

# 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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ate minerals can add only a few tenths of a milligram per liter of  $\text{Na}^+$  to freshwater in the aquifer; the remainder apparently is derived from evaporated precipitation recharging the system and other mineral sources, including ion exchange. Higher concentrations of  $\text{Na}^+$  present in some inland areas are generally the result of remnant seawater in the Upper Floridan aquifer, as indicated by high  $\text{Cl}^-$  concentrations. For example, in Gadsden County, Fla., low-permeability zones in the Upper Floridan retain moderately saline water; water samples from the aquifer in this area contain high concentrations of all major ions in seawater (Pascale and Wagner, 1981). High concentrations of the major ions in seawater also occur in the Upper Floridan aquifer in the valley of the St. Johns River, where seawater may have entered the aquifer during the Pleistocene. In the western panhandle of Florida, high  $\text{Cl}^-$  concentrations (pl. 6) indicate that remnant seawater is present in the Upper Floridan in extreme southwestern Santa Rosa County and in southern Escambia County. Sodium concentrations increase in a downgradient direction, beginning about 30 mi northeast of this area, in southwestern Okaloosa County (pl. 4). Where increases in  $\text{Na}^+$  begin,  $\text{Na}^+/\text{Cl}^-$  ratios are high (fig. 21A) and are accompanied by progressive downgradient decreases in  $\text{Ca}^{2+}$  concentrations (pl. 1). These concurrent changes in concentration in the downgradient direction are apparently due to ion exchange of  $2\text{Na}^+$  for  $\text{Ca}^{2+}$ . The large area of slightly higher  $\text{Na}^+$  concentrations centered near Brunswick, Ga., is due to upward seepage of deeper saline water induced by many years of heavy pumpage. The hydraulic effects of the pumpage are discussed in detail by Krause and Randolph (in press); earlier studies of the chemical effects of pumpage in the Brunswick area emphasized local increases in chloride concentration (Wait, 1965; Gregg and Zimmerman, 1974). The pattern shown in plate 4 is not exactly duplicated in plate 6 because the maps were drawn with different ranges of concentration.

A map of  $\text{K}^+/\text{Cl}^-$  molar ratios in the Upper Floridan aquifer (fig. 21B) shows characteristically low ratios ( $<0.06$ ) in coastal areas and in south Florida where seawater is present in the aquifer; the lowest ratios are near 0.02 (the ratio in seawater) where both  $\text{Cl}^-$  and  $\text{K}^+$  concentrations are highest in the Upper Florida. Low  $\text{K}^+/\text{Cl}^-$  ratios also occur in Volusia County, Fla., and in outcrop areas of northwestern Florida, southern Alabama, and north-central Georgia. The ratios in these areas are less than 0.14, the average ratio in precipitation over the region (table 1). The loss of  $\text{K}^+$  relative to  $\text{Cl}^-$  is probably due to uptake of  $\text{K}^+$  by plants, as  $\text{K}^+$  and  $\text{Cl}^-$  concentrations in ground water are not much more than average values for precipitation in these areas. Higher  $\text{K}^+/\text{Cl}^-$  ratios occur throughout most of central and panhandle Florida, and in southern Georgia; in these

areas, evaporation increases both  $\text{K}^+$  and  $\text{Cl}^-$  concentrations in water recharging the system, but the  $\text{K}^+/\text{Cl}^-$  ratios are nearer values for precipitation. The highest  $\text{K}^+/\text{Cl}^-$  ratios occur in east-central Georgia and in western panhandle Florida. As previously discussed, ion exchange is probably responsible for the relative increase in  $\text{K}^+$  concentrations in the panhandle area. In east-central Georgia, dilute water may be leaking into the Upper Floridan aquifer from underlying sand aquifers; this recharge could slightly increase  $\text{K}^+$  concentrations and raise  $\text{K}^+/\text{Cl}^-$  ratios in the Upper Floridan. The high  $\text{K}^+/\text{Cl}^-$  ratios in southwestern Georgia occur in an area of extensive agriculture development and where the confining unit overlying the Upper Floridan is thin; surficial recharge enters the aquifer containing increased concentrations of  $\text{K}^+$  due to leaching of fertilizers.

Potassium concentrations in most water from the Upper Floridan aquifer are low, because  $\text{K}^+$  concentrations in precipitation are very low and  $\text{K}^+$ -bearing minerals in the aquifer are present only in trace amounts. Aluminosilicate minerals containing potassium (glauconite, potassium feldspar, and micas?) that are present in trace quantities can dissolve and add very small amounts of  $\text{K}^+$  to ground water. Unlike  $\text{Na}^+$ ,  $\text{K}^+$  does not occur as a trace constituent in calcite or dolomite, owing to the much larger size of the  $\text{K}^+$  ion. Except for western panhandle Florida,  $\text{K}^+$  concentrations are therefore closely related to the amount of seawater (as indicated by chloride concentrations) in the Upper Floridan aquifer. In the western panhandle area, ion exchange ( $2\text{K}^+$  for  $\text{Ca}^{2+}$  or  $\text{Mg}^{2+}$ ) increases  $\text{K}^+$  concentrations by about 5 mg/L. As discussed in a later section, silicate weathering is not considered a primary source of  $\text{K}^+$  (or  $\text{Na}^+$ ) in this part of the system, because dissolved-silica concentrations do not increase, and silica cements (or grain overgrowths) have not been reported in well cuttings or cores from the area.

