops. The formations dip in all directions from the Ocala uplift. The thickness of the Tertiary formations ranges from less than 1,600 feet in Lafayette and Suwannee Counties on the northwest side of the Ocala uplift to about 4,500 feet in western Florida. South of the Ocala uplift in southern Florida, the thickness increases to 5,500 feet or more. North of the Ocala uplift in southern Georgia, the thickness increases to about 2,600 feet and then decreases to the northward to zero in the belt of the outcrops adjacent to the Fall Line. In South Carolina the maximum is about 2,400 feet thick at Parris Island.

The Tertiary formations are the chief source of ground-water supplies, except in some outcrop areas in Alabama, Georgia, and South Carolina, where the underlying Cretaceous formations may be the chief source. Late Tertiary and Quaternary deposits are the chief source of ground water in a few places, such as the Miami area in southeastern Florida and the Pensacola area in western Florida, where the principal aquifer of Tertiary age contains water of poor quality.

The Midway Group of Paleocene age is at or near the surface only in a belt of outcrops extending from southeastern Alabama into central Georgia. The water-bearing formations include limestone and sand, which are important sources of water in southeastern Alabama and southwestern Georgia. The Clayton, an argillaceous limestone containing solution cavities, is the chief water-bearing formation in some areas in Georgia and Alabama. The outcrops of the Clayton extend as far east as central Georgia, where they are overlapped by younger formations. In Florida, Paleocene deposits are not an important aquifer because of low permeability or because the water has a relatively high chloride content. The estimated thickness of the Clayton along the Chattahoochee River in southeastern Alabama is about 130 feet. The thickness reported at Savannah, Ga., is 385 feet. In Florida, the Paleocene is represented by the Cedar Keys Limestone, which ranges in thickness from about 165 feet in northern Florida to about 2,250 feet in southern Florida. The maximum thickness of the undifferentiated clastic equivalent in western Florida is about 1,000 feet.

The Eocene series, overlying the Paleocene, includes formations of Wilcox age (early Eocene), Claiborne age (middle Eocene), and Jackson age (late Eocene). Formations consisting of sand, sandstone, marl, and clay of early Eocene age crop out in a belt across Alabama to western Georgia where they are overlapped by middle Eocene formations. In southeastern Alabama and southwestern Georgia, sands of middle Eocene age are very permeable. The Nanafalia forms an excellent aquifer as much as 100 feet thick in Alabama. The sands and other clastic formations in Florida and southeastern Georgia merge into dolomite and limestone. In South Carolina, the Black Mingo Formation, as much as 250 feet thick, represents the early Eocene. The formation consists of sand and clay, but the permeability is so small that it is of no significance as an aquifer.

The Oldsmar Limestone represents the early Eocene in the Florida peninsula. It grades into a sandy facies in western Florida. It is less than 250 feet thick in the northern part of the peninsula over the Ocala uplift but increases in thickness to more than 1,000 feet in the southern part of Florida. Little information is available on the water-bearing properties of the Oldsmar. Most, if not all, of the water in the Oldsmar is salty. However, a sample of water from a depth of 2,258 feet in the South Lake well in Lake County, Fla., had a chloride content of only 781 ppm, indicating that some parts of the formation are almost completely flushed of salty water.

Middle Eocene formations overlying the Oldsmar Limestone consist chiefly of limestone and dolomite in Florida and southeastern Georgia. They are represented by the Lake City Limestone and Avon Park

Limestone in the peninsula and by undifferentiated clastics in the Florida panhandle. The Tallahassee Limestone forms part of the middle Eocene in the panhandle and part of the peninsula.

The Lake City Limestone is the oldest and deepest of the water-bearing formations of the principal aquifer in Florida and southeastern Georgia. It overlies the Oldsmar unconformably and is overlain unconformably by the Tallahassee Limestone or the Avon Park Limestone. In the Tallahassee area and in the northern part of the Florida peninsula, the Lake City Limestone is 400 to 500 feet thick. In the central part of the Florida peninsula in Lake County, it is about 990 feet thick, with the top about 1,010 feet below sea level. It is 420 feet thick in Polk County with the top about 1,540 feet below sea level. The clastic facies in western Florida thickens from about 575 feet in Jackson County to 800 feet in Walton County, Fla.

In central and north-central Florida, the Lake City is a productive water-bearing formation. The formation does not occur at or near the surface. It is recharged through sinkholes filled with permeable sands and through lakes which occupy sinkholes. Because wells as much as 1,550 feet deep yield relatively soft calcium bicarbonate water from the Lake City Limestone in Highlands County, Fla., local recharge is indicated. The mineral content of water from the Lake City Limestone is relatively low and is less than that in the overlying Avon Park and Ocala Limestones in some areas such as Seminole County, Fla. The low mineral content may be due to local recharge and relative solubility of the different formations. Silicified limestone, chert, and some dolomite in the Lake City Limestone may be less soluble than the pure limestone in the overlying formations.

The Avon Park Limestone, consisting chiefly of chalky limestone and dolomite, unconformably overlies the Lake City Limestone at the type locality between depths of 600 and 930 feet in a well at Avon Park in Polk County in central Florida. The Tallahassee Limestone, where recognized as a formation, underlies the Avon Park Limestone. At the type locality, the Avon Park Limestone is overlain by the lower member of the Ocala Limestone. The Avon Park Limestone is the oldest of the Eocene formations exposed in Florida. However, surface exposures have been found only on the Ocala uplift in Citrus and Levy Counties. The Avon Park is very permeable and cavernous in some areas. It is one of the most productive water-bearing formations of the principal artesian aquifer in parts of Florida and southeastern Georgia. In the Fernandina area, Florida, it apparently is less productive than in some other parts of Florida. The thickness of the formation is 50 feet or less in the northern part of the peninsula, 150 to 300 feet in the central part, and 450 to 650 feet thick in the southern part. A maximum of 845 feet has been reported in Polk County. In western Florida and adjacent parts of Alabama and Georgia the beds of equivalent age include glauconitic, calcareous sands, cherty limestone, and fossiliferous bentonitic clay. These beds are correlated with the Gosport Sand and Lisbon Formation in part.

In southeastern Alabama and adjacent parts of Georgia, the middle Eocene formations include the Tallahatta, Lisbon, and Gosport Formations. In South Carolina, the middle Eocene consists of the Congaree Formation at the bottom, overlain by the Warley Hill, Santee, and McBean Formations, with the Castle Hayne Limestone at the top. The formations consist chiefly of sands and other marine clastics that grade into limestone downdip in Florida.

Upper Eocene formations are separated from the underlying middle Eocene series by an inconspicuous disconformity in some areas. In southeastern Alabama, the upper Eocene formations consist of the Moodys Branch Formation overlain by the Yazoo Clay and by the Ocala Limestone. In Escambia County, Ala., the Moodys Branch Formation, 55 feet thick, consists of glauconitic limestone and marl. It is relatively impermeable but may be the source of small quantities of water. The Yazoo Clay, 75 feet thick, consists of clay and glauconitic sand which is the source of small quantities of water. The Ocala Limestone, 60 feet thick, contains solution cavities which yield moderate amounts of water to wells. In Florida and southeastern Georgia, the Ocala Limestone, with upper and lower members, represents the upper Eocene rocks. It rests unconformably on older Eocene formations. In the outcrop area in east-central Georgia the Ocala merges laterally with the Barnwell Formation, which is a marine pebbly sand and sandy limestone.

The Florida Geological Survey regards the Ocala Limestone as a group consisting of, from bottom to top, the Inglis Formation, Williston Formation, and the Crystal River Formation. In the present report the upper member of the Ocala Limestone is considered the equivalent of the Crystal River, and the lower member, the equivalent of the Inglis and Williston Formations.

The Ocala Limestone is about 100 to 300 feet thick in much of the panhandle of Florida, but it is much thicker in the Apalachicola embayment. It is thin in most of the central and northern part of the peninsula but reaches a thickness of 400 feet in the northeastern part. In the southern part of the peninsula, it generally is 200 feet or less thick and probably is absent in the vicinity of Miami and Key West.

In addition to a belt of outcrops extending from Alabama into Georgia, the Ocala Limestone crops out in two large areas in Florida. The largest area borders the gulf coast in the northwestern part of the Florida peninsula on the Ocala uplift. The other area is in western Florida in the north half of Washington and Jackson Counties and the eastern part of Holmes County. The outcrop area of the Ocala extends from western Florida into southeastern Alabama, then northeastward into east-central Georgia, where it merges with the Barnwell Formation. The Barnwell in the outcrop area and the Ocala downdip in Georgia extend into South Carolina.

