Geochemistry of the Floridan Aquifer System in Florida and in Parts of Georgia, South Carolina, and Alabama

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REGIONAL AQUIFER-SYSTEM ANALYSIS—FLORIDAN AQUIFER SYSTEM

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work, geochemistry, and regional ground-water flow of the Floridan aquifer system. The Floridan study is one of several such studies in the Geological Survey's Regional Aquifer-System Analysis (RASA) program, which is a systematic effort to investigate aquifer systems that supply a major part of the Nation's water supply. The results of the Floridan RASA study are reported in U.S. Geological Survey Professional Paper 1403, which consists of the following chapters: A, summary (Johnston and Bush, 1988); B, hydrogeologic framework (Miller, 1986); C, hydraulics and regional flow (Bush and Johnston, 1988); D through H, subregional descriptions, including simulation of local water-supply problems; and I, geochemistry (this report).

PURPOSE AND SCOPE

The purposes of this report are to (1) summarize the available information on the mineralogy of the rocks and the quality of the water in the Floridan aquifer system and (2) describe the principal processes that have produced the present water chemistry.

One constraint of the RASA program was to use available data to the extent possible, in order to minimize costs and shorten time of study. Therefore, this report contains the published and unpublished results of many previous investigations. New chemical and isotopic data were collected in some areas, but a comprehensive program of water and rock sampling for chemical or isotopic analysis was not within the scope of the project. This report contains descriptions of climate, geological framework, hydrology, mineralogy, and chemistry of the Floridan aquifer system. The report concludes with a discussion of conceptual geochemical models and results of mass-transfer modeling of major chemical constituents in the Upper Floridan aquifer.

PREVIOUS REPORTS

A comprehensive bibliography of studies of the Floridan aquifer system published prior to 1965 is given in Stringfield (1966). A brief list of papers that discuss aspects of Floridan aquifer system geochemistry includes Back (1963), Hsu (1963), Hanshaw and others (1966), Kaufman and others (1969), Back and Hanshaw (1970), Hanshaw and others (1971), Rightmire and others (1974), Osmond and others (1974), Plummer (1975), Briel (1976), Kaufmann and Bliss (1977), Plummer (1977), Dalton and Upchurch (1978), Randazzo and Hickey (1978), Hanshaw and Back (1979), Rye and others (1981), Steinkampf (1982), and Plummer and others (1983). The other chapters of Professional Paper 1403 and interim reports by Ryder (1982), Tibbals (1981), and Krause (1982) should be consulted for more detailed descriptions of the geology and hydrology of the Floridan aquifer system.

ACKNOWLEDGMENTS

The data used in this study were obtained from published reports of the Geological Survey, many of which were prepared in cooperation with State and local water resources agencies and from unpublished data in the files of Geological Survey offices in Florida, Georgia, Alabama, and South Carolina. I thank the personnel of Geological Survey offices in Georgia and Florida for their help with ground-water sampling and data verification, including J.B. McConnell, M.H. Brooks, D.W. Hicks, R.T. Kirkland, D.L. Stanley, C.N. Geller, D.P. Brown, A.C. Lietz, L.A. Bradner, J.B. Martin, P.E. Meadows, R.A. Orr, and J.D. Fretwell. I am especially grateful to the members of the Southeastern Limestone RASA Study team and G.D. Bennett for their help, advice, and encouragement during the course of this study. Thanks also to L.N. Plummer, William Back, D.C. Thorstenson, and R.W. Lee for their help with and review of the geochemical interpretations presented in this paper.

HYDROGEOLOGIC SETTING

CLIMATE AND RECHARGE

The study area (fig. 1) has a climatic range from temperate in the north to subtropical in the south and along the Gulf Coast. Mean annual temperatures range from about 18.6 °C in east-central Georgia to about 25.4 °C in the Florida Keys. These moderate air temperatures are partially reflected in ground-water temperatures measured in the Upper Floridan aquifer (fig. 2).

Precipitation is the primary source of recharge to the Floridan aquifer system. Annual precipitation (mostly rainfall) ranges from 40 inches (in) in Key West, Fla., to more than 65 inches in the Florida Panhandle and in southern Alabama. Most of the rainfall in Florida and the coastal areas of Alabama, Georgia, and South Carolina occurs as thunderstorms during the summer months. A significant part of the average annual rainfall in coastal areas may also be produced by tropical storms and hurricanes. In central Georgia, annual rainfall is more evenly divided between summer thunderstorms and cyclonic (frontal) storm systems that occur during winter and spring.

Stable isotope chemistry of the water that recharges the aquifer system is affected by the seasonal distribution of rainfall. As discussed by Gat (1980, p. 30), rainfall during the winter months is lighter in isotopes of ^{18}O and ^{2}H than during the summer months. Because evapo-

