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HYDROGEOLOGIC FRAMEWORK OF THE FLORIDAN AQUIFER SYSTEM IN FLORIDA AND IN PARTS OF GEORGIA, ALABAMA, AND SOUTH CAROLINA

REGIONAL AQUIFER-SYSTEM ANALYSIS

U.S. GEOLOGICAL SURVEY PROFESSIONAL PAPER 1403–B

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

By JAMES A. MILLER

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FOREWORD

The Regional Aquifer-System Analysis Program

The Regional Aquifer-System Analysis (RASA) program was begun in 1978 after a congressional mandate to develop quantitative appraisals of the major ground-water systems of the United States. The RASA program represents a systematic effort to study a number of the Nation's most important aquifer systems, which, in aggregate, underlie much of the country and which represent important components of the Nation's total water supply. In general, the boundaries of these studies are identified by the hydrologic extent of each system and thus transcend the political subdivisions to which investigations have often been arbitrarily limited in the past. The broad objectives for each study are to assemble geologic, hydrologic, and geochemical information, to analyze and develop an understanding of the system, and to develop predictive capabilities that will contribute to effective management of the system. The use of computer simulation is an important element of the RASA studies, both to develop an understanding of the natural, undisturbed hydrologic system and of any changes brought about by human activities, and to provide a means of predicting the regional effects of future pumping or other stresses.

The final interpretive results of the RASA program are presented in a series of U.S. Geological Survey Professional Papers describing the geology, hydrology, and geochemistry of each regional aquifer system. Each study within the RASA program is assigned a single Professional Paper number; where the volume of interpretive material warrants, separate topical chapters dealing with the principal elements of the investigation may be published. The series of RASA interpretive reports begins with Professional Paper 1400 and will continue in numerical sequence as the results of subsequent studies become available.

Dallas L. Peck

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Director

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CONVERSION FACTORS

For readers who prefer to use metric units, conversion factors for terms used in this report are listed here.

Multiply	By	To obtain
foot (ft)	0.3048	meter (m)
square foot (ft^2)	.0929	square meter (m^2)
square foot per day (ft^2/d)	.0929	square meter per day (m^2/d)
foot per day (ft/d)	.3048	meter per day (m/d)
mi (mi)	1.609	kilometer (km)
square mile (mi^2)	2.590	square kilometer (km^2)
gallon per minute (gal/min)	.06308	liter per second (L/s)
million gallons per day (Mgal/d)	.0438	cubic meter per second (m^3/s)

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ABSTRACT

The Floridan aquifer system of the Southeastern United States is comprised of a thick sequence of carbonate rocks that are mostly of Paleocene to early Miocene age and that are hydraulically connected in varying degrees. The aquifer system consists of a single vertically continuous permeable unit updip and of two major permeable zones (the Upper and Lower Floridan aquifers) separated by one of seven middle confining units downdip. Neither the boundaries of the aquifer system or of its component high- and low-permeability zones necessarily conform to either formation boundaries or time-stratigraphic breaks.

The rocks that make up the Floridan aquifer system, its upper and lower confining units, and a surficial aquifer have been separated into several chronostratigraphic units. The external and internal geometry of these stratigraphic units is presented on a series of structure contour and isopach maps and by a series of geohydrologic cross sections and a fence diagram. Paleocene through middle Eocene units consist of an updip clastic facies and a downdip carbonate bank facies, that extends progressively farther north and east in progressively younger units. Upper Eocene and Oligocene strata are predominantly carbonate rocks throughout the study area. Miocene and younger strata are mostly clastic rocks.

Subsurface data show that some modifications in current stratigraphic nomenclature are necessary. First, the middle Eocene Lake City Limestone cannot be distinguished lithologically or faunally from the overlying middle Eocene Avon Park "Limestone." Accordingly, it is proposed that the term Lake City be abandoned and the term Avon Park Formation be applied to the entire middle Eocene carbonate section of peninsular Florida and southeastern Georgia. A reference well section in Levy County, Fla., is proposed for the expanded Avon Park Formation. The Avon Park is called a "formation" more properly than a "limestone" because the unit contains rock types other than limestone. Second, like the Avon Park, the lower Eocene Oldsmar and Paleocene Cedar Keys "Limestones" of peninsular Florida practically everywhere contain rock types other than limestone. It is therefore proposed that these units be referred to more accurately as Oldsmar Formation and Cedar Keys Formation.