In the peninsula and northern Florida, the Ocala overlies the eroded surface of the Avon Park Limestone except at Live Oak, Suwannee County, and at Lake City, Columbia County, where the Avon Park is absent and the Ocala rests on the nonfossiliferous lower unit of the late middle Eocene. In Duval and Clay Counties, the Ocala rests on the basal part of the Avon Park. In western Florida where late middle Eocene formations are absent the Ocala apparently lies on deposits of early middle Eocene age.

In the Florida peninsula it is usually possible to separate the Ocala into an upper and a lower member. The upper member is the typical limestone exposed at the surface on the Ocala uplift. It is a soft white chalky permeable limestone consisting chiefly of large foraminifers. The basal beds may contain a few beds of secondary dolomite as much as 12 feet thick. The youngest part of the upper member has been removed by erosion in the area of outcrop. The maximum thickness reported for the upper member is 380 feet.

The lower member of the Ocala, the equivalent of the Inglis and Williston Formations of the Florida Geological Survey, is generally harder than the upper member and is commonly very calcitic. The Inglis is 50 feet thick near Inglis in Levy County. The maximum thickness may be more than 100 feet. The base is generally marked by a barnacle bed and rubble of pebbles, concretions, and soil eroded from the underlying Avon Park Limestone. The Williston is about 30 feet thick and conformably overlies the Inglis. Silicified limestone is common in outcrops and generally is near the contact with the Inglis.

In western Florida, these units of the Ocala apparently cannot be recognized. The upper and lower members are recognized in Georgia.

The Ocala Limestone is one of the major water-bearing formations of the principal artesian aquifer. Some parts of the limestone are very permeable. Solution channels formerly occupied by water but now filled with sand and clay are exposed in some of the limestone quarries in Marion County, Fla. One exposed cavern has a vertical dimension of 30 feet.

The chert and silicified limestone are relatively impervious and do not yield water to wells, but water is commonly encountered beneath these rocks.

The Flint River Formation appears to be the updip equivalent of the Suwannee and consists chiefly of siliceous limestone, residual chert, and sandy clay, representing the Oligocene in the Flint River valley in southwestern Georgia. The Cooper Marl in South Carolina and Georgia is of Oligocene age.

In southeastern Alabama, the Oligocene includes (1) the Marianna Limestone with the Red Bluff Clay at its base, (2) the Byram Formation, and (3) the Chickasawhay Limestone at the top. The Byram Formation includes the Bucatunna Clay at the top, a marl member in the middle, and the Glendon Limestone Member at the bottom. In the Florida panhandle, the Marianna Limestone is present with the Red Bluff Clay at the base. The equivalents of the Byram and Chickasawhay are not easily differentiated. However, the Bucatunna Clay has been recognized in Santa Rosa and Escambia Counties, where it separates the principal artesian aquifer into two parts.

The Oligocene Series thickens downdip to a maximum of 800 feet in the Apalachicola area, Florida. The Suwannee Limestone, one of the most extensive of the Oligocene formations, crops out in the Suwannee River valley in Florida. It is at or near the surface in the west-central part of the peninsula. It is absent in southwestern Georgia and throughout the eastern and central parts of the peninsula, as far south as Palm Beach County on the Atlantic coast. In north-central Florida it is absent from coast to coast.

The maximum thickness of the Suwannee in Georgia is about 200 feet in the south-central part near Florida. It is 300 to 350 feet thick at Tallahassee and 450 feet thick in a well at Key West.

Although the Suwannee is not as extensive as the underlying limestone of Eocene age, it is one of the major water-bearing formations of the principal artesian aquifer. The limestone contains many solution cavities which yield large quantities of water to wells. Parts of the limestone consisting chiefly of foraminifers are very permeable. The Cooper Marl in Georgia and South Carolina yields little or no water to wells. At Charleston, S.C., the permeability is so low that an unlined tunnel in the marl is used as a conduit for the public water supply.

Miocene time may be divided into three parts in the area of this report. Each part was ushered in by an expansion of the sea upon land. In Florida and Georgia, the early Miocene is represented by the Tampa Limestone, which lies on the eroded surface of Eocene limestone or on the Suwannee Limestone and Flint River Formation of Oligocene age.

In middle Miocene time, the sea may have spread out over all of Florida and covered part of Georgia, South Carolina, and Alabama. In western Florida, the Alum Bluff Group, consisting of the Chipola Formation and the overlying Shoal River Formation including the Oak Grove Sand Member, was deposited. The Hawthorn Formation was deposited in the remainder of the area covered by the middle Miocene sea.

After the Hawthorn was deposited, the sea presumably withdrew beyond the present shoreline. In late Miocene time, the sea advanced and the Duplin Marl was deposited in some areas.

The Tampa Limestone is at or near the surface in two general areas in Florida. One area, which includes the type locality near Tampa, is in Hillsborough, Pasco, and adjacent parts of Pinellas County. The other area is in the panhandle and extends westward from the Apalachicola River valley in western Gadsden and Liberty Counties to the west side of Holmes County. It extends from Florida into Georgia and South Carolina but is absent in eastern and northeastern Florida.

The thickest natural exposure of the Tampa Limestone is 117 feet on the Apalachicola River at Chattahoochee, Fla. In southern Florida, it is as much as 250 feet thick. The Tampa unconformably overlies Oligocene and Eocene limestone formations. It is overlain by the Hawthorn Formation. In some places the Tampa appears to merge upward into the overlying Hawthorn; in other places the two formations appear to be separated by an unconformity.

The Tampa generally consists of relatively impure limestone with considerable clay and sand in contrast to the Suwannee. However, in some places the Tampa also contains much pure limestone, ranging from 73 to 96 percent calcium carbonate. In some places, the limestone has been replaced by silica, which ranges from 20 to 70 percent. The Tampa is an important water-bearing formation of the principal artesian aquifer.

The Hawthorn Formation consists essentially of as much as several hundred feet of interbedded clay, sand, limestone, and sandy phosphatic limestone and marl. Lenses of fuller's earth are widely distributed in the Hawthorn. Extensive deposits in the east half of Gadsden County in western Florida have been mined many years.

The maximum thickness of the Hawthorn is about 550 feet in southeastern Florida. It is almost 500 feet thick in northeastern Florida. It is thin or absent in north-central Florida, western Florida, and other places where older Miocene or Eocene formations are exposed. Except in southeastern Florida, the top of the formation is at or near the surface. In southeastern Florida, it is overlain by more than 100 feet of younger formations, which form the productive shallow aquifer in that area.

The Hawthorn includes some permeable, water-bearing beds of sand, limestone, and marl, above and below which are less permeable beds. In some localities the water-bearing limestone contains solution channels that yield water to wells and springs. In general the lower part of the formation yields the most water, but usually wells supplied by water from the Hawthorn have only moderate yields. Where large supplies are required, the wells are drilled into the underlying limestone. With adequate development, however, relatively large supplies of water can be obtained from the formation. Much of the water is under artesian pressure, and the pressure in the lower part of the formation is comparable with that in the underlying limestone of the principal artesian aquifer. Under these conditions, the lower part of the Hawthorn constitutes the top of the principal artesian aquifer. The relatively impervious clay and marl beds in the formation prevent or retard upward movement of artesian water.

The Tamiami Formation, now assigned to late Miocene age and consisting of limestone, sand, and marl in the Miami area, Florida, was formerly regarded as Pliocene in age. It is as much as 150 feet thick in southern Florida. Permeable limestone in the upper part forms the lower part of the very productive shallow aquifer, which ranges in age from the late Miocene to Recent.

The Duplin Marl of late Miocene age in South Carolina locally yields small supplies of hard water. The Alachua and Bone Valley Formations, considered Pliocene by the U.S. Geological Survey, in west-central Florida appear to range from Miocene to Pliocene. Both formations are at or near the surface and contain phosphate deposits. The Alachua contains the valuable hard rock phosphate deposits of Florida. The Bone Valley Formation is the source of the pebble phosphate deposits of Florida. The Alachua is as much as 75 to 100 feet thick and overlies an irregular, eroded surface of the Ocala and older Eocene limestone, on which are residual pieces of Suwannee Limestone. This solution-pitted erosion surface was probably formed before the Hawthorn and Alachua Formations were deposited. The Bone Valley Formation, with a maximum thickness of about 50 feet, was apparently deposited in a broad delta of a stream that flowed southward into the ocean. Some parts of the formation may be from the Hawthorn, weathering in place. Although these formations contain permeable sands which probably would yield water to wells, they are not known to be important aquifers.

