STATE OF FLORIDA

STATE BOARD OF CONSERVATION

Ernest Mitts, Director

FLORIDA GEOLOGICAL SURVEY

Herman Gunter, Director

REPORT OF INVESTIGATIONS NO. 17

BISCAYNE AQUIFER OF DADE AND BROWARD COUNTIES, FLORIDA

By

Melvin C. Schroeder, Howard Klein, and Nevin D. Hoy

U. S. Geological Survey

Prepared by the

UNITED STATES GEOLOGICAL SURVEY

in cooperation with the

FLORIDA GEOLOGICAL SURVEY

CENTRAL AND SOUTHERN FLORIDA FLOOD CONTROL DISTRICT

DADE COUNTY

CITIES OF MIAMI, MIAMI BEACH and FORT LAUDERDALE

TALLAHASSEE, FLORIDA

1958

FLORIDA STATE BOARD OF CONSERVATION

LETTER OF TRANSMITTAL

Florida Geological Survey

Tallahassee

December 5, 1957

Mr. Ernest Mitts, *Director*
Florida State Board of Conservation
Tallahassee, Florida

Dear Mr. Mitts:

I am forwarding to you a report entitled, BISCAYNE AQUIFER OF DADE AND BROWARD COUNTIES, FLORIDA, which was prepared by Melvin C. Schroeder, Howard Klein, and Nevin D. Hoy, Geologists of the United States Geological Survey. The report was submitted for publication March 15, 1956, and it is recommended that it be published as Report of Investigations No. 17.

The Biscayne Aquifer is the principal source of water for the heavily populated area in the vicinity of West Palm Beach and Miami. The publication of this data is timely and will assist in the intelligent development of the water resources of the area.

Respectfully submitted,

Herman Gunter, *Director*

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BISCAYNE AQUIFER OF DADE AND BROWARD COUNTIES, FLORIDA

ABSTRACT

The Biscayne aquifer is the only source of fresh ground water in Dade and Broward counties, Florida. Composed of highly permeable limestone and sand mainly of Pleistocene age, the aquifer supplies large quantities of water, of excellent quality except for hardness, for municipal, industrial, and irrigational use. The aquifer attains its maximum thickness in the Atlantic coastal areas and wedges out in western Dade and Broward counties.

Water-table conditions prevail in the Biscayne aquifer, and the water table fluctuates with variations in rainfall, evapotranspiration, and pumping. High ground-water levels occur during the fall months and low levels during spring and early summer. The highest water levels of record occurred in October 1947, when intense rainfall accompanying a hurricane flooded large areas throughout the two counties. Major discharge from the aquifer occurs by natural outflow and evapotranspiration. The average daily pumpage from the Biscayne aquifer in 1950 is estimated to have been 130 million gallons.

Permeability tests show that the limestones of the Biscayne aquifer rank among the most productive aquifers ever investigated by the U. S. Geological Survey.

Salt-water encroachment in the aquifer has taken place in coastal areas of southeastern Florida. The greatest inland advance of salt-water intrusion has occurred as tongues along tidal drainage canals and rivers.

INTRODUCTION

LOCATION AND GEOGRAPHY OF AREA

Dade and Broward counties are in southeastern Florida, bordering the Atlantic Ocean (fig. 1). The Atlantic Coastal Ridge, whose average elevation is between 8 and 10 feet above mean sea level, occupies the eastern portion of the area from the coast to a few miles inland. Maximum elevations at isolated highs range from 20 to 25 feet above sea

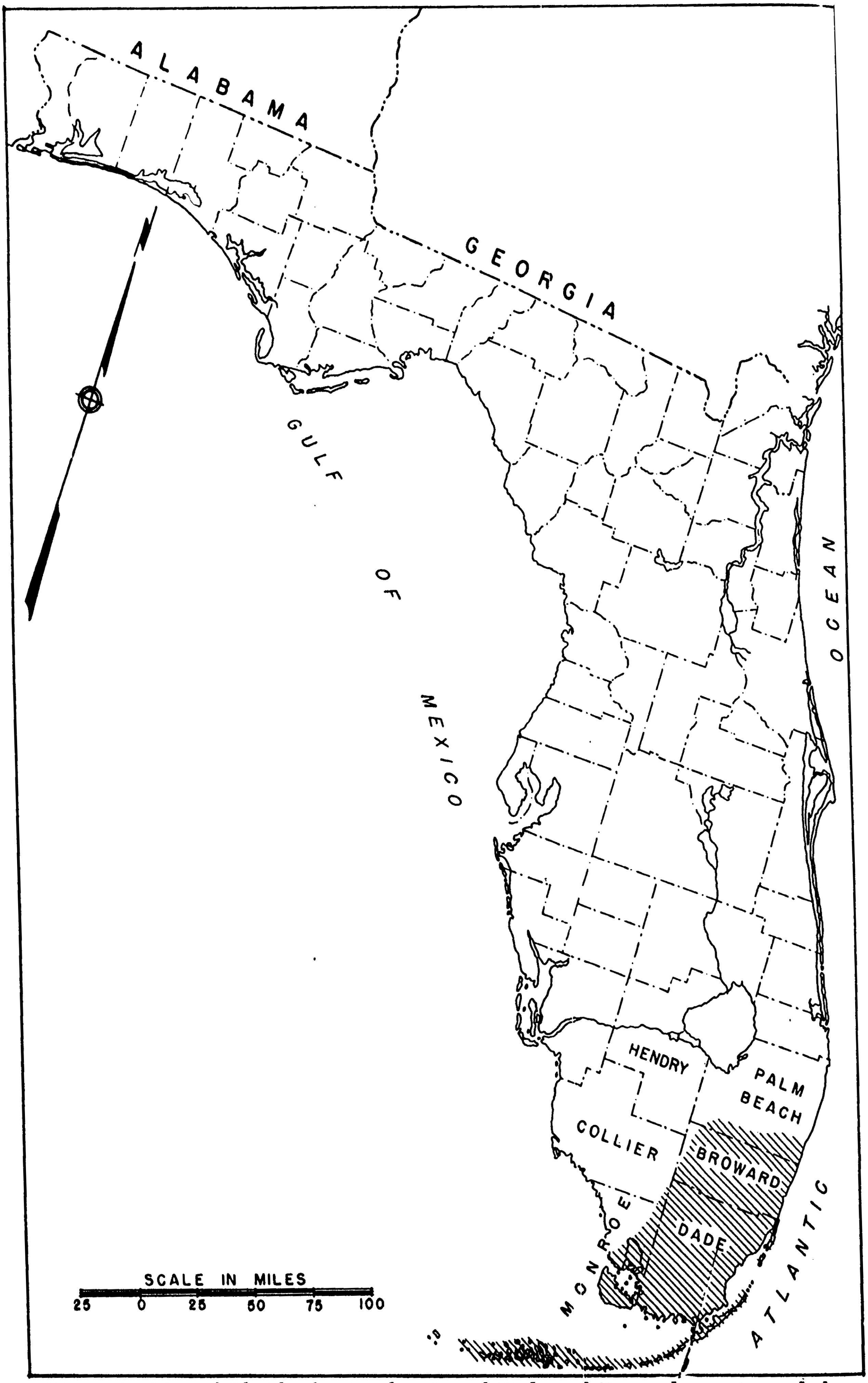

Figure 1. Map of Florida showing location of Dade and Broward counties and the approximate extent (shaded area) of the Biscayne aquifer.

level. In Dade County the ridge is composed principally of limestone, but in Broward County it is composed of both sand and limestone. Most of the population in the two counties is concentrated in the coastal and ridge areas. The Florida Everglades, and area of organic soils, lies west of the ridge and is devoted chiefly to agriculture and conservation areas. The climate is semitropical to tropical. Rainfall averages 60 inches per year, about 75 percent of the total falling in the period from May through October. The average temperature is about 75°F.

PURPOSE AND SCOPE OF INVESTIGATION

The ground-water resources of Dade and Broward counties are one of the greatest natural assets of the region. This report describes the geology and hydrologic characteristics of the Biscayne aquifer and defines its geographic distribution. The factors involved in the adequacy of the supply are discussed and an evaluation of data on fluctuations in water level is presented.

PREVIOUS INVESTIGATIONS

The surface geology in Dade and Broward counties was first investigated by Sanford (1909). Sellards (1919) added considerable data when the drainage canals were cut across the Everglades. The geologic formations in southern Florida were described by Cooke and Mossom (1929). Matson and Sanford (1913), Parker (1942), and Parker and others (1944) described the geology and occurrence of water in the water-table (Biscayne) aquifer. Parker and Cooke (1944) presented physiographic and geologic descriptions of southern Florida, with special reference to the late Cenozoic material in southeastern Florida. The major part of the aquifer was then identified as belonging to the Tamiami formation. Parker (1951) proposed the name Biscayne aquifer for the shallow materials and revised the geologic correlations of the formations in the aquifer. A report by Parker, Ferguson, Love, and others (1955) presents hydrologic data on the Biscayne aquifer in greater detail than does this report.

Data on fluctuations of water levels in wells in Dade and Broward counties have been reported in the following U. S. Geological Survey Water-Supply Papers for the years 1939-1952 inclusive: 886, 907, 937, 945, 987, 1017, 1024, 1072, 1097, 1127, 1157, 1166, 1192, and 1222. Subsequent data will be published in the water-supply papers entitled "Water Levels and Artesian Pressures in Observation Wells in the United States, Part 2, Southeastern States."

PERSONNEL AND ACKNOWLEDGMENTS

The data presented in this report cover the results of studies made by the U. S. Geological Survey in cooperation with the Florida Geological Survey, Dade County, the cities of Miami, Miami Beach, Coral Gables, and Fort Lauderdale, and the Central and Southern Florida Flood Control District. The continued interest and help of the officials of these agencies have made it possible to develop the necessary program to study the aquifer and the fluctuations of the ground-water levels.

The investigation was made under the general supervision of A. N. Sayre, Chief, Ground Water Branch, U. S. Geological Survey. V. T. Stringfield and Garald G. Parker of the U. S. Geological Survey gave valuable advice. The Corps of Engineers, U. S. Army, cooperated by permitting examination of the cores and records of a great number of core borings.

BISCAYNE AQUIFER

DEFINITION

Meinzer (1923, p. 52, 53) has defined an aquifer as a rock formation or stratum that will yield water in sufficient quantity to be of consequence as a source of supply. A formation yielding meager amounts of water might not be considered to be an aquifer in an area where there are other formations that yield prolifically but might be considered to be one in an area where little water is available.

Wherever possible, an aquifer is identified by the name or names of the stratigraphic units composing it. Where an aquifer crosses stratigraphic lines, or where its stratigraphy is uncertain, yet it is well known to constitute a hydrologic unit, an aquifer may be given a proper name. The principal aquifer in this area is such a unit.

The name Biscayne aquifer was proposed by Parker (1951, p. 820-823) for the hydrologic unit of water-bearing rocks that carries unconfined ground water in southeastern Florida. The aquifer is a single hydrologic unit of permeable materials ranging in age from late Miocene through Pleistocene. The boundaries of the aquifer, both horizontal and vertical, are set not by formational contacts or age restrictions but by differences in the hydrologic properties of the sediments. The lowermost component of the Biscayne aquifer is a limestone or shelly calcareous sandstone of the upper part of the Tamiami formation in the northeastern part of Dade County and the southeastern part of Broward County. The remaining and major portion of the Biscayne aquifer is composed of rocks ranging in age from Pliocene through Pleistocene in the following sequence from bottom to top: Caloosahatchee marl (as erosion remnants), Fort Thompson formation, Key Largo limestone, Anastasia formation, Miami oolite, and Pamlico sand. The aquifer is underlain by a relatively impermeable greenish marl of the Tamiami formation. The contact between the marl and the limestone of the Tamiami, Fort Thompson, or Anastasia formations, or the Key Largo limestone, forms the lower boundary of the aquifer.

In the Miami area the base of the Biscayne aquifer is easily determined by the occurrence of the impervious marl of the Tamiami formation. However, it is more difficult to define the basal or lateral limits in Broward County where clastic sediments rather than limestones constitute a major part of the Pleistocene sequence. The interfingering and the vertical and horizontal gradation of sands and calcareous materials present a problem similar to determining the demarcation between two different lithologic facies of the same geologic time unit. In an aquifer the ground water should be free to move in any direction, under the proper hydraulic gradient. In northwesternmost Broward County (fig. 1) the water in sands whose elevation and stratigraphic position are similar to those in the Biscayne aquifer to the southeast apparently does not move freely, as shown by its high mineralization. These sands, therefore, are not considered a part of the Biscayne aquifer.

AREAL EXTENT AND THICKNESS

The Biscayne aquifer underlies all the coastal areas and most of the Everglades to and a little beyond the Broward-Palm Beach county line (fig. 1).

The thickness of the aquifer is greatest along the coast in the Miami area and northward in the vicinity of Fort Lauderdale, where it is 200 feet in places. The aquifer decreases in thickness gradually southward from Miami, and rapidly westward into the Everglades; beyond its thickest portion in the Everglades it thins out to a featheredge in eastern Collier and Monroe counties.

Figure 2 shows contours on the base of the highly permeable rock in Dade and Broward counties. The base of the Biscayne aquifer is commonly drawn at the base of the formations of Pleistocene age except for the coastal area in Broward County and in northeastern Dade County, where the boundary occurs within the Tamiami formation, and other isolated areas where the base is placed at the bottom of limestone

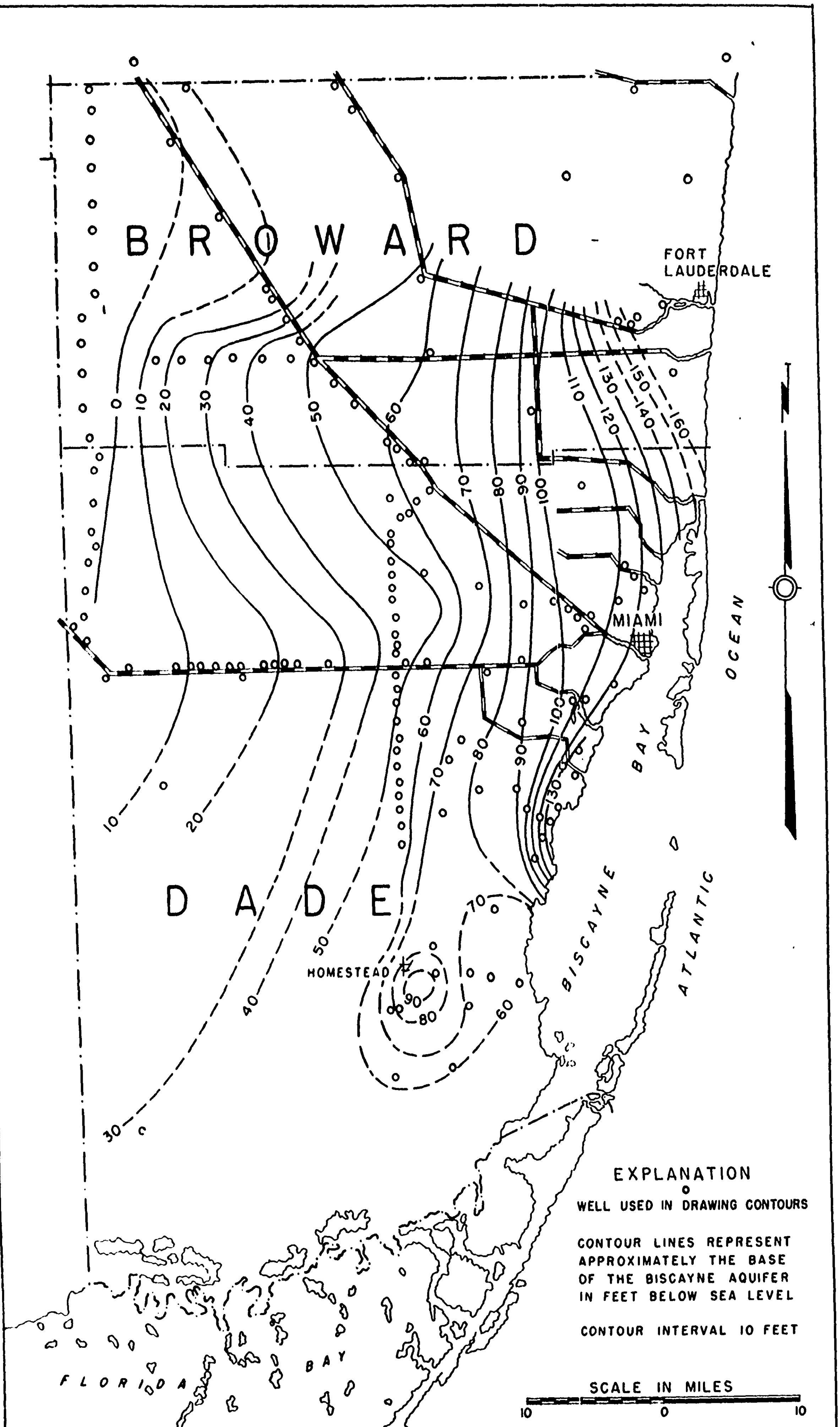

Figure 2. Structure contour map of Dade and Broward counties showing base of Biscayne aquifer.

that perhaps is the Caloosahatchee marl. Subsurface geologic data in southern Dade County are scanty because very few core holes have been drilled.

The areal extent of the Biscayne aquifer as shown in figure 1 is based upon the available data, and collection of additional information concerning the geology and the hydrologic characteristics may either increase or decrease the areal extent shown.

GEOLOGIC FORMATIONS COMPOSING THE BISCAYNE AQUIFER

GENERAL FEATURES

The Biscayne aquifer includes the following stratigraphic units: the upper part of the Tamiami formation in the coastal areas of Broward County and northeastern Dade County; the small erosional remnants of the Caloosahatchee marl in southern Broward County; the Anastasia formation in Broward County and southern Palm Beach County; the Fort Thompson formation in Dade and Broward counties, except the western part of Dade County north of the Tamiami Trail and northwest Broward County where the formation is relatively impermeable; the Key Largo limestone in Dade and Monroe counties; and the Miami oolite and the Pamlico sand in Broward and Dade counties. The Lake Flirt marl and more recent deposits, including the organic soils of the Everglades and marine marls bordering the coast, are excluded from the Biscayne aquifer.

The generalized surface distribution of the various geologic formations is shown on figure 3. The map is based upon recent observations of both surface exposures and well cuttings and is adapted and revised from geologic maps of Florida by Cooke (1945, pl. 1) and R. O. Vernon (in Black and Brown, 1951, p. 7) and of southern Florida by Parker and Cooke (1944, pl. 15). The field notes of Mr. Parker have been used extensively for descriptions of exposures and borrow pits no longer in existence.