The uppermost hydrologic unit in the study area is a surficial aquifer that can be divided into (1) a fluvial sand-and-gravel aquifer in southwestern Alabama and westernmost panhandle Florida, (2) limestone and sandy limestone of the Biscayne aquifer in southeastern peninsular Florida, and (3) a thin blanket of terrace and fluvial sands elsewhere. The surficial aquifer is underlain by a thick sequence of fine clastic rocks and low-permeability carbonate rocks, most of which are part of the middle Miocene Hawthorn Formation and all of which form the upper confining unit of the Floridan aquifer system. In places, the upper confining unit has been removed by erosion or is breached by sinkholes. Water in the Floridan aquifer system thus occurs under unconfined, semiconfined, or fully confined conditions, depending upon the presence, thickness, and integrity of the upper confining unit.

Within the Floridan aquifer system, seven low permeability zones of subregional extent split the aquifer system in most places into an Upper and Lower Floridan aquifer. The Upper Floridan aquifer, which consists of all or parts of rocks of Oligocene age, late Eocene age, and the upper half of rocks of middle Eocene age, is highly permeable. The middle confining units that underlie the Upper Floridan are mostly of middle Eocene age but may be as young as Oligocene or as old as early Eocene. Where no middle confining unit exists, the entire aquifer system is comprised of permeable rocks and for hydrologic discussions is treated as the Upper Floridan aquifer.

The Lower Floridan aquifer contains a cavernous high-permeability horizon in the lower part of the early Eocene of southern Florida that is called the Boulder Zone. A second permeable unit that is cavernous in part, herein called the Fernandina permeable zone, occurs in the lower part of the Lower Floridan in northeastern Florida and southeastern Georgia. Both these permeable zones are overlain by confining units comprised of micritic limestone. The confining unit that overlies the Boulder Zone is of subregional extent and is mapped as a separate middle confining unit within the Lower Floridan.

Major structural features such as the Southeast and Southwest Georgia embayments, the South Florida basin, the Gulf Coast geosyncline, and the Peninsular arch have had a major effect on the thickness and type of sediment deposited in the eastern gulf coast. The effects of smaller structures are also evident. For example, the Gilbertown-Pickens-Pollard fault system in Alabama locally forms the updip limit of the Floridan aquifer system. The series of grabens that comprise the Gulf Trough of central Georgia serves as a low-permeability barrier to ground-water flow there. These Gulf Trough faults have downdropped low-permeability rocks opposite permeable limestones to create a damming effect that severely retards ground-water movement across the fault system. Their

effect can be seen on potentiometric surface maps of the aquifer system. Other small-displacement faults in peninsular Florida do not appear to affect the regional flow system because there is no apparent change in the permeability of the rocks that have been juxtaposed by fault movement.

Variations in permeability within the Floridan aquifer system result from a combination of original depositional conditions, diagenesis, large- and small-scale structural features, and dissolution of carbonate rocks or evaporite deposits. Local permeability variations are accordingly more complex than the generalized regional portrayal presented in this report.

INTRODUCTION

PURPOSE AND SCOPE

In 1977 the U.S. Geological Survey began a nationwide program to study a number of the regional aquifers that provide a significant part of the country's water supply. This program, termed the Regional Aquifer-System Analysis (RASA), is discussed in detail by Johnston and Bush (1985). In brief, the general objectives of each RASA study are (1) to describe the ground-water system as it exists today and as it existed before development, (2) to analyze changes between present and predevelopment systems (3) to integrate the results of previous studies dealing with local areas or discrete aspects of the system, and (4) to provide some capability for evaluating the effects (particularly the hydraulic effects) that future ground-water development will have on the system. These objectives can best be met by a regional-scale digital computer simulation of the aquifer system, supplemented where necessary by more detailed subregional simulations and by interpretations of the distribution of observed water-quality variations. Because of its importance as a source of ground-water supply and because of various problems that have arisen from intensive use, the Floridan aquifer system of the Southeastern United States was among the first regional aquifer systems chosen for study.

The Floridan aquifer system is comprised of carbonate rocks of Tertiary age and includes but is not limited to the sequence of rocks generally called the "Floridan aquifer" in Florida and the "principal artesian aquifer" in Georgia. Tertiary limestones also yield water, locally in appreciable quantities, in parts of southwestern South Carolina and southeastern Alabama. These limestones are included in the Floridan aquifer system in this report. The approximate areal extent of the aquifer system is shown in figure 1. The system includes rocks of Paleocene to early Miocene age that combine to form a vertically continuous carbonate sequence that is hydraulically connected in varying degrees. Very locally, in the Brunswick, Ga., area, beds assignable to the uppermost part of the Upper Cretaceous System are included in the Floridan aquifer system. Over much of the area where the aquifer system crops out, it consists of one vertically continuous permeable unit. Downdip, the aquifer system generally consists of two major permeable zones, herein called the Upper Floridan aquifer and the Lower Floridan aquifer, that are separated by less-permeable rock of highly variable hydraulic properties (very leaky to virtually nonleaky). Hydraulic conditions for the aquifer system vary from confined to unconfined, depending upon whether the argillaceous middle Miocene and younger rocks that form the upper confining unit of the system have been breached or removed by erosion.