#### CHLORIDE

The second important anion in water in the Floridan aquifer system is chloride ( $\text{Cl}^-$ ). The principal source of  $\text{Cl}^-$  is seawater; natural salts of  $\text{Cl}^-$  (evaporite minerals) are not present in the system, and addition of  $\text{Cl}^-$  salts to remove road ice is not common practice in the region. The data in table 1 indicate that recharge water should be very low in  $\text{Cl}^-$  concentration, and  $\text{Cl}^-$  concentrations in the Upper Floridan aquifer are nearly zero in recharge areas. In nearly all coastal areas, wells that fully penetrate the Upper Floridan yield water having  $\text{Cl}^-$  concentrations that approach that of seawater, about 19,500 mg/L. Plate 6 depicts the general distribution of  $\text{Cl}^-$  concentration in water produced from the Upper Floridan aquifer. The map shows higher  $\text{Cl}^-$  concentrations in

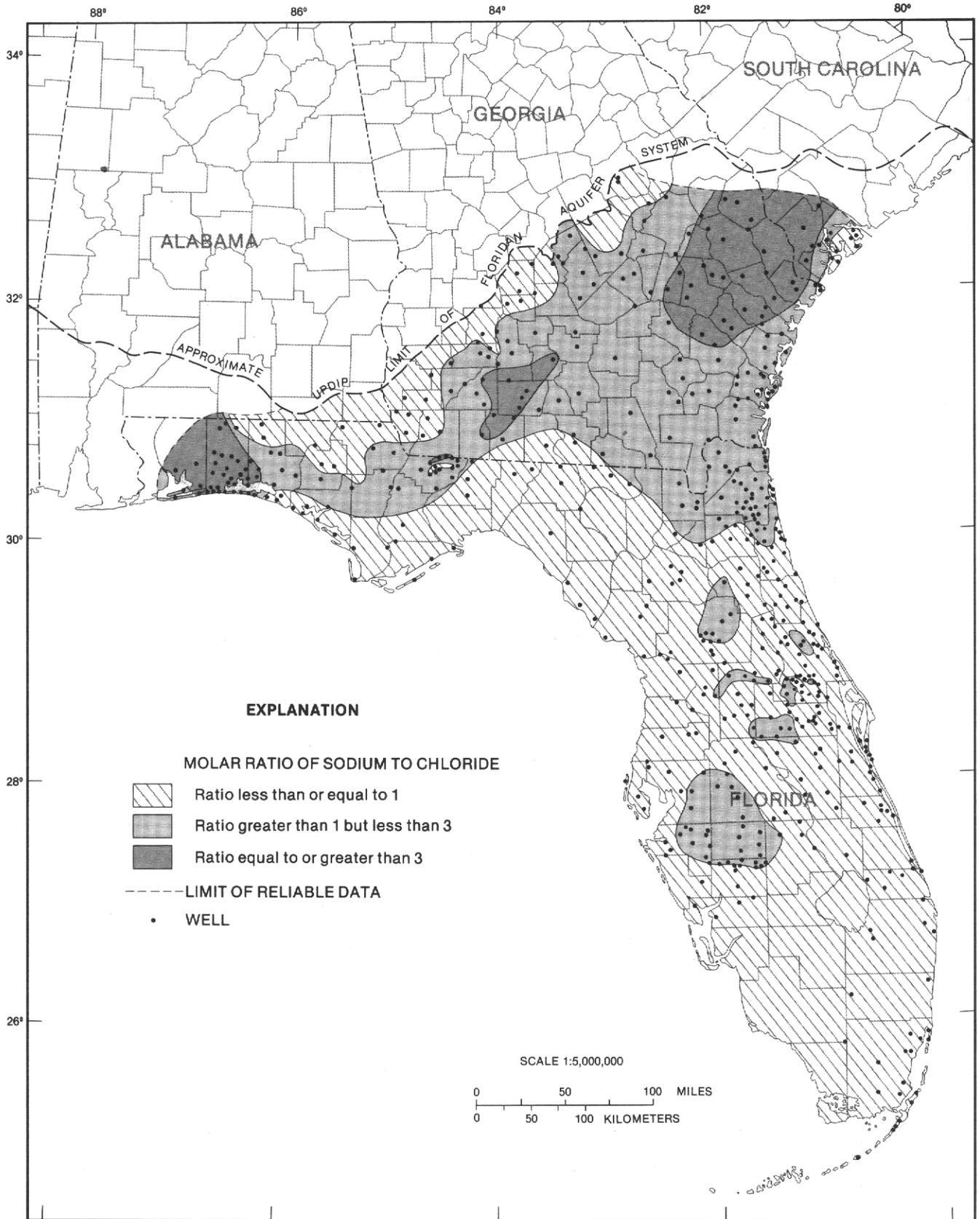


FIGURE 21A.—Sodium-to-chloride molar ratios in water samples from wells in the Upper Floridan aquifer.