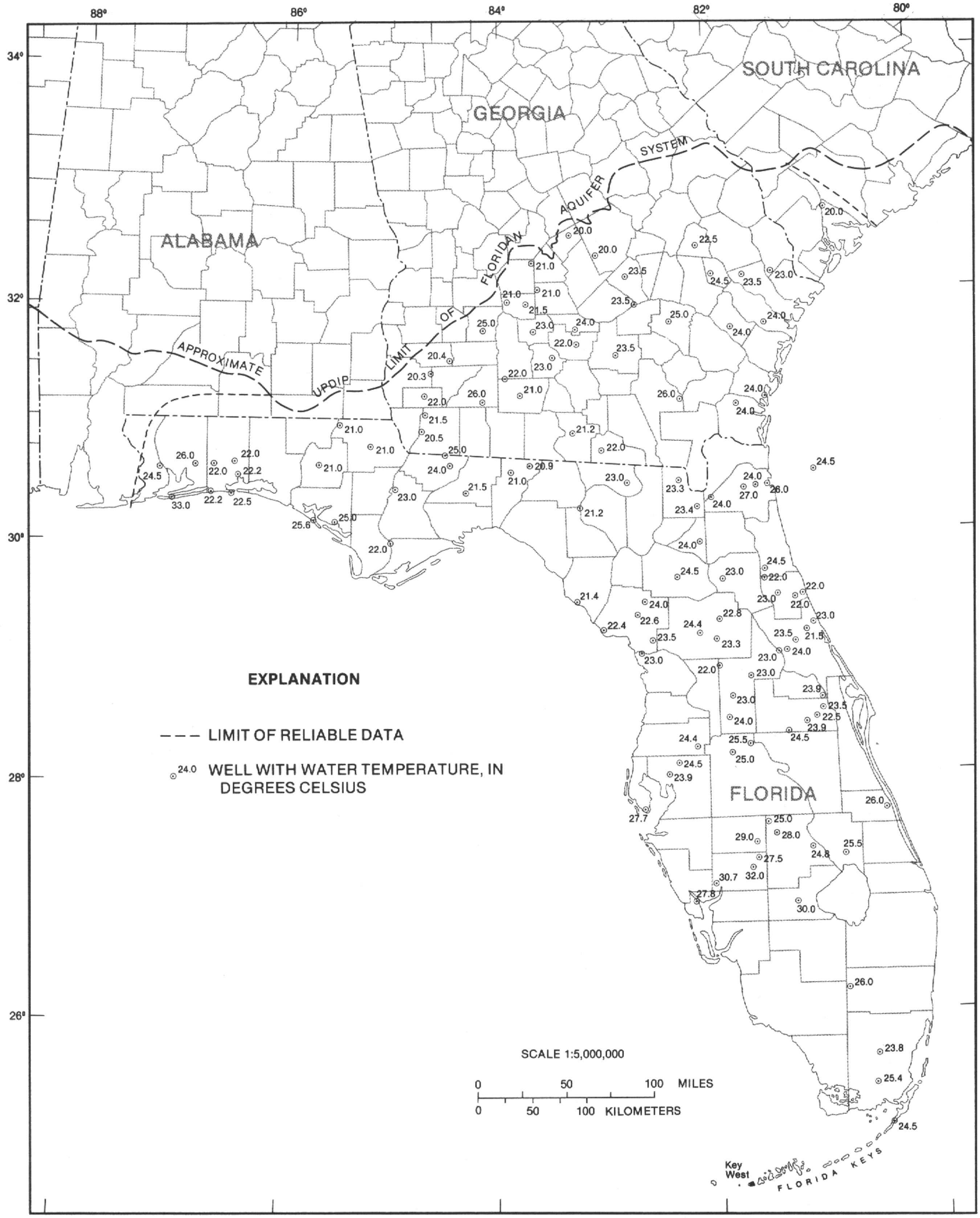


FIGURE 2.—Temperatures measured in water samples from selected wells in the Upper Floridan aquifer.

transpiration is less during winter than during summer, more winter rainfall recharges the aquifer system.

Isotopic data from wells in the Floridan aquifer system (fig. 3*A*) are plotted in figure 3*B*. The meteoric water line (Craig, 1961) in figure 3*B* is a relation developed from the isotopic composition of freshwater worldwide. As shown in figure 3*B*, the rainwater recharging the aquifer system in central Georgia is isotopically lighter (values of $\delta^{18}O$ and $\delta^{2}H$ are more negative) than recharge in central Florida. The Georgia data generally lie near and to the left of the meteoric line; the Florida data lie to the right and away from the line. This pattern probably results from subtle differences in the rate of the evaporation and condensation cycles of the rainfall recharging the aquifer system in the two States.

A few isotopic data plotted in figure 3*B* lie off the meteoric line, toward the point that represents standard mean ocean water (SMOW). The data points of shallow-deep pairs show a similar trend toward the SMOW reference point. These data suggest that mixing of seawater with freshwater has occurred in the aquifer system. In some areas, there is seawater deep within the aquifer system which may be tapped directly by wells (for example, wells 1, 2, and 3, fig. 3*A*). In other areas, remnant seawater at depth has been diluted by the freshwater flow system (for example, wells 4 and 6, fig. 3*A*).