As one of several chapters of a Professional Paper describing different aspects of the Floridan aquifer system and discussing the results of computer simulations, this report presents the hydrogeologic framework of the aquifer system as determined from subsurface geologic and hydrologic data. The objectives of this part of the study were:

1. To identify the aquifer system regionally in terms of the geologic and hydrologic units that comprise it and to define its extent.
2. To delineate regional permeability variations within the aquifer system, primarily on the basis of rock composition and texture and, to a lesser extent, on the development of secondary (solution) porosity.
3. To establish the influence of geologic structure and of variation in rock type on the ground-water flow pattern of the aquifer system.
4. To identify and map regional stratigraphic units and to establish a correlation framework between surface and subsurface geologic units.
5. To determine variations in the geometry and physical makeup of the aquifer system that affect either hydraulic parameters or the water quality of the system.

PREVIOUS WORK

Numerous reports have been published, chiefly by the U.S. Geological Survey and State geological surveys, that discuss various aspects of the geology and ground-water resources of the study area. For the most part, the scope of these reports is local or subregional. Extensive lists of publications on the geology and hydrology of the Floridan aquifer system are contained in reports by Murray (1961), Stringfield

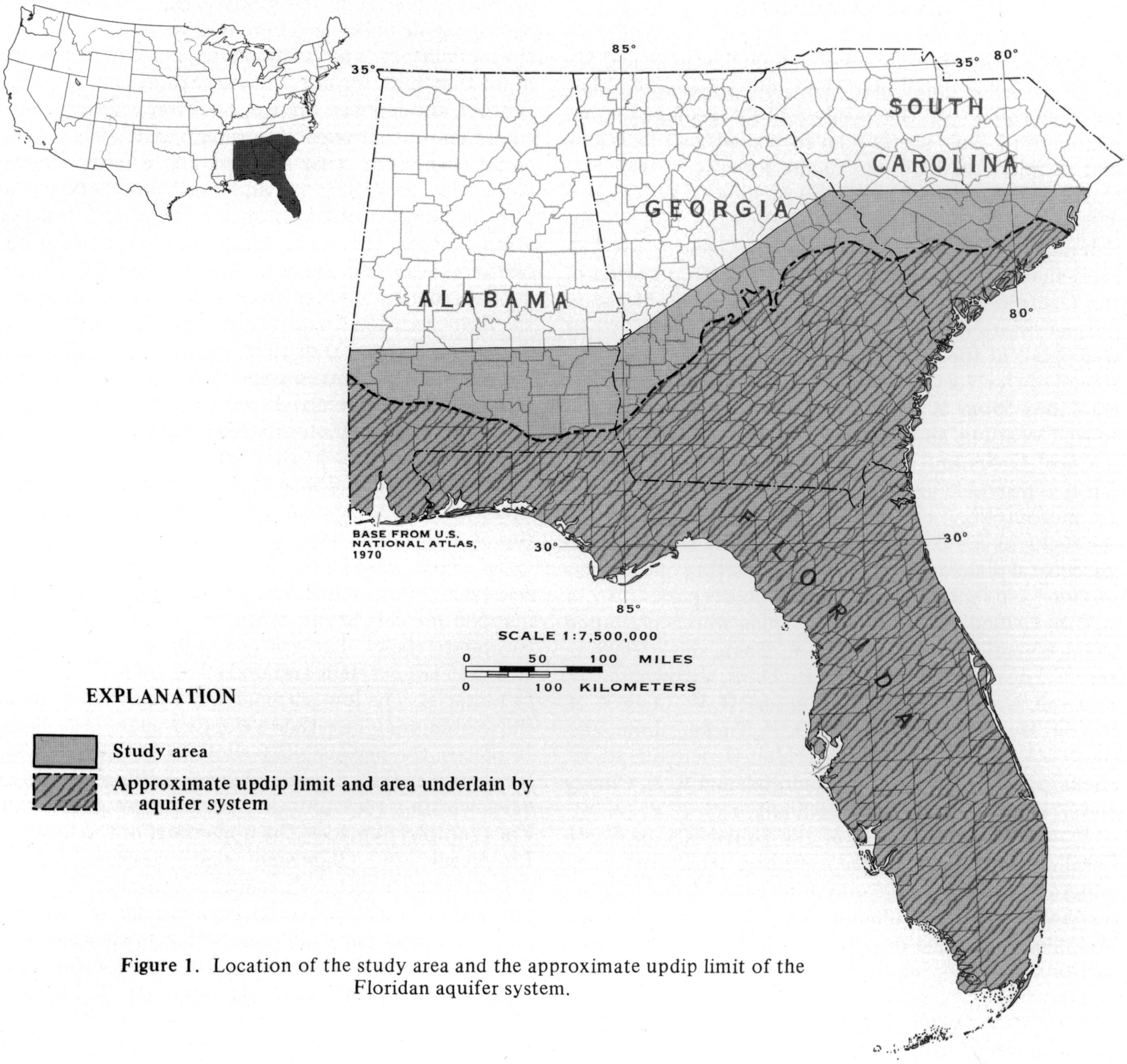

Figure 1. Location of the study area and the approximate updip limit of the Floridan aquifer system.

(1966), Braunstein (1970, 1976), Heath and Conover (1981), and Krause (1982). Reports dealing with the regional surface and subsurface geology of the Tertiary rocks in the report area include those of Applin and Applin (1944, 1964), Chen (1965), Cooke (1943, 1945), Copeland (1968), Herrick (1961), Herrick and Vorhis (1963), LaMoreaux (1946), Maher (1965, 1971), Maher and Applin (1968), Murray (1961), Puri (1953b, 1957), Puri and Vernon (1964), Randazzo and others (1977), and Randazzo and Hickey (1978). Reports that discuss regional aspects of ground water in the Floridan aquifer system have been written by Callahan (1964), Cederstrom and others (1979), Hanshaw and others (1971), Hayes (1979), Parker and others (1955), Stephenson and Veatch (1915), Stringfield (1936, 1966), and Warren (1944).

In places, the lithologic differences between strata that form the Floridan aquifer system are subtle. Accordingly, the microfauna contained in these strata have been used by some workers to establish stratigraphic subdivisions within the system. Reports on the microfauna of the Tertiary limestones include those of Applin and Jordan (1945), Cole (1938, 1941, 1942, 1944, 1945), Cushman (1935, 1951), Cushman and Ponton (1932), Levin (1957), and Loeblich and Tappan (1957).

ACKNOWLEDGMENTS