In the present report, the Caloosahatchee Marl, Charlton Formation, Waccamaw Formation, and Citronelle Formation are included in the Pliocene. These formations, except the Citronelle, include shell marl and limestones and occur as surficial formations. The Citronelle consists chiefly of brown or orange sand, gravel, and clay on the uplands but extends under the highest and oldest Pleistocene terrace. The Caloosahatchee occurs in southeastern Florida where the maximum thickness is probably about 50 feet. The Charlton is in northeastern Florida and adjacent parts of Georgia. The Waccamaw Formation is in South Carolina, with a maximum thickness of 40 feet.

All these formations will yield water to wells. The mineral content and hardness of the water from the Citronelle generally is low. Water from the formations which contain limestone and marl is hard.

Pleistocene and Recent surficial sands cover most of the area. Shorelines of marine terraces up to 270 feet above sea level have been recognized. Locally the sand is the source of shallow water supplies. Among the largest supplies from the shallow sands is the public supply for Pensacola, Fla.

The Fort Thompson Formation, Miami Ooolite, Key Largo Limestone, Anastasia Formation, and Lake Flirt Marl consist chiefly of limestone, marl, and coquina. All are present only in southeastern Florida, except the Anastasia Formation, which extends along the east coast from Anastasia Island, St. Johns County, to the south boundary of Broward County, where it merges with the Miami Oolite. It extends westward into the Lake Okeechobee-Everglades area where it forms the marine members of the Fort Thompson Formation. The Anastasia Formation, which is chiefly coquina, and the Miami Oolite, which is oolitic limestone, form the Atlantic Coastal Ridge where both formations reach the maximum thickness. The maximum thickness of the Anastasia may exceed 100 feet. The thickness of the Miami Oolite may be as much as 40 feet. It is crossbedded to massive with many vertical and horizontal solution channels filled with permeable quartz sand. It yields large quantities of water to wells and forms the upper part of the shallow aquifer which is the municipal source of water of the Miami area and other parts of southeastern Florida. The Fort Thompson Formation consists of only about 6 feet of alternating fresh-water, marine, and brackish-water marls, limestone and shell beds, and sand at Fort Thompson, its type locality, near La Belle, west of Lake Okeechobee. It underlies all of the Everglades and extends to the coast. In the Miami area, it has an average thickness of about 80 feet. It has vertical and horizontal solution channels like the overlying Miami Oolite. Most of the channels are filled with permeable sands. The Fort Thompson is one of the principal sources of fresh ground water in southeastern Florida.

The Key Largo Limestone is chiefly a fossil coral reef which interfingers with the Miami Oolite and the Fort Thompson Formation in the Miami area. It underlies the Florida Keys. The Key Largo Limestone is very permeable but is exposed to sea water. Locally small supplies of fresh water floating on the salt water may be obtained from the formation.

The Pleistocene terraces from sea level to 270 feet above sea level consist chiefly of sands which are a good source of water for shallow wells in many areas. Seven marine shorelines from 25 to 270 feet above sea level are recognized. These are approximately parallel to the present coastline and extend up the valleys of some of the streams. A shoreline about 5 to 8 feet above sea level, formerly assigned to Recent time, is now assigned to the Pleistocene.

The Pleistocene shorelines may be divided into four groups, three of which formed during three interglacial stages and the fourth in a recession in the Wisconsin Glaciation. The first group consists of the Hazlehurst, the highest and oldest of the Pleistocene shorelines, which was formed at an altitude of about 270 feet during the Aftonian Interglaciation following the Nebraskan Glaciation. The sea then declined to a level below its present level during the Kansan Glaciation. The second group consists of the Coharie at an altitude of about 215 feet, the Sunderland at about 170 feet, Okefenokee at 150 feet, Wicomico at 100 feet, Penholoway at 70 feet, and Talbot at 42 feet. These formed after the Kansan Glaciation and during the Yarmouth Interglaciation, when the sea rose to about 215 feet above the present level and then declined. The sea halted at the 170-foot level and lower levels as it declined. During Illinoian Glaciation, emergence continued with the accumulation of continental ice.

At the close of the Illinoian Glaciation, the sea rose to 25 feet above its present level during the Sangamon Interglaciation when the Pamlico shoreline was formed. At the end of the Sangamon Interglaciation, the sea retreated below its present level and then rose about 6 feet above its present level in middle Wisconsin time at which time the Silver Bluff terrace was formed.

These advances and retreats of the sea had a significant effect on the solution of the limestone and the permeability of the Tertiary limestone. The salinity of the water also was affected in some coastal areas.

GEOLOGIC STRUCTURE

The formations dip in general toward the coasts except for broad gentle anticlines and basins including the (1) peninsular arch, (2) Ocala uplift, (3) Chattahoochee anticline, (4) Apalachicola embayment, (5) southwestern Georgia embayment, (6) southeastern Georgia embayment, and (7) the southern Florida embayment.

The peninsular arch, a dominant structural feature, forms the axis of the Florida peninsula from southern Georgia to the vicinity of Lake Okeechobee. Its crest of Paleozoic sedimentary rocks is about 60 miles west of Jacksonville. The crest was above sea level in Early Cretaceous and part of Late Cretaceous time, but sediments were deposited around it. During the remainder of Late Cretaceous and early Tertiary time, sedimentation was continuous with the exception of intervals of general emergence, as for example, at the end of the Cretaceous.

The Ocala uplift was formed in Tertiary sediments as a gentle flexure approximately 230 miles long and 70 miles wide where exposed in the peninsula. During Miocene time, the northern part of the peninsula was affected by the Ocala uplift in Levy and Citrus Counties. The crest of the structure is as much as 150 feet above sea level southwest of the crest of the peninsular arch. The uplift resulted in the complete removal of Oligocene rock and the irregular erosion of the late Eocene rocks over a broad arch. On the east flank of the uplift, an arch extends to the coast at New Smyrna.

Vernon (1951) showed that the north side of the uplift is composed of two shallow folds which converge southward in Levy and Citrus Counties, where they are separated by only a few miles and their crests are extensively fractured and faulted. On the southeast flank, one of the folds merges with a wedge-shaped block (Kissimmee faulted structure) approximately 90 miles long. It is 54 miles wide on the northwest border and 17 miles wide on the southeast margin. It is bounded by faults except on the northwest side. The fault on the southeast side forms the northwest boundary of a triangular block, the Osceola low in Osceola County. This faulted structure crosses the New Smyrna arch. East of the Kissimmee faulted flexure in Seminole and Volusia Counties, Vernon mapped a relatively high area of the arch as the Seminole high.

A regional pattern of joints or fractures consists of two systems—one trending northwest-southeast, parallel to the axis of the Ocala uplift, and the other, northeast-southwest. The two systems form approximately a rectangular pattern as shown by Vernon. In addition to the regional pattern there are local joint patterns such as those in Union County, Fla., over the crest of the peninsular arch and the Osceola low. The pattern in Union County is radial, resembling the fracturing over structural domes. The pattern in Osceola County is similar to that on the Ocala uplift, but the northwest trend is more westerly than on the uplift.

The jointing and fracturing on the Ocala uplift appear to reflect structural movement during late Tertiary. The patterns in Union and Osceola Counties may reflect adjustment of relatively unconsolidated sediments over stable pre-Mesozoic rock.

SOLUTION IN LIMESTONE

The water-bearing capacity of carbonate and associated rocks depends in part on the original permeability of the formation and on the secondary permeability which is formed by fracturing, solution, and other processes after the beds have been formed. The permeability due to solution of limestone, dolomite, anhydrite, and gypsum accounts for much of the large yield of the Tertiary and Quaternary limestone aquifers.

Solution cavities are numerous in the aquifer and also are reported to occur in the older Eocene and Cretaceous formations. The record of a well in Monroe County, Fla., shows a cavity 18 feet high between 2,846 and 2,864 feet; one 4 feet high between 2,959 and 2,963 feet; and one 11 feet high between 2,986 and 2,997. Among the deeper cavities reported is one 40 feet high at a depth of 6,100 feet in Collier County. Also, an oil-producing horizon at depths of 11,613 to 11,262 feet in the Sunniland field in Collier County is cavernous limestone (Hughes, 1944, p. 75). These cavities at great depths were developed when the formations were nearer to the surface where water could enter the aquifer and discharge from it. The water in the deep cavities is essentially static without discharge. The discharge at submarine outcrops is controlled by the relation of the fresh-water head and the back pressure from the salt water.

After deposition in the sea, most of the water-bearing formations of the principal artesian aquifer were exposed above sea level, and solution cavities formed in the limestone and other carbonate rocks before they were covered by the sea and by a younger formation. Many solution cavities were filled by the overlying formations. The cavities filled with Pleistocene and Recent deposits formed since the deposition of the Citronelle Formation, which is regarded as Pliocene in the present report.