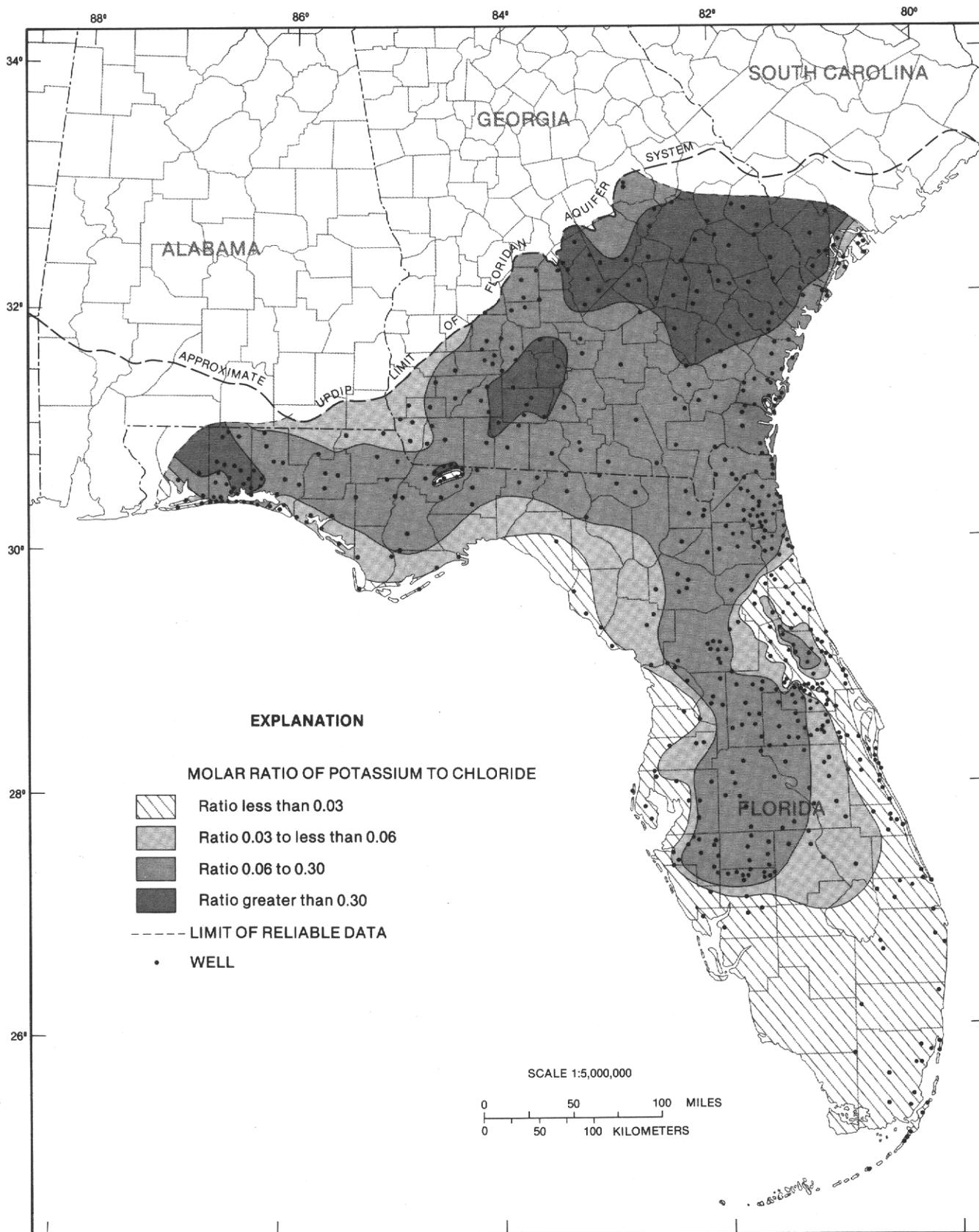


FIGURE 21B.—Potassium-to-chloride molar ratios in water samples from wells in the Upper Floridan aquifer.

inland areas than did earlier chloride maps of the Upper Floridan (Shampine, 1965a; Stringfield, 1966, fig. 3b), because this map was made using data from selected deep wells that penetrate at least half the thickness of the Upper Floridan. Deep wells tend to have higher  $\text{Cl}^-$  concentrations than shallow wells because the water in the Upper Floridan is chemically stratified. Figure 22 shows the  $\text{Cl}^-$  concentration in the upper 200 ft of the aquifer system. Throughout most of the region, the upper 200 ft of the system are either Ocala or Suwannee Limestone (see Miller, 1986, pl. 26). Both formations are highly permeable, generally contain water having  $\text{Cl}^-$  concentrations of less than 250 mg/L, and are capable of supplying very high yields to wells. Along the Gulf Coast and in south-central Florida, wells that penetrate only a few tens of feet into the Upper Floridan may produce water having  $\text{Cl}^-$  concentrations of less than 250 mg/L, but wells penetrating more than 100 ft will probably yield water of higher  $\text{Cl}^-$  content.

A map (fig. 23) of the base of freshwater flow in the Floridan aquifer system was compiled using  $\text{Cl}^-$  concentration data from deep wells and the estimated predevelopment potentiometric surface map (fig. 10) by Johnston and others (1980). The base of freshwater flow was defined as the midpoint of the saltwater-freshwater transition zone in coastal areas; where available, known  $\text{Cl}^-$  concentrations of 10,000 mg/L were used as the chemical definition of the midpoint. Where variations in  $\text{Cl}^-$  concentration with depth were not available, the location of the midpoint was calculated using the Hubbert interface relation (Hubbert, 1940, p. 864) and known (or estimated) predevelopment freshwater heads. The depth of the midpoint calculated from freshwater heads in inland areas is generally below the base of the Floridan aquifer system; in those areas, the geologic base of the aquifer system (Miller, 1986, pl. 33) is shown (fig. 23).

High chloride concentrations shown in plate 6 along the St. Johns River, along the eastern coast of Florida, and in southern Florida may be the result of incomplete flushing of Pleistocene seawater by the modern-day freshwater flow system (Stringfield, 1966, p. 209). Wyrick (1960) and Leve (1983) believed deeper, brackish water rises along fault zones in northeastern Florida because of higher freshwater heads in the Lower Floridan aquifer. Recent studies (Miller, 1986) suggest that faults mapped in the St. Johns River valley affect only the uppermost part of the Upper Floridan aquifer and do not penetrate deeply into the aquifer system. At this time, the known hydrologic effects of faults mapped in Duval, St. Johns, Putnam, and Volusia Counties are limited to ground-water chemical changes. The necessary measurements to determine whether the faults affect the hydraulic characteristics of the aquifer at depth have not been made (Tibbals, in press). In eastern

and southern Florida, both incomplete flushing of Pleistocene seawater and brackish-water intrusion along fault zones appear to contribute, in varying amounts, to the  $\text{Cl}^-$  content of water in the Upper Floridan aquifer.

In south Florida, ground water from the Upper Floridan aquifer discharges upward by diffuse leakage through thick confining beds. Simulations of the steady-state aquifer system indicate very sluggish ground-water circulation south of Lake Okeechobee, with upward leakage of freshwater less than 0.1 inch per year (in/yr) (Bush, 1982, p. 18–19). Kohout (1967) proposed a new conceptual flow system for the Floridan aquifer system in south Florida. His theory suggests that geothermal energy drives a cyclic flow system: as seawater flows inland at the base of the aquifer system, brackish water returns to the sea in the upper parts of the Floridan. This theory assumes that sufficient freshwater flows through the system in south Florida to mix with the seawater, lower its density, and maintain the required hydraulic gradients. The theory further assumes good hydraulic connection between the deep, highly permeable Boulder Zone in the Lower Floridan aquifer of southern Florida and the overlying parts of the Floridan aquifer system. Chemical data from deep test wells in Broward County, Fla., (Meyer, in press b) have established a landward  $^{14}\text{C}$  gradient in the Boulder Zone. Using data from deep test wells at Fort Lauderdale and in western Broward County, Meyer (in press b) has shown that an inland hydraulic gradient of about  $8.5 \times 10^{-7}$  foot per foot (ft/ft) exists between the wells. The available data indicate that seawater flow is very sluggish through the highly permeable Boulder Zone. Meyer used estimates of hydraulic parameters of the Boulder Zone and head measurements to show that average particle velocities between the wells in western Broward County and Fort Lauderdale range between about 30 and 60 feet per year (ft/yr), which compares favorably with a velocity of about 55 ft/yr calculated from differences in  $^{14}\text{C}$  activity in the seawater samples from each well. The flow path(s) and flow zone(s) that carry the brackish water back to the sea, completing Kohout's proposed cycle, were not identified during this study.