Appreciation is due several organizations and individuals who contributed data and suggestions during the course of the study. State geologists and members of their staffs who furnished well locations and geophysical logs and made libraries of well cuttings available for examination include C. W. Hendry (Chief) and T. M. Scott, R. W. Hoenstine, and Walter Schmidt of the Florida Bureau of Geology; W. H. McLemore (State Geologist) and P. H. Huddleston of the Georgia Geologic Survey; and P. E. LaMoreaux (former State Geologist) and C. W. Copeland (Chief Geologist) of the Geological Survey of Alabama. Personnel of the Northwest Florida, Suwannee River, and St. Johns River Water Management Districts provided well locations and some geophysical logs.

Carol Gelbaum, formerly of the Georgia Geologic Survey, provided extensive information on the lithology, paleontology, and water-bearing characteristics of the rocks in the Gulf Trough area of the central Georgia coastal plain and did the initial drafting of the cross sections and fence diagram used in this report.

U.S. Geological Survey colleagues who contributed to the investigation include M. E. Davis, J. G. Newton, and C. A. Pascale (Alabama); D. P. Brown, J. D. Fretwell, H. G. Healy, G. H. Hughes, G. W. Leve, A. S. Navoy, Horace Sutcliffe, Jr., D. F. Tucker, John Vecchioli, and F. A. Watkins (Florida); H. E. Gill, R. W. Hicks, and S. E. Matthews (Georgia); and R. N. Cherry and P. W. Johnson (South Carolina).

P. A. Thayer, formerly of the University of North Carolina at Wilmington, studied the carbonate mineralogy and petrography of cores collected during test-hole drilling conducted for this study. Valerie McCollister did the preliminary drafting of the cross sections and other related illustrations.

METHOD OF STUDY

APPROACH

The study area (fig. 1) extends from the southern part of the Atlantic Coastal Plain, a geologic province that has been affected primarily by compressional tectonics (Brown and others, 1972) westward into the eastern part of the Gulf Coastal Plain, which has been affected predominantly by gravity tectonics (Murray, 1961), and southward to encompass the Florida platform, which is underlain by a thick sequence of shallow-water platform-type carbonate rocks. Rapid and complex facies changes occur in the area, especially in places where carbonate rock grades laterally into clastic rock. Correlation between clastic and carbonate units or between surface and subsurface units is at present imprecise in the study area. Accordingly, the stratigraphic units used herein have been delineated in the subsurface and mapped as chronostratigraphic units that may include several formations. Structure contour and isopach maps have been prepared for six such Cenozoic chronostratigraphic units. These maps, along with eight cross sections and a fence diagram, show the geometry of and relations between the mapped units. Altitudes on the maps and cross sections and on the fence diagram are related to the National Geodetic Vertical Datum (NGVD) of 1929, a geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada. The NGVD of 1929 was formerly called mean sea level. For convenience of usage, however, the NGVD of 1929 is referred to as sea level in the text and on the figures and plates in this report.