Although sinkholes are formed and solution cavities may be enlarged above the water table, a cavity in the zone of saturation near the water table is enlarged continuously by water, and the opportunity for solution in this zone is therefore greater than that in the zone of aeration. Solution channels in caves show that most of the solution has occurred in the zone of saturation. Solution which forms vertical pipes, natural wells, and similar features occurs chiefly in the zone of aeration.

Most of the cavities penetrated by wells in the principal artesian aquifer at different depths seem to be in zones which correlate with levels at which the sea paused in its declines and rises in Pleistocene time. The principal artesian aquifer probably has caves and solution channels comparable in size and extent to those in Mammoth Cave, Ky. However, only the caves near the land surface, as in Marianna State Park in western Florida, are above the zone of saturation at the present time. In general, the solution cavities and channels are developed by vertical and lateral circulation of water. The vertical pipes and natural wells and similar features are formed by downward movement of water, chiefly in the zone of aeration. The horizontal cavities and channels are formed in the zone of saturation.

Sinkholes generally are caused by solution and by collapse of the roofs of underground channels and caverns. Sinkhole topography, also known as karst topography, has formed chiefly in areas where the limestone is at or near the surface. As the Hawthorn Formation was removed by erosion in Florida and Georgia, more and more surface drainage went underground into solution channels. Sinkholes formed in the Hawthorn and in the underlying limestone as the Hawthorn was eroded. The removal of the Hawthorn progressed from parts of the coastline and from streams which cut into the underlying limestone. The escarpment formed by the more resistant beds of the Hawthorn retreated from the coast and from some of the streams. For example, in Leon, Wakulla, and Jefferson Counties, in Florida, an escarpment which is now at the edge of the Tallahassee Hills retreated northward from the coast to its present position, while surface erosion and underground solution removed the Hawthorn and part of the underlying limestone. In southwestern Georgia, the Flint River cut through the Hawthorn into the underlying Ocala Limestone. The escarpment formed by resistant beds of the Hawthorn retreated to the southeast to its present position.

Where the Hawthorn was removed in Florida and Georgia, karst topography similar to that on the Pennyroyal Plateau of Kentucky developed. However the area was modified by invasions of the Pleistocene sea. The submarine conditions probably were similar to those at the present time in the submerged karst topography in the Gulf of Mexico west of the coast of Florida from Pinellas County to Wakulla County.

Sinkholes are being formed at the present time in areas where (1) the limestone is near the surface, (2) the water level in the limestone is near the surface, and (3) the material overlying the limestone is too weak to prevent collapse into the underground streams. Sinks are not known to form in areas of artesian flow because the limestone is overlain by relatively impervious beds thick enough to prevent collapse into underground cavities. The water in the cavities is under artesian pressure which gives some support to the roof of the cavity.

Lake basins due to solution of limestone are chiefly in areas where the limestone is at or near the surface. However, in the upland ridge section of southern Florida, as in Polk and Highlands Counties, sinkholes which later became lake basins formed in areas where the limestone is as much as several hundred feet below the land surface. The basins range from a few feet to several miles in diameter. The depths range from a few feet to more than 200 feet. The deepest lakes recorded have a diameter of 600 feet or less.

Although the direction of artesian water may be controlled over considerable distances by geologic structure and although the movement may be parallel to the dip of the formations, the relative positions of the recharge and discharge areas are generally more important than the geologic structure in controlling the direction of movement of the water. In many parts of the Coastal Plain, the artesian aquifer is exposed at the surface, and it dips toward the coast beneath relatively impervious beds which prevent upward movement of the water. In these areas, the gradient of the artesian water is generally parallel to the dip. However, where there is no discharge area downdip, the water will move in the direction of the nearest discharge area, which may not be in the same direction as the dip. A comparison of the direction of movement of the water in Polk County with the structure of the aquifer shows that the water moves laterally in all directions from the recharge area without being affected by the structure of the limestone.

Joints or fractures and bedding planes may have a pronounced effect on the patterns of movement of water in limestone and other carbonate rocks. Most of the vertical pipes or natural wells, also known as vertical shafts, apparently form at the intersection of two sets of joints. Long narrow vertical openings develop along joint planes. Lateral movement of the water may be along bedding planes locally but the movement does not appear to be affected by the regional structure.

Faults may affect both vertical and lateral movement of the water in some areas, such as the Balcones fault zone in the Coastal Plain in Texas. Major and minor faults are recognized in Florida, but the faulting occurred prior to the development, in Pleistocene time, of solution in the limestone. The faults therefore appear to have little or no effect on the movement of the water and the quality of the water. Some shallow local faulting occurs in areas where solution of the limestone has caused a collapse of the overlying material. However, these structures have little or no effect on the lateral movement of the water.

ARTESIAN AQUIFERS

Artesian aquifers in the Tertiary limestone of the Southeastern States consist of many local aquifers and one principal aquifer. The principal aquifer underlies Florida, southern Georgia, and adjacent parts of South Carolina and Alabama. Most of the local artesian aquifers consist of sand and limestone in the Hawthorn Formation. In some places sand and other permeable material overlying the Hawthorn contain water under artesian pressure. These shallow artesian aquifers generally do not yield large quantities of water. Where large supplies are required, wells are drilled into the underlying principal artesian aquifer, except in areas where the deep artesian water is too highly mineralized to be satisfactory for use.

The most productive shallow aquifer in the area of this report is in southeastern Florida, where the aquifer extends from the surface to a depth of more than 100 feet in the Miami area. It consists chiefly of cavernous sandy limestone and calcareous sandstone, ranging in age from late Miocene to Recent. Most of the cavities are filled with permeable sand. The transmissibility of the shallow aquifer in the Miami area ranges from 4 to 15 mgd per ft. If there were a thickness of 100 feet, the average permeability would range from 40,000 to 150,000 gpd per sq ft. Wells 18 inches in diameter yield as much as 5 mgd, with a drawdown of 2 to 3 feet.

The principal artesian aquifer, which is the source of practically all the artesian water in Florida and southeastern Georgia, consists chiefly of limestone ranging from middle Eocene to middle Miocene in age. It is as much as 1,500 feet thick. In Florida, the top of the aquifer ranges in altitude from more than 100 feet above sea level on the Ocala uplift and the Chattahoochee anticline to as much as 1,000 feet below sea level in southeastern Florida. The maximum altitude of the aquifer is as much as 300 feet above sea level in the belt where it crops out in Georgia, South Carolina, and Alabama. The aquifer includes the following formations or equivalents, from bottom to top: Lake City, Tallahassee, and Avon Park Limestones of middle Eocene age, Ocala Limestone of late Eocene age, Marianna Limestone, Suwannee Limestone, and Flint River Formation of Oligocene age, and the Tampa Limestone and the lower part of the Hawthorn Formation of Miocene age.

In southwestern Georgia and southeastern Alabama, where the Tertiary limestone formations merge into sandy formations, some act as separate aquifers. These have been designated in Georgia as Paleocene and Eocene limestone-sand aquifers.

In Florida, the principal artesian aquifer is also called the Floridan aquifer. In the present report it is designated as the principal artesian aquifer because it is the principal aquifer in a large part of Florida and southeastern Georgia. In South Carolina and parts of Georgia and Alabama, where the Tertiary formations are thin or absent, the principal aquifers may be sands of Cretaceous age. In southeastern and western Florida and other areas where water in the principal artesian aquifer is too highly mineralized to be satisfactory for most uses, shallow aquifers are the principal source of ground water.

As a hydrologic unit, the principal artesian aquifer is unusual in its great thickness and areal extent. It is the source of the large limestone springs in Florida and Georgia. Silver Springs, in the north-central part of Florida near Ocala, is one of the largest, if not the largest, limestone spring in the world. The aquifer yields water to thousands of artesian wells, which are the source of some of the largest ground-water supplies in the country.

Parts of the aquifer consist chiefly of soft masses of foraminifers or coquina that is very permeable. Part of the Ocala Limestone is chalky without bedding planes. Some of the formations are bedded. Many formations contain dolomite, dolomitic limestone, anhydrite, and gypsum. Apparently, all the formations have two intersecting joint systems. Solution of the limestone along these joints, fractures, and bedding planes forms channels and cavities which account for the very large water-bearing capacity of the aquifer. In general, the cavities are largest and most numerous where the aquifer is near the surface, as on the crest of the Ocala uplift in north-central Florida and in regions where sinkholes extend to the aquifer.