In the Savannah area of Georgia and South Carolina, the high chloride concentrations in water from the Upper Floridan aquifer are attributed to lateral saltwater encroachment (Counts and Donsky, 1963). Long-term withdrawals in this area have lowered the freshwater head, resulting in very slight migration of the freshwater-saltwater interface toward the center of pumpage. Similarly, long-term pumpage in coastal cities of southeastern Georgia and northeastern Florida has caused decline of the freshwater head in the Upper Floridan aquifer. In this area, however, the decline in head has induced upward migration of brackish water

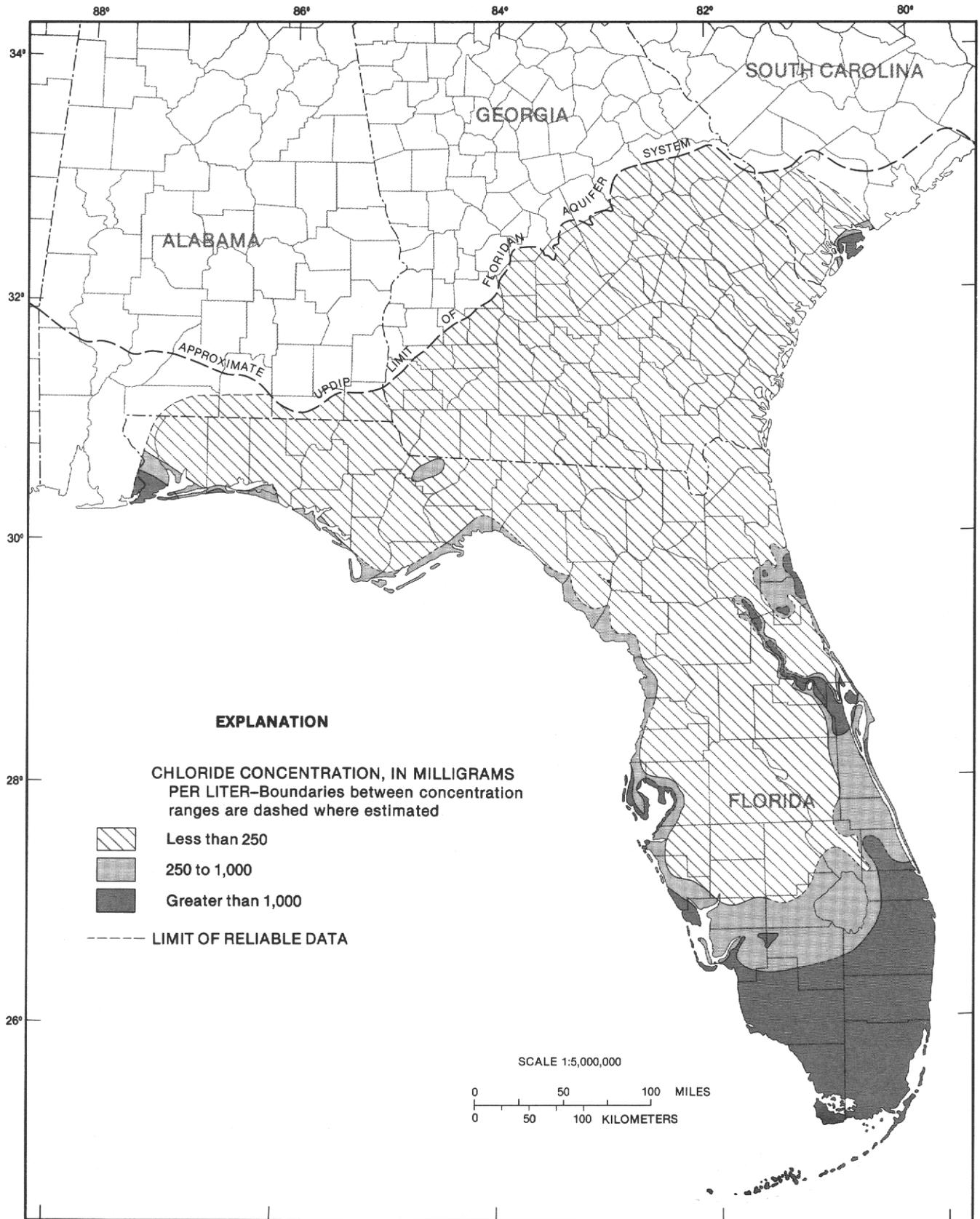


FIGURE 22.—Chloride concentrations in water from the upper 200 feet of the Floridan aquifer system.