The top and base of the Floridan aquifer system, as well as the top and base of major permeability variations within the system, commonly coincide with the top of a chronostratigraphic unit or a particular rock type. Such coincidence is not the case everywhere, however. The vertical limits of the aquifer system as mapped for this study represent the top and base of carbonate rocks that are generally highly permeable and that are overlain and underlain by low-permeability material. The low-permeability rock that delineates the system may be either a clastic rock or a carbonate. In places, the permeability contrast between the aquifer system and its upper and lower confining units may exist within a rock unit or a chronostratigraphic unit. For example, in places, the upper part of the Suwannee Limestone of Oligocene age consists of low-permeability micritic limestone underlain by highly permeable limestone comprised largely of pelecypod and gastropod casts and molds that is also part of the Suwannee. In this case, the top of the Floridan aquifer system would be placed at the top of the highly permeable cast-and-mold limestone rather than at the top of the Suwannee. The aquifer system is thus defined on the basis of its permeability characteristics rather than on the basis of lithology. Accordingly, the structure contour map of the top of the Floridan aquifer system presented in this report differs considerably from previously published maps that represent either the top of vertically continuous limestone or the top of a particular geologic horizon, regardless of its permeability. Structure contour maps representing the base of the aquifer system and the base of the upper major permeable zone within it (the Upper Floridan aquifer) were presented for the first time by Miller (1982a, b) in preliminary open-file publications and are reproduced in this report with minor modifications. Isopach maps of the total aquifer system and of the Upper Floridan aquifer are also presented.

Tops and thicknesses of both chronostratigraphic and permeability units were determined in each of 662 wells selected as key data points. The tops and bottoms of both types of units were established on the basis of the lithologic, paleontologic, and hydraulic characteristics of each unit as revealed in certain deep test wells. Geophysical log (chiefly electric log) patterns representative of each stratigraphic and permeability unit were determined, and the units were extrapolated subregionally primarily on the basis of these log patterns and supplementary descriptions of cores and drill cuttings. The mineralogic composition of rock samples from certain test wells was determined primarily by examining the samples with a binocular microscope. Three assumptions were made in extending relatively permeable and impermeable zones: (1) most of the porosity observed in drill cuttings and in core was effective porosity and therefore indicated a relatively permeable rock, (2) high- and low-porosity rocks were expressed on electric logs by different resistivity characteristics, and (3) once the electric log pattern of a zone was established as representing high or low permeability, the permeability of that zone was considered to remain essentially the same forthe geographic area in which the log pattern remained the same.

The locations of the wells that comprise the data network used in constructing the various maps and cross sections are shown on plate 1. On the cross sections (locations also shown on pl. 1) and in the text of the report, each well is designated by an abbreviation that identifies the State and county within which the well is located and a sequential project number within that county. On the cross sections, wells in Florida and Alabama are also located by the section-township-range grid of the Federal System of Rectangular Surveys within which they lie. For the well-numbering system used herein, the State abbreviations are those in common usage. The county abbreviations are as follows:

Alabama

Baldwin	BAL
Clarke	CL
Covington	COV
Escambia	ES
Geneva	GEN
Houston	HO
Mobile	MOB
Monroe	MON

Florida

Alachua	AL
Baker	BA
Bay	BAY
Bradford	BRA
Broward	BRO
Calhoun	CAL
Charlotte	CHA
Citrus	CI
Clay	CL
Collier	COL
Columbia	CO
Dade	DA
DeSoto	DE
Dixie	DIX
Duval	DUV
Escambia	ESC
Flagler	FL
Franklin	FRA
Gadsden	GA
Gilchrist	GIL
Glades	GL
Gulf	GF
Hamilton	HAM
Hardee	HAR
Hendry	HEN
Hernando	HER
Highlands	HI
Hillsborough	HIL
Holmes	HOL
Indian River	IR
Jackson	JX
Jefferson	JEF
Lafayette	LAF
Lake	LK
Lee	LEE
Leon	LN
Levy	LV
Liberty	LIB
Madison	MAD
Manatee	MAN
Marion	MAR
Martin	MTN
Monroe	MON
Nassau	NA
Okaloosa	OKA
Okeechobee	OKE
Orange	OR
Osceola	OS
Palm Beach	PB
Pasco	PAS
Pinellas	PIN
Polk	POL
Putnam	PUT
St. Johns	SJ
St. Lucie	SL
Santa Rosa	SR
Sarasota	SAR
Suwannee	SUW
Taylor	TAY
Union	UN
Volusia	VO
Wakalla	WAK
Walton	WAL
Washington	WAS