The transmissibility of the aquifer differs considerably from place to place and at different depths. However, most if not all the wells yield water. In some places, as in southwestern Florida, the transmissibility decreases with depth. In others, as in Highlands County, Fla., the Lake City Limestone at the bottom of the aquifer is reported to be more productive than the overlying Avon Park Limestone. The greatest transmissibility of the aquifer probably is in the cavernous limestone in the areas of the large limestone springs.

The coefficient of transmissibility of the aquifer, as computed from a test on a well 26 inches in diameter and 1,200 feet deep in the vicinity of Lakeland in northwestern Polk County, Fla., is 1,000,000 gpd per ft. The average permeability estimated from that test is 1,100 gpd per sq ft, about 300 less than the highest average permeability recorded at Jacksonville, even though the aquifer appears to be more cavernous in the Lakeland area than the Jacksonville area. This difference in permeability of the aquifer in the two areas may be due in part to the fact that many of the cavities in the Lakeland area may be filled with sand and clay that entered the cavities through sinkholes. The differences in transmissibility from one area to another in the coastal area of Georgia and northwestern Florida are large enough to be revealed by the shape of the piezometric surface in areas of large withdrawal of water.

In the vicinity of Jacksonville, tests indicate that the transmissibility of the aquifer ranges from 50,000 to 1,000,000 gpd per ft. The smallest is from a well that penetrates only 250 feet of the aquifer, and the largest is from a well that penetrates 700 feet. Much of the water is from cavities in the limestone. The transmissibility from a well that penetrates 550 feet of the aquifer at Fernandina, Nassau County, Fla., is about 150,000. This gives a permeability of about 260 gpd per sq ft, which is only slightly more than the upper 250 feet of the aquifer at Jacksonville.

Tests indicate that the coefficient of storage is about 0.00025 at Fernandina and 0.017 at Jacksonville. In Georgia, tests on wells give an average transmissibility of 250,000 gpd per ft and a coefficient of storage of 0.0003 for the aquifer in the immediate vicinity of Savannah. Southwest of Savannah at Camp Stewart, near Hinesville, Liberty County, the transmissibility is 780,000 gpd per ft. Farther south, in Glynn County, the results of the tests show a range of 75,000 to 1,000,000 gpd per ft. In the St. Marys area, in Camden County near the Florida State line and the Fernandina area in Florida, the transmissibility ranges from 104,000 to 177,000 with an average of 140,000.

The rate of movement of water in open channels in the aquifer may be comparable to turbulent flow in surface streams with a similar gradient. However, throughout most of the aquifer, the movement is laminar. The velocity is proportional to the hydraulic gradient, the permeability, and effective porosity of the aquifer. Viscosity of the water also affects the flow, but generally the differences in temperature in ground water are not large enough to have a sufficient effect on the viscosity. An exception to this is an aquifer recharged by cold water from a surface stream.

Where there is a permeability of 500 gpd per sq ft and an effective porosity of 20 percent, the average velocity with which the water would move through the aquifer for each foot of hydraulic gradient would be 0.063 foot a day, or 23 feet a year. If there were a permeability of 1,500 and an effective porosity of 20 percent, the movement would be three times as fast, but only about 70 feet a year. If the effective porosity were 10 percent, the velocity would be twice as much, or 140 feet a year. If there were a hydraulic gradient of 5 feet per mile, the velocity would be five times as much, or 700 feet.

However, the gradient is less than that except in a few areas of recharge and discharge.

ARTESIAN HEAD AND WATER LEVELS

Differences in head and artesian flow at different depths may be expected in different parts of the area of this report. The head in the lower part of the Hawthorn Formation generally is the same as that in the underlying limestone of the principal artesian aquifer, but it is different from that in the middle and upper parts of the Hawthorn and overlying formations, which may yield water locally under artesian pressure. In coastal counties and the southern part of Florida, where wells in the principal artesian aquifer will overflow at the surface, the head is higher in the aquifer than in the middle and upper parts of the Hawthorn and younger formations. Although the principal artesian aquifer contains relatively impervious beds that retard vertical movement of the water locally, the head generally is the same throughout the aquifer except in recharge and discharge areas where the vertical and lateral movement of the water in the aquifer may not be in equilibrium.

In general, in recharge areas such as the one in Highlands County, Fla., the head may decrease with depth of well. In areas of artesian flow, the head may increase with depth of well, especially if the artesian pressure has been lowered in the upper part of the aquifer by withdrawal of water from wells or by natural leakage upward, as described for wells at Jacksonville, St. Augustine, and Daytona Beach.

The head in water-bearing formations below the principal artesian aquifer is generally higher than that in the aquifer. For example, a test well for oil drilled to a depth of 2,130 feet at Cherokee Hill, 21.5 feet above sea level, 7 miles northwest of Savannah, Ga., flowed salt water from a depth of 1,980 to 2,130 feet. The piezometric surface of the artesian water in the overlying aquifer was about 2 feet above sea level.

Loss of head is a normal process that invariably accompanies withdrawal of large amounts of artesian water. In a few areas, withdrawal of water has lowered artesian head to such an extent that pumps are installed on wells. The temporary loss due to pumping may be many tens of feet in a few hours. Uncontrolled flow and subsurface leakage in wells is stopped, thereby saving some of the water which formerly was lost when the wells flowed under artesian pressure. However, loss of head increases the cost of pumping and may permit mineralized water to enter the aquifer in areas where salt water is present.

Artesian head and water levels in wells fluctuate continuously. These fluctuations range from a fraction of a foot to many feet. Among the causes of these fluctuations are the following: (1) Rainfall in recharge areas such as in Marion County, Fla., where water levels in wells may rise 10 feet or more after rains, (2) surface drainage into wells, as in Orange County, Fla., where water levels may rise as much as 10 feet after periods of heavy rains, (3) fluctuations in discharge or recharge from rivers, such as the Suwannee River, which has cut its channel in the principal artesian aquifer along its course in Florida, (4) changes in atmospheric pressure and wind, (5) ocean tides and earth tides, (6) compression of aquifers by temporary loads, such as railroads trains, (7) earthquakes, and (8) natural artesian flow or pumping from wells. Withdrawal of water from wells may cause fluctuations much larger than those from other causes. However, the smaller natural fluctuations give significant information on the properties of the aquifer.

The areas in which artesian water is under sufficient pressure to rise in wells and to overflow on the ground surface include the Atlantic coastal area, southern Florida, and the gulf coast. The area of flow along the Atlantic coast extends from the Savannah area, Chatham County, Ga., to the Florida Keys. The area of flow originally covered most of Chatham County, the southern part of Effingham County, and adjacent parts of South Carolina. However, withdrawal of water from wells in the Savannah area has lowered the piezometric surface and reduced the area of flow. The withdrawal of water from wells at Fernandina, Fla., has lowered the pressure in the principal artesian aquifer and the overlying Hawthorn Formation to the extent that wells no longer flow in that vicinity either.

The area of flow extends far inland up some of the river valleys, beyond the area underlain by the principal artesian aquifer of Tertiary age, almost to the Fall Line. Artesian water between the Fall Line and the area of the Tertiary aquifer is from Cretaceous formations. The area of flow covers the southern part of Florida and extends along the Kissimmee River valley into northern Osceola County and along Peace Creek valley to the southern part of Polk County. In a few local areas, such as northern Collier County, wells do not flow. From southern Florida, the area of flow extends northward in a narrow belt along the Gulf of Mexico. Along the coast, where the aquifer is at or near the surface from Pasco County to Wakulla County, flowing wells may be expected only where the land surface is near sea level. The area of flow extends westward from Wakulla County along the coast to Alabama. It extends inland up the valleys of rivers. Wells in shallow aquifers overlying the principal artesian aquifer will flow in the valleys of Escambia and Perdido Rivers.

PIEZOMETRIC SURFACE OF WATER

Movement of the water in the principal artesian aquifer is much more widespread than the movement in the overlying formations. Water that enters the aquifer in some places may travel more than 50 miles before it leaves the aquifer through a well or spring or by upward leakage into an overlying formation.

The piezometric surface in this report has been adjusted, insofar as practicable, to represent conditions in 1961. Where there is natural fluctuation of artesian pressure, the position of the piezometric surface is changing almost constantly, and the representation at one time shows only approximately the conditions at other times. However, the major features remain essentially the same. A comparison of the map compiled in 1961 with maps made 25 years earlier shows no detectable net rise or decline of the piezometric surface except in areas of heavy withdrawal. Away from areas directly affected by changes in recharge and discharge, the fluctuations generally are less than a foot. In recharge areas the piezometric surface may fluctuate as much as 10 feet or more in accordance with seasonal changes in rainfall. In areas of heavy draft, the fluctuations may be tens of feet, many times larger than the largest natural fluctuation.