The formations appearing on the geologic map and mentioned in the report are as follows:

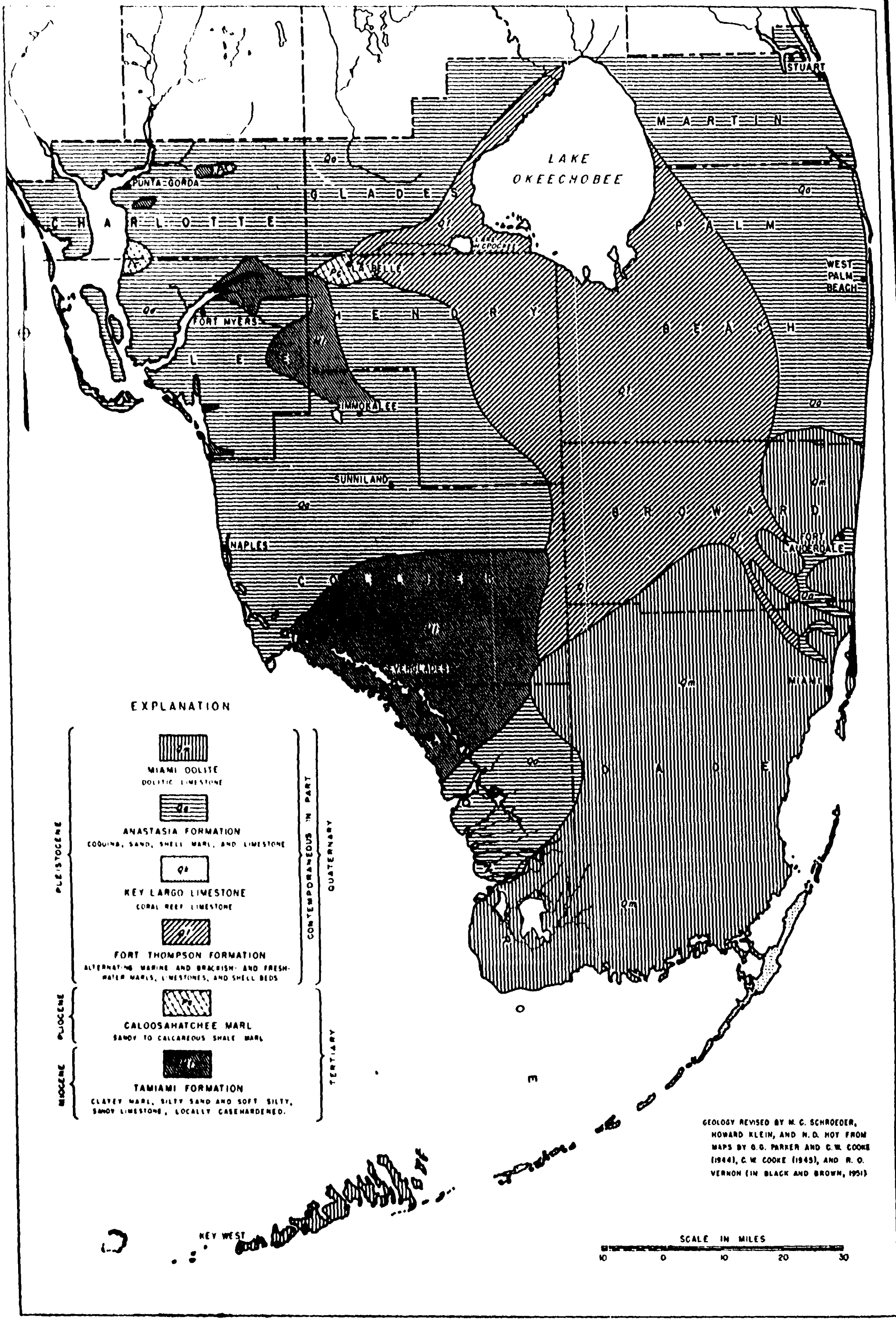

Figure 3. Geologic map of southern Florida.

LATE CENOZOIC FORMATIONS OF DADE AND BROWARD COUNTIES

Age	*Formation*	*Characteristics*	*Thickness (feet)*
Recent and Pleistocene	Soils	Peat and muck; laterite.	0-12
	Lake Flirt marl	White to gray calcareous mud, rich with shells of *Helisoma* sp., a fresh-water gastropod. In some places casehardened to a dense limestone. Relatively impermeable.	0-6
Pleistocene (Formations are contemporaneous in part)	Pamlico sand	Quartz sand, white to black or red, depending upon nature of staining materials, very fine to coarse, average medium. Mantles large areas underlain by Miami oolite and Anastasia formation.	0-40
	Miami oolite	Limestone, oolitic, soft, white to yellowish, containing streaks or thin layers of calcite, massive to crossbedded and stratified; generally perforated with vertical solution holes. Fair to good aquifer.	0-40
	Anastasia formation	Coquina, sand, calcareous sandstone, sandy limestone, and shell marl. Probably composed of deposits equivalent in age to marine members of Fort Thompson formation. Fair to good aquifer.	0-120
	Key Largo limestone	Coralline reef rock, ranging from hard and dense to soft and cavernous. Probably interfingers with the marine members of the Fort Thompson formation. Crops out along southeastern coast line of Florida from Soldier Key in Biscayne Bay to Bahia Honda. Excellent aquifer.	0-60
	Fort Thompson formation	Alternating marine, brackish-water and fresh-water marls, limestones, and sandstone. A major component of the highly permeable Biscayne aquifer of coastal Dade and Broward counties, which yields copious supplies of ground water.	0-150
Pliocene	Caloosahatchee marl	Sandy marl, clay, silt, sand, and shell beds. Yields ground water less abundantly than most other parts of the Biscayne aquifer.	0-25
Miocene	Tamiami formation	Cream, white, and greenish-gray clayey marl, silty and shelly sands, and shell marl, locally hardened to limestone. Upper part, where permeability is high, forms the lower part of the Biscayne aquifer. Lower and major part of formation is of low permeability and forms the upper beds of the aquiclude that confines water in the Floridan aquifer (Ocala and associated limestones) below.	0-100

MIOCENE SERIES

TAMIAMI FORMATION

The Tamiami formation as redefined by Parker (1951, p. 823) includes all the upper Miocene materials in southern Florida, including the Tamiami limestone of Mansfield (1939, p. 8). Excluded from the formation is the "Tamiami" formation of Parker and Cooke (1944, p. 62-65) in Dade County. Parker and Cooke correlated the limestone that Mansfield found cropping out along the Tamiami Trail in Collier and Monroe counties with the highly permeable limestones and sandstones which unconformably underlie the Miami oolite of Pleistocene age in the eastern Everglades and Miami area. Their correlation was based on cuttings from percussion-type or cable-tool drilled wells, which penetrated the aquifer, but the comminuted condition of the cuttings prevented identification of any fresh-water limestones intercalated with marine limestones. Subsequent exploratory core drillings in the Everglades and Miami area by the Corps of Engineers, U. S. Army, and the U. S. Geological Survey revealed the occurrence of fresh-water gastropods in limestone beds underlying the Miami oolite to a depth of 55 feet below sea level. Because the oldest known fresh-water limestones in this region are of Pleistocene age, most of the material underlying the eastern Everglades and the Miami area has been tentatively referred to the Pleistocene, by Parker (1951, p. 822, 823), and Hoy and Schroeder (1952, p. 283-285).

The Tamiami formation is divisible lithologically and hydrologically into two units: a relatively impermeable clastic unit, and a permeable limestone and sandstone unit. The two units have no stratigraphic significance, although in many places the clastics form the base and sandstones or limestones the uppermost part of the formation. However, the units are primarily geographic. Limestone is commonly exposed at the surface in the outcrop of the Tamiami formation in the Big Cypress Swamp and the Sunniland area; permeable sandstone composes the upper part of the formation in the subsurface of the coastal area of Broward County and northeastern Dade County. The subsurface Tamiami formation near Carnestown, Sunniland, and Immokalee in Collier County is a creamy-white, clayey, shelly marl, which in part has been indurated to a permeable limestone as a result of water-table fluctuation and ground-water percolation. Toward the east the formation increases in sand and marl content, and in Dade and Broward counties most of the formation consists of relatively impermeable clastics composing the upper part of the aquiclude that confines water in the Floridan aquifer, the principal artesian aquifer of the Florida Peninsula and adjacent area.

PLIOCENE SERIES

CALOOSAHATCHEE MARL

The Caloosahatchee marl is the only Pliocene material found in southern Florida. It was named by Matson and Clapp (1909, p. 123) for the soft, semiconsolidated sediments that form low bluffs along the Caloosahatchee River between La Belle and Denaud in Hendry County.

The Caloosahatchee marl is commonly a light greenish-gray silty, shelly marl, with varying amounts of sand. Sand and shells, occurring both in beds and in lenses, locally form a shell marl. Ground-water movement and exposure to air have locally casehardened and cemented the more sandy and shelly material to a calcareous rock which subsequently has been made permeable by solution of limestone and washing out of clastic material. Generally the formation is relatively impermeable, except locally where very shelly layers or lenses predominate.

The Caloosahatchee marl is known to extend 25 miles southward from Lake Okeechobee where it underlies Pleistocene rocks in the form of thin permeable limestone and sandstone reefs or "shoestring" sands. Present data are not yet sufficient to determine the extent of Pliocene deposits beneath the lower Everglades, but faunal evidence from a well near Kendall suggests the possibility of the occurrence in Dade County of isolated remnants of the Caloosahatchee marl.

It was previously thought by Parker and Cooke (1944, p. 59) that, south of Lake Okeechobee between the Dade-Broward county line and the approximate latitude of Twenty-Six Mile Bend of the North New River Canal, the Caloosahatchee and Tamiami formations were possibly contemporaneous and interfingered in the subsurface. However, more recent exploratory drilling has indicated that this material to about 60 feet below sea level is probably of Pleistocene age. This would mean that the Caloosahatchee marl, which is 30 to 50 feet thick near Lake Okeechobee, thins to 6 feet at a place a mile south of the Broward-Palm Beach county line and the North New River Canal. The marl has not been definitely recognized in well cuttings south of that place in Broward or Dade counties.

PLEISTOCENE SERIES

FORT THOMPSON FORMATION

The Fort Thompson formation is the name applied to the alternating fresh-water and marine limestones and marl beds which unconformably overlie the Caloosahatchee marl at old Fort Thompson 1¾ miles east of La Belle. Originally referred to as the Fort Thompson beds by Sellards

(1919, p. 71, 72), the unit was later named the Fort Thompson formation by Cooke and Mossom (1929, p. 211-215), and was defined to include the overlying marine Coffee Mill Hammock marl. In the lower Everglades the Fort Thompson formation overlies the Tamiami formation, or, where present, erosional remnants of the Caloosahatchee marl, and underlies the Miami oolite unconformably. In the northern part of the area the Fort Thompson is overlain by the younger portion of the Anastasia formation, the Lake Flirt marl, or the Pamlico sand.

The Fort Thompson formation at the type locality is a succession of shelly marine and nonmarine limestones and marls, including three distinct marine beds. The uppermost, the Coffee Mill Hammock member, is a shell marl, consisting chiefly of shells of *Chione cancellata.* The marine marl members are separated by gray, shelly, marl beds, in part indurated to limestone, containing the fresh-water gastropods *Helisoma* and *Ameria.* The fresh-water beds are pierced by vertical and lateral solution cavities formed by ground-water percolations. Subsequent filling of the cavities by marine marls has produced a network of interconnected and isolated marine and fresh-water marls and limestones. In places, holes penetrate the entire thickness of the formation so that the Coffee Mill Hammock member lies directly upon the Caloosahatchee marl of Pliocene age as a solution-hole filling. The alternation of marine and fresh-water beds indicates, according to Parker and Cooke (1944, p. 94-96, fig. 4), onlapping and offlapping seas from the end of Pliocene time through the Sangamon interglacial stage of the Pleistocene.

Core borings of the thick section of permeable limestone and sandstone in the lower Everglades, between the Miami oolite and the Tamiami formation, similarly show interbeds and cavity fillings of fresh-water limestone with marine limestone (figs. 4-9). This interbedded material forms the major part of the Biscayne aquifer and, as previously mentioned, has been tentatively correlated by Hoy and Schroeder (1952, p. 283-286) with the Fort Thompson formation.

The Fort Thompson formation in the Dade-Broward county area is predominantly light gray to cream, fossiliferous, marine, sandy limestone and calcareous sandstone, with a few thin beds of gray and tan fresh-water limestone. The entire section has been subjected to solution by ground water, and the result is a cavity-riddled mass of permeable rock. Solution cavities are as much as several feet in diameter; some are filled or partially filled with fine and medium quartz sand. Some sand filling possibly occurred during flooding by Pleistocene seas. Loose sand such as this decreases the permeability of the aquifer, but if wells are heavily pumped much of the sand will be removed and a high permeability adjacent to a well will result.

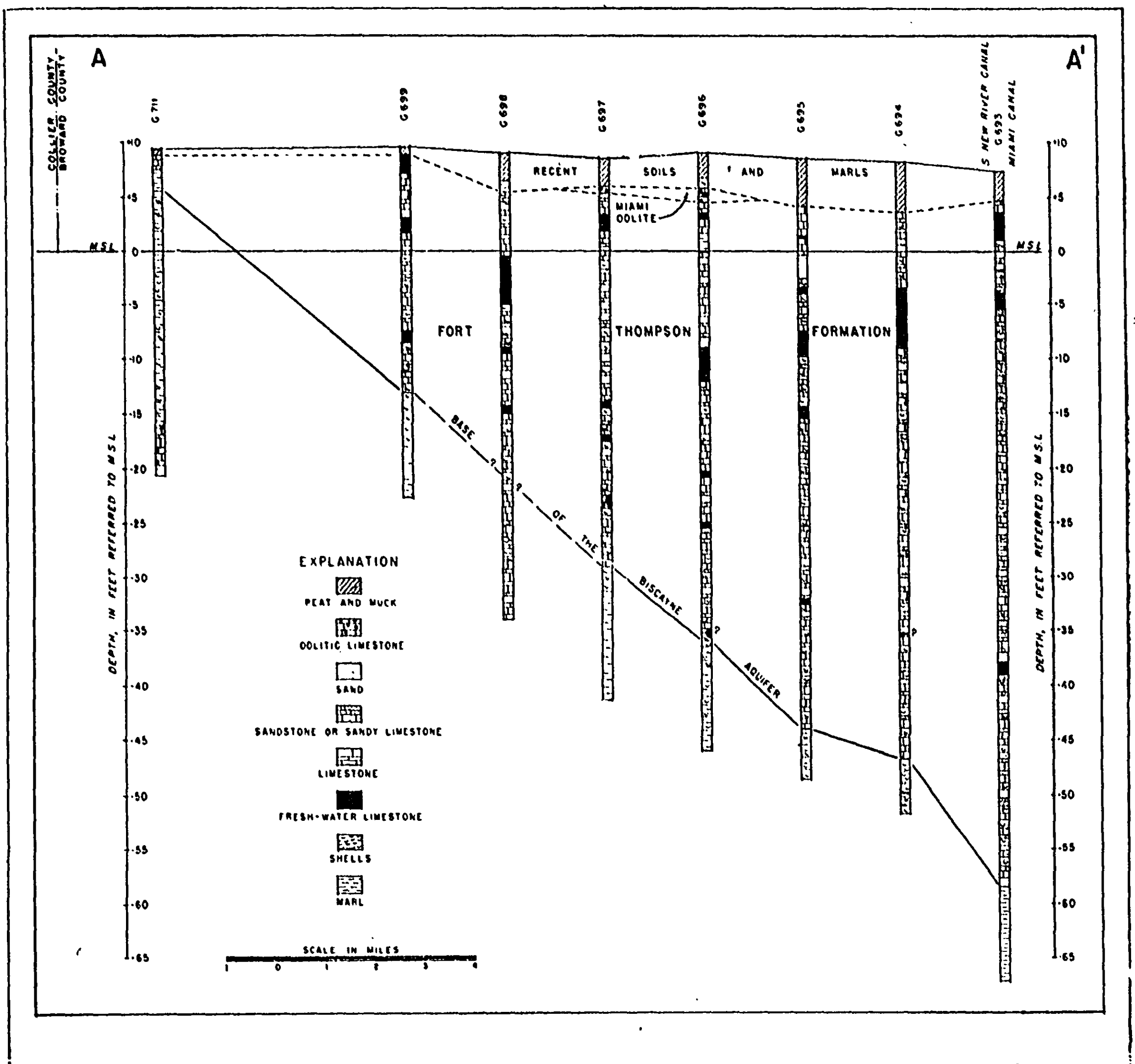

Figure 4. West-east geologic cross section in western Broward County.

Cementation and redeposition of materials by ground-water movement are very much in evidence throughout the Fort Thompson formation. Cementation of sand bodies by calcium carbonate has produced layers of hard, dense sandstone. Locally the cement is siliceous, producing a very hard quartzitic sandstone. An examination of limestone cores frequently shows secondary deposits of calcite crystals inside cavities or within concavities of marine shells. Fossils are preserved chiefly as molds and casts, rarely in their original form. Some cores of the Fort Thompson formation show indications of bedding planes which provide zones of weakness along which ground-water solution takes place. Part of the Fort Thompson formation is composed of very dense, hard nonfossiliferous limestone exhibiting little or no effect of ground-water action. In general, highly fossiliferous beds are markedly pitted with solution holes.

Because no unconformable relationship has been noted between the Fort Thompson and older formations, the contact is normally placed beneath the lowest sandy marine limestone which underlies fresh-water beds. It is recognized that a part of this basal material in some places may include formations of either Pliocene or late Miocene age.

The contact between the Fort Thompson formation and the Miami oolite, as observed in spoil banks along canals in the Everglades, is unconformable and is usually placed at the maximum depth at which oolites appear. The upper surface of the Fort Thompson is uneven and is characterized by solution pits and depressions and vertical solution holes. Oolitic material admixed with loose, sandy detritus from the Fort Thompson was deposited on this eroded surface and filled depressions to depths a few feet below the actual contact. These cavity fillings are easily discerned in core samples because the filling material is heterogeneous and shows a color contrast. A layer of very hard, dense, cream to gray, sandy limestone, which is peculiarly mottled or banded with brown and tan limestone, occurs in the Fort Thompson below the contact. In places the material appears to be a conglomerate containing weathered pebbles of the Fort Thompson formation, but in at least some of these places the "conglomerate" is the result of irregular deposition of iron oxide in interstices of the Fort Thompson, along with differential cementation of those areas. The banding may denote an old eroded surface or may be the result of water-table fluctuations.

The occurrence of fresh-water limestones in a great number of core borings that penetrate the aquifer west of the coastal ridge has been plotted in cross sections (figs. 4-6), the locations being shown on figure 7. In addition, a series of shallower borings, 25 to 30 feet below mean sea level, along U. S. Highway 27 (Miami Canal northward to North New River Canal) across Broward County between the Dade and Palm Beach county lines, were examined. Fresh-water limestones are present at shallow depth along U. S. Highway 27 where it adjoins the South New River Canal north to the Palm Beach county line. In another series of holes bored to a depth of about 20 to 25 feet below mean sea level and extending from the North New River Canal to the Hillsboro Canal, along a line approximately 8 miles west of Florida Highway 7, no fresh-water material was noted in the cores. Obviously, it is difficult to determine exactly where the Fort Thompson and Anastasia formations merge, but they seem to merge near the eastern edge of the Everglades.