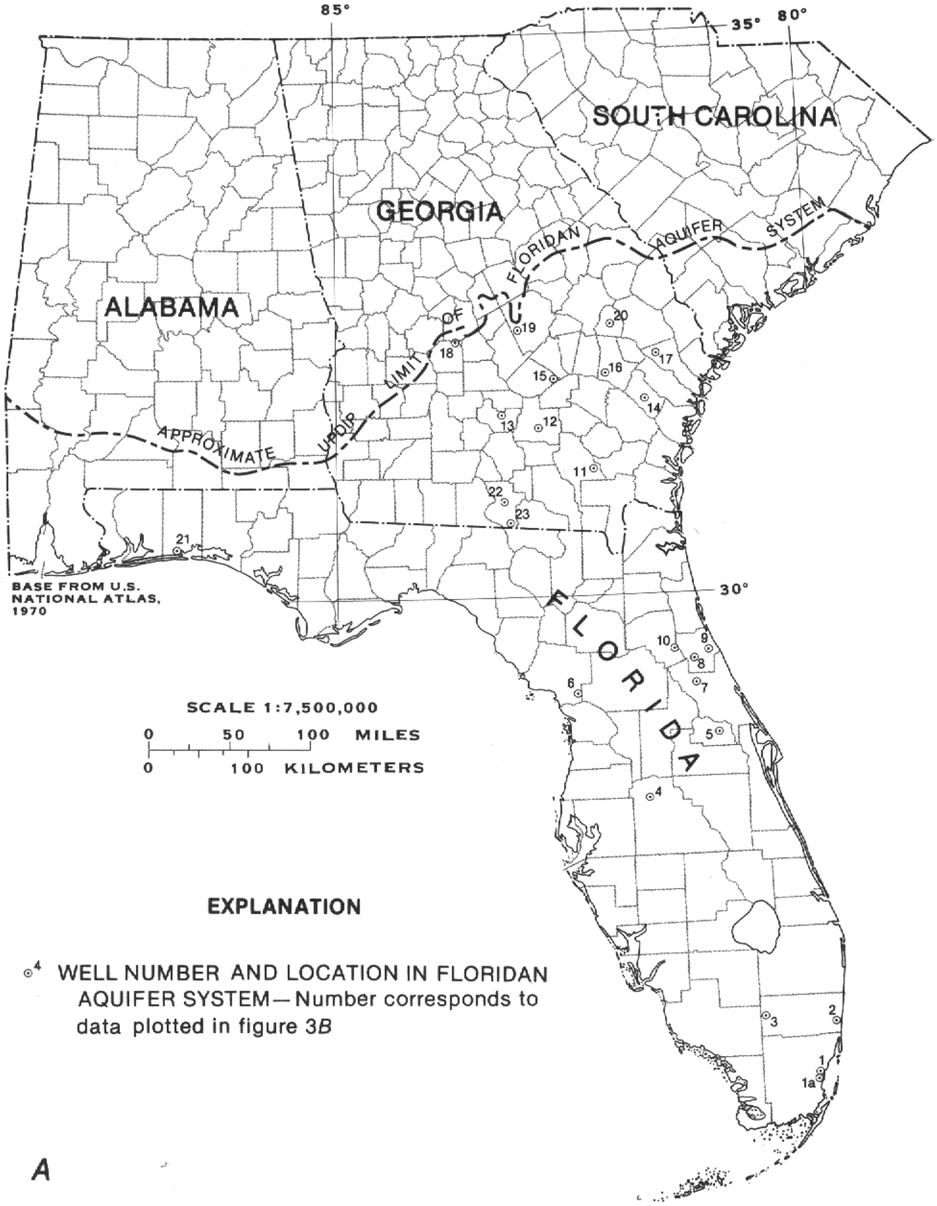
The chemical quality of ground water in the Upper Floridan aquifer is derived initially from the chemical quality of recharge. The quality of ground water at any point in the Upper Floridan aquifer has evolved from a sequence of chemical reactions between the recharge water and aquifer materials. Later sections of this paper discuss reaction models that simulate the chemical evolution of ground water in the Upper Floridan. The chemistry of infiltration recharge is affected by processes, such as evaporation and dissolution of natural and manmade salts in soils, that tend to increase the concentrations of major ions in ground water above those of rainwater. Yet, for modeling purposes, estimates of the quality of recharge in areas where the aquifer is unconfined can be made from the chemistry of precipitation.

Available data on the chemistry of precipitation over the study area are sparse (fig. 4). A few studies have been made (for example, Junge and Werby, 1958; Lodge and others, 1968; Hendry and Brezonik, 1980; Irwin and Kirkland, 1980; National Atmospheric Deposition Program, 1980a–e, 1981a–c; Tanaka and others, 1980), but complete regional coverage is not available. The available data are summarized in table 1. As discussed by Gambell and Fisher (1966), sea salt is the most significant source of chloride in rainfall in coastal areas; they also noted a sharp decrease in chloride concentrations in rainfall collected farther inland. It is possible, therefore, that the data reported in table 1 for coastal cities are not representative of precipitation chemistry farther inland, where most of the recharge to the Upper Floridan occurs.

GEOLOGIC FRAMEWORK

The Floridan aquifer system as defined by Miller (1986, p. 44) is a vertically continuous sequence of carbonate rocks of generally high permeability that are mostly of Tertiary age; the rocks are hydraulically connected in varying degrees, and their permeability is generally an order to several orders of magnitude greater than that of the rocks bounding the system above and below. The system consists of rock units varying in age from Late Cretaceous to early Miocene and is composed of stratigraphic units previously included in the principal artesian aquifer described by Stringfield (1966) and in the Floridan aquifer in Florida described by Parker and others (1955). Figure 5 gives the general correlation of stratigraphic units and aquifer terminologies. The base of the system is shown in figure 6, simplified from a map by Miller (1986, pl. 33). As explained by Miller (1986), correlation of the geologic units that form the base of the system is imprecise at this time and, consequently, similar rocks may have different formation names in different States. Because the base of the aquifer system is a hydrologic boundary, corresponding to a substantial change in permeability, the age and lithology of the rock in which the base is mapped may vary considerably. In much of the region, the base of the system is in low-permeability, clastic rocks (locally calcareous) which separate the limestones of the Floridan aquifer system from deeper clastic aquifers. In peninsular Florida and southeastern Georgia, rocks containing bedded anhydrite form the base of the Floridan aquifer system.

The top of the aquifer system, shown in figure 7, is placed at the top of highly permeable carbonate rocks that are hydraulically connected (Miller, 1986, p. 46). This means the top of the system may lie within a stratigraphic unit rather than at its top. The approximate landward extent of the aquifer system is shown in figure 1. The line marking the approximate updip limit of the system has been placed where the system is less than 100 feet (ft) thick and where the clastic rocks interbedded with the limestone make up more than 50 percent of the section (Miller, 1986, p. 48). In central and southwestern Georgia, some clastic units that are stratigraphically equivalent to limestone units in the Floridan aquifer system are considered part of the Southeastern Coastal Plain sand aquifer system (Renken, 1984). In southern Georgia, the sand aquifer system transmits water generally in a southeasterly direction. Discharge from