Georgia

Appling	AP
Atkinson	AT

Bacon	BAC
Baker	BAK
Ben Hill	BH
Berrien	BER
Brantley	BRA
Brooks	BRO
Bryan	BRY
Bullock	BUL
Burke	BU
Calhoun	CAL
Camden	CAM
Charlton	CHN
Chatham	CHA
Clinch	CLI
Coffee	COF
Colquitt	COQ
Cook	COK
Crisp	CRP
Decatur	DE
Dodge	DOE
Dooly	DO
Dougherty	DOG
Early	EA
Echols	EC
Effingham	EFF
Emanuel	EM
Evans	EV
Glynn	GLY
Grady	GR
Houston	HOU
Irwin	IR
Jeff Davis	JD
Jenkins	JEN
Laurens	LA
Lee	LEE
Liberty	LIB
Long	LO
Lowndes	LOW
McIntosh	MC
Mitchell	MIT
Montgomery	MO
Pierce	PI
Pulaski	PU
Screven	SCR
Seminole	SE
Tattnall	TAT
Telfair	TEL
Terrell	TER
Thomas	THO
Tift	TF
Toombs	TO
Treutlen	TR
Ware	WA
Wayne	WAY
Wheeler	WH
Wilcox	WX
Worth	WOR

South Carolina

Allendale	AL
Bamberg	BAM
Beaufort	BEA
Charleston	CHN
Colleton	COL
Dorchester	DOR
Hampton	HAM
Jasper	JAS

The designation SC-HAM-3, for example, means that the well is located in Hampton County, S.C., and that it is the third well within that county for which data were obtained. In general, wells selected as key wells are those for which geophysical logs are available along with drill cuttings and (or) core.

The tops and thicknesses of the different stratigraphic and permeability units delineated have been tabulated for each of the 662 wells used as control points. The tables are arranged alphabetically by the State and county in which the wells are located. This tabulation has been published as a data report by Miller, (1984) and is available from the Open-File Services Section, Central Distribution Branch, U.S. Geological Survey, P.O. Box 25425, Federal Center, Denver, CO 80025. The well tables are also on file in the office of the Regional Hydrologist, Southeastern Region, Water Resources Division, U.S. Geological Survey, 75 Spring Street, S.W., Atlanta, GA 30303, and are available for examination. The well data are stored in the U.S. Geological Survey computer and may be obtained as a computer printout or as card images from the Automatic Data Section, Office of the Assistant Chief Hydrologist for Scientific Publications and Data Management, Water Resources Division, U.S. Geological Survey, National Center, 12201 Sunrise Valley Drive, Reston, VA 22092.

Most of the key wells used as control points are oil test wells, which are generally the only wells deep enough to penetrate the entire Floridan aquifer system. Oil test wells can be recognized in the well tables by a number accompanying the property owner's name in the "Lease" column. For example, a well whose lease is designated as "#1 Gulf and Western 7-4" is an oil test well. The oil test data were supplemented by data from numerous water wells, particularly those drilled to test the potential for water production from or waste injection into deep zones in the aquifer system. In places where deep well control of any type is sparse, data were used from some of the thousands of shallow water wells in the project area, primarily in mapping the top of the aquifer system. All pertinent offshore well data were examined, although contouring was not extended seaward of the present-day shoreline. Interpretations made from borehole data were extended and supplemented by examination of publicly and privately owned reflection and refraction seismic data, particularly in southern Florida, southeastern Georgia, and offshore.

CORRELATION PROCEDURE

Correlation difficulties always arise in any study of regional scope because of the wide variations in depositional environments and, consequently of rock types that one encounters in mapping geology and permeability distribution over a large area. The present study was no exception. Complex facies changes occur between those parts of the region where mostly carbonate rocks were deposited and those parts that received mostly clastic sediments. Within the areas that are underlain mostly by carbonate rocks, such as the Florida peninsula, thick sequences of limestones were deposited in warm, shallow marine water over long periods of geologic time. Because the same shallow-marine environment persisted in much of Florida throughout Tertiary time, the textural or mineralogic changes in the carbonate rock column may be subtle in places. Diagenetic alteration at many locales has affected the carbonate rocks as much as or more than changes in primary depositional conditions. Also, in much of the Florida peninsula, the same rock type may recur at several horizons in the geologic column because the exact depositional and (or) diagenetic conditions that produced it were repeated several times.