A similar situation exists in Dade County where fresh-water limestones are not known to occur in coastal areas. Along the western edge of the coastal ridge, a few beds of fresh-water limestone are present, as well as some indications of reef corals. The fresh-water limestones, ranging in thickness from 1 to 3 feet, were noted in the following wells (fig. 7) which are not included in the cross sections:

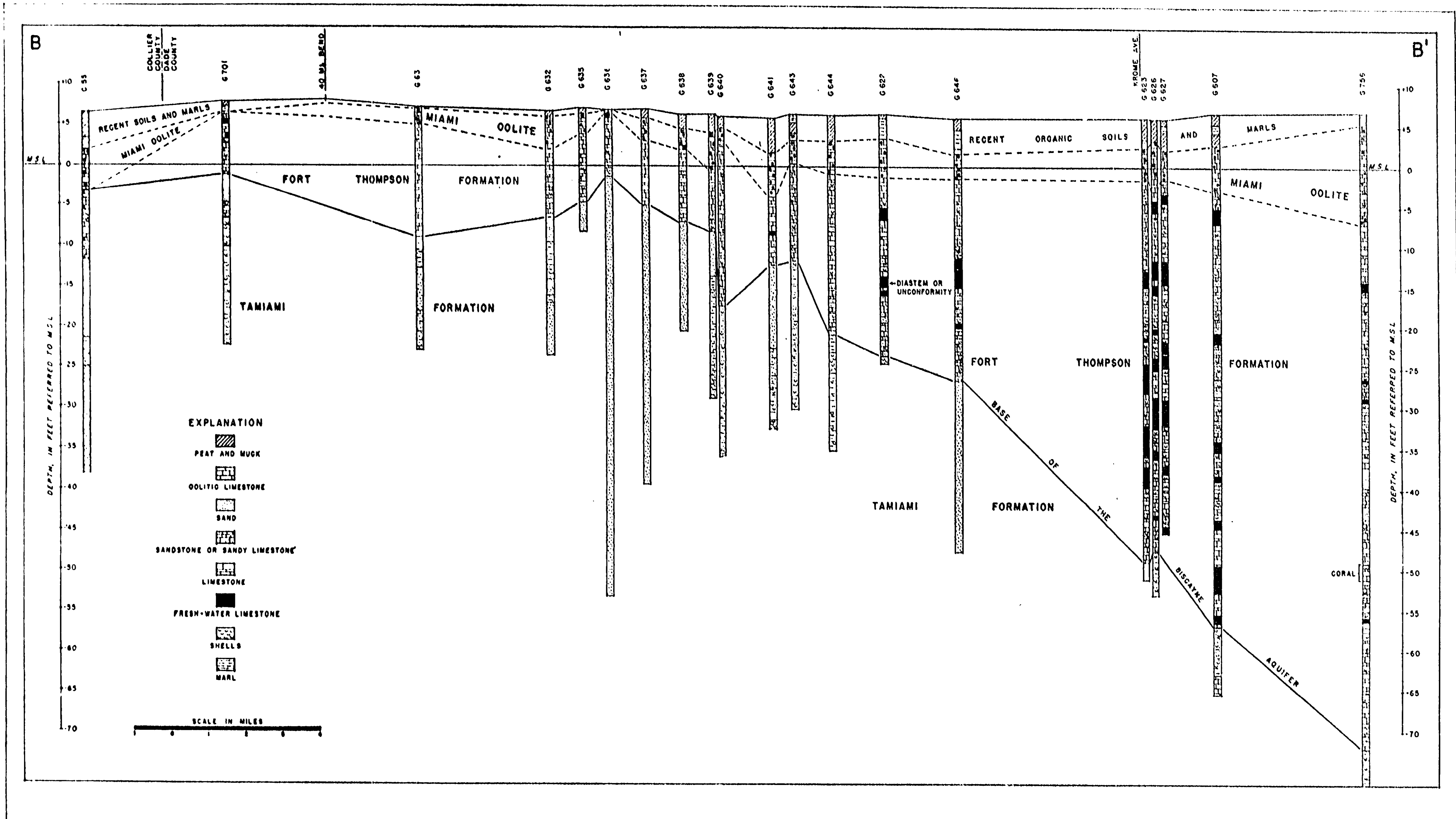

Figure 5. West-east geologic cross section in Dade County.

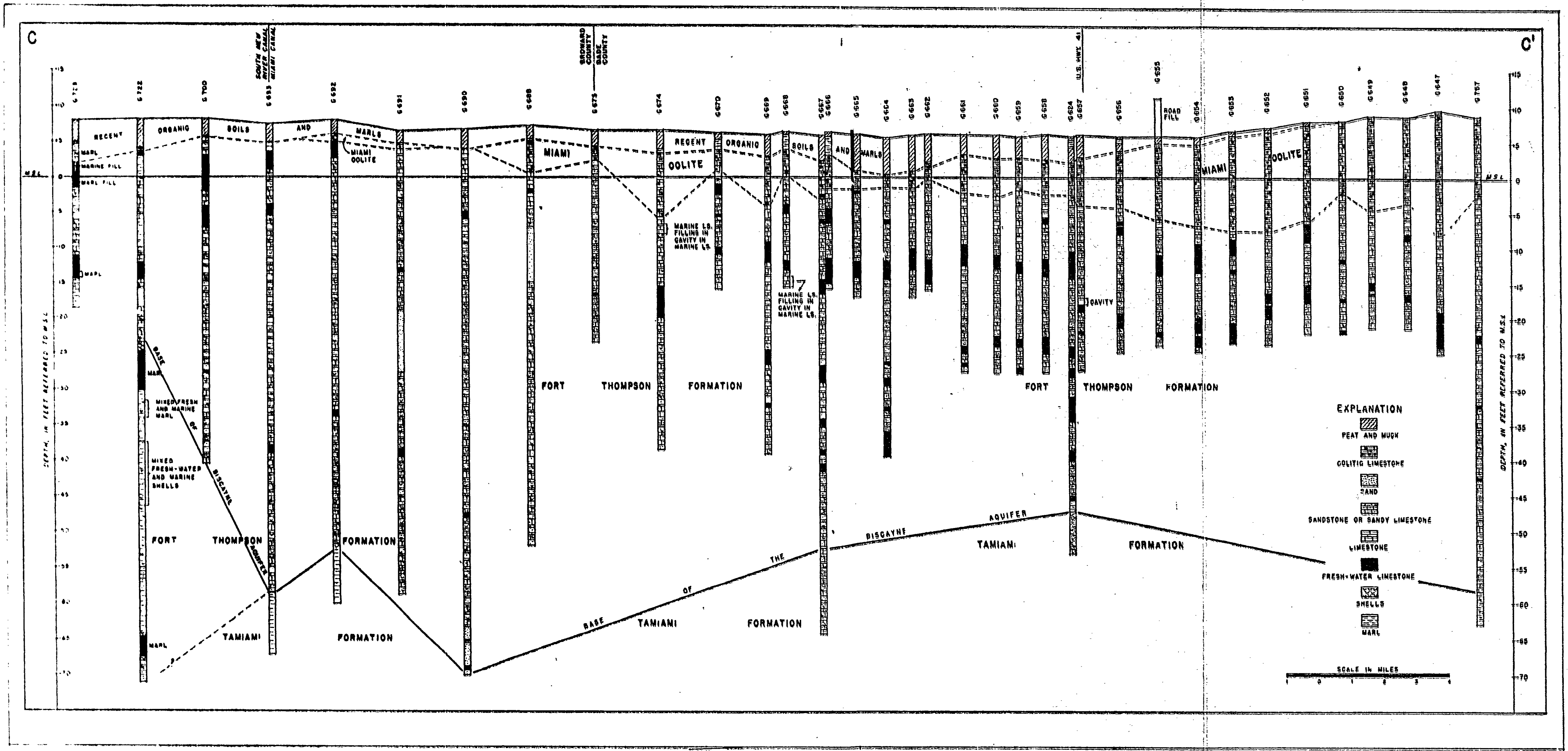

Figure 6. North-south geologic cross section in the Everglades.

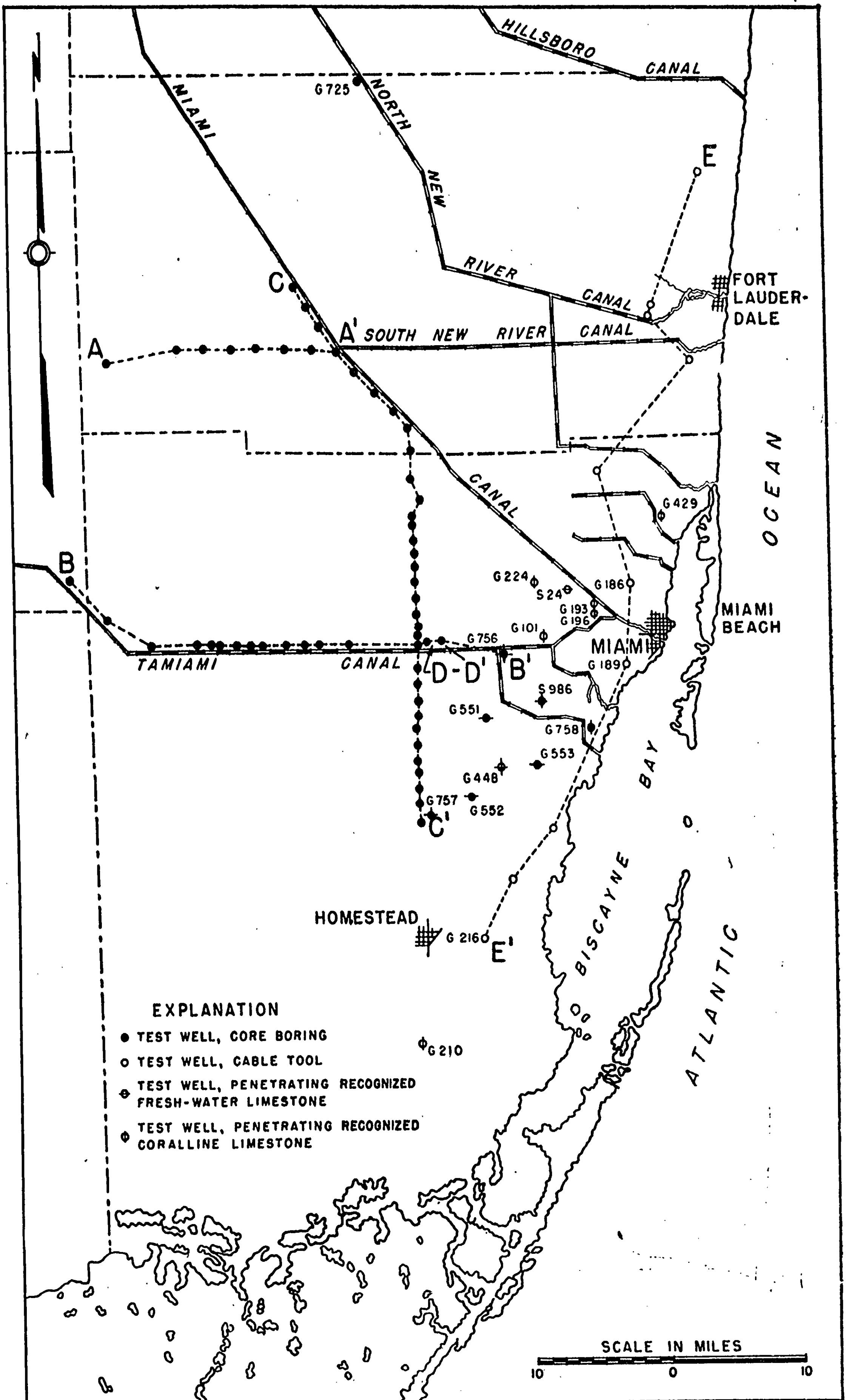

Figure 7. Map of Broward and Dade counties showing location of geologic cross sections and certain test wells.

Well No.	*Depth to top of fresh-water limestone, in feet below msl*
G 448	41
G 551	37 and 50
G 553	42
G 552	10
S 24	40 to 45 (depth uncertain)
S 986	39

Reference to the section on the Anastasia formation, and to figure 7 showing wells that have penetrated coralline rocks, makes it evident that the Fort Thompson, Key Largo, and Anastasia formations interfinger. Pleistocene marine limestones in certain areas of coastal Dade County cannot be definitely assigned to one of the three formations, because of their transitional character. In some instances the limestone has been arbitrarily placed in the Fort Thompson formation, although it does not contain fresh-water beds, but in others the limestone is placed in the Key Largo, although it is not coralline.

Figures 4 and 5 show west-east geologic sections across the lower Everglades, and figure 6 shows a north-south section at the longitude of Krome Avenue. Figure 8 shows a short west-east section along the Tamiami Trail east of Krome Avenue, where wells were closely spaced, and a possible correlation of fresh-water limestones. Several zones of fresh-water limestone are apparent between wells G 670 and G 624, shown in figure 6, where the uppermost zone occurs between the base of the Miami oolite and a position 8 feet below mean sea level. The most persistent zone and one that definitely appears to be a single layer occurs between 8 and 15 feet below mean sea level and extends southward from well G 670 to well G 653, and possibly farther. The thickness of the fresh-water limestone of this zone ranges from 1 to nearly 5 feet, although the greater thickness may be due to filling of solution holes. This fresh-water limestone is not found at comparable depths in wells G 657 and G 656. Possibly the core pierced a marine cavity fill within the fresh-water limestone, or the bed has been eroded and subsequently covered by younger marine limestone. However, limestone beds plotted a few feet below the minus 15-foot mean-sea-level horizon in these 2 wells may indicate that this bed was deposited in a locally depressed area or a wide solution hole.

A second fresh-water limestone occurs approximately 20 to 30 feet below sea level. This zone extends between wells G 661 and G 653, and wells G 669, G 667, and G 664 farther north containing fresh-water

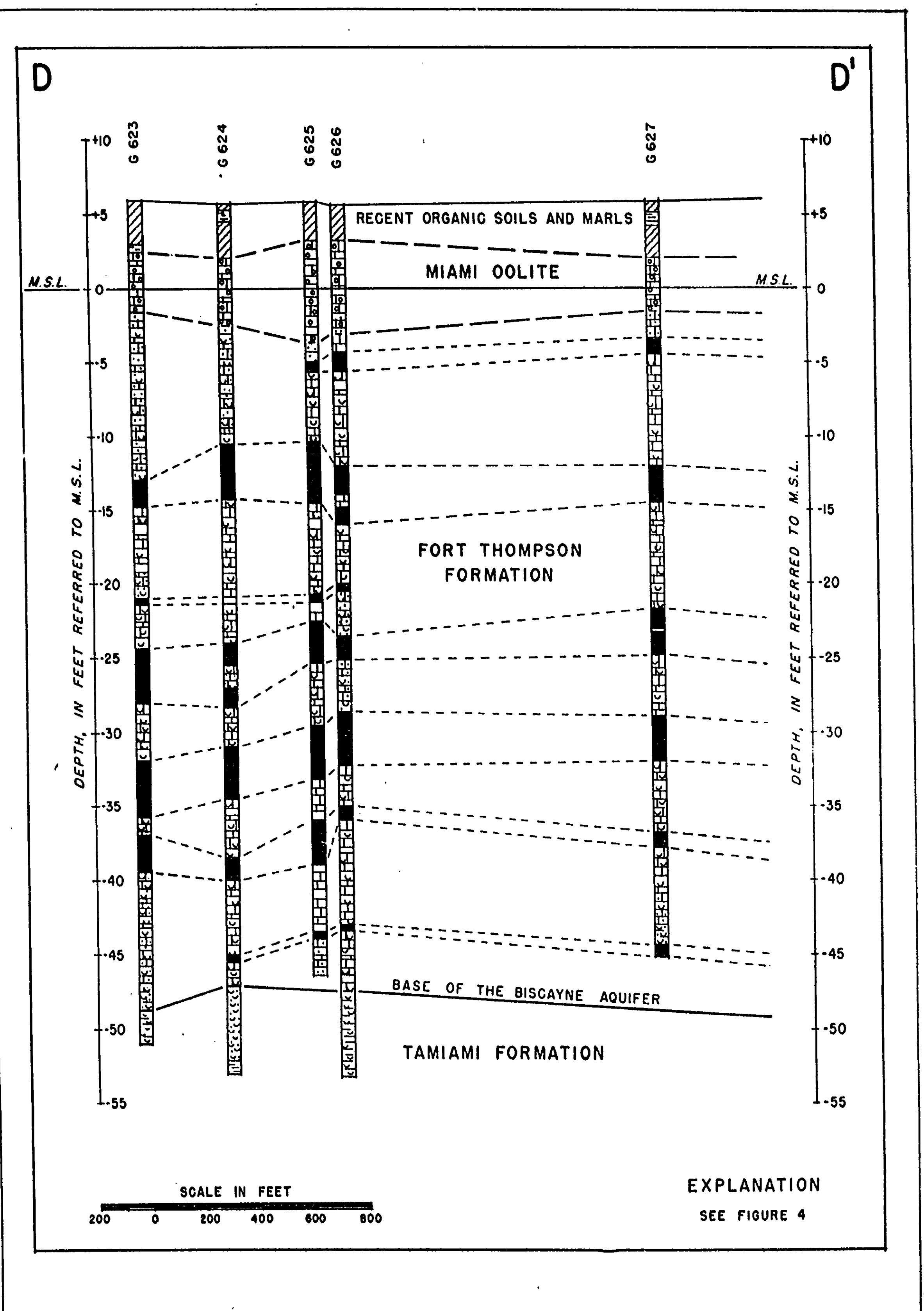

Figure 8. West-east geologic cross section near Krome Avenue at Tamiami Trail.

limestones, at slightly lower elevations, which are probably a continuation of this zone. A similar situation may be true of the wells south of G 653, although these limestones are generally at slightly higher elevations.

Cores from wells G 667, G 664, G 624, and G 757 indicate that 2 or possibly 3 zones of fresh-water limestone may be present between the second zone and the base of the Fort Thompson formation, but definite correlation between wells cannot be made with the information available.

In well G 667 the highest fresh-water limestone is associated with oolitic material and may be part of the Miami oolite. North of the Dade-Broward county line the distribution of fresh-water material was such that it could not be correlated with the more uniformly bedded strata to the south.

Figure 8 shows a locality east of Krome Avenue along the Tamiami Trail, where some of the closely spaced core borings penetrate the entire thickness of the highly permeable aquifer. This section again shows a possible correlation of 6 fresh-water limestone zones similar to that shown in figures 5 and 6. Well G 607 (fig. 5) penetrated 6 beds of fresh-water limestone and a well 42 feet east pentrated the same 6 beds.

At least four limestone beds of fresh-water origin occur within the Pleistocene section at the Palm Beach-Broward county line and the North New River Canal (fig. 7), as shown by the following log of well G 725:

Description	*Depth, in feet, with reference to msl*
Peat and muck, dark brown	+ 10.9 to + 6.1
Clay, mucky, black	+ 6.1 to + 4.8
Limestone, fresh-water, brown, dense, shelly	+ 4.8 to + 4.7
Marl, sandy, marine, in places indurated to sandstone	+ 4.7 to + 1.7
Limestone, fresh-water, dense, brown	+ 1.7 to + 1.1
Sandstone, calcareous, fossiliferous, marine	+ 1.1 to 0.0
Limestone, fresh-water, cream	0.0 to — 1.0
Sandstone, shelly, marine, calcareous	— 1.0 to — 6.0
Limestone, cream, shelly, probably fresh-water (?)	— 6.0 to — 6.5
Marl, very sandy, shelly, tan, marine, with a few fresh-water shells	— 6.5 to — 8.6
Marl, fresh-water, sandy, shelly	— 8.6 to — 10.7
Marl, fresh-water, partially shelly, indurated to limestone	— 10.7 to — 11.5
Sand, marly, tan, very shelly, fresh-water gastropods from — 11.5 to — 12.0, apparently as cavings, containing some marine shells (*Chione cancellata*)	— 11.5 to — 13.5
Sandstone, cream to tan, very shelly, mixed marine and fresh-water at bottom	— 13.5 to — 16.5

A glance at the geologic sections indicates that each fresh-water bed was probably deposited on an undulating and solution-pitted marine limestone. The beds range in thickness from 0.2 foot to nearly 5 feet. Their upper surfaces were probably eroded to some extent by shallow encroaching seas which removed less resistant materials. It is recognized that a few of the fresh-water limestones as plotted are cavity fillings which were deposited in what is definitely marine material. Fresh-water materials could easily have been washed in and deposited in subsurface cavities as well as at the surface.

It is possible that, during major portions of the Pleistocene glacial stages, the lower Everglades was a low-lying marginal area bounded on the west by slightly higher land and on the east by the coastal ridge composed of reef materials. Because of the marginal character of the area, slight rises in sea level would bring about marine floods during which thin marine limestones were deposited. However, with a fall in sea level, the land emerged so that the resulting weathering and eroding of the marine limestones accompanied the deposition of some thin fresh-water limestone. A major advance of the continental ice sheet would cause an extended lowering of sea level, thus allowing a greater thickness of fresh-water limestone to be deposited over a larger area. On the other hand, a major or complete retreat of the ice sheet probably resulted in inundation of the area for a long period, and in deposition of a greater thickness of marine limestone in which were thin, isolated bodies of reworked older material.

The lower Everglades appears to have been a depressed area which, during Pleistocene time, was intermittently shut off from the sea by a barrier along the coastal ridge of southeastern Florida. This barrier was formed by the deposition of the Anastasia formation, the Key Largo limestone, and the Miami oolite. During times of lowered sea level the Everglades lay exposed and contained swamps and fresh-water lakes, and fresh-water limestones were deposited as fills in the lower materials and as beds. The sea level probably was not stable during the glacial stages but rose and fell with relatively short retreats and advances of the ice. Such activity produced thin layers of marine limestone during short sea floodings, interbedded with thin fresh-water or brackish-water deposits during recessions. However, after a complete retreat of the continental ice sheet, the resulting rise of sea level would permit thick marine sections to be deposited. Optimum conditions for the most widespread deposition of fresh-water limestone in the lower Everglades probably occurred at times between the beginning of a glacial stage and of maximum advance of the continental ice sheet. Times of maximum advance of the ice and lowering of sea level were most favorable for channel cutting, resulting in draining of the land.