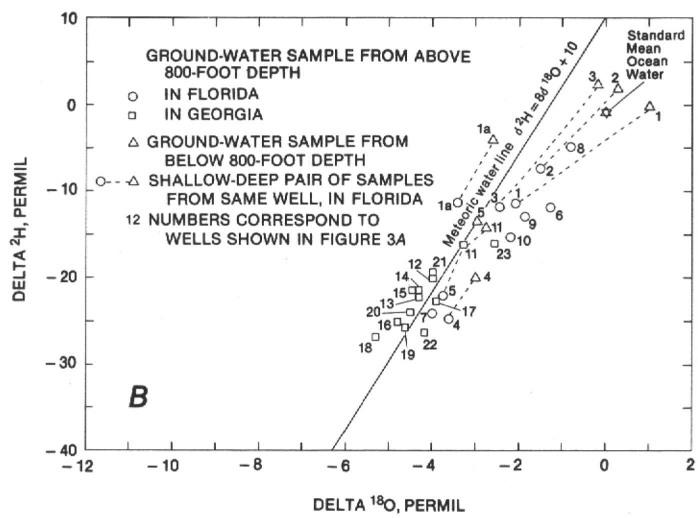


FIGURE 3—*A*, Location of wells in the Floridan aquifer system sampled for hydrogen and oxygen stable isotopes; *B*, Delta^{2}H and delta^{18}O of ground water from the Floridan aquifer system.

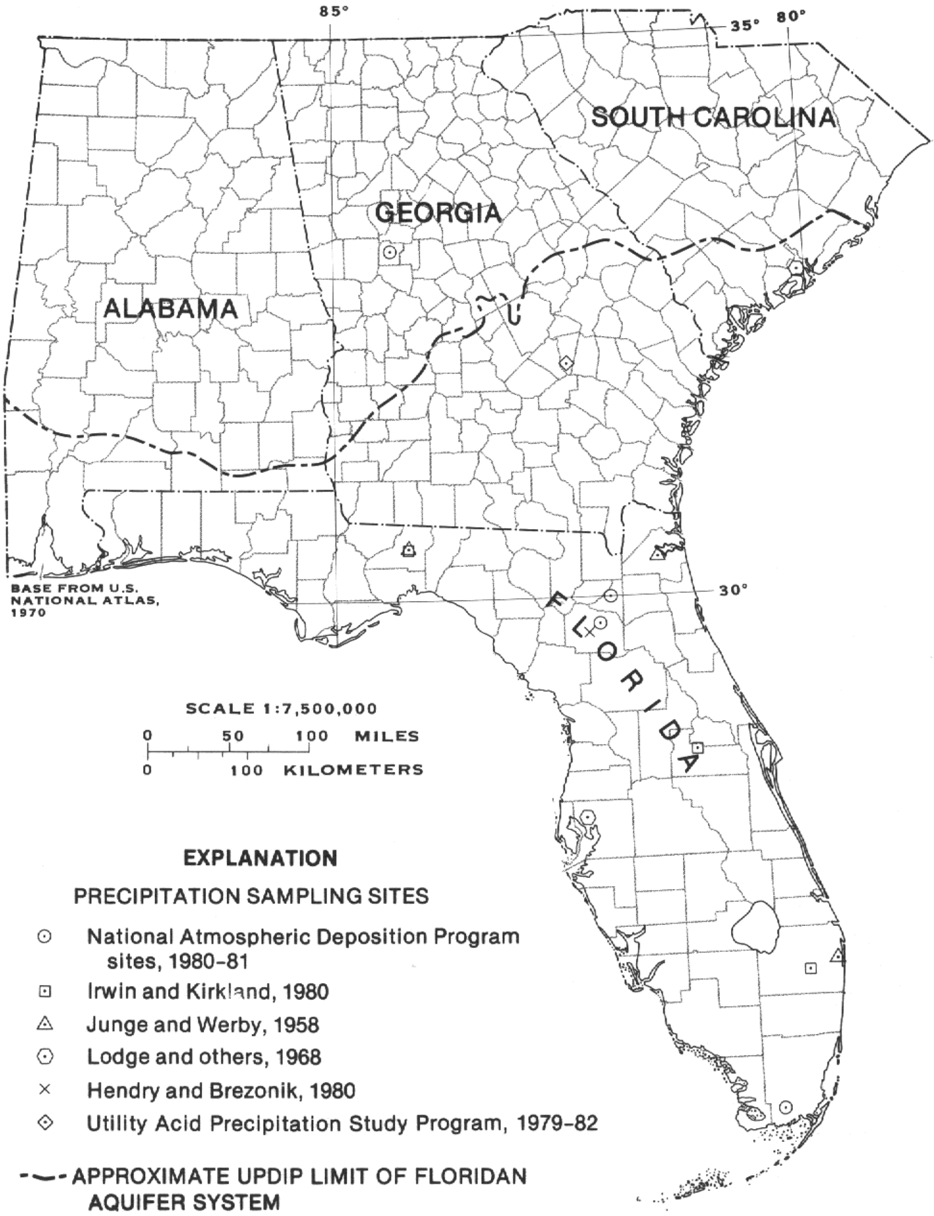
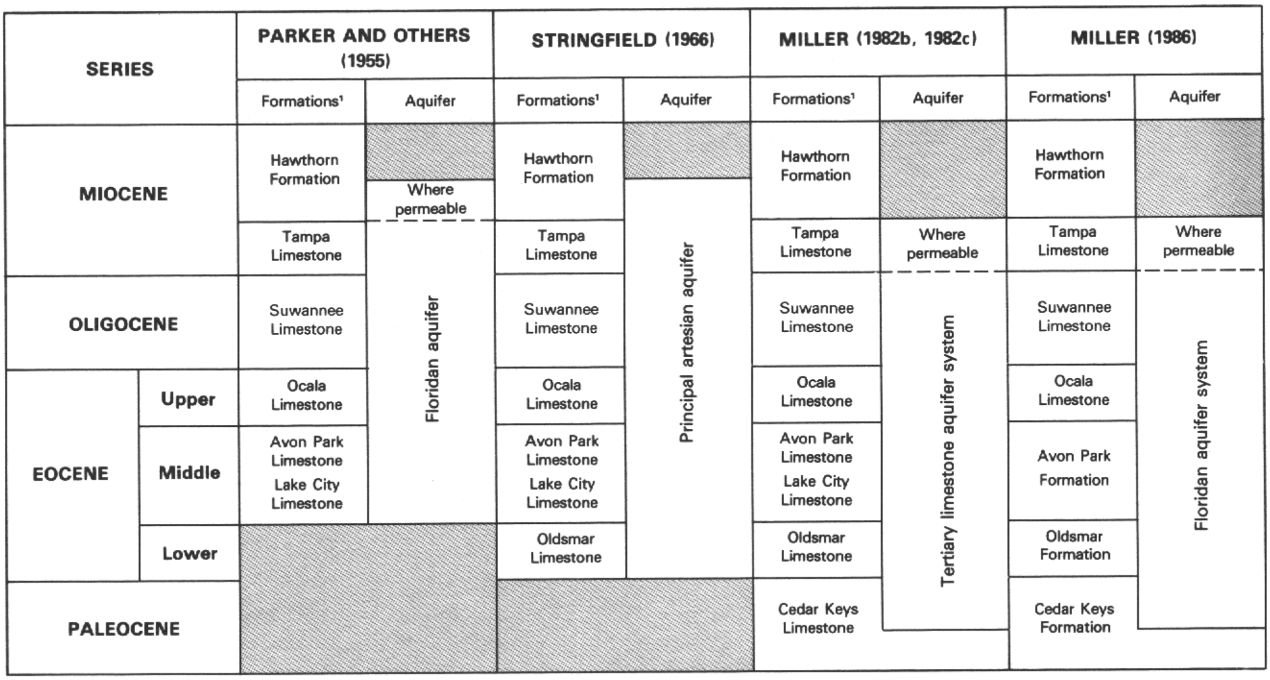