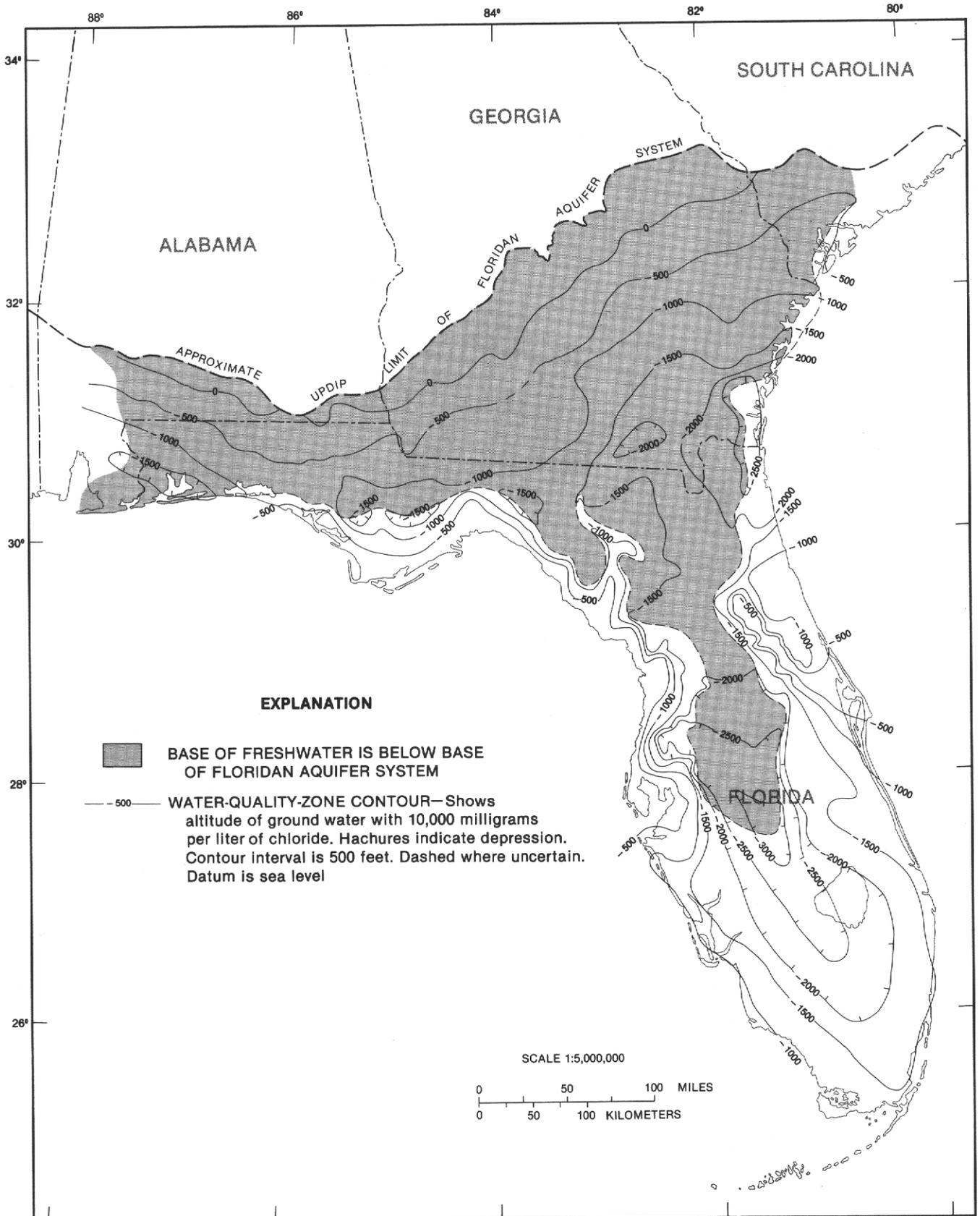


FIGURE 23.—Altitude of the estimated base of freshwater flow in the Floridan aquifer system.

(Stewart, 1960; Wait, 1965; Gregg and Zimmerman, 1974; Fairchild and Bentley, 1977; Leve, 1983). The possibility that lateral seawater encroachment could affect  $\text{Cl}^-$  concentrations along the coast of southeastern Georgia and northeastern Florida was discounted by Johnston and others (1982) because the freshwater-saltwater interface in the Upper Floridan aquifer is more than 50 mi offshore from Jacksonville, Fla.

The high chloride concentrations in Escambia and Santa Rosa Counties in the western panhandle of Florida probably result from incomplete flushing of residual seawater. Lateral ground-water movement toward the west and south is restricted in this area because there is a gradual facies change to low-permeability clastics, pinching out the aquifer system. Northwest of this area, faults associated with grabens in western Alabama (fig. 8) form a barrier to lateral ground-water flow. Under modern-day head conditions, fresh ground water may gradually displace the brackish ground water, which must leak slowly upward through thick confining beds. The high chloride concentrations in Gadsden County, northwest Florida, also appear to result from incomplete flushing of residual seawater (Pascale and Wagner, 1981). Although Johnston and others (1981) show a potentiometric high in this area, freshwater recharge to the aquifer is probably very low. As mentioned previously, the Upper Floridan aquifer in this area has low transmissivity (less than  $1,000 \text{ ft}^2/\text{d}$ ), and vertical head differences as great as 40 ft are sustained with virtually no pumping. Plate 6 also shows high chloride concentrations along most of the Gulf Coast of Florida, where heads in the Upper Floridan aquifer are near sea level and the freshwater-saltwater interface occurs within the aquifer (Reichenbaugh, 1972; Mills and Ryder, 1977; Trapp, 1977; Sinclair, 1978; Hickey, 1979; Hickey and Barr, 1979). As stated previously, only very shallow wells in the Upper Floridan aquifer along the Gulf Coast should produce water of low chloride content.

A map of chloride concentrations in the Lower Floridan aquifer (fig. 24) was prepared using available chemical data and estimated predevelopment heads. Because available data are few and the deep wells are generally not fully penetrating,  $\text{Cl}^-$  concentrations in many areas must be estimated. The two principal assumptions used to map the available data were as follows: (1) data from fully penetrating wells were given more weight than shallower wells and (2) at boundaries of the Lower Floridan where it merges with the Upper Floridan,  $\text{Cl}^-$  concentrations in both the Lower and Upper Floridan aquifers were assumed to be equal. In areas for which there were no chemical data, predevelopment head differences between the Upper and Lower Floridan aquifers were assumed to be 1 to 5 ft (Bush, 1982, p. 19). Figure 24 shows freshwater (low  $\text{Cl}^-$ ) in many areas

extending to the base of the aquifer system. In central Florida, chemical data are available to verify that freshwater is present in the Lower Floridan aquifer. Areas of low- $\text{Cl}^-$  water shown in figure 24 might be explored as a potential supply if dissolved solids (pl. 8) are not too high and shallow supplies are insufficient. Areas of high  $\text{Cl}^-$  concentrations in figure 24 correspond to the presence of saltwater. Pumpage in coastal cities of southeastern Georgia and northeastern Florida has lowered the freshwater heads in the Upper Floridan aquifer (and also presumably lowered the heads in the Lower Floridan) so that saltwater is migrating upward. The areal extent of head declines in the Lower Floridan aquifer are not well known; thus the area affected by saltwater is restricted to the regions of greatest head decline in the Upper Floridan. In the valley of the St. Johns River, high  $\text{Cl}^-$  concentrations are mapped on the assumption that the Lower Floridan has been incompletely flushed of seawater that invaded the aquifer system during the Pleistocene.