Correlation of the six postulated beds of fresh-water limestone with specific glacial stages of the Pleistocene is a more difficult problem than the correlation by Parker and Cooke (1944, p. 89) of the beds at the site of old Fort Thompson. The data suggests that the tentative correlation by Parker and Cooke of individual beds with specific glacial and interglacial stages may need revision.

KEY LARGO LIMESTONE

The Key Largo limestone, named and described by Sanford (1909, p. 214-218), is a dead coral reef that makes up the Florida Keys from Soldier Key southwest to Bahia Honda. The Key Largo limestone is a part of the Biscayne aquifer along the coastal area of Dade County. It constitutes the whole of the aquifer in the part of the Florida Keys described. The rest of the Keys southwest from Bahia Honda are composed of the Miami oolite and there the Key Largo limestone may constitute only a small part of the aquifer. The aquifer in the Keys yields saline water to wells.

The Key Largo limestone consists chiefly of recemented reef detritus and precipitated limestone surrounding coral heads of the old reef. The corals were subjected to wave action, which eroded the softer parts and deposited the waste in the openings along with other bioherm material. The formation in general is very permeable, containing solution cavities which were produced in the same manner as in the Fort Thompson formation.

Corals, most of them of the reef-building type, have been found in material from the following wells (fig. 7), at the noted depths:

Well No.	*Depth, in feet below msl*
G 101	20 to 56
G 186	39 to 43
G 189	13 to 32, and 41 to 48
G 193	35 to 43
G 196	41 to 54
G 210	13 to 19
G 216	15 to 20, 24 to 33, and 44 to 60
G 224	18 to 44
G 429	18 to 23
G 448	31 to 40
G 756	56
G 757	44 and 49
G 758	52 and 56
S 986 (and nearby wells)	38, 40, 60, and 70

All except the last four wells, which were cored, were drilled by the cable-tool method. The coralline material in well G 448 directly overlies fresh-water limestone, whereas in well S 986 a fresh-water limestone bed at 39 feet is overlain and underlain by reef-limestone material. Coral was noted in wells G 756 and G 757 below the lowest fresh-water limestone. In many wells that were not cored the coralline limestone appears to be discontinuous, because only a trace of coralline limestone was noted in the samples from wells G 101 and G 224. The comminution of the material by the bit action prevents any possible indentification of fresh-water limestone in such samples. However, along the eastern part of the coastal ridge, fresh-water limestones are not apparent in the underlying limestones and only an occasional bed is penetrated in the western part of the coastal ridge. The occurrence of coral in the vicinity of the western part of the ridge demarks the area of interfingering between the Key Largo limestone and the Fort Thompson formation. The nature of this interfingering is not known nor is the western limit of coralline limestone. An abundance of reef coral was excavated from the borrow ditch for the levee which crosses the Tamiami Trail a mile west of Krome Avenue. The corals apparently are from the top part of the Fort Thompson formation, although it is possible that they are in the Miami oolite also.

A great number of wells along the coastal ridge penetrate Pleistocene limestones that apparently include neither fresh-water limestones nor coralline limestone. These limestones have been placed in the Anastasia formation.

The upper part of the Key Largo limestone, according to Parker and Cooke (1944, p. 68), interfingers with the lower part of the Miami oolite.

ANASTASIA FORMATION

The Anastasia formation was named by Sellards (1912) from its typical development of coquina on Anastasia Island, near St. Augustine, Florida, and as defined in this report includes all pre-Pamlico marine sand, limestone, and shell beds of Pleistocene age along the coastal area.

The Anastasia formation represents the chief component of the Biscayne aquifer in the vicinity of Fort Lauderdale and along the coastal ridge as far north as Delray Beach in Palm Beach County. In the area to the west, the Anastasia is equivalent to the marine portions of the Fort Thompson formation, and to the south the upper part of the Anastasia merges with the Miami oolite and the lower part merges and interfingers with the Key Largo limestone (fig. 9). The formation is composed of marine sandy limestone, calcareous sandstone, in part coquinoid, and shelly sand. It was initially laid down in a shallow beach environment as an offshore bar which was exposed from time to time by eustatic sea-level fluctuations during the Pleistocene. An outcrop of

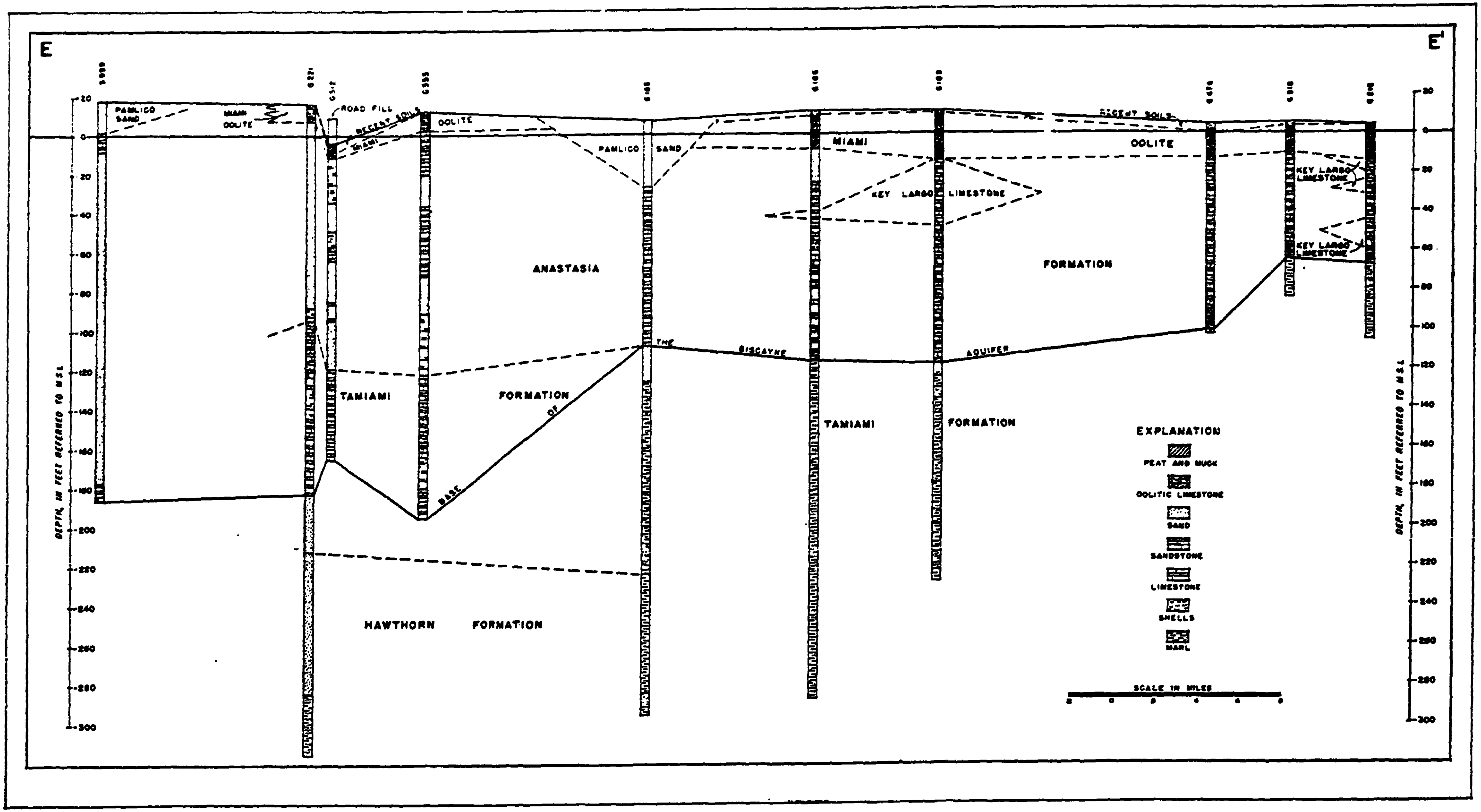

Figure 9. North-south geologic cross section on the coastal ridge.

the Anastasia formation at Palm Beach shows younger eolian crossbedded sandstone lying unconformably on marine calcareous sandstone. The unconformity is characterized by brown sandy soil which fills solution holes in the older material. The Anastasia formation represents sediments deposited throughout all or a major part of the Pleistocene, according to Parker and Cooke (1944, p. 66).

The permeability of the Anastasia formation ranges widely from place to place. Away from the coastal areas, where it is well indurated, groundwater action has produced large solution cavities and the permeability high. Adjacent to the coast the material contains more sand and silt so that the permeability is markedly reduced.

MIAMI OOLITE

The Miami oolite was named by Sanford (1909, p. 211-214). Cooke and Mossom (1929, p. 204-207) redefined the formation to include all the oolitic limestone of southern Florida, including that on the Keys.

The Miami oolite is the surface rock that blankets nearly all of Dade County, parts of eastern and southern Broward County, the southern mainland area of Monroe County, the Florida Keys from Big Pine Key to Key West, and a triangular area extending from Dade County westward along the Collier-Monroe county line. The formation thins out at its western extremity and gradually thickens to the east, attaining a maximum thickness of about 40 feet.

In the lower Everglades the Miami oolite unconformably overlies and fills cavities in the upper surface of the Fort Thompson formation. Along the coast the formation interfingers with the upper portions of the Fort Thompson, Anastasia, and Key Largo formations. Where not exposed at the surface in the lower Everglades, it is covered by Recent organic materials. In northwest Dade County and southwest Broward County, it is overlain unconformably by the Pamlico sand, a terrace deposit of Pleistocene age, or by the Lake Flirt marl of Pleistocene and Recent age.

The Miami oolite is typically a white to yellowish massive crossbedded oolitic limestone containing varying amounts of sand, usually in solution holes. Where exposed to weathering, as in the Silver Bluff area, the surface of the oolite turns a dull gray color. Crossbedding and cone-in-cone structures are outstanding features. The angle of dip of the crossbedded material changes from place to place, and the material is apparently a dune or beach-ridge deposit. The high angle crossbeds in places are beveled by flat-lying oolitic material containing marine shells. In the Silver Bluff area large pieces of crossbedded oolitic limestone are incorporated in portions of oolite which show no evidence of bedding. This is definite evidence of reworking of younger oolite deposits and, according to Parker and Cooke (1944, p. 71), might indicate either that the Miami oolite represents deposits of two or more interglacial stages or that the deposition, reworking, and redeposition occurred during a single stage. In either case, oscillation of the sea level was involved. At many places in Broward County the formation is composed almost entirely of calcareous oolitic sand or of mixtures of calcareous and quartz sand.

PAMLICO SAND

The Pamlico sand is a late Pleistocene terrace deposit of marine origin (Parker and Cooke, 1944, p. 75). Parker and Cooke (p. 74, 75) extended the term Pamlico sand from North Carolina to southern Florida, and defined it to include all the marine Pleistocene deposits younger than the Anastasia formation.

The Pamlico sand blankets much of the Everglades north of the latitude of Fort Lauderdale and covers the coastal area as far south as Coral Gables. It unconformably overlies and fills cavities in the Miami oolite, the Fort Thompson formation, and the Anastasia formation. In the northern part of the region the sand is covered by Recent marls and organic soils.

The Pamlico sand is chiefly a quartz sand ranging in color from light gray or white to red and gray-black, depending on the amount of incorporated iron oxide or carbonaceous material. In localities where shells are admixed, the Pamlico sand may be semiconsolidated as a result of solution and redeposition of calcium carbonate. The quartz sand ranges in size from very fine to coarse, the medium-sized grains predominating. Where the material is medium to coarse, and well sorted, it will furnish adequate fresh-water supplies for domestic purposes.

The Pamlico sand lies below the 25-foot contour; areas within its outcrop that lie at higher elevations represent dunes or shore ridges formed during the Recent. The formation increases in thickness from a featheredge to perhaps 40 feet, the greatest thickness being along the coastal ridge.

GROUND-WATER OCCURRENCE

GENERAL FEATURES

All the water that recharges the Biscayne aquifer is derived from local rainfall. When rain falls to the surface, a part is evaporated, a part is used by plants, another portion runs off as surface water, in streams or to fill lakes and ponds, and the remainder percolates rapidly through the thin sandy mantle to the water table. Only in the Everglades does any major surface runoff occur.

The water table is the upper surface of the zone of saturation except in areas (rare in southern Florida) where that zone is formed by an impermeable body. The water table is open to the atmosphere and is marked by the level at which water stands in wells. It is an undulating surface which in a general way conforms to the topography, being at higher elevations under hills and lower under valleys. The water table in the Biscayne aquifer normally lies within the Miami oolite, the Pamlico sand, or the organic soils of Recent age. Parker (in Parker and others, 1955), in relating precipitation to water-table rises, estimates that about two-thirds of the annual rainfall reaches the water table in southern Dade County.

The water table fluctuates in response to local rainfall in the area and to natural discharge (seepage into streams or canals or to the sea, and evapotranspiration), and pumping.

Water for small domestic supplies is derived through small diameter sand-point wells from the Pamlico sand. The Miami oolite is more permeable than the Pamlico sand, and the contained water is obtained by means of shallow open-hole (unscreened) wells. Large supplies of water are obtainable from uncased wells in this formation in the grove area of southern Dade County. The Key Largo limestone, the Anastasia formation, and the Fort Thompson formation in Dade County will yield large amounts of water to open wells. For example, an 18-inch well southwest of Miami yielded 7,600 gallons per minute, or about 11 million gallons a day, with a drawdown of only 7 feet. Along the coastal areas of Broward County, the water in the Anastasia formation generally is obtained by means of screened wells. At Fort Lauderdale the Tamiami formation, which is a friable, very calcareous sandstone, yields large quantities of water to both open-hole and screened wells.

SHAPE AND SLOPE OF THE WATER TABLE

The water table of the Biscayne aquifer may be mapped at any given time by determining its elevation in a network of wells. Eastern Dade County has a large number of control wells, whereas those in Broward County are relatively few and scattered. Irregularities in the shape and slope of the water table are common and are produced chiefly by rainfall and to a lesser extent by pumping, both of which are highly variable from place to place. The water table in Broward and Dade counties commonly slopes eastward toward the coast, although in the central part of the Everglades it slopes southward. In wet periods the water table may slope both east and west from the coastal ridge.

Water-table contour maps have been prepared for the eastern part of Dade County. These show modifications and changes in the shape of the water table brought about by the various drainage canals and the heavy local rains. The maps were prepared principally from records of the present network of observation wells that are equipped with automatic recording gages; however, when interpreted in conjunction with maps showing high, intermediate, and low water stages, these records give coverage that is nearly as complete as that of the much larger number of wells measured for preparing a detailed water-table contour map. Figure 10, which represents the average elevation of the water table for the period 1940-1950, shows the general shape and slope of the water table in Dade County. Although several maps of different water stages have been made, the maps of the lowest (fig. 14) and highest (fig. 16) ground-water stages of record in Dade County emphasize the irregularities.

FLUCTUATIONS OF THE WATER TABLE

Major fluctuations of the water table are caused by recharge and natural or artificial discharge. The magnitude of water-level fluctuation during any one year in Dade County varies from 2 to 8 feet, depending upon the amount and distribution of the rainfall in the local area. Figure 11 shows a hydrograph of well S 196 compared with a graph of rainfall.

The water table in the coastal areas fluctuates in response to ocean tides, the time lag increasing and the magnitude of fluctuations decreasing with distance inland. The greatest observed inland distance of the tidal effect on water levels is 6,700 feet in well F 179, in Miami, where the fluctuation amounted to 0.01 foot. Although the Biscayne aquifer generally shows nonartesian characteristics, pumping tests indicate that the aquifer temporarily responds as an artesian aquifer having a very leaky roof. Thus, water levels in many wells respond to earthquake shocks and to changes in barometric pressure. The effect of barometric pressure is usually slight and is commonly masked by other fluctuations. Parker and Stringfield (1950) have discussed the effects of earthquakes, winds, tides, and atmospheric pressure changes on ground-water levels in southern Florida.

High and low water-table conditions are of economic importance in both rural and urban areas. Extremely high water-table conditions cause the flooding of the low-lying lands in southern Florida, destroying crops,

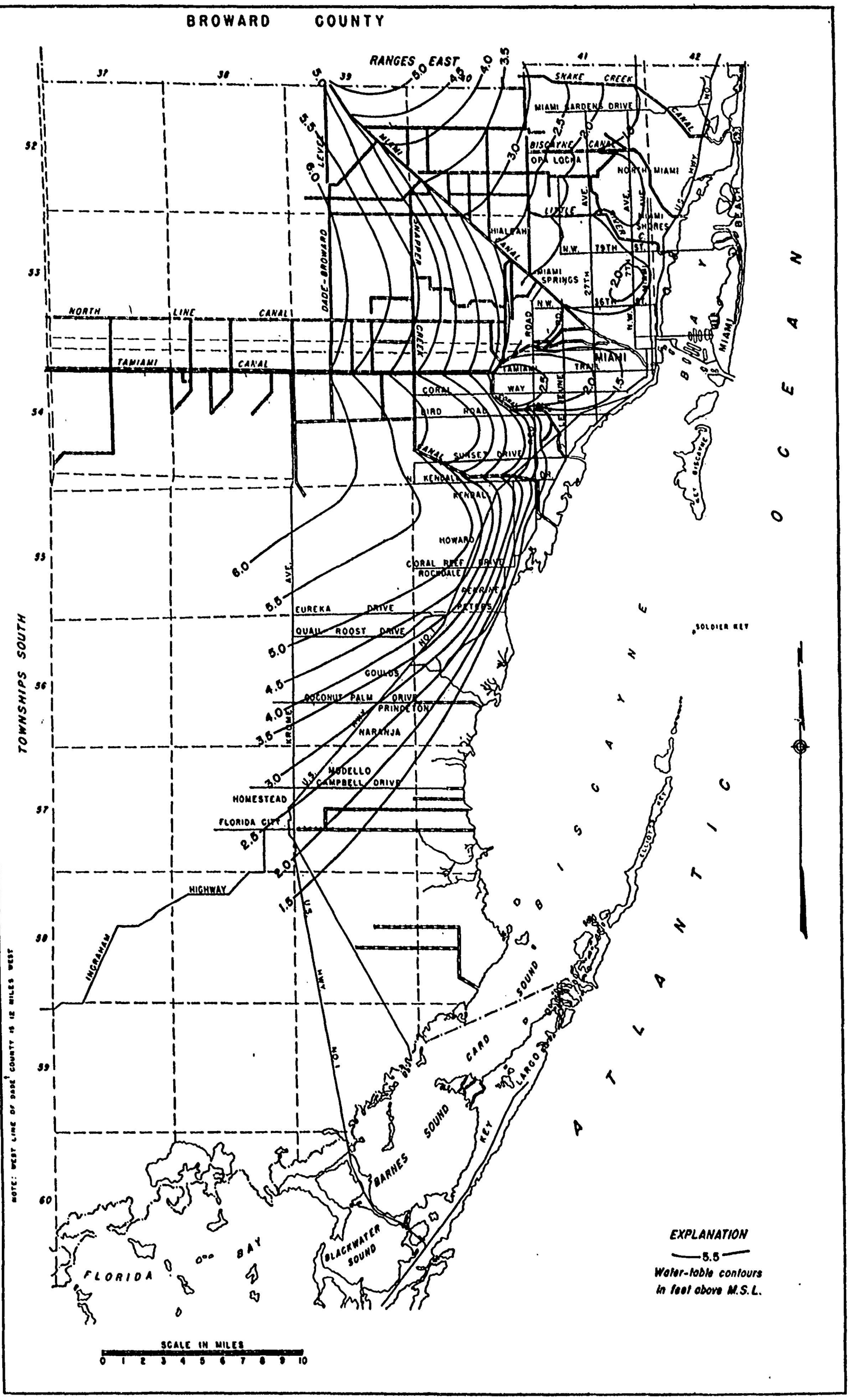

Figure 10. Map of Dade County showing average water levels in eastern part, 1940-1950.