All the preceding factors preclude regional correlation of stratigraphic units on the basis of lithology alone. They also account in large part for some of the uncertainty in correlation between surface and subsurface units in the project area and for the controversy that surrounds some published correlations. The existing stratigraphic correlation framework used in the study area is twofold, consisting of (1) detailed correlations involving many formation names in outcrop (largely clastic rock) areas and based primarily on lithology and supplemented by macropaleontology and (2) generalized, regionally extensive correlations involving only a few "formation" names in the deep subsurface (largely carbonate rock) areas and based primarily on micropaleontology. The subsurface correlations were made and many of the subsurface Tertiary "formations" were named at a time when only a few widely scattered deep wells existed and when no uniform procedure for naming geologic units was followed. The lithologic differences (often subtle) between such "formations," some of which were named because they contained a unique microfauna, are in many cases confined to a local area. The rock type supposedly characteristic of a given "formation" in a given well can often be found in a nearby well at a completely different stratigraphic horizon.

A worker attempting to make regional correlations in a particular study area is thus faced with the problem of trying to tie together well-defined surface or near-surface rock-stratigraphic units with nebulous subsurface biostratigraphic units (North American Commission on Stratigraphic Nomenclature, 1983) through an intervening area of complex facies change. Neither the surface nor the subsurface correlation framework traditionally used is adequate to describe the physical (or biologic) situation that exists in the rocks.

The equivalency of surface and subsurface geologic units in a project area can best be established by mapping time-rock or chronostratigraphic units. The units chosen for mapping in this report correspond mostly to the series within the Tertiary System or to parts of such series. Chronostratigraphic units include rocks deposited during a particular span of geologic time, regardless of whether they have the same lithology everywhere. The upper and lower boundaries of the time-rock units mapped in this report coincide with changes in rock type that occur in specific wells from which cores and (or) reliable drill cuttings are available. The different chronostratigraphic units delineated were then extended to other wells primarily on the basis of geophysical (mostly electric) log patterns. As correlations of a chronostratigraphic unit are extended laterally over a wide area, the rock types included in that unit may change, and the log pattern of the unit will also change. Different strata are grouped with a given chronostratigraphic unit if they can be shown to represent a logical lateral facies change or to be isochronous with other strata included in the unit elsewhere.

Because the units mapped in this report are time-rock units, their upper and lower boundaries are determined in part by the fauna (chiefly microfauna) that they contain. In general, the vertical range of the microfossils considered characteristic of a given time-rock unit coincides with the vertical boundaries of the various rock types assigned to that unit. Obvious exceptions are reworked or caving faunas. Benthic and planktic Foraminifera, supplemented by Ostracoda, were used chiefly for correlation. The different species considered characteristic of a particular time-rock unit in the study area are listed in table 1, along with a letter-number designation assigned to each species. On the cross sections in this report, the highest occurrence of a given characteristic species identified from a given well is shown by plotting the letter-number code for that species alongside the well column. All of the species that are considered in this report to be time diagnostic are illustrated elsewhere and are accordingly not illustrated herein. The principal reference used for identification, taxonomy, and stratigraphic range determination for the planktic Foraminifera was a paper by Stainforth and others (1975), supplemented by reports by Postuma (1971) and Berggren (1977).

GEOLOGY

REGIONAL SETTING

The Coastal Plain province of the Southeastern United States is underlain by a thick sequence of unconsolidated to semiconsolidated sedimentary rocks that range in age from Jurassic to Holocene. These sediments thicken seaward in the study area from a featheredge where they crop out against older metamorphic and igneous rocks of the Piedmont and Applachian provinces to a maximum penetrated thickness of more than 21,100 ft in Mobile County in southern Alabama. In southern Florida, the thickness of Coastal Plain sediments probably exceeds 25,000 ft; however, the maximum thickness penetrated there as of this writing (1984) is slightly more than 18,600 ft. Coastal Plain rocks generally dip gently toward the Atlantic Ocean or the Gulf of Mexico, except where they are warped or faulted on a local to subregional

Table 1.—*Microfauna characteristic of the several chronostratigraphic units in the study area, and their cross-section designations*