The piezometric surface is above sea level, except in a few areas such as Savannah, Ga., and Fernandina and Panama City, Fla. The highest part of the piezometric surface is about 250 feet above sea level, in a recharge area in Worth, Turner, and Wilcox Counties, Ga. This high area extends northeastward across Georgia into South Carolina and southwestward into Alabama. The piezometric surface is as much as 100 feet above sea level in the Valdosta area and in Lowndes and Brooks Counties in Georgia where there is local recharge through sinkholes and drainage wells. In recent years, withdrawal of water from wells has lowered the water level in part of the area. The gradient between the 230- and 80-foot contours in Georgia is relatively steep, as much as 15 feet per mile in comparison with a low gradient of less than a foot per mile between this area and the coast. This change from the steep gradient to the low gradient indicates an increase in permeability or thickness of the aquifer, or both.

North of Glynn County in Georgia, the water moves northeastward toward Savannah and to natural discharge areas in the ocean east and northeast of Savannah. In adjacent parts of South Carolina, it moves southeastward. At the present time, part of the water that normally would flow to the natural discharge area is withdrawn through wells in the Savannah area. This withdrawal has created a cone of depression in the piezometric surface and has reversed the direction of the movement of the water east of Savannah. Along the Atlantic coast, the piezometric surface is below sea level at present in the Savannah area of Georgia and South Carolina. It rises north and south of that area. The piezometric surface is as much as 40 feet above sea level in southeastern Georgia, even though there are areas of heavy withdrawal of water.

A comparison of the shape of the piezometric surface with the withdrawal of water in the coastal area of Georgia and northeastern Florida shows that the aquifer is more productive at Brunswick and Jacksonville than at St. Marys and Fernandina. As the thickness of the aquifer is approximately the same in these areas, the differences in productivity appear to be due to differences in the permeability of the aquifer.

In Florida the piezometric surface shows several conspicuous recharge and discharge areas. The highest parts of the surface are in the recharge areas in Polk County, Pasco County, and Putnam County areas in the peninsula and in Jackson County area in western Florida. The highest of these is as much as 120 feet above sea level in Polk County and Jackson County area. Recharge is largely through sinkholes that pass from the surface to the underlying limestone of the principal artesian aquifer. Many of these sinks are filled with permeable sands. Many depressions formed by the sinks are occupied by lakes. In all recharge areas through sinks, water moves laterally in all directions without reference to the dip of the aquifer.

Recharge occurs in the Madison County and Jackson County areas, where the aquifer is at or near the surface. Recharge occurs through sinkholes in central Washington County, south of the area where the aquifer crops out. The aquifer also is recharged in a large area where the aquifer is at or near the surface on the Ocala uplift, in the Marion County and Citrus County areas. Although recharge is large, there is also large discharge in these areas.

In the Marion County area, large quantities of water are discharged through Silver Springs and Rainbow Springs. This large discharge through springs accounts in part for the saddlelike shape of the piezometric surface 40 to 55 feet above sea level. Along the coast the piezometric surface is approximately at sea level because of the large discharge into the Gulf of Mexico.

Other places of discharge and recharge are in the Suwannee River area and Wakulla County area. Large quantities of water are discharged from the artesian aquifer to the Suwannee River during low stages of the river. The aquifer is recharged by the river during flood stages. The aquifer is recharged in a large part of the Wakulla County area, but there is large discharge at Wakulla Spring and along the coast.

The piezometric surface is near sea level in the St. Johns River valley, east of the Marion County area, where the artesian water discharges into the river. Along the east coast of the St. Johns River, where the aquifer is 100 feet or less below sea level, there is discharge through submarine springs, such as the one about 2½ miles east of Crescent Beach. Although the Hawthorn Formation is as much as 50 feet thick, the artesian water discharges through sinkholes in the Hawthorn.

In southern Florida the piezometric surface south of the Polk County area is relatively flat, sloping from about 50 feet above sea level in the northern part to only a few feet below sea level on the Florida Keys. Some discharge occurs along the Atlantic coast where the aquifer crops out at the edge of the Continental Shelf. The amount of discharge depends in part on the relation of the artesian head to the back pressure from the salt water at the outcrop.

CHEMICAL QUALITY

The ground water in the area of this report may be divided in the following types:

1. Calcium bicarbonate water whose hardness ranges from about 50 to several hundred parts per million. Most of the artesian water is of this type except in southern Florida and some of the coastal areas where the fresh artesian water is mixed with remnants of sea water that has not been flushed from the aquifer. The hardness of the salt water is much higher than that of the fresh artesian water.
2. Calcium sulfate water whose hardness is as much as 900 ppm as reported in Manatee County. This type occurs only locally where the aquifer contains anhydrite or gypsum.
3. Sodium bicarbonate water whose hardness is less than 50 ppm but whose total dissolved solids is relatively high. This type of water occurs in the principal artesian aquifer in western Florida and adjacent parts of Alabama and Georgia, where the limestone grades into sands, clay, and other clastics. The water is softened naturally as it moves through the aquifer, exchanging calcium for sodium.
4. Sodium chloride water, which is a mixture of fresh ground water with salt water. This type of water occurs in some parts of the coastal areas and in the southern part of Florida. In a few places in the interior, salt water has been found in formations underlying the principal aquifer.
5. Water in shallow surficial sands whose total dissolved solids is less than 50 ppm. The public supply of Pensacola and other supplies in Escambia County, Fla., are of this type.

The amount of silica reported in the ground water of this region ranges from about 2 to 63 ppm. In general, it is less than 10 ppm in water in surficial aquifers and some recharge areas. Some formations are more siliceous than others. However, the available information does not indicate whether the siliceous rocks yield water of a high silica content. The silica content of the water appears to correlate in a general way with the alkalinity and pH of the water and the length of time in the water-bearing formation.

Iron, generally as ferrous bicarbonate, is objectionable in water in amounts of more than 0.3 ppm because it gives the water an unpleasant taste and stains plumbing fixtures. Iron as bicarbonate may be removed simply by aeration. Iron in small amounts, generally not exceeding a few parts per million, is present in some places in water in shallow surficial sands. However, iron is absent or present only in trace amounts in water of the principal artesian aquifer and the limestone overlying the aquifer. The iron content of samples from four of the largest springs that received water from the principal artesian aquifer ranged from 0.04 to 0.15 ppm.

In most of the area of this report, water having a low chloride content had a calcium content of less than 50 ppm and a magnesium content of less than 25 ppm. In the soft sodium bicarbonate water in western Florida, the calcium content was as low as 4.4 ppm and the magnesium, 3.5 ppm. Calcium is high in comparison with magnesium, where the aquifer consists chiefly of pure limestone, as at

Cross City in Dixie County, Fla., where the calcium ranged from 81 to 120 ppm and the magnesium ranged from 4.5 to 6.8 ppm. The sulfate ranged from 1.6 to 4.5 ppm.

The maximum calcium content is in the calcium sulfate water. One sample from the aquifer from a well in Manatee County in southwestern Florida had a calcium content of 352 ppm. The magnesium content was 8.5 ppm, the sulfate was 650 ppm, and the chloride was 50 ppm.

The concentration of magnesium is as little as one-tenth to one-twentieth of that of calcium in the artesian water that is not mixed with sea water. Where mixed with sea water, the ground water may contain more magnesium than calcium; however, in some areas the aquifer contains anhydrite or gypsum, which gives water a relatively high calcium sulfate content, as in Sarasota County in southwestern Florida. In some areas such as Martin County, Fla., where the artesian water is mixed with remnants of sea water, the magnesium content is about as high as that of calcium. Generally, in areas where the ground water is not mixed with sea water, the total sodium and potassium ranges from a few parts per million to 40 ppm. Many samples are less than 10 ppm. However, where mixed with sea water or other salt water in the water-bearing formations, the amounts of sodium and potassium may be as much as that of sea water.

Bicarbonate in samples of water from the principal artesian aquifer ranged from 50 to about 350 ppm. The bicarbonate in samples of ground water in the shallow aquifer in some parts of the Everglades is as much as 1,000 ppm.

Sulfate is dissolved in large quantities from gypsum or anhydrite in some water-bearing formations. Some of it is from sea water or salt in the aquifer. Sulfate in the water in the principal artesian aquifer ranges from a trace to as much as 1,000 ppm. However, in much of the area of this report the sulfate is less than 10 ppm. The sulfate generally is highest in the southeastern part of Georgia, the northeastern part of Florida, the Atlantic coastal area, southern Florida, and the gulf coastal areas from the Florida Keys to Tampa Bay.