#### SULFATE

The sulfate radical ( $\text{SO}_4^{2-}$ ) is a principal component of gypsum and anhydrite, two highly soluble minerals which are likely to occur throughout the aquifer system.  $\text{SO}_4^{2-}$  concentrations in the Upper Floridan aquifer vary from nearly zero in recharge areas to as much as 4,000 mg/L where gypsum may occur as a few percent of the total rock volume. Plate 7 depicts the general distribution of  $\text{SO}_4^{2-}$  concentration in water produced from wells that yield from the entire Upper Floridan aquifer. This map has a different appearance from an earlier  $\text{SO}_4^{2-}$  concentration map of the Upper Floridan (Shampine, 1965c) because plate 7 was drawn using data from selected deep wells. Some analyses of sulfate-rich ground water known to be present in middle and upper Eocene rocks in the Floridan aquifer system were not used in the preparation of plate 7. The base of the Upper Floridan aquifer is established in places by the presence of intergranular gypsum (or anhydrite) (Miller, 1986), and plate 7 was constructed using chemical data from wells that do not penetrate the base of the Upper Floridan. Thus, a few high  $\text{SO}_4^{2-}$  concentrations previously reported in the Ocala Limestone and Avon Park Formation of southern Georgia and northern Florida (for example, Wait, 1960; Meyer, 1962; Sever, 1965, 1972; Krause, 1979) do not appear on this map. Over most of the region,  $\text{SO}_4^{2-}$  concentrations are less than 0.5 mmolar (about 50 mg/L). Available data on  $^{34}\text{S}$  content of sulfate in the Upper Floridan aquifer (table 17) indicate that almost all the sulfate is derived from gypsum dissolution or seawater mixing; very little sulfate is derived from the oxidation of sulfide minerals (which have very low  $^{34}\text{S}$  content). Since

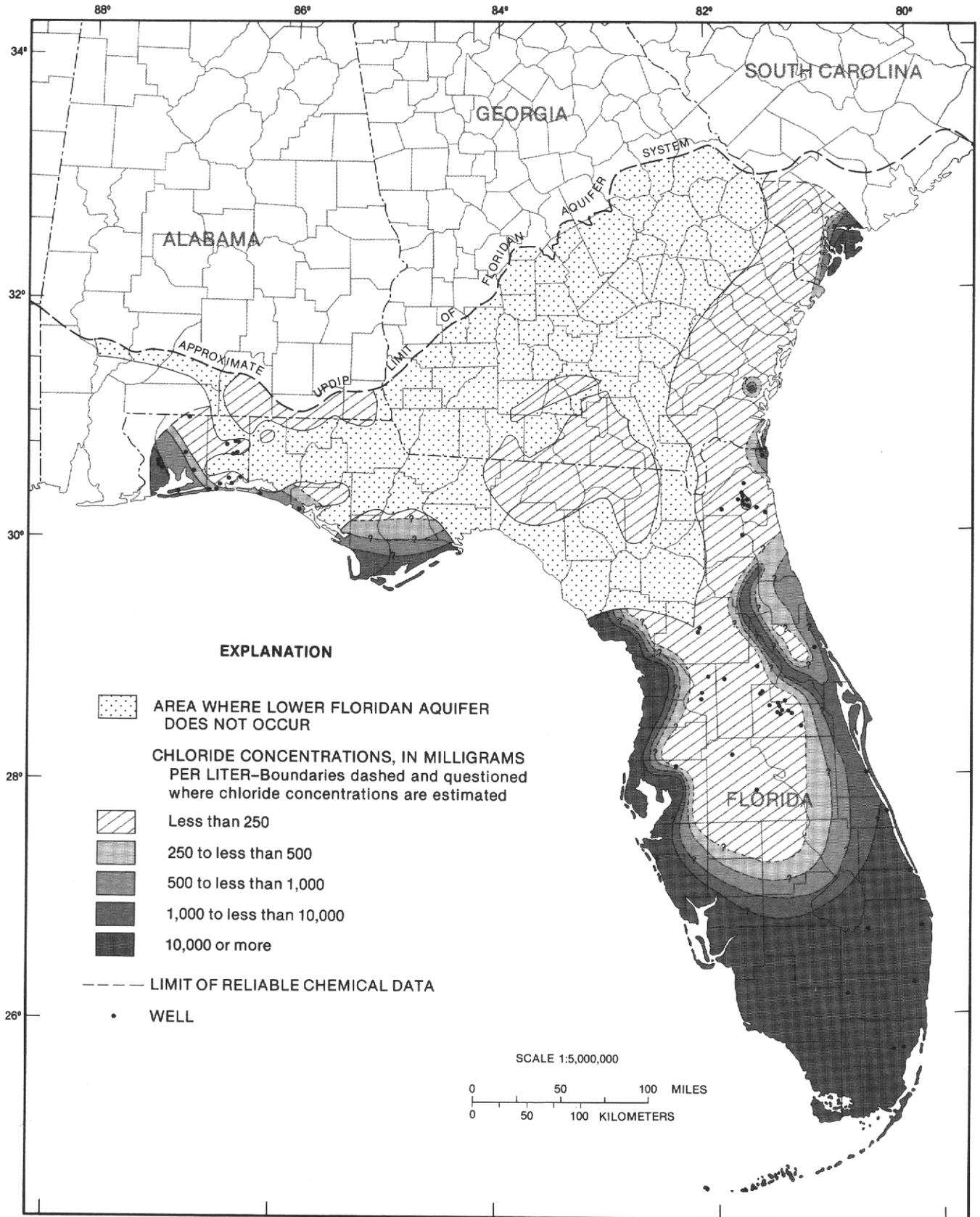


FIGURE 24.—Chloride concentrations in water from the Lower Floridan aquifer.