FIGURE 4.—Selected sampling sites for water quality of precipitation in Florida, Georgia, and South Carolina.

underlying clastics into the Floridan aquifer system is occurring; some of the chemical effects of this discharge are discussed in later sections of this report. However, the total quantity and areal distribution of water transferred between the Floridan aquifer system and the Southeastern Coastal Plain sand aquifer system are not well understood. The Floridan aquifer system grades westward by facies change into clastic rocks but is interrupted in Alabama by the Mobile Graben and Gilbertown-Pickens-Pollard fault zones (fig. 8). On the downthrown sides of these faults, low-permeability clastics form a hydraulic barrier between the limestones of the Floridan on the east and stratigraphically equivalent limestones lying north and west. In southeastern South Carolina, the younger limestone units of the system change facies into low-permeability clastics. Thus, in South Carolina, contours shown in figure 7 indicate the top of older limestone units, until they also become predominantly clastic toward the northeast (Miller, 1986).

The rocks making up the Floridan aquifer system vary in thickness from less than 100 ft in outcrop areas in Alabama, Georgia, and South Carolina to about 3,500 ft downdip in southwestern Florida. The system is composed primarily of limestones and dolomites throughout most of Florida and southeastern Georgia. Formations



¹ Names apply only to peninsular Florida and southeast Georgia except for Ocala Limestone and Hawthorn Formation.

FIGURE 5.—Generalized correlation chart and aquifer terminology of the Floridan aquifer system. (Modified from Johnston and Bush, 1988.)

TABLE 1.—*Average concentration of major ions and nutrients in wet precipitation in Florida, Georgia, and South Carolina*

[Concentrations in milligrams per liter. Dashes indicate constituent not analyzed]

Location of precipitation collector[1]	Major ion						Nutrient			
	Ca	Mg	Na	K	Cl	SO_4	NO_3	NH_4^+	Organic C	PO_4
Tampa, Fla.[2]	1.61	0.20	1.01	0.15	1.54	3.34	0.34	----	----	----
Charleston, S.C.[2]	0.44	0.82	1.06	0.22	1.43	2.75	0.71	----	----	----
Gainesville, Fla.[3]	0.41	0.12	0.44	0.20	0.98	2.05	0.84	0.13	5.20	----
Tallahassee, Fla.[4,5]	0.43	----	0.53	0.13	0.66	0.48	0.17	0.18	0.8	----
Loxahatchee, Fla.[4]	3.4	0.6	2.3	0.4	3.9	3.2	1.4	0.41	2.2	----
Maitland, Fla.[4]	1.1	0.3	1.0	0.5	1.6	2.6	1.3	1.0	4.0	----
Jacksonville, Fla.[5]	0.89	----	0.96	0.11	1.02	1.48	----	----	----	----
West Palm Beach, Fla.[5]	0.56	----	1.62	0.10	2.44	0.99	----	----	----	----
Bradford Forest, Fla.[6]	0.32	0.10	1.14	0.12	2.00	2.27	1.05	0.15	----	0.02
Austin-Cary Forest, Fla.[6]	0.76	0.11	1.29	0.34	1.23	2.52	2.70	0.13	----	0.01
Everglades National Park, Fla.[6]	0.23	0.11	0.73	0.11	1.23	1.37	0.74	0.17	----	0.07
Griffin, Ga.[6]	0.19	0.06	1.01	0.11	0.54	3.03	1.16	0.37	----	0.23
Uvalda, Ga.[7]	0.12	0.04	0.26	0.04	0.53	1.50	0.97	0.18	----	0.01

[1] Location map given in figure 4.
[2] Lodge and others, 1968. Nitrogen reported by authors as inorganic nitrogen (unspeciated).
[3] Hendry and Brezonik, 1980.
[4] Irwin and Kirkland, 1980. Average of bulk precipitation.
[5] Junge and Werby, 1958.
[6] National Atmospheric Deposition Program 1980–81. Average of weekly wet samples.
[7] Utility Acid Precipitation Study Program 1981–82. Average of 98 precipitation events.