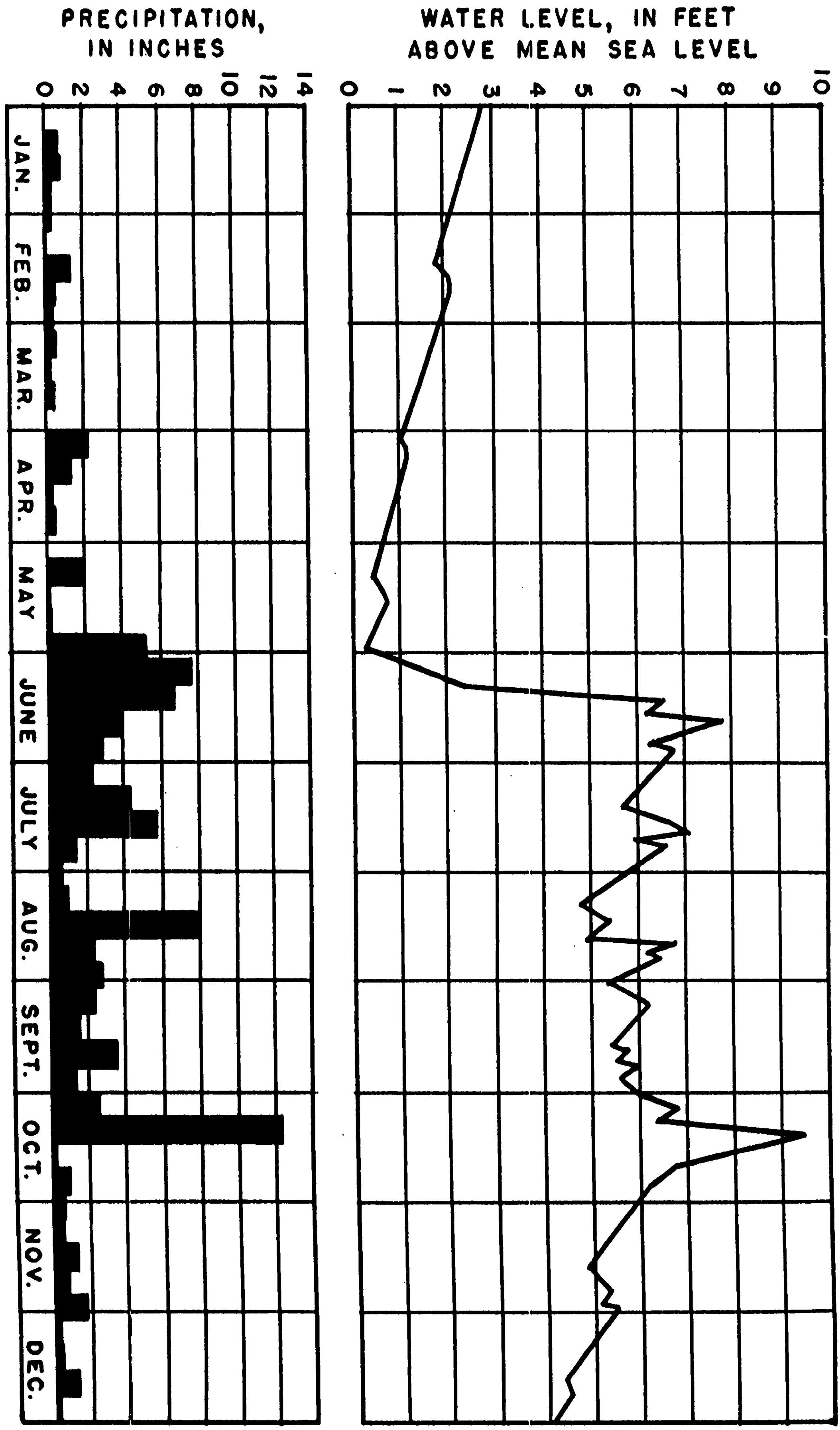

Figure 11. Graphs showing fluctuation of water level in well S 196 and rainfall at University of Florida Subtropical Experiment Station during 1947.

damaging buildings and other structures, and delaying the planting of crops. Low water conditions cause nonirrigated crops to die, allow the organic soils to shrink or to be destroyed by fire, and permit the encroachment of salt water at accelerated rates. The difference between the highest and lowest water levels of record (1940-1951), as recorded in observation wells, ranges from 6 to 11 feet along the coastal ridge and from 7 to 8 feet in the Everglades.

The duration of water-level peaks resulting from rapid rises is generally only a few minutes; hence, an average water level for a month is a better guide to use in evaluating high water-level conditions. The average monthly water level in a well is computed by averaging the daily water-level readings. The range between the highest and lowest average monthly water levels of record is about 7 to 7.5 feet in the upper Everglades and 4.5 to 8.5 feet along the coastal ridge. The maximum, minimum, and mean of the average monthly water levels in selected wells are shown in figure 12.

The net of observation wells equipped with recording instruments in operation in Dade County since 1949 is adequate to determine the annual average water-level conditions in the eastern part of the county. The average water level in 1949 in Dade County was approximately the same as the average water level in the period from 1940-1950 in those wells for which water-level records were available during this 11-year period. Therefore, the map showing average water levels for the period 1940-1950 represents average water levels in 1949.

In Broward County, the average water level for a 10-year period in well S 329 (see fig. 13 for location) is about 4 feet above mean sea level. This coincides fairly well with the average water level in 1949, and it is inferred that the 1940-1950 average for other wells on the coastal ridge may be nearly the same as the 1949 average. The 1949 average levels in wells F 291 and G 561 were about 2 and 1.5 feet above mean sea level, respectively.

The lowest water levels of record (1934-1951) occurred during May and June 1945. The total rainfall during the years 1944-1945 scarcely exceeded that of one normal year, so that the recharge to the aquifer was well below normal. For the most part the numerous drainage canals were uncontrolled during 1944 and only partially controlled in 1945. These canals accelerated the lowering of water levels by the continuous draining of ground water during the drought.

In the southern part of Dade County, in an area centering west and southwest of Florida City, the water table declined to almost 3 feet below

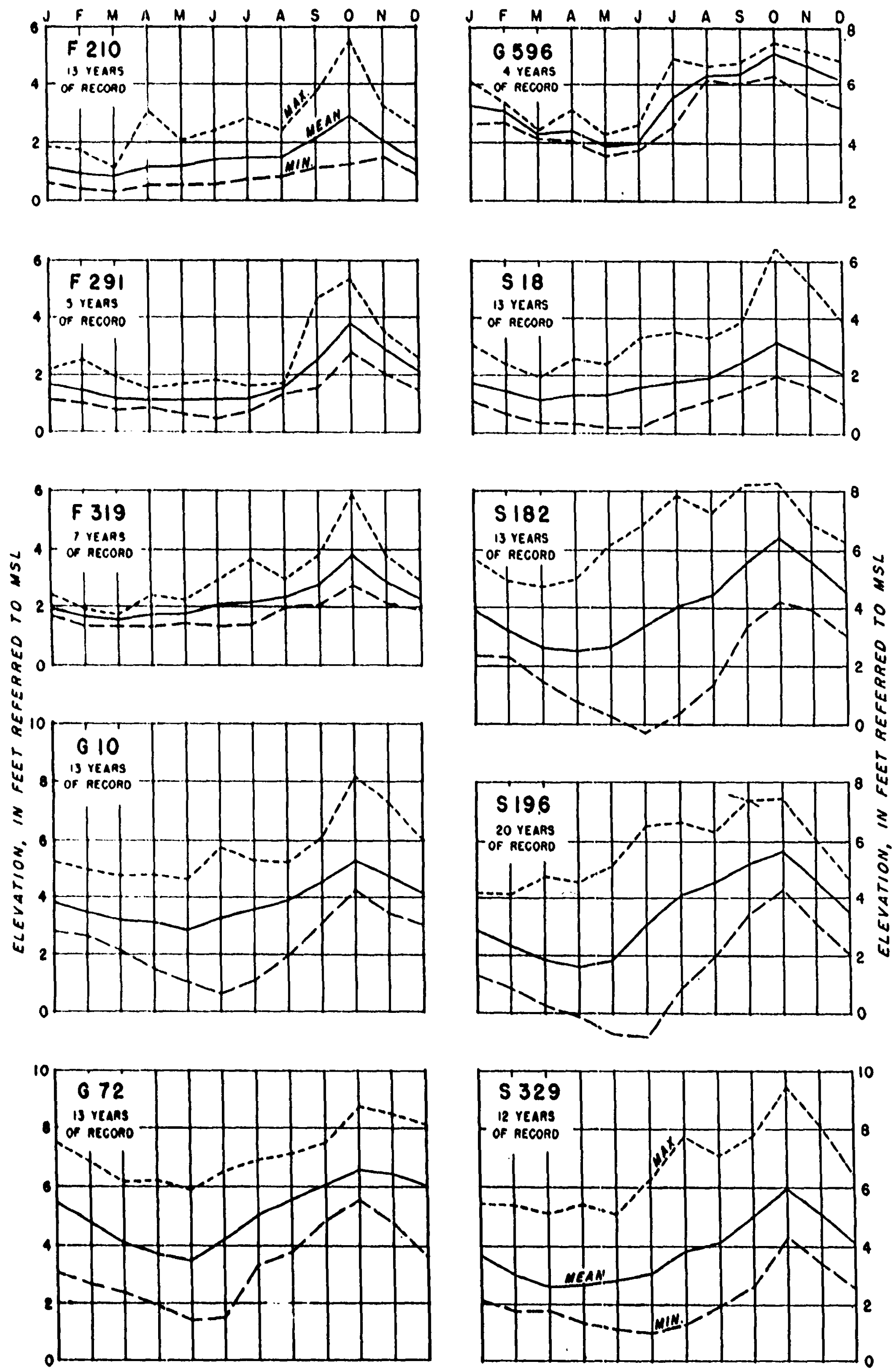

Figure 12. Chart of comparative average monthly water levels in selected wells.

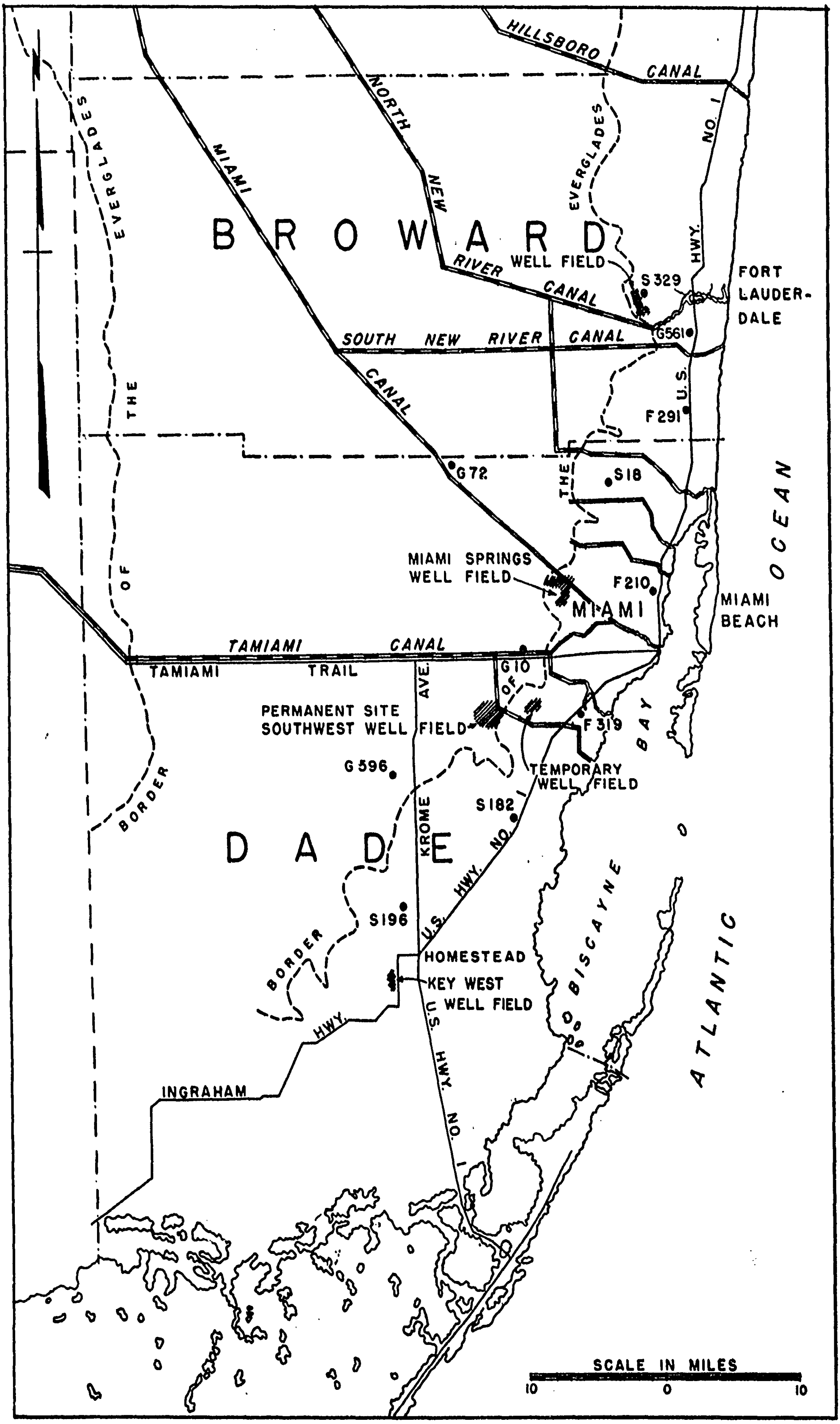

Figure 13. Map showing location of certain observation wells and locations of large municipal well fields.

the average level in Biscayne Bay (the average level in the Bay being about 0.5 foot above U. S. Coast and Geodetic Survey mean-sea-level datum). Parker, Cooper, and Hoy (1948, p. 16) state: "This lowering of the water table below ocean level was largely brought about by the exceedingly high rate of evapo-transpiration acting upon a water table already reduced to sea level by lack of rainfall and by drainage. But, in addition to the natural withdrawal of ground water by evapo-transpiration, irrigation helps reduce water levels still lower. The greater the drought the greater the withdrawal of ground water for irrigation and, thus, the greater the lowering of the water table. It should be emphasized, however, that irrigation withdrawal had very little to do with the development of the large area of below-ocean-level water table in the area centering west and south of Florida City – evapo-transpiration, which may possibly account for more than 71 inches of water a year in this area, was principally responsible. The U. S. Weather Bureau reports the evaporation of 70.704 inches from the Hialeah pan in 1945." A ground-water contour map of Dade County for May 19, 1945, is shown in figure 14.

The lowest stage of record was reached during the period June 17-20, 1945, a month after the detailed measurements used for figure 14 were made, and estimated contours for that period also are shown in figure 14. The position of the contours is based on a few isolated measurements and records from wells equipped with recording instruments. Water levels ranged between 0.3 and 0.4 foot lower than those recorded on May 19 except in the Miami area and the area southwest of Florida City, where they remained the same. A slight amount of rainfall southwest of Florida City maintained the same water levels there.

The lowest ground-water levels of record (1940-1951) in Broward County occurred in 1945 also. Water-level measurements in a number of wells in the eastern part of the county were made on April 14, 1945. The lowest water level probably did not occur until late May; however, the low water levels shown in figure 15, as interpreted from the measurements of April 14, probably were not significantly different from those reached several weeks later.

The highest water-table conditions of record in Dade County occurred during October 1947 (fig. 16). At the end of September the water table along the coastal ridge, especially in the Miami area, was the highest of record (1940-1947) for September, owing to excessive rainfall. The rainfall at Miami in the month of September was 13.65 inches, 5.00 inches above normal for the month. The intense rainfall accompanying a small

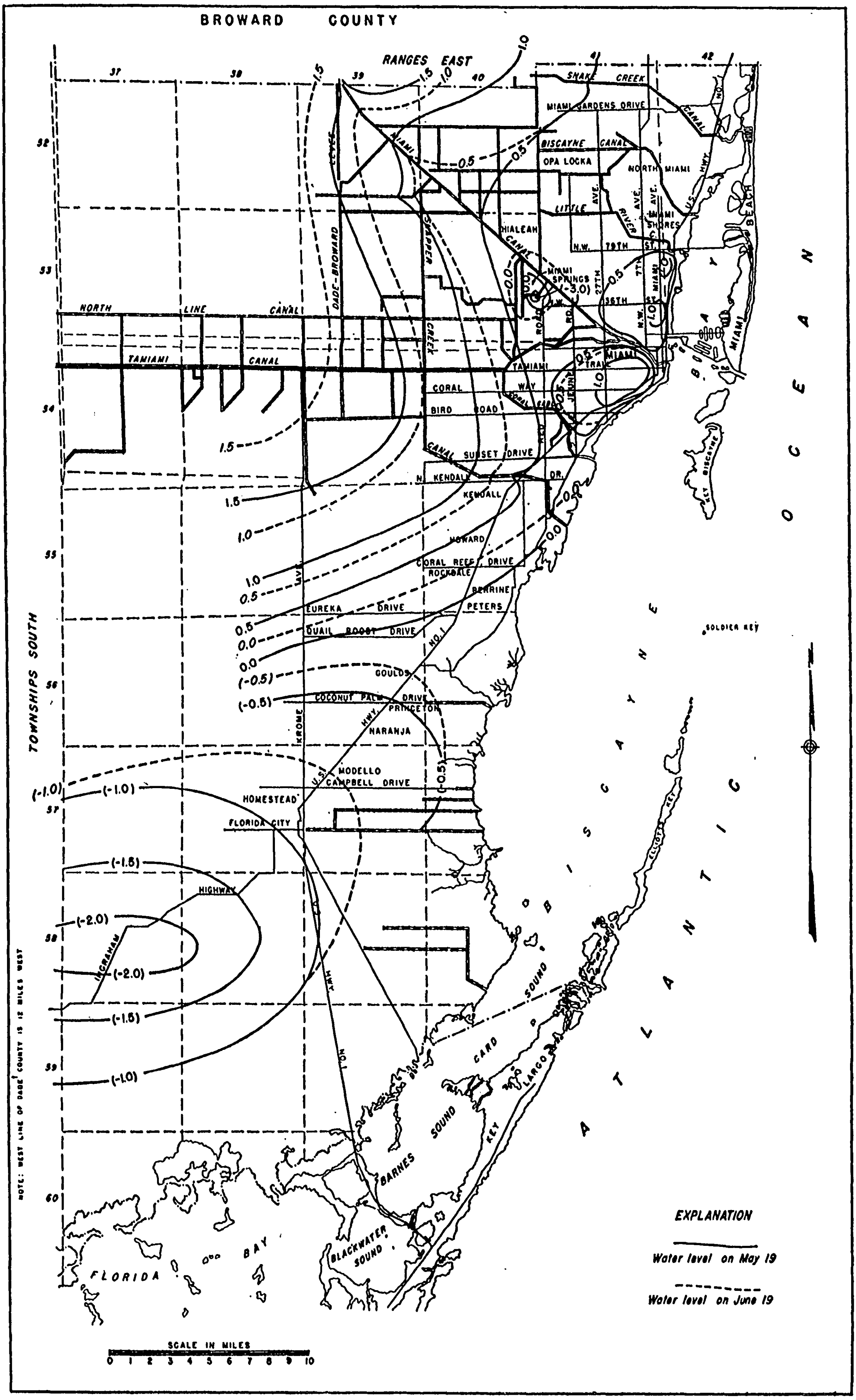

Figure 14. Low stage water-level map of eastern and southern Dade County, May, June 1945.