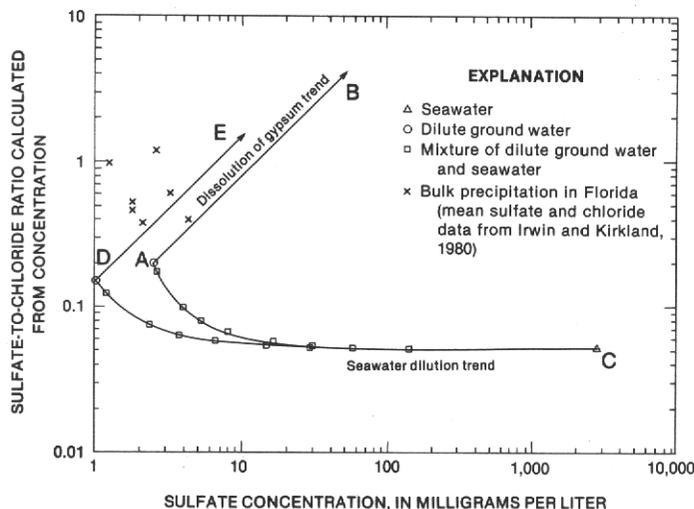


FIGURE 25. — Relation of sulfate-to-chloride ratios to sulfate concentrations in water from the Upper Floridan aquifer. (Modified from Rightmire and others, 1974.)

seawater contains about 2,750 mg/L of  $\text{SO}_4^{2-}$ , plate 7 shows high  $\text{SO}_4^{2-}$  concentrations along the west coast of Florida where predevelopment freshwater heads are low. Only very shallow wells along the Gulf Coast should produce water with low sulfate content from the Floridan aquifer system.

In south Florida and along the eastern coast of Georgia and Florida, high  $\text{SO}_4^{2-}$  concentrations are present as a result of both seawater and dissolution of gypsum (Counts and Donsky, 1963; Stringfield, 1966; Rightmire and others, 1974). Figure 25 (modified from Rightmire and others, 1974, fig. 2) shows two trends between  $\text{SO}_4^{2-}$  concentration and the  $\text{SO}_4^{2-}/\text{Cl}^-$  ratio that may be used to identify the source(s) of  $\text{SO}_4^{2-}$  in an individual ground-water sample. The trend lines shown in figure 25 were drawn using assumed  $\text{SO}_4^{2-}$  and  $\text{Cl}^-$  concentrations in dilute ground water (points A and D). If more mineralized ground water were the "starting point," the trend of gypsum dissolution would be shifted to the right but would retain the same slope, whereas the seawater dilution line would show more curvature (see Steinkampf, 1982, fig. 10). Analyses that plot near line A-B or D-E in the figure indicate that solution of gypsum (or anhydrite) is the primary source of  $\text{SO}_4^{2-}$ . Analyses plotting near the line A-C or D-C indicate a conservative mixing trend between dilute ground water and seawater. Analyses that plot in the region between the trend lines indicate that both solution of gypsum and mixing with seawater are sources of  $\text{SO}_4^{2-}$  in the water sample.

Precipitation samples plot on figure 25 considerably above the seawater dilution line, indicating that the ratios of  $\text{SO}_4^{2-}/\text{Cl}^-$  in precipitation samples from Florida (table 1) are higher than the ratio in seawater. If rainfall over central Florida were composed of distilled water and seawater spray, lines A-C and D-C would originate

at the precipitation values of  $\text{SO}_4^{2-}$  and  $\text{Cl}^-$ , extend parallel to the horizontal axis, and terminate at the seawater plot position. The "additional"  $\text{SO}_4^{2-}$  in precipitation may come from land-derived solid particulates containing sulfate,  $\text{H}_2\text{S}$  formed by decay of organic material, volcanic emissions of  $\text{H}_2\text{S}$  and  $\text{SO}_2$ , and  $\text{SO}_x$  emissions from industrial processes and combustion of fossil fuels. Junge and Werby (1958, p. 424) calculated that in 1956 as much as 33 percent of the excess  $\text{SO}_4^{2-}$  in rainfall worldwide was due to industrial emissions. All the reduced sulfur emissions are ultimately oxidized to  $\text{SO}_4^{2-}$ , creating acidic rainfall, the topic of many recent papers (Dailey and Winslow, 1980). Of course the acidity of rainfall should have no measurable effect on pH of ground water in the Upper Floridan aquifer because of the abundance of carbonates in the Floridan aquifer system. The sulfur isotopic content of these emissions varies according to the source(s); the  $\text{SO}_x$  emissions can only be estimated to be lighter than either volcanic emissions or the gypsum-derived sulfate in the Upper Floridan aquifer (Hoefs, 1980, p. 45-51, 88).

Isotopically light sulfate (from  $\text{SO}_x$  sources?) in rainfall may be responsible for the anomalously light  $\delta^{34}\text{S}_{\text{SO}_4}$  values reported in ground water in Upper Floridan recharge areas (table 17; Rightmire and others, 1974, table 2). Testing of this hypothesis must await more data on the sulfur isotope content of both rainfall and ground water in the recharge areas. Such data might also be used to quantify the total  $\text{SO}_x$ -derived sulfate in recharge to the Upper Floridan.

The variation in sulfate concentration with depth in the Upper Floridan aquifer is another example of chemical stratification within the aquifer. For example, in central and northwestern Florida,  $\text{SO}_4^{2-}$  concentrations of more than 250 mg/L occur at depth in areas of high recharge. Although deep circulation is minimal in these areas, the shallow flow system is extensive and supports large springs: Silver Springs in Marion County, Fla., one of the largest such springs, has an average  $\text{SO}_4^{2-}$  concentration of about 40 mg/L and an average discharge of 825  $\text{ft}^3/\text{s}$ . Osmond and others (1974, p. 1095) calculated that about 60 percent of the flow of Silver Springs originates in the "upper 100 feet of the . . . [Ocala Limestone] which is at or near the land surface." High  $\text{SO}_4^{2-}$  concentrations also occur in some shallow wells in the Upper Floridan in the Gulf Trough area of southwestern Georgia and in Gadsden County, Fla. The relation of  $\text{SO}_4^{2-}/\text{Cl}^-$  ratios and  $\text{SO}_4^{2-}$  concentrations indicates that remnant seawater containing small amounts of dissolved gypsum is the source of the high  $\text{SO}_4^{2-}$  concentrations in the Gadsden County area. In southwestern Georgia, the  $\text{SO}_4^{2-}/\text{Cl}^-$  and  $\text{SO}_4^{2-}$  concentration data indicate that gypsum is the source of high  $\text{SO}_4^{2-}$  concentrations. High  $\text{SO}_4^{2-}$  concentrations also occur in the vicinity of Val-