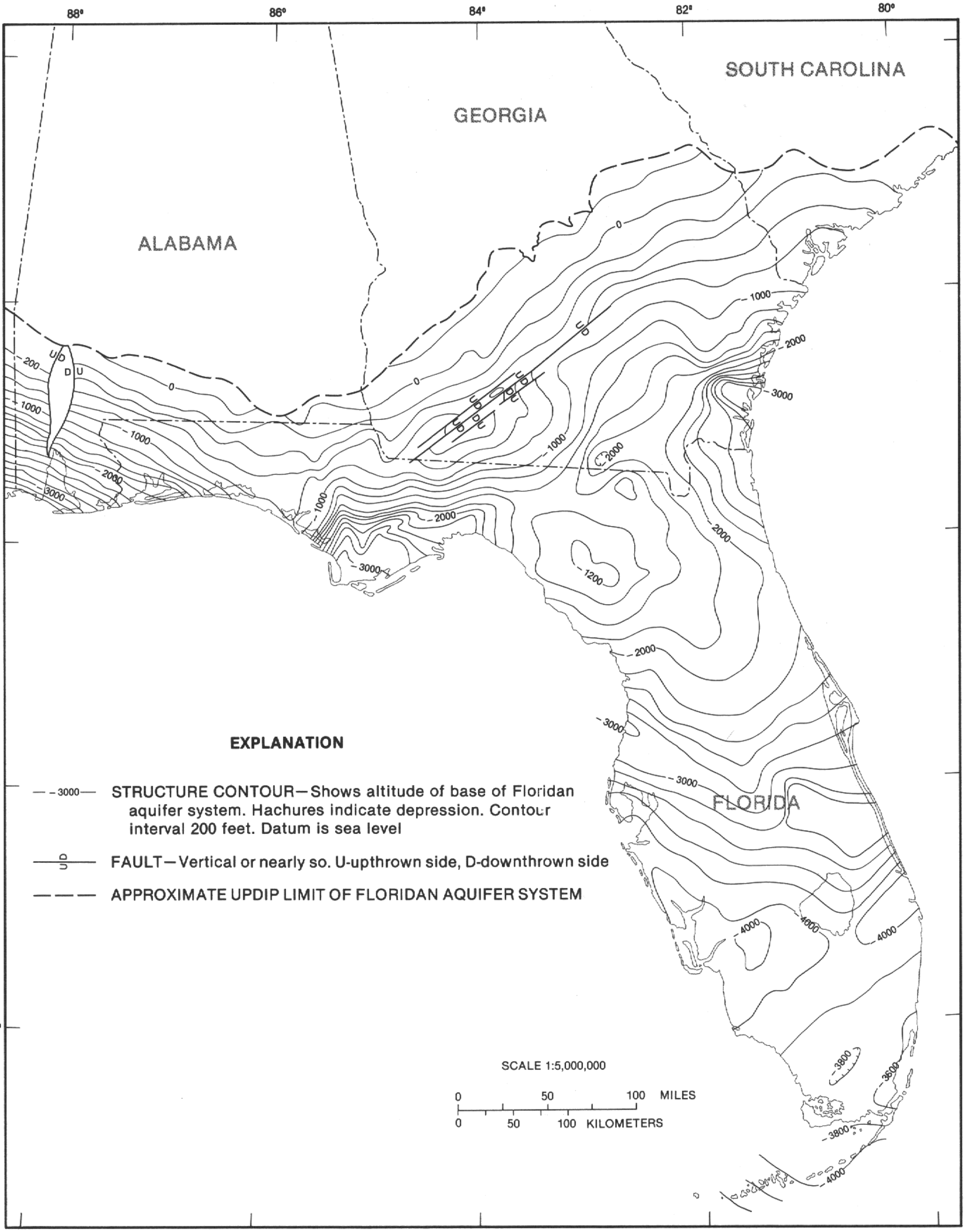


FIGURE 6.—Configuration of the base of the Floridan aquifer system. (Modified from Miller, 1986.)