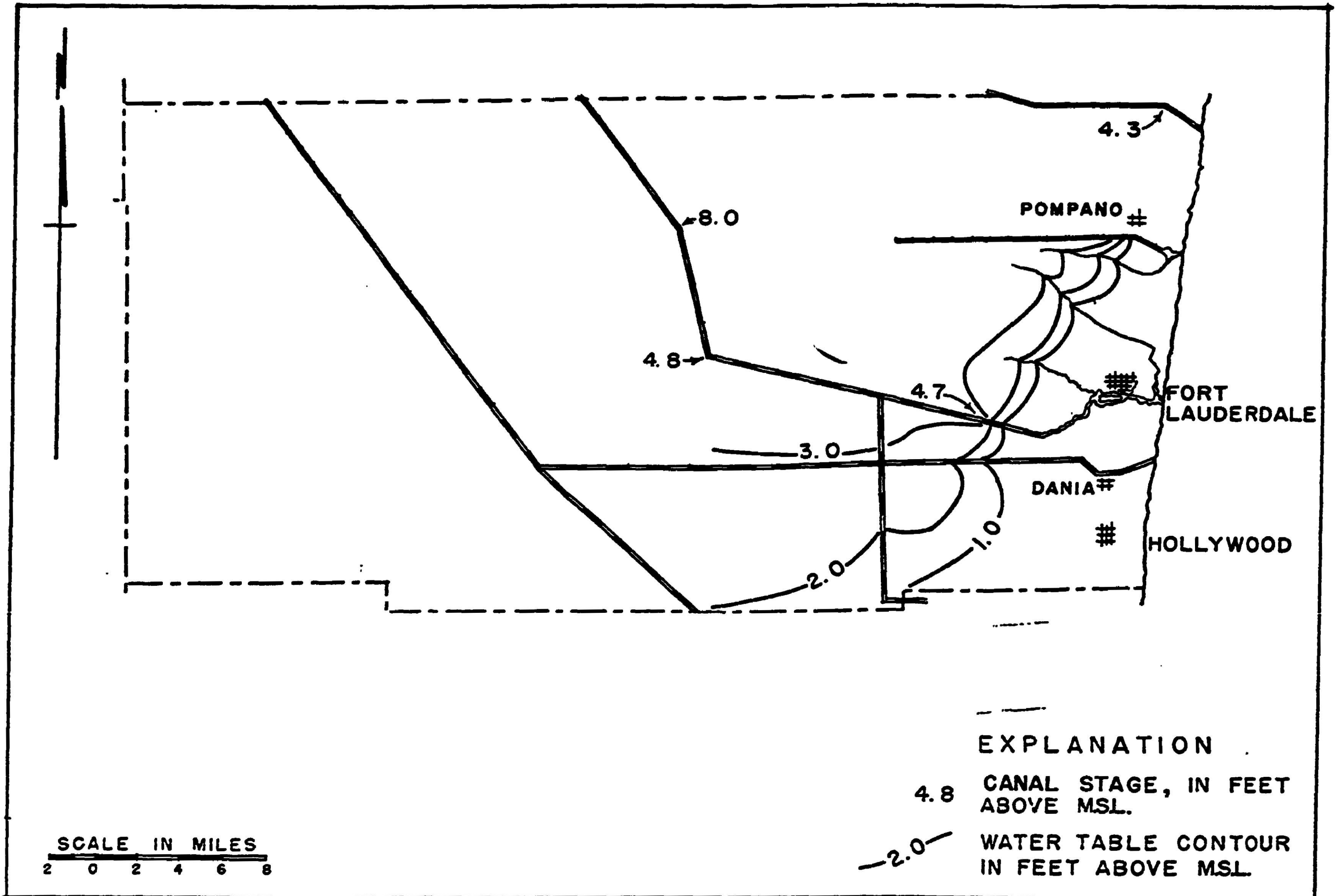

Figure 15. Low stage water-level map of eastern Broward County, April 14, 1945.

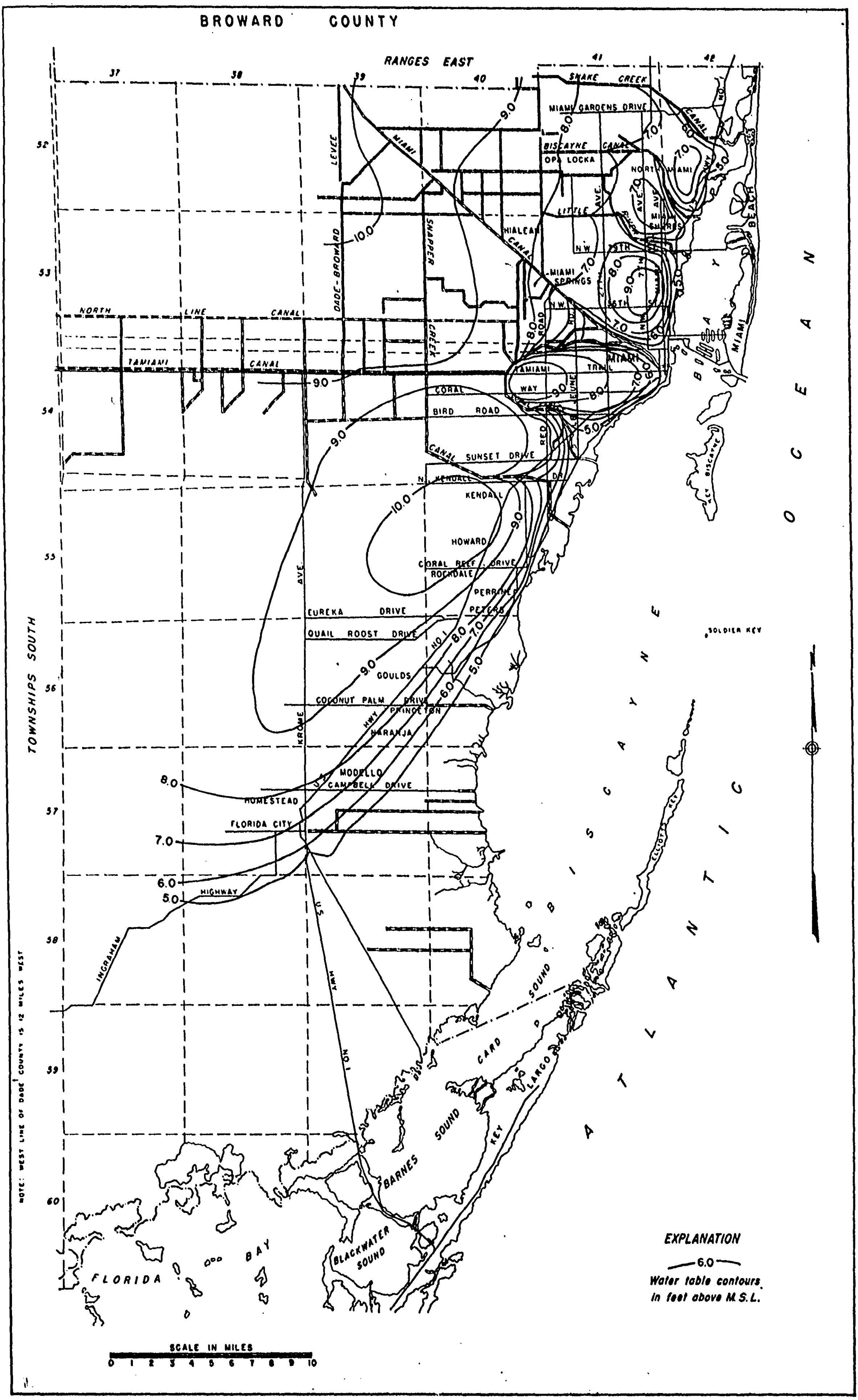

Figure 16. High stage water-level map of eastern Dade County, October 11, 12, 1947.

hurricane on October 11, 12 resulted in water levels reaching what are probably the highest stages that have occurred since the major Everglades canals were completed in 1913.

Rainfall at representative stations in southern Florida ranged as follows:

January 1-October 30, 1947	65.9 to 96.1 inches
June 1-October 30, 1947	50.0 to 74.2 inches
Normal yearly rainfall	53.8 to 62.6 inches

Rainfall on October 11 ranged from 5 to 15 inches and averaged about 10 inches in northern Dade County.

Practically the entire area west of the coastal ridge that was not already flooded became inundated, and the already large overland flow south in the Everglades was increased. The Miami Canal was out of its banks as far east as Hialeah and Miami Springs. Outflow across U. S. Highway 27 occurred from a mile northwest of Pennsuco to the vicinity of the Russian Colony Canal. Other canals were similarly out of their banks. The actual peak lasted several hours at the most, although many areas remained flooded for several weeks.

The water-level map for October 11, 12 showing the peak (fig. 16) was prepared from records of observation wells equipped with recorders, and from measurements made during the flood period, leveled measurements of flood marks, and interpolation of the measurements made in a large number of wells on or about October 7. In a few places the water levels are estimated. However, the map is believed to be a good approximation of actual conditions. In the area between Snapper Creek and Krome Avenue, south of the Tamiami Canal, the presence of several small ground-water mounds and the network of canals make it difficult to visualize the actual shape of the water table, but the general slope was as indicated.

RECHARGE AND DISCHARGE

Local rainfall is the principal source of recharge to the Biscayne aquifer. The amount of rainfall varies within relatively short distances, but it averages about 60 inches annually in Dade County. In Broward County, rainfall records for periods ranging from 5 to 25 years indicate an average annual rainfall ranging from 51 to 65 inches. The lower averages commonly pertain to the Everglades, and the higher ones to the coastal ridge.

A small amount of ground water moves into the aquifer in Broward County from Palm Beach County and from the North New River Canal. In areas where canals are controlled by dams and in areas where the ground-water levels are lowered by pumping, as in the well field in Miami Springs, the canals provide recharge to the Biscayne aquifer.

Discharge from the Biscayne aquifer occurs by ground-water flow into the canals, the Atlantic Ocean, or Biscayne Bay, by evapotranspiration, and by pumping.

Of the 60 inches of average annual rainfall in the coastal ridge area of Dade County, Parker (1951, p. 825) estimates that 22 inches is discharged by evapotranspiration and surface runoff without reaching the water table and 38 inches reaches the water table. Of this, 20 inches is discharged as ground-water flow, and 18 inches is discharged by evapotranspiration of ground water and by pumping from wells. It is estimated that, as of 1950, approximately 4 inches gross was discharged by wells. In areas where heavy pumping forms significant cones of depression, ground water is salvaged because of the decreased evapotranspiration resulting from the lowered water levels.

Ground water is utilized for municipal, industrial, domestic, and irrigation supplies. The estimated pumpage in Dade County, in 1945 and 1950 in gallons per day, is as follows:

	1945	1950
Municipal supplies	35,000,000	65,000,000
Industrial use	12,000,000	20,000,000
Rural use and irrigation	11,000,000	15,000,000
Total average daily pumpage	58,000,000	100,000,000

These estimates do not include the amounts from wells used for air-conditioning and then returned to the ground. In 1954 about 28 mgd was being pumped in this way, although an unknown part of this was saline water. One new hotel under construction in the Miami Beach area will pump 4 mgd of saline water from the ground for air-conditioning and will discharge it into the ocean.

In Broward County sufficient data are not available to estimate the total ground-water withdrawal, but the municipal supplies in the county delivered about 4 billion gallons (11 mgd) in 1951. Percentagewise, the industrial and agricultural uses are about the same as in Dade County; however, a smaller percentage of the people obtain their domestic water from municipal supplies. The total withdrawal probably was not in excess of 30 mgd.

HYDROLOGIC CHARACTERISTICS OF THE BISCAYNE AQUIFER

Ground water is stored in joints, pore spaces, and solution cavities in the rock. In the Biscayne aquifer the major portion of the ground water is stored in cavities formed by the dissolving action of percolating ground water. Ground water moves laterally and vertically under gravitational influence to points of discharge in streams, canals, lakes, and the ocean, and carries, in both solution and suspension, materials removed from the rock.

The permeability of a rock is a measure of its ability to transmit water. Porosity is the property of containing openings or interstices. Materials such as clay or marl are highly porous but relatively impermeable because the components are so finely divided that the molecular attraction between the clay-sized particles tends to hold the contained water in place, thereby restricting movement. High permeability is usually associated with clean, well-sorted gravel or open shell beds. The material that forms the Biscayne aquifer has a permeability equivalent to that of coarse, well-sorted gravel, because the interconnected solution cavities greatly facilitate ground-water movement.

Several pumping tests have been made on wells penetrating the Biscayne aquifer in the Greater Miami area. The purpose of these tests was to determine values for the coefficients of transmissibility and storage of the aquifer at different localities. The coefficient of transmissibility may be defined as the number of gallons of water per day that will move through a complete section of the aquifer one mile wide, under a hydraulic gradient of one foot per mile. A value for the field coefficient of permeability may be determined by dividing the coefficient of transmissibility by the saturated thickness of the aquifer, in feet; thus, the coefficient of permeability refers to the hydrologic characteristic of a unit of the water-bearing rock, whereas transmissibility refers to that characteristic of the aquifer as a whole. The coefficient of storage of an aquifer is defined as the volume of water it releases from or takes into storage per unit surface area of the aquifer per unit change in the component of head normal to that surface. The Biscayne aquifer on a long-term basis behaves as an unconfined or water-table aquifer (although in short tests it may behave as an artesian aquifer having a leaky roof), and the coefficient of storage is essentially equal to the specific yield – 0.10 to 0.35.

The average transmissibility (T) of the Biscayne aquifer, as stated by Parker (1951), is about 5 million gallons per day per foot, the lowest value observed being about 3 million. The storage coefficient (S) ranges from 0.10 to 0.35 and averages about 0.20.

Pumping rates for these tests were about 3,500 gpm, except for the test on well G 218 which was at a rate of about 1,500 gpm. The results of these tests computed by the Theis nonequilibrium formula (1935,

p. 519-524) and as reported by Parker (Parker, Ferguson, Love, and others, 1955, p. 239-274) are summarized in the following table (see fig. 14 for location of test sites).

Test site	*Range in computed coefficient of transmissibility (gpd/ft)* Lowest	Highest
S 1	3,250,000	4,300,000
G 551	9,000,000	14,000,000
G 552	2,800,000	5,700,000
G 553	2,500,000	3,900,000
G 218	3,900,000	4,400,000

At all the test sites the Miami oolite forms the upper part of the Biscayne aquifer, and at most of them it is underlain by a bed of sand. The permeability of the oolite and sand is lower than that of the underlying cavernous limestone of the Fort Thompson formation and thus acts as a leaky roof during the pumping of a well, and the formation initially acts as an artesian aquifer. The Bessel function then can be used in the computations using formulas developed by Jacob (1945, p. 198-208). John G. Ferris (1950, personal communcation) determined the following values from the test data:

Well No.	*Coefficient of transmissibility (gpd/ft)*
S 1	3,200,000
G 551	9,700,000
G 552	3,200,000
G 553	3,200,000

The T value of the test for well G 551 by both calculations is inconsistent with the values for the other tests. The results of the other three tests using the Bessel function are extraordinarily consistent considering the character of the aquifer. The permeability of the Biscayne aquifer probably averages between 50,000 and 70,000 gallons per day per square foot, according to Parker (1951). No satisfactory computation of the storage coefficient has yet been obtained.

Several assumptions concerning the aquifer must be applied in using formulas to determine these coefficients: (1) the aquifer is homogeneous and isotropic and transmits water with equal readiness in all directions; (2) the discharging well penetrates the entire thickness of the aquifer; (3) there is no turbulent flow within the aquifer, and during the pumping there is no vertical convergence of flow lines toward the pumped well; and (4) water is discharged from storage instantaneously with reduction in head.

Inaccuracies in these tests must be assumed because the Biscayne aquifer does not conform adequately to ideal conditions. Owing to the size of the cavities in the aquifer, turbulent flow develops near the pumped wells. Sand-filled cavities locally reduce the flow within the aquifer, so that the permeability is not the same in all directions. Ground-water movement is significantly less through the Miami oolite than through the Fort Thompson formation. Also, within the Miami oolite itself the rate of movement is less in a horizontal than in a vertical direction.

Slight errors or differences in drawdown due to irregularities in the aquifer can cause errors in the value of T. The aquifer is so permeable that pumping causes only small drawdowns; hence, even small observational errors produce large errors in the computed values. However, the various determinations indicate that the general order of magnitude of the value of T is correct, although its value at any specific place is difficult to determine exactly and its value from place to place cannot be estimated without field tests.

By far the most permeable unit within the Biscayne aquifer is the Fort Thompson formation. It is from this formation that most of the irrigation, industrial, and public supply wells in Dade County draw water. Wells may be pumped at high rates for extended intervals with small drawdowns. The character of the rock is such that in many cases short pieces of surface casing are all that are required to complete a well. The remainder of the hole stands open with no danger of caving. However, in some of the coastal ridge areas and in localities a few miles inland from the ridge, sand is more prevalent than it is farther to the west, so that greater lengths of casing are required. Sand occurs in most places as residual fills in solution cavities, although at the coast it occurs as beds of variable thickness, depth, and areal extent. The aquifer grades into a predominantly sandy phase in the Fort Lauderdale area and contains so much unconsolidated material that wells often must be cased to the main water horizon, at which depth screens provide the well finish.

The Biscayne aquifer at Fort Lauderdale, in the vicinity of well G 221, is composed of the Pamlico sand, Miami oolite, Anastasia formation, and Tamiami formation. The Tamiami formation is the most important component. The coefficient of transmissibility of the Biscayne aquifer there was calculated by Vorhis (1948, p. 20, 21), using the graphical method of Cooper and Jacob, to be about 1,200,000. The nature of the test suggests that the value of the coefficient is only tentative but that the general magnitude of the coefficient is valid. The small coefficient, as compared with coefficients at Miami, reflects the unconsolidated character and predominance of sandy material in the Fort Lauderdale area.

Water levels in many water-table wells in southern Florida respond to earthquake shocks in a manner similar to that of an artesian well. The Miami oolite or the sand separating the oolite from the limestone of the Fort Thompson formation acts as a shallow semiconfining layer. These layers, where locally present, do not affect normal water-table conditions within the aquifer. However, they indicate that the components of the aquifer have variable hydrologic characteristics. They cause a difference in water levels immediately after pumping has started or stopped in two adjacent wells, one ending in the Miami oolite or sand and one penetrating the deeper Fort Thompson formation.

QUALITY OF THE WATER

The quality of the water, rather than the quantity, which is very large, is the limiting factor in the use of water from the Biscayne aquifer. Parker and others (1944, p. 13-22) state that unconfined ground water in southeastern Florida may be grouped into three general divisions: (1) the highly mineralized water in the sands that underlie a part of the Everglades in the area north of the margin of the Biscayne aquifer (fig. 1), (2) the fresh water from the highly permeable rocks of the Biscayne aquifer beneath the Everglades and coastal ridge, and (3) the water that has been contaminated by salt-water encroachment.

The ground water from the uncontaminated part of the aquifer is fairly uniform in quality, although along the coastal ridge north and south of Miami it contains somewhat less dissolved minerals and is slightly softer than elsewhere. The hardness generally ranges from 200 to 300 ppm, averaging 250 ppm. The chloride concentration normally ranges from about 20 to 30 ppm. Nearly all the ground water is colored with either organic material or iron, or both. As rainfall percolates down to the water table, it carries small amounts of minerals dissolved from the surface organic soils. Usually the water obtained from the upper portion of the aquifer is the most highly colored, the color decreasing with depth.

One of the most troublesome mineral constituents in water from the Biscayne aquifer is iron. Generally most of the iron can be removed by aeration and settling or filtration, but when not removed it stains clothing and fixtures, and the water has an objectionable taste. There is no apparent consistency in the amount of iron present in the ground water, and predictions cannot be made as to the localities and depths at which water will have a high content of dissolved iron. Analyses of water from wells only a few hundred feet apart, and penetrating the aquifer to the same depth, may show large differences in iron content.