dosta and Brunswick, Ga., where large ground-water withdrawals have induced upward migration of highly mineralized water from deeper formations (Wait, 1965; Krause, 1979). Data from deep wells indicate that high  $\text{SO}_4^{2-}$  concentrations occur at depth in most of the study area except east-central and panhandle Florida. Thus, where the Upper Floridan aquifer is stressed by heavy pumpage, increases in  $\text{SO}_4^{2-}$  concentration may occur.

Bacterial reduction of sulfate probably occurs in all parts of the aquifer system; the importance of this process over the entire study area is difficult to determine owing to a lack of mineralogic and sulfur isotopic data. What is known is that bisulfide ( $\text{HS}^-$ ) is present over most of the region, but in highly variable concentrations (fig. 26). This variability in measured concentrations depends on several factors (Rye and others, 1981, p. 1943), such as (1) availability of organic material for sulfate reduction, (2) degree of confinement of the aquifer and loss of  $\text{H}_2\text{S}$  by diffusion, (3) availability of trace metals for reaction with the sulfide, and (4) loss of  $\text{H}_2\text{S}$  during sample collection or by inadequate sample preservation. The amount of  $\text{HS}^-$  measured in water samples might be only a fraction of the total sulfate reduction occurring in the Upper Floridan aquifer. It is possible that the trace amounts of dissolved iron in the system are sufficient over time to form iron sulfides (pyrite?) and consume most of the sulfide formed in the biochemical reaction. Plummer and others (1983, table 4) tested this hypothesis by assuming that the source of dissolved iron was the trace amounts of iron in carbonates; their mass-balance models showed that large amounts of sulfate could be reduced by methane oxidation with concurrent precipitation of pyrite. However, calculations of sulfur isotope balance indicated that such models were not feasible; the methane oxidation-pyrite formation models predicted values of  $\delta^{34}\text{S}_{\text{SO}_4}$  more than 20 ‰ heavier than was analyzed in water samples. The work of Plummer and others (1983) indicates that reduction of large amounts of sulfate and formation of large amounts of pyrite in the Upper Floridan are rather unlikely, especially since no enrichment of as much as 10 ‰  $\delta^{34}\text{S}_{\text{SO}_4}$  has been measured in water samples (table 17). The role of bacterial sulfate reduction in lowering  $\text{SO}_4^{2-}$  concentrations is probably limited to panhandle Florida, where gypsum is scarce and ground-water flow is sluggish. The low  $\text{SO}_4^{2-}$  concentrations mapped in southern Escambia and southwestern Santa Rosa Counties, Fla., occur in an area of high  $\text{Cl}^-$  concentrations, indicating that residual seawater is present in the aquifer system. Locally, the  $\text{SO}_4^{2-}/\text{Cl}^-$  ratio is lower than expected from dilution of seawater, and high concentrations of  $\text{HCO}_3^-$  indicate that bacterial reduction of sulfate may be an important factor in lowering  $\text{SO}_4^{2-}$  concentrations.

#### DISSOLVED SOLIDS AND HYDROCHEMICAL FACIES

In water from the Upper Floridan aquifer, dissolved-solids concentrations vary from less than 25 mg/L near outcrops to more than 25,000 mg/L along the coasts. Within the system, the dominant cations are  $\text{Ca}^{2+}$ ,  $\text{Mg}^{2+}$ ,  $\text{Na}^+$ , and  $\text{K}^+$  and the dominant anions are  $\text{HCO}_3^-$ ,  $\text{Cl}^-$ , and  $\text{SO}_4^{2-}$ . Locally, smaller amounts of dissolved iron, manganese, nitrate, phosphate, fluoride, strontium, sulfide, and silica also contribute to the dissolved-solids concentration. Generally, the dissolved-solids concentration of water from the Upper Floridan aquifer is less than 250 mg/L. In coastal areas, the Upper Floridan contains seawater, and fully penetrating wells may yield water with dissolved-solids concentrations approaching that of seawater, about 36,000 mg/L. Plate 8 shows the general distribution of dissolved-solids concentrations in water produced from wells that yield from the entire Upper Floridan aquifer. The map in plate 8 shows more mineralized water in inland areas than was shown in an earlier map by Shampine (1965b), because plate 8 was made using data from selected deep wells. In coastal and south-central Florida, very shallow wells in the Upper Floridan may produce water with concentrations of dissolved solids of less than 500 mg/L, but wells penetrating deeper than 100 ft will probably yield more mineralized water.

Generally, dissolved-solids concentrations in the Upper Floridan aquifer are maintained at less than 500 mg/L by saturation with calcite and dolomite, and by the limited presence of more soluble minerals such as gypsum; higher concentrations are generally due to the presence of seawater. High dissolved-solids concentrations along the coast of southeastern Georgia and northeastern Florida cannot entirely be attributed to seawater, however, because chloride concentrations in the Upper Floridan are not high. Extensive development of the Upper Floridan aquifer in this area has produced large head declines from predevelopment levels (Bush and Johnston, 1988, pl. 6). Declining heads apparently have induced water from the Lower Floridan aquifer to move upward or laterally, gradually increasing dissolved-solids concentrations over a large area. Recent studies of the effects of ground-water development in northeastern Florida (Fairchild and Bentley, 1977; Leve, 1983; Brown, 1984) indicate that water entering the Upper Floridan aquifer has increased the chloride concentrations in only a few wells as much as 50 mg/L, even though test wells indicate that water in the deepest parts of the Lower Floridan aquifer is a very saline, sodium-chloride type (Brown, 1980). Other data and studies cited in Brown (1984) indicate that highly mineralized, low-chloride water may have been present throughout most of the upper part of the Lower Floridan aquifer prior to devel-