Chloride is present in large quantities in ground water mixed with sea water. Outside the coastal areas and the southern part of Florida, the chloride content is generally less than 50 ppm in the principal artesian aquifer, except in some deep wells that may reach water having a relatively high chloride content. In some recharge areas, the chloride content is less than 10 ppm. Generally, below depths of 2,000 feet salt water may be expected.

Fluoride is present in small quantities in some of the ground water in the Southeastern States. Water having fluoride in concentrations in excess of 1.5 ppm may cause mottling of the enamel of children's teeth during calcification. However, a fluoride content of 0.7 to 1.5 ppm in public water supplies is reported to result in a 50 to 65 percent reduction in dental caries among children.

Water samples from the Hawthorn Formation almost invariably contained small amounts of fluoride, generally more than 1 ppm. In a few samples, fluoride was as much as 2.5 ppm. Apparently, water in the principal artesian aquifer has little or no fluoride except in areas where (1) the lower part of the Hawthorn Formation has phosphatic material in the upper part of the aquifer and (2) in western Florida, southeastern Alabama, and southwestern Georgia where the aquifer grades laterally into sands and clays, which yield soft sodium bicarbonate water having a fluoride content of as much as 6.5 ppm. Fluoride in the Hawthorn is associated with the phosphatic material. Volcanic ash, bentonitic material, and glauconite appear to be the source of the fluoride in some water-bearing sands in the Coastal Plain.

The hardness of ground water in the Coastal Plain in the Southeastern States, including that of the principal artesian aquifer, generally ranges from 5 to 1,000 ppm. Generally, the softest water in the principal artesian aquifer is in recharge areas, and the hardest water is some distance from recharge areas. An exception is in Okaloosa, Santa Rosa, and Escambia Counties, Fla., where natural softening has removed the hardness by exchange of calcium for sodium as the water moves through the aquifer. In a recharge area such as Clay County, the hardness of samples of water from the principal aquifer ranged from 60 to 100 ppm. Northeast of that recharge area at Jacksonville in Duval County, Fla., the hardness ranged from 200 to 300 ppm. In a recharge area in Highlands County in central Florida, the hardness of the water from the principal artesian aquifer was less than 70 ppm. In Sarasota County southwest of that recharge area, the hardness was as much as 1,000 ppm. However, part of the hardness is due to the presence of anhydrite and gypsum in the aquifer.

In the principal artesian aquifer, the hydrogen sulfide ranged from 0 to more than 4.0 ppm. As little as 1 ppm of the gas will give the water a noticeable sulfur odor. Part of the gas is eliminated, and the remainder is rapidly oxidized by dissolved oxygen that is absorbed upon aeration.

The pH of the water from the principal artesian aquifer ranges from 7 to 8.75.

Organic color is present in much of the surface water in swamps, the Everglades, and some streams. Shallow aquifers in the Everglades contain colored water. There is little or no noticeable color in most of the water in the principal artesian aquifer although it receives surface-water recharge through sinkholes. Most of the large springs are clear where they flow from the principal artesian aquifer. Silver Springs and Rainbow Springs, two of the largest, are always clear. Water having noticeable color enters Wakulla Spring through sinks after rains.

Water from the principal artesian aquifer and the overlying formations is satisfactory for irrigation, except where fresh artesian water is mixed with salt water.

Three radioactive elements—tritium, uranium, and radium—were included in the analyses of a few samples of water. Tritium, or hydrogen-3, having a half-life of 12½ years, is the only known radioactive isotope of hydrogen found in nature. It occurs naturally in water and in fallout from nuclear tests and nuclear reactors. Analyses have been made on the tritium content of water in the principal artesian aquifer to determine the relative age and rate of movement of the water. The quantity of tritium occurring naturally is so small that its presence has no effect on the use of the water.

A few analyses show that small quantities of uranium and radium are present in the principal artesian aquifer in some areas. As uranium is present in small quantities in some of the phosphatic material in the Hawthorn and some of the younger formations in Florida, it seems likely that phosphatic material may be the source of the uranium in the artesian water. Natural uranium in water is not known to have a harmful effect. However, radium that results from radioactive disintegration of radium and thorium may occur in harmful amounts. The maximum permissible concentration of radium for general use has been set by the U.S. Public Health Service at 3.3 $\mu\mu$c per l. One sample from Martin County, Fla., had 11 $\mu\mu$c Ra per l. Further studies are needed to determine the source and extent of the radium in artesian water in that part of Florida.

TEMPERATURE OF ARTESIAN WATER

The temperature of ground water at a depth of about 30 to 60 feet will generally exceed by 2° to 3°F the mean annual air temperature. At a depth of 20 feet, the temperature of ground water may range 10°F above or below the mean annual temperature of the air. The temperature of ground water increases with depth. The rate of increase differs considerably from one area to another because of hydrologic conditions. The temperature of artesian water in the principal artesian aquifer, as measured at the mouths of wells, ranged from about 62°F in South Carolina to 91°F in Martin County in southern Florida. The highest temperature recorded for the artesian water in the Cretaceous aquifers underlying the principal artesian aquifer of Tertiary age was 103° to 109°F at depths from 2,610 to 3,450 feet in a well at Parris Island, S.C. Most of the measurements of the temperature of water from the large surface springs ranged from 69°F in northern Florida and southern Georgia to about 70° to 74°F in central Florida. Thermal gradient, as indicated by the temperature of water from wells of different depths in the principal artesian aquifer, ranged from a maximum of 1°F for each 55 feet of depth to 1°F for each 140 feet of depth. Both of these ranges are from wells in Martin County in southern Florida. Some of the differences may be due to the fact that wells were not cased below the top of the aquifer. Water may enter the wells at various depths.

SALT WATER IN AQUIFERS

Salt water in the fresh-water aquifers may be from (1) encroachment of sea water in coastal areas, (2) connate water and sea water which entered the aquifer during a high stand of the sea in Pleistocene time, (3) salt as thin beds or disseminated in the geologic formations, and (4) sea water which became more concentrated by evaporation in tidal lagoons or other enclosed areas which received sea water during storms. There is no evidence of shallow salt domes or upward movement of salty water from the deep formations underlying the principal artesian aquifer.

In coastal areas where the aquifer is exposed to sea water, salt water will move into the aquifer if there is not a sufficient fresh-water head. Such encroachment has occurred in the principal aquifer in only a few of the coastal areas. Although the artesian aquifer is exposed to the sea in some places at the edge of the Continental Shelf in the Atlantic Ocean and the floor of the Gulf of Mexico, in a large area along the coast from Pasco County to Wakulla County, the artesian head generally is sufficient to prevent salt-water encroachment into the aquifer.

Water with a relatively high chloride content is present in the artesian aquifer in the coastal areas of Florida, south of St. Augustine and in southern Florida. It includes part of the St. Johns River valley. From southern Florida it extends along the west coast to Tampa Bay. Also, it is present along the coast in western Florida. This water having relatively high chloride content appears to be chiefly from sea water which has not been flushed from the aquifer. Some of it is connate water, and some of it entered the aquifer during Pleistocene time.

SPRINGS

The principal artesian aquifer is the source of many large springs, including 17 first-magnitude springs which have an average flow of 100 cfs or more. All these are in Florida. Silver Springs and Rainbow Springs in Marion County are the largest, having a combined maximum flow of more than 2,310 cfs. Radium Springs, formerly known as Blue Springs, near Albany, with a yield ranging from less than 18 to 135 cfs, is the largest in Georgia. The largest known submarine spring from the aquifer is about 2½ miles east of Crescent Beach, Fla. Many springs are along the Suwannee River and its tributaries in Florida. All the large springs are artesian and are chiefly where the aquifer is at or near the surface. Many of them appear to rise through sinkholes. The low tritium content of water from Silver Springs and from Radium Springs indicates that the water travels long distances and is a mixture of young and old water. Chemical analyses of samples from several springs indicate that the springs represent three of the four types of water present in the artesian aquifer. No spring yields soft sodium bicarbonate water, such as that from deep wells in the aquifer in western Florida. Most of the springs have water of the calcium bicarbonate type, a few of the springs yield water with a high chloride content, and a few yield soft water with a low mineral content.

Most of the measurements of the approximate temperature of the water from the springs range from 69°F in northern Florida and southern Georgia to 70° to 74°F in central Florida.

WELLS

Thousands of wells, both flowing and nonflowing, have been drilled into the principal artesian aquifer. Most of the wells in limestone are cased to the first hard rock or to the top of the aquifer. Some wells, as much as 1,000 feet deep, may have only about 100 feet of casing. Where the Hawthorn Formation is present, the casing generally is set in the lower part of that formation. Where there are differences in head at different depths in the aquifer, there may be leakage of water from one formation to another through wells.