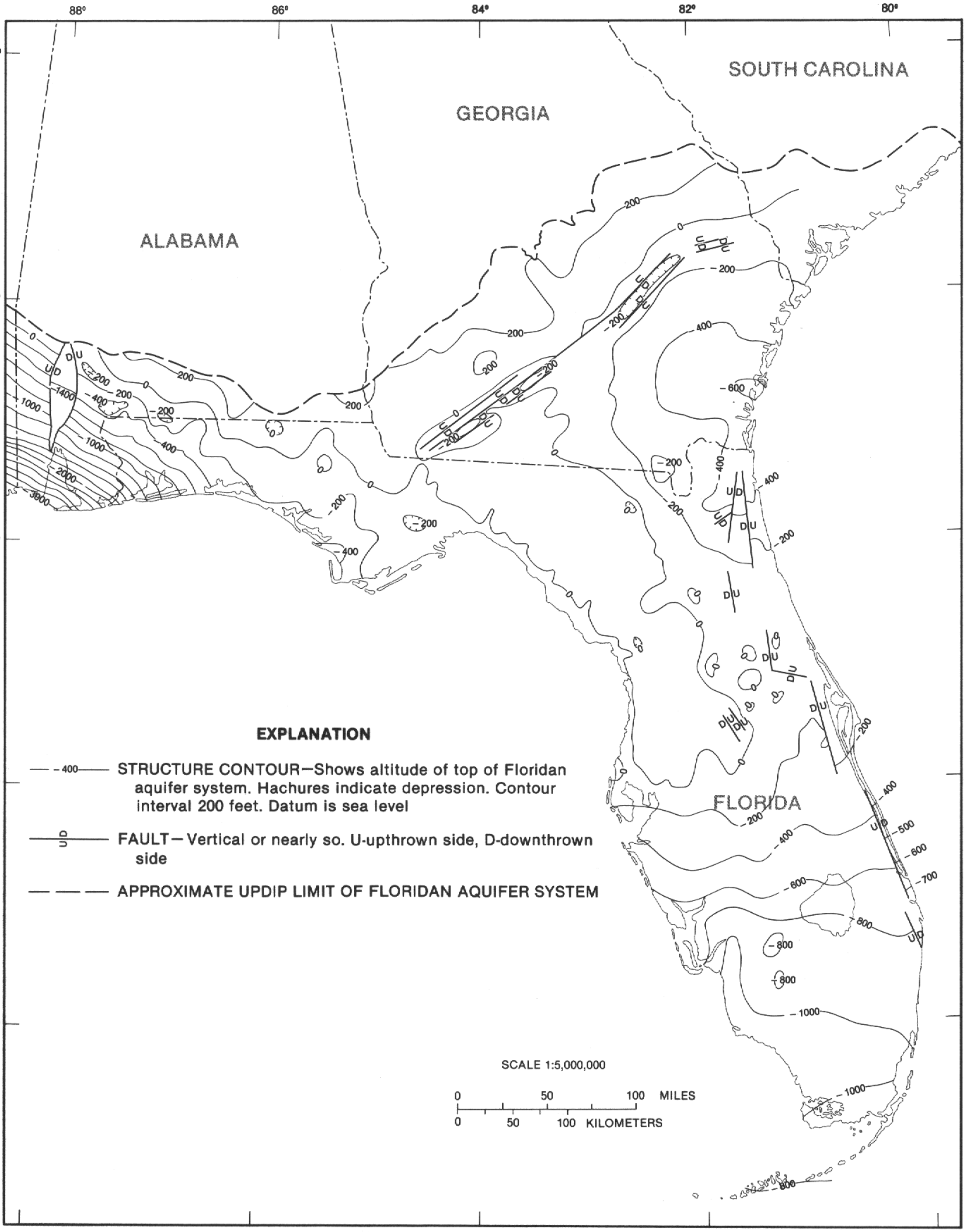


FIGURE 7.—Configuration of the top of the Floridan aquifer system. (Modified from Miller, 1986.)

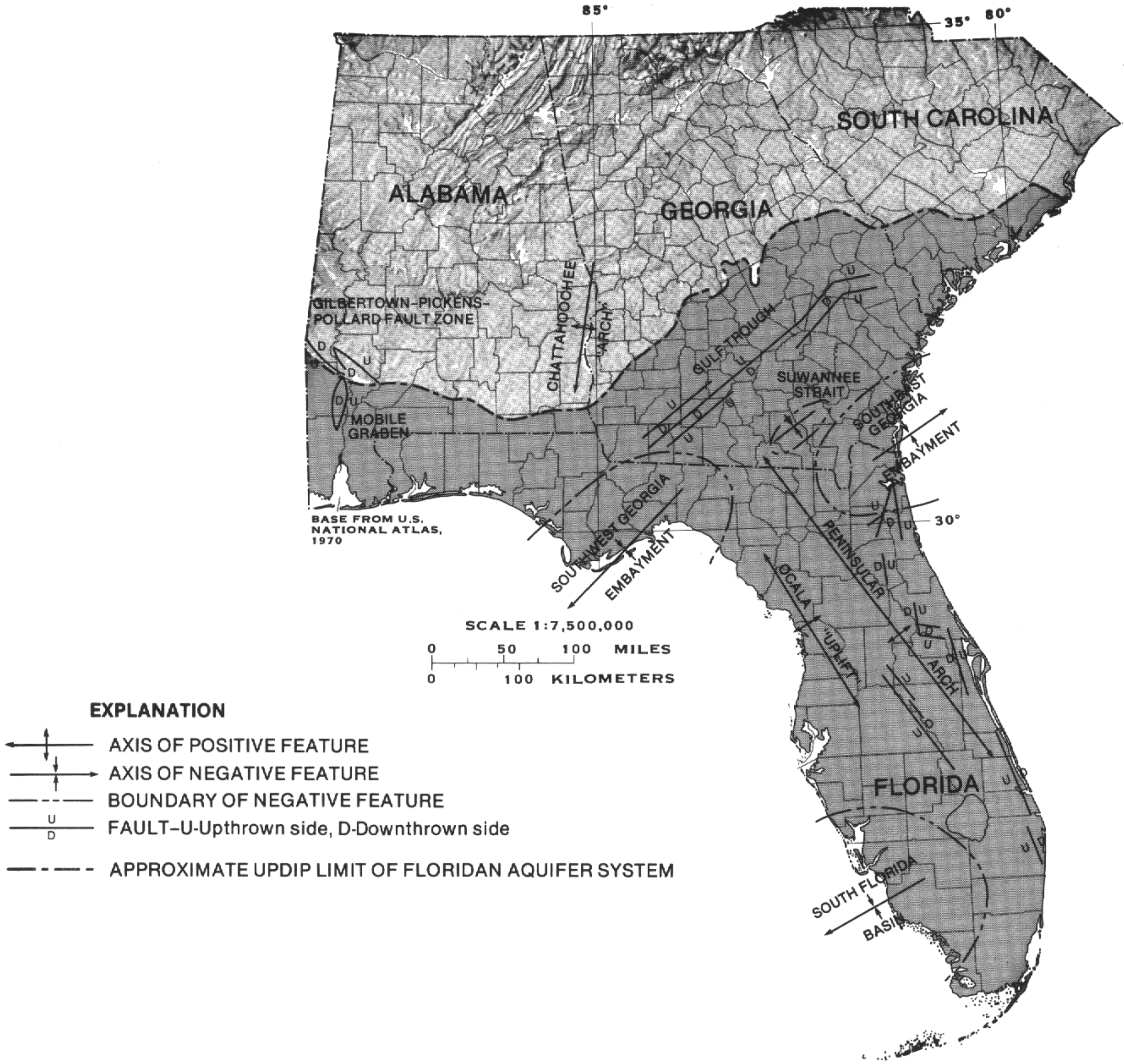


FIGURE 8.—Geologic structures affecting the Floridan aquifer system. (From Miller, 1986.)

within the aquifer system change facies, however, into more arenaceous clastics in western Florida and southeastern Alabama. In the southwestern and northeastern parts of the Coastal Plain of Georgia and in adjacent South Carolina, the limestones grade into limy sand and clay, both laterally and vertically. Between periods of deposition, limestone units of the Floridan aquifer system were locally exposed to subaerial weathering. Where weathering was extensive, sinkholes and other karst features developed. In many areas these paleosinkholes were filled with younger clay and sand, when the seas again drowned the landscape (Stringfield, 1966, p. 200–202).