SALT-WATER CONTAMINATION

Salt-water encroachment along the coastal area in Broward County is not yet a critical problem except in the vicinity of certain canals. The high water levels in the northern part of the coastal area have prevented intrusion of salt water from the ocean into the aquifer. Wells drilled to depths of 200 feet at Pompano, three miles inland, show no indication of salt-water encroachment.

In the southern part of Broward County, in the vicinity of Hollywood and Dania, salt water has not yet encroached as far inland as U. S. Highway 1, which is about 1.5 miles from the ocean. The water levels in that area are apparently lower than in the Pompano area, averaging about 2.0 feet above sea level near well F 291. Because of the greater thickness of the aquifer there, an average fresh-water head of 4 to 5 feet above sea level is theoretically required to prevent the intrusion of salt water into the lower part of the aquifer. However, the salt front does not appear to be moving inland at present; therefore, the actual position of equilibrium between salt water and fresh water in the aquifer may be east of the theoretical position. It may be that, if no detrimental change in the present water-table conditions occurs, the salt front in that area will not progress any farther inland.

Salt-water encroachment in the Fort Lauderdale area may have progressed inland about two miles in the vicinity of the North New River and South New River canals; however, in most of that area it is believed to have progressed only a mile or so from the shore.

Salt-water contamination due to direct encroachment from the ocean certainly has not advanced as far as the Fort Lauderdale well field, which is six miles inland. However, Vorhis (1948) indicates that the well field is underlain at a depth of 200 feet by salty connate (or residual) water. He points out also that chloride encroachment into the aquifer underlying the well field can be from any of four sources: (1) the ocean, (2) salt-water tongues along the canals extending from the ocean, (3) brackish water, residual from Pleistocene encroachment seeping into the canals from parts of the Fort Thompson formation in the Everglades, and (4) the salty connate or residual water underlying the well field at depth. The most serious threat of well-field contamination is from the

North New River Canal. When the salt-water tongue extends up the canal during low-water stages, lateral movement of salt water from the canal into the aquifer can occur.

Although salt-water encroachment is important in Broward County, it is of greater importance in Dade County. The physical and theoretical aspects of encroachment in Dade County have been studied in detail continuously since 1939.

The encroachment of salt water into the aquifer in Dade County has been described in detail by Brown and Parker (1945) and Parker (1945). Parker (1951, p. 826, 827) states that in the Miami area "The canals have effectively induced encroachment by two chief means:

"1. They have served to drain off fresh water stored in the aquifer in the coastal zone.

"2. They have acted during certain dry periods as inland extensions of the sea, carrying salty water inland for several miles and allowing it to leak out to contaminate the aquifer all along their course.

"Lowering the water table nearly to sea level under the coastal ridge has caused a loss in head in some places of approximately 5 ft. compared with the original head before drainage began. Not only is this a large actual loss of fresh water in storage, but it is the factor that led to the inland movement of a salt water wedge from Biscayne Bay, operating in accordance with the Ghyben-Herzberg principle.

"The five maps in Fig. 5 [extended through 1953 in fig. 17 of this report] show the general pattern of encroachment into the Biscayne aquifer in the Miami area for a period of 47 years. They show that the major spread of the salt water wedge occurred between 1943 and 1946. During that time, a lengthy drought occurred, and in 1945, water levels fell to all time lows in this area. Parker [1945, p. 526] reckoned, on the basis of studies in the Silver Bluff area, that the rate of encroachment until 1943 had been approximately 235 ft. per year. In a 27-month period that overlapped 1943-44, the front of the salt wedge advanced 2,000 ft., or at a rate of approximately 890 ft. a year."

Dams were placed in the Miami, Biscayne, and Little River canals, with the result that there was an actual seaward retreat of the salt-water tongue from 1946 to 1951. Dams were placed also in the Tamiami Canal and Coral Gables Canal, but they were so far inland that they had little, if any, effect in opposing the salt-water encroachment; salt-water contamination continues to spread in those two areas. Figures 19 through 24 show profiles along the canals, indicating the relative positions of the

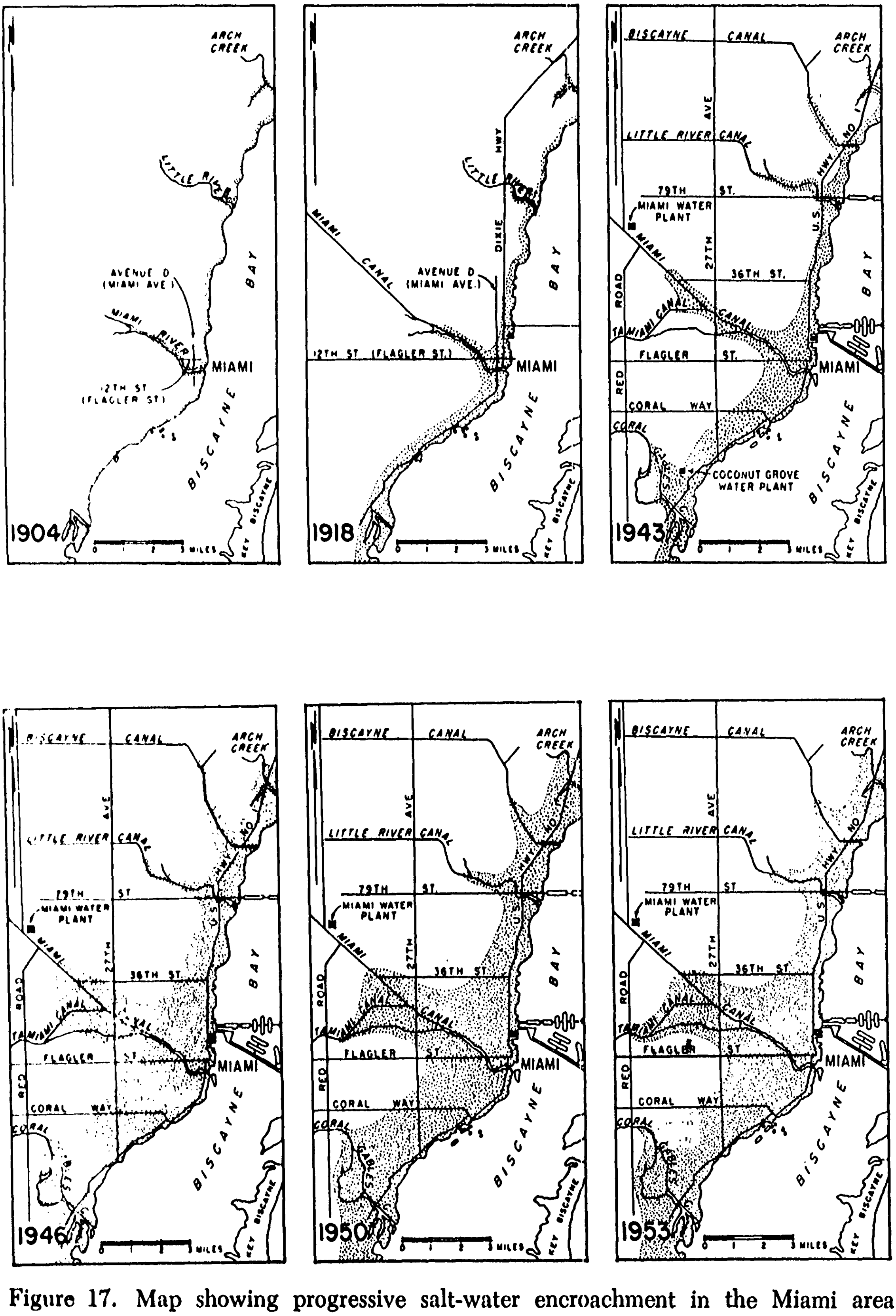

Figure 17. Map showing progressive salt-water encroachment in the Miami area from 1904 through 1953. (Note: stippling shows extent of areas that have chloride concentration approximating 1,000 ppm or more, at the base of the aquifer.)

salt-water front (defined as the point where the water contains 1,000 ppm of chloride) in 1946 and 1950, based upon the interpolation of chloride analysis of wells at varying distances from the canals. Figure 18 is an index map showing the location of the profiles.

The dams, where placed in effective positions, have largely prevented the inland intrusion of salt water up the canals during the dry seasons and have raised the fresh-water head in the aquifer to some degree. The wedge of salt water in the intercanal area is in the same relative position as in 1946 (fig. 17), probably as a result of the water-control program and increased rainfall since 1947 which have maintained the average water levels in those areas at higher stages than in 1946.

The depth of the base of the aquifer is shown in figure 2. In the areas in Dade County where salt-water encroachment is a threat, the base of the aquifer is about 100 feet below sea level. Relatively impermeable materials floor the aquifer, thus making only lateral encroachment possible. Under strict application of the Ghyben-Herzberg principle, a 2.5-foot head of fresh water above bay level or 3.0-feet above mean sea level is required to hold salt water out completely; however, modifying factors make the required fresh-water head somewhat less. The progressive reduction in the depth to the bottom of the aquifer westward from the bay means that progressively less fresh-water head is needed inland.

ADEQUACY OF SUPPLY

The area underlain by the aquifer, excluding the part that now contains salt water, is about 3,000 square miles. The average water-saturated thickness in that area is about 72 feet. There is about 9,000 billion gallons of fresh water stored in the aquifer, if the average storage coefficient is assumed to be 0.2. At a low-water stage, such as that in 1945, the storage is reduced by only about 5 to 7 percent. Although the storage is large and there is a large area where water supplies could be located, the economics related to transmission make it most desirable that the supplies be located as close as possible to the area of use. Therefore, most of the present and future pumping will be on and closely adjacent to the coastal ridge, an area of about 700 square miles.

In considering the potential of the aquifer in the eastern parts of Dade and Broward counties, flow of ground water into the coastal area from the Everglades must be considered. There is a lack of information, however, concerning the direction of movement in much of the area of the Everglades. In the coastal ridge and part of the adjacent Everglades,

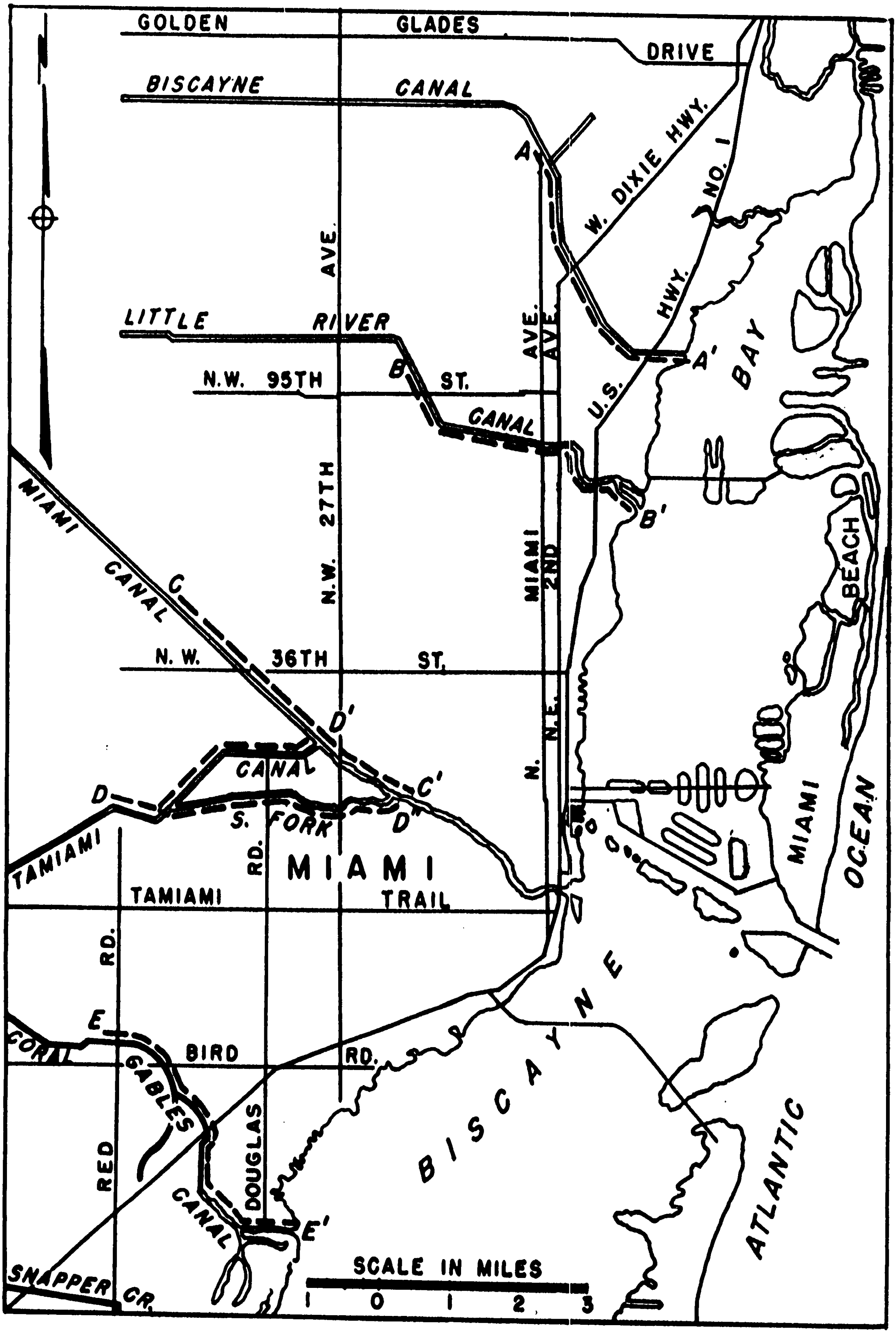

Figure 18. Map showing location of chloride profiles of figures 19 through 24.

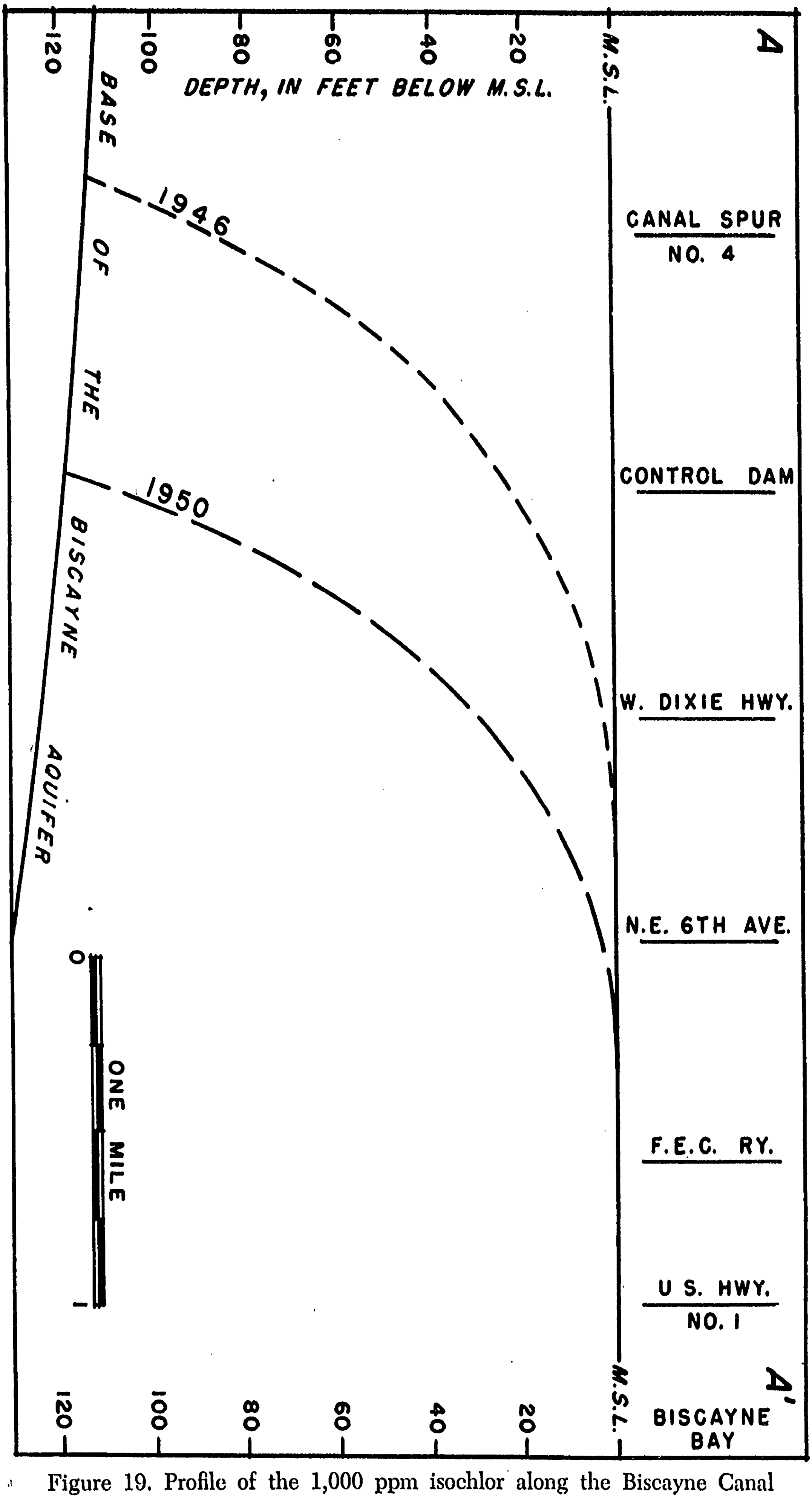

Figure 19. Profile of the 1,000 ppm isochlor along the Biscayne Canal in 1946 and 1950.

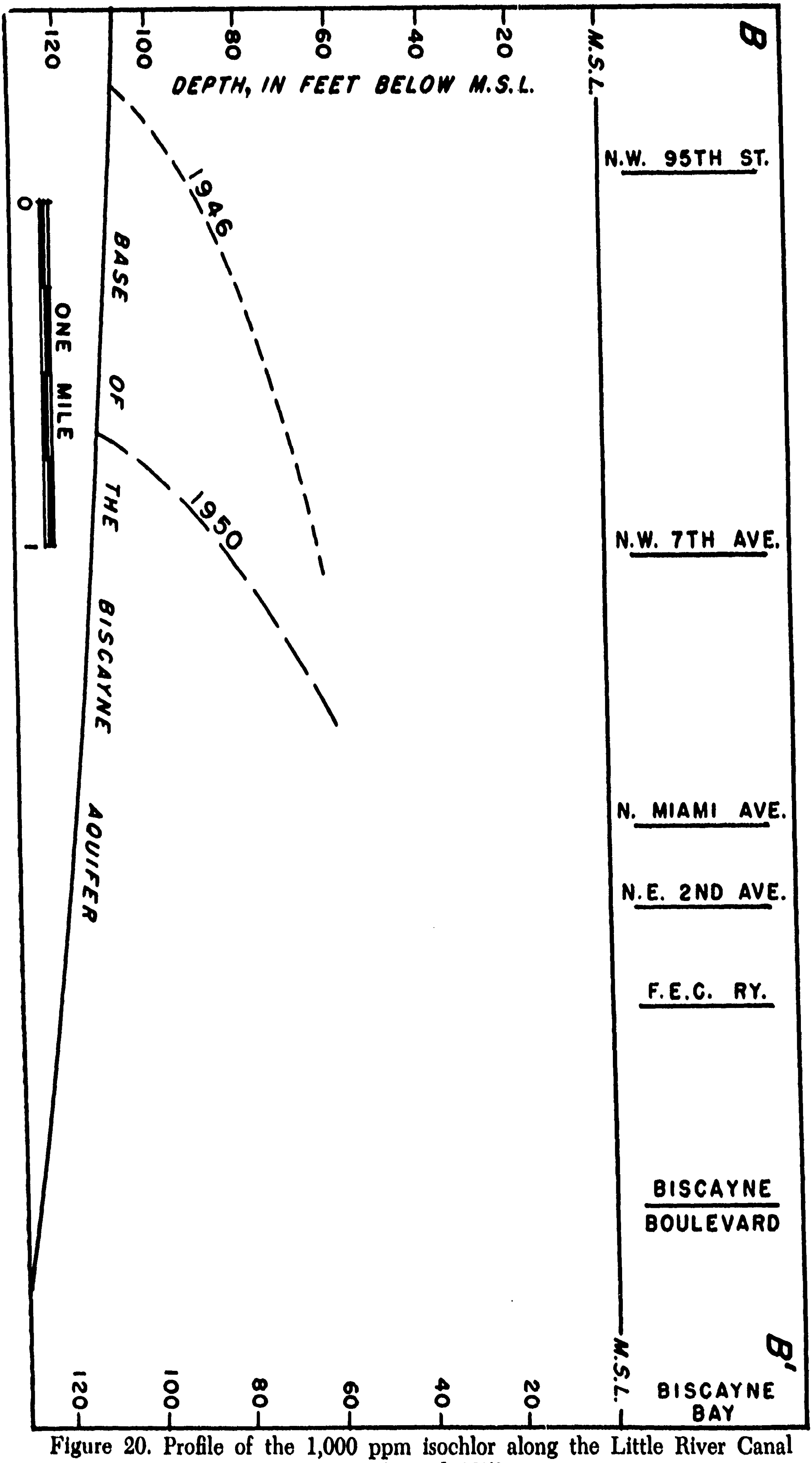

Figure 20. Profile of the 1,000 ppm isochlor along the Little River Canal in 1946 and 1950.