The artesian wells range from about 50 to more than 1,000 feet in depth and from 2 to more than 24 inches in diameter. Many of the deeper wells may range from 6 to 12 inches in diameter. In some wells where the aquifer is near the surface, as in parts of Seminole County, flowing wells may be obtained from depths less than 100 feet. The diameter of many of these wells ranges from 2 to 6 inches. Several thousand have been drilled for irrigation of celery and other truck crops in the area of artesian flow of Seminole County, Fla.

Wells in the principal artesian aquifer are finished without screens, except in western Florida, southeastern Alabama, and southwestern Georgia, where the water-bearing formations consist of sand and other unconsolidated material.

The yield of wells having natural flow ranges from a few gallons to several thousand gallons a minute. The largest yields by natural flow are in the coastal areas and southern Florida, where the artesian pressure is relatively large and the surface of the ground is relatively low. One of the largest yields was 6,500 gpm from a 12-inch well in Duval County in northeastern Florida. The largest yield reported from nonflowing wells in the principal artesian aquifer is 7,500 gpm from a well 18 inches in diameter and 852 feet deep in Polk County. One well is known to yield 833 gpm with each foot of drawdown of the water level, and the flowing wells range from a fraction of a gallon to 248 gpm for each foot of drawdown.

As most of the wells in the principal aquifer are not cased, water may move from one formation to another through the wells. Such subsurface leakage through wells has been detected in a few areas where there is a difference of head in the water-bearing formation because of local recharge or discharge.

In some areas, such as Orlando, where the water levels in wells in the principal artesian aquifer stand below the land surface, surface water is drained into the wells in cavernous limestone of the principal artesian aquifer. This drainage disposes of surface water and recharges the aquifer.

The principal artesian aquifer is the chief source of ground water for municipal, industrial, and irrigation supplies in the area of this report. Although the aquifer yields water through the large limestone springs, almost all the water used for water supply from the aquifer is from wells. Many of the springs are used for recreation. A few small springs are used for water supply. A few mineral springs are used at health resorts.

The estimated quantity of ground water used in 1960 for public supplies in Florida, chiefly from the principal artesian aquifer, was 502 mgd; the quantity for private supplies for industrial and commercial use was 657 mgd.

Large quantities are used for irrigation, especially for truck crops and citrus crops in the Florida peninsula. The average consumption for irrigation is difficult to estimate because of the differences in rainfall from one growing season to another. During dry seasons, many artesian wells are used to irrigate citrus crops in the area of artesian flow.

In Georgia, the largest quantities of artesian water are used in ten coastal counties, where the estimated annual discharge was 279 mgd. Of that amount 197 mgd was for industrial use, 31 mgd for public supply, and 21 mgd for domestic supply. About 30 mgd flowed continuously for domestic use, stock, and game preserves. A large part of that water was not used.

FUTURE STUDIES

Systematic and detailed studies of the geology and hydrology should be continued to give more information on the water-bearing properties of all the geologic formations and the perennial yield of all aquifers. Studies of the geochemistry of the water and the relation of fresh ground water to salt water should be continued. Additional information is needed on all the subjects discussed in this report.

Geologic investigations should include all geologic formations which control the yield and quality of the water of the aquifers. More information is needed on conditions under which the formations were deposited and on the changes which have affected the permeability and other water-bearing properties of these formations. A better understanding of the relation of the water-bearing formations of the principal artesian aquifer and the underlying and overlying formations is needed.

Joint systems in limestone appear to have been significant in the solution of limestone in the zone of aeration. Bedding planes, unconformities, and faults may be significant, but more information is needed to understand the effects of these features. Tests on wells penetrating the aquifer and other geologic studies on both sides of faults would aid in determining the extent to which faults affect the movement and the chemical quality of the water.

Additional studies are needed on the submarine hydrogeology. The geologic structure and places of outcrops of the geologic formations on the ocean floor and at the edge of the Continental Shelf should be understood to determine discharge areas and the relation of the fresh water to sea water in that part of the aquifer.

The solution channels and cavities, sinkholes, and lake basins appear to have formed chiefly when the sea stood above and below its present level. Further studies are needed to determine the lateral and vertical distribution of the existing solution cavities in the limestone and the extent to which they have been filled by unconsolidated material. Adequate information on the geologic history, from late Miocene time to the present, especially during Pleistocene and Pliocene time, will give much additional information on the solution of the limestone, which accounts for a large part of the capacity of some of the limestone aquifers.

The shallow aquifer overlying the principal artesian aquifer in the Miami area has been studied locally in considerable detail in southeastern Florida and also in the Pensacola and Cantonment areas in Escambia County, Fla. Shallow aquifers in other areas may also be important sources of water especially where the underlying principal artesian aquifer contains water of poor quality.

The available information on the fluctuations of sea level in Pleistocene time suggests that many sinkholes and solution channels were formed during low stands of the sea. These cavities were filled with unconsolidated sediments when the sea rose high enough to cover the area. Channels of surface streams may also have been filled and concealed by terrace deposits. If such buried channels are present, they might contain permeable water-bearing material that would be a good source of water. Buried sinkholes might form concealed recharge areas of the principal aquifer.

Studies of the shallow aquifers on the Wicomico terrace and lower terraces might reveal some of these concealed recharge areas. The recharge and discharge areas of the principal artesian aquifer are known only in a very general way. Piezometric maps of the artesian water show some of the recharge areas, but more information is needed on the quantity of recharge, especially in the lake regions where recharge occurs through sinkholes and lake basins. The extent to which artificial recharge through wells or other methods is practical should be determined.

The rate of lateral movement of the water in the principal artesian aquifer ranges from a fraction of a foot to many feet a day. More studies are needed to determine the rate of movement in different parts of the area.

Considerable information has been obtained on the geochemistry of the water, but more is needed on the occurrence and source of trace elements, as fluoride, strontium, uranium, and radium. There is evidence of natural softening of the artesian water in the principal artesian aquifer in western Florida and adjacent parts of Alabama where the limestone aquifer grades into sand and clay. Adequate information on the geology and hydrology from the recharge area to wells downgradient should reveal the minerals which cause the natural softening and also the source of the fluoride in the water. Adequate information on the occurrence of tritium in the principal artesian aquifer will aid in determining recharge, discharge, and the rate of movement of water in that aquifer.

The information on the temperature of artesian water gives a general idea of the thermal gradient of the water at different depths, but it is not sufficient to explain some results which appear to be anomalous. As the wells are not cased in the principal artesian aquifer, temperature measurements of the water should be made at different depths in the wells instead of measuring the temperature at the mouth of the well. Accurate information on the thermal gradient should show whether the differences in temperature are due to geologic structure or to some other factor.

Salt water in some of the formations may be from several sources, such as connate water, Pleistocene sea water, salt in the water-bearing formations, and salt-water encroachment from the Atlantic Ocean and Gulf of Mexico in some coastal areas. The lateral and vertical extent of the water with a relatively high chloride content is known in a general way. It is known that the contact between the fresh water and salt water in the principal artesian aquifer is some distance offshore along the coast from northeastern Florida to South Carolina. Estimates of the position may be made by assuming certain conditions for structure, distance to outcrop, salinity of water, and depth of salt water at the outcrop. However, the future potential of the fresh artesian water in these areas may depend on the exact position of the contact of the fresh water with salt water. Therefore, studies of the geology and hydrology offshore should include the relation of salt water to fresh artesian water in the aquifer.

The formations underlying the principal artesian aquifer in some areas contain salt water. The relation of salt water to the overlying fresh water is being studied in a few areas, but that relation should be studied throughout the region to determine whether the salt water would move upward into the overlying aquifer when the artesian head in that aquifer is reduced by withdrawal of water.

Although the total quantity of water withdrawn from the principal artesian aquifer is remarkable, it is only part of the billions of gallons a day discharged naturally. The discharge of the largest limestone springs indicates the large capacity of the principal artesian aquifer. The combined flow of the springs in Florida has been estimated at 3,700 mgd. The estimated consumption of ground water in 1960 in Florida, exclusive of water used for irrigation, was about 1,160 mgd. This is less than half the amount which leaves the aquifer through springs. The large use of water from the principal artesian aquifer emphasizes the fact that this water is one of the most valuable of the mineral resources of the region. The abundance of this resource, which is not fully utilized in much of the region, shows the need for continued systematic local and regional investigations of the geology and hydrology to provide information required for wise and careful planning of its development and conservation.

As stated by Leopold (1959, p. 827), wise development and management of a resource requires continuing appraisal. Adequate management requires intelligent application of data and knowledge in a framework that permits flexibility of action.

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