Miller (1986) has described the geology of the Floridan aquifer system in detail; therefore, the following discussion is much abbreviated. The youngest rocks making up the aquifer system crop out along an area extending through Alabama, Georgia, and South Carolina that approximately parallels the Fall Line. Outcrops in central peninsular Florida are related to major geologic structures—the Peninsular arch and the Ocala uplift (fig. 8). Where present in Alabama, Georgia, and South

Carolina, the rocks making up the aquifer system dip gently toward the sea. In Florida, the formations generally dip away from the positive structural features shown in figure 8 and dip toward the negative features. Development of the structures affecting the aquifer system began in the Early Cretaceous and extended through the late Tertiary.

The rocks of the aquifer system in peninsular Florida were deposited in shallow marine environments typified by the modern-day Bahama Banks. The nearshore intertidal deposits of coquina and coarse-grained limestones may grade laterally into lagoonal and subtidal micrites, locally containing peat and evaporites. In some units, bedded evaporites (primarily anhydrite or gypsum) that may have formed in sabka or tidal flat environments are present. The deep-water limestones are characteristically fine grained and fossil bearing, with only trace amounts of noncarbonate minerals.

Throughout most of the Paleocene and Eocene, deep-sea environments separated the northern Florida peninsula from panhandle Florida, Alabama, and Georgia. Into this trough were carried continental sediments from the north and northwest. Thus, the shallow marine carbonates of the Cedar Keys, Oldsmar, and Avon Park Formations grade progressively northward into limy muds, silts, and sands. During the late Eocene, a major transgression occurred and the Ocala Limestone was deposited over nearly all the region shown in figure 1. The Ocala is commonly a soft, chalky coquina containing minor chert and dolomite locally. This formation has high permeability throughout most of the study area; in fact, most of the water that discharges from the aquifer system comes from springs in the Ocala Limestone (Bush, 1982; Bush and Johnston, 1988). After the late Eocene, continentally derived sand, silt, and clay again were deposited with carbonates in Alabama, Georgia, and northern Florida. In peninsular Florida, the Suwannee Limestone was deposited in a shallow marine environment during the late Oligocene. Where present, the Suwannee Limestone is also a highly productive water-bearing formation.

During the early Miocene, parts of the region underwent cycles of emergence and submergence beneath the sea. The Tampa Limestone was deposited during this period, and in west-central Florida it contains both marine and freshwater limestones. In areas where the sea did not retreat, the Tampa Limestone merges without definite boundary into the overlying Hawthorn Formation; in emergent areas, an unconformity is present between these units. The Hawthorn Formation is a thick sequence of interbedded clay, sand, limestone, sandy phosphatic limestone, and marl. The Hawthorn is present over more than 50 percent of the area underlain by the Floridan aquifer system and is the major upper confining unit for the system.

MINERALOGY

The matrix of the Floridan aquifer system is composed primarily of calcite and dolomite, with minor gypsum, apatite, glauconite, quartz (or chert), clay minerals (kaolinite and montmorillonite?), and trace amounts of metallic oxides and sulfides. Locally, measurable amounts of peat are present as thin (1–5 millimeters; mm) layers in the limestone.

MAJOR MINERALS

Calcite, the most abundant mineral in the Floridan aquifer system, ranges in composition from stoichiometric calcite ($CaCO_3$) to magnesian calcite ($Ca_{0.96}Mg_{0.04}CO_3$) (Hanshaw and others, 1971, table 1). The magnesium content of calcite from aquifer cores in Waycross, Ga., and Polk City, Fla., ranged from 0 to 2.7 mole percent Mg, with three of four samples less than 1 percent. Although cores of the entire Floridan aquifer system have not been systematically analyzed, "magnesian calcites probably account for less than 0.1 percent of the [Floridan] limestones by weight" (Plummer, 1977, p. 802), owing to the instability of magnesian calcites relative to stoichiometric calcite in fresh or slightly saline water. Other elements present at trace levels in calcite are sodium, strontium, iron, and manganese. Data on iron and manganese content of calcite from the aquifer system are scarce; sodium and strontium may be present in calcite in concentrations as high as 440 and 600 parts per million (ppm) (Metrin, 1979), respectively, depending on the aqueous environment during formation of the mineral. The sodium and strontium contents of calcite analyzed by Metrin (1979) averaged less than 200 ppm and less than 500 ppm, respectively; these values were interpreted by Randazzo and others (1983) to indicate a brackish ground-water environment of diagenesis of middle and upper Eocene rocks (Upper Floridan aquifer) in west-central Florida.

The amount of dolomite in the aquifer system varies both laterally and vertically within and between formations. In a core obtained from a deep test well near Polk City, Polk County, Fla. (pl. 1), dolomite accounted for about 8 percent of the rocks of the Upper Floridan aquifer, about 95 percent of the rocks of the underlying confining unit, and about 9 percent of the rocks penetrated in the Lower Floridan aquifer (A.S. Navoy, U.S. Geological Survey, written commun., 1982). Near Waycross, Ga. (pl. 1), where the base of the Upper Floridan aquifer is also the base of the aquifer system, cores and cuttings from a deep test well were about 30 percent