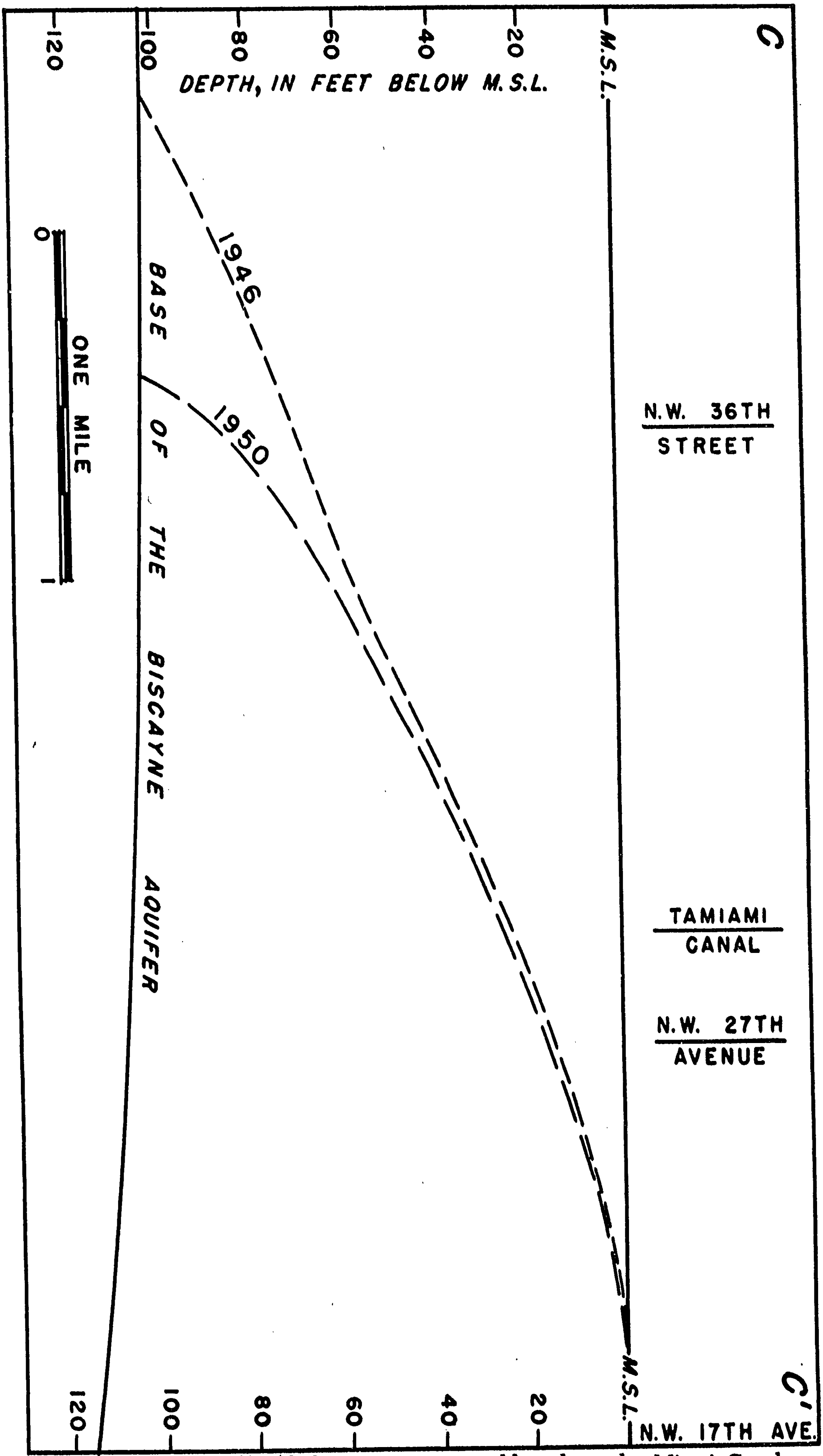

Figure 21. Profile of the 1,000 ppm isochlor along the Miami Canal in 1946 and 1950.

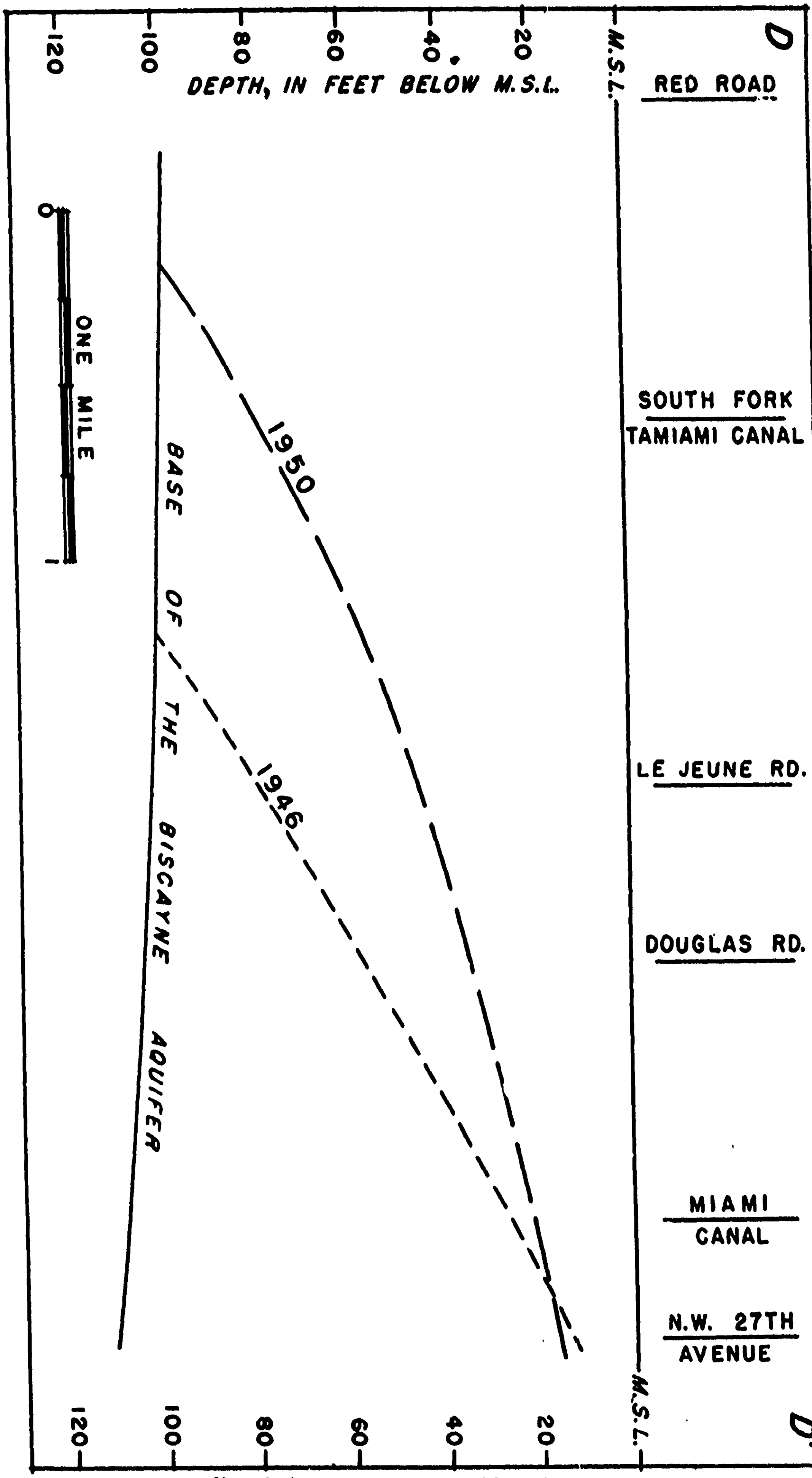

Figure 22. Profile of the 1,000 ppm isochlor along the Tamiami Canal in 1946 and 1950.

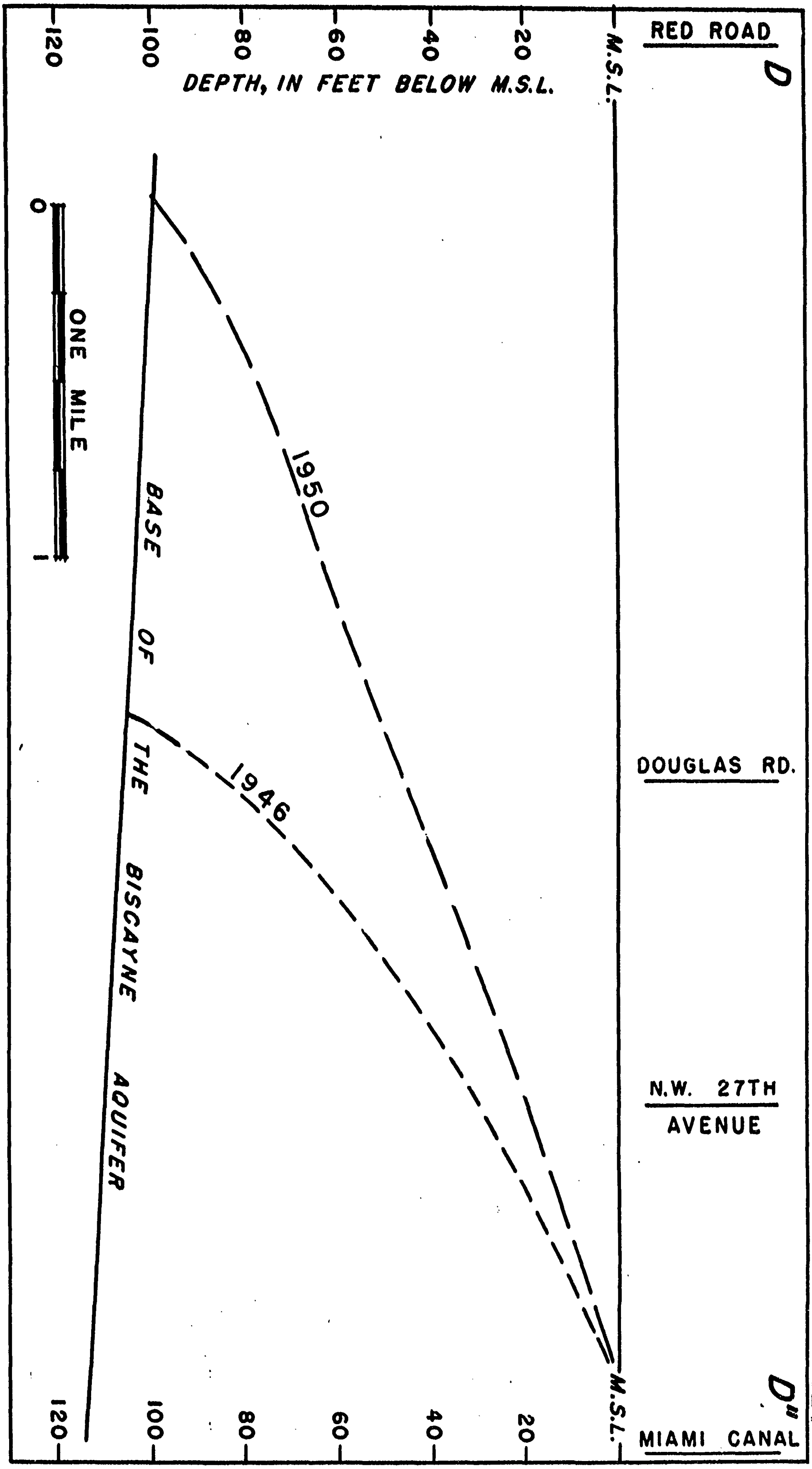

Figure 23. Profile of the 1,000 ppm isochlor along the South Fork of the Tamiami Canal in 1946 and 1950.

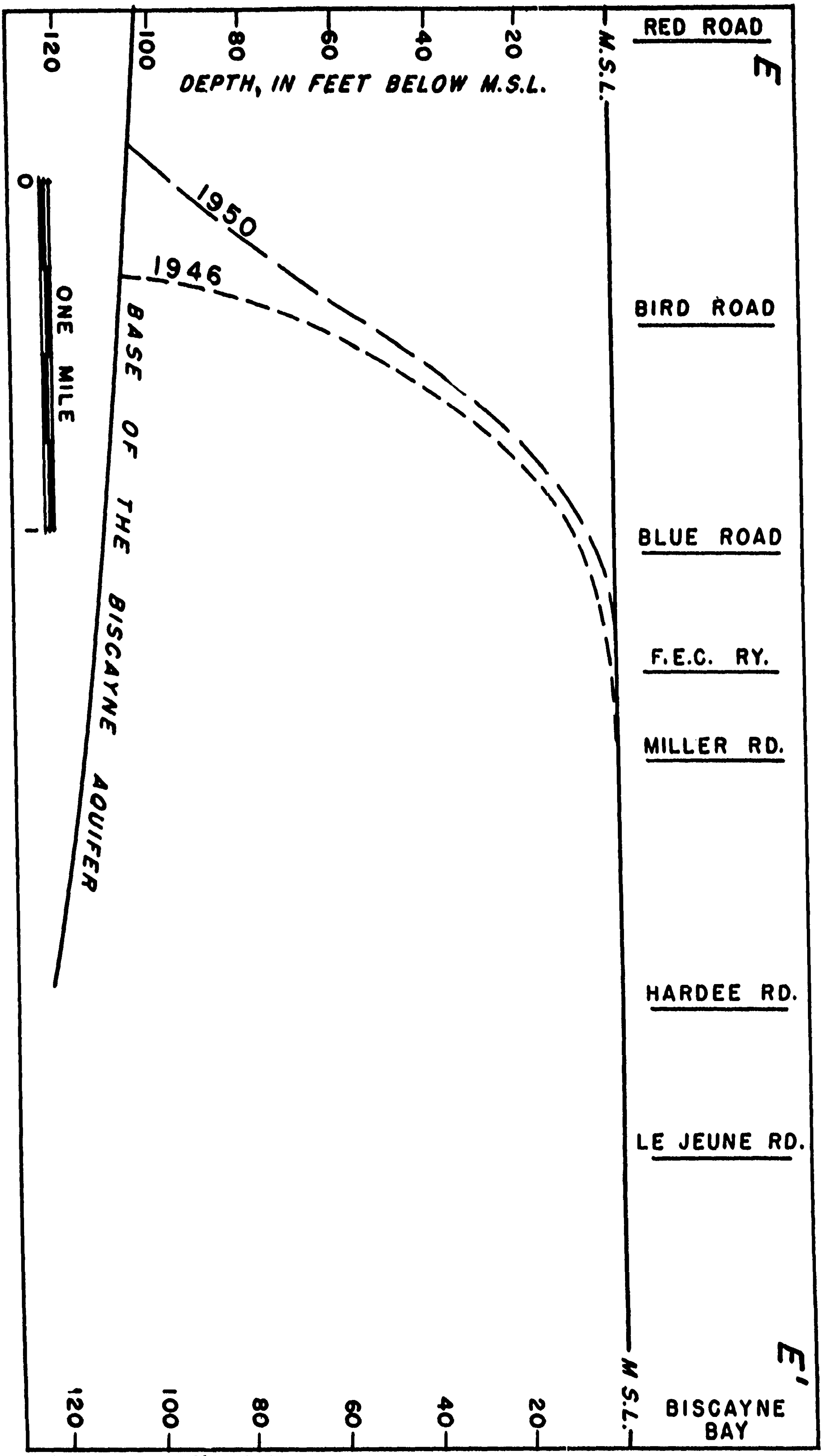

Figure 24. Profile of the 1,000 ppm isochlor along the Coral Gables Canal in 1946 and 1950.

an area which composes about one-third of the extent of the aquifer, the ground-water flow is to the east and southeast during most of the year. In the remainder of the Everglades ground water presumably flows to the south, and, under the conditions that were prevalent in 1950, this flow was not a direct source of water for the coastal ridge. However, flood control structures and the establishment of proposed conservation areas in the western two-thirds of the area may make large additional quantities of water available for recharge, thus changing the water-table gradient and increasing ground-water flow from the Everglades toward the coast.

An estimate of the ground-water potential of the aquifer requires an inventory of the recharge that would include rainfall, the inflow from Palm Beach County to the conservation areas, and the recharge from drainage wells, septic tanks, and irrigation; and the discharge, consisting of evapotranspiration, ground-water outflow to the ocean directly from the aquifer and from the canals, and losses due to pumping. The lack of detailed data, particularly canal discharge data, makes a complete water inventory impossible at this time. Rainfall over the 3,000 square miles ranges from about 54 to 64 inches, averaging 60 inches. Computations for the coastal ridge area indicate that about one-third of this rainfall, or about 1,000 billion gallons a year, is eventually discharged from the aquifer by ground-water flow. The total amount of this annual water might be pumped if the aquifer were not bound by salt water on the eastern and southern sides.

The lowering of water levels due to pumping in an area salvages some of the water that might otherwise be lost by evapotranspiration. The southwest well field (fig. 3) of the city of Miami, as planned, will eventually withdraw 100 mgd. It is estimated by Parker and others (1955, p. 287) that 15 mgd may be salvaged from reduced evapotranspiration.

The estimated pumpage of 100 mgd in Dade County is about 20 percent of the estimated ground-water discharge into the ocean and canals. At present a large part of the use is not consumptive and the water recharges the aquifer through irrigation, septic tank drains, and drainage wells. Enlargement of the sewer system for the city of Miami, and the construction of similar but smaller systems in other municipalities, will diminish this type of recharge. It appears likely that, under the present system of canal control, additional wells so located as to leave a buffer strip (an area in which water levels are not affected by pumping) between them and the ocean could withdraw 10 times the amount of water pumped in 1950 without causing salt-water encroachment. It is estimated that at least 2 billion gpd could be pumped from areas west of the coastal ridge, if the ridge were used as a buffer zone. These estimates are based partly on the fact that more water would be available because of reduced evapotranspiration when the water table is lowered, and that more of the aquifer would be available for storage of rainwater that is normally rejected when the aquifer is full or nearly full, and on the possibility of recharge in the flood control conservation areas by water diverted from Palm Beach County. These factors increase the amount of water computed as available for withdrawal.

A large supply of ground water is available in the part of the aquifer lying west of the salt-water front in Dade County and west of U. S. Highway 1 in Broward County. To protect this supply, salt-water encroachment must be strictly controlled by maintaining proper placement of dams or locks in canals, by proper control of water levels in the canals, and by locating well fields and other centers of large withdrawals so that pumping will not lower water levels below the minimum stage required to prevent additional encroachment. Storage in the aquifer should be continually measured and evaluated, and future development of the ground-water resources carried out in accordance with the principles outlined.

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