Cross-section designation	Fossil
	Miocene Series
M-1	*Amphistegina chipolensis* Cushman and Ponton
M-2	*Amphistegina lessoni* d'Orbigny
M-3	*Bolivina floridana* Cushman
M-4	*Bolivina marginata multicostata* Cushman
M-5	*Elphidium chipolensis* (Cushman)
M-6	*Sorites* sp.
M-7	*Aurila conradi* (Howe and McGuirt)
M-8	*Hemicythere amygdula* Stephenson
	Oligocene Series
OL-1	*Pararotalia byramensis* Cushman
OL-2	*Miogypsina* sp.
OL-3	*Pulvinulina mariannensis* Cushman
OL-4	*Robulus vicksburgensis* (Cushman) Ellisor
OL-5	*Palmula caelata* (Cushman) Israelsky
OL-6	*Globigerina selli* (Borsetti)
OL-7	*Lepidocyclina leonensis* Cole
OL-8	*Lepidocyclina parvula* Cole
OL-9	*Aurila kniffeni* (Howe and Law)
OL-10	*Pararotalia mexicana mecatepecensis* Nuttall
	Eocene Series
Late Eocene:	
UE-1	*Bulimina jacksonensis* Cushman
UE-2	*Robulus gutticostatus* (Gumbel) var. *cocoaensis* (Cushman)
UE-3	*Amphistegina pinarensis* Cushman and Bermudez var. *cosdeni* Applin and Jordan
UE-4	*Lepidocyclina ocalana* Cushman
UE-5	*Lepidocyclina ocalana floridana* Cushman
UE-6	*Eponides jacksonensis* (Cushman and Applin)
UE-7	*Gyroidina crystalriverensis* Puri
UE-8	*Globigerina tripartita* Koch
UE-9	*Operculina mariannensis* Vaughn
UE-10	*Cytheretta alexanderi* Howe and Chambers
UE-11	*Clithocytheridea caldwellensis* (Howe and Chambers)
UE-12	*Clithocytheridea garretti* (Howe and Chambers)
UE-13	*Jugosocythereis bicarinata* (Swain)
UE-14	*Haplocytheridea montgomeryensis* (Howe and Chambers)
UE-15	*Asterocyclina* sp.

scale. Coastal Plain sediments were laid down on an eroded surface developed on igneous intrusive rocks, low-grade metamorphic rocks, mildly metamorphosed Paleozoic sedimentary rocks, and graben-fill sedimentary deposits of Triassic to Early Jurassic age (Barnett, 1975; Neathery and Thomas, 1975; Chowns and Williams, 1983). Because rocks older than Early Jurassic lie at great depths, their relations and configurations are not as well known as those of the shallower Coastal Plain rocks.

The poorly consolidated Coastal Plain sediments are easily eroded. The carbonate rocks are dissolved by downward-percolating water, the result being the formation of karst topography where such rocks are at or near the surface. Accordingly, the topography developed in much of the study area is characterized by (1) extensive, slightly dissected plains, (2) low, rolling hills, and (3)widely spaced drainage. Local to subregional sinkhole topography is present where limestone rocks lie at or near land surface. A series of

Middle Eocene:	
ME-1	*Asterigerina texana* (Stadnichenco)
ME-2	*Dictyoconus* sp.[1]
ME-3	*Spirolina coreyensis* (Cole)
ME-4	*Lituonella floridana* (Cole)
ME-5	*Discorbis inornatus* Cole
ME-6	*Valvulina cushmani* Applin and Jordan
ME-7	*Valvulina martii* Cushman and Bermudez
ME-8	*Discorinopsis gunteri*[1] Cole
ME-9	*Fabularia vaughani* Cole and Ponton
ME-10	*Textularia coreyensis* Cole
ME-11	*Gunteria floridana* Cushman and Ponton
ME-12	*Pseudorbitolina cubensis* Cushman and Bermudez
ME-13	*Globorotalia bullbrooki* Bolli
ME-14	*Amphistegina lopeztrigoni* Palmer
ME-15	*Ceratobulimina stellata* Bandy
ME-16	*Globorotalia spinulosa* Cushman[2]
ME-17	*Clypeina infundibuliformia* Morellet and Morellet (alga)
ME-18	*Leguminocythereis petersoni* Swain
ME-19	*Lepidocyclina antillea* Cushman (=*L. gardnerae* Cole)
Early Eocene:	
LE-1	*Miscellanea nassauensis* Applin and Jordan
LE-2	*Helicostegina gyralis* Barker and Grimsdale[3]
LE-3	*Lockhartia* sp.
LE-4	*Globorotalia formosa gracilis* Bolli
LE-5	*Globorotalia subbotinae* Morozova
LE-6	*Globorotalia wilcoxensis* (Cushman and Ponton)
LE-7	*Pararotalia trochoidiformis* (Lamarck)
LE-8	*Brachycythere jessupensis* Howe and Garrett
LE-9	*Haplocytheridea sabinensis* (Howe and Garrett)
LE-10	*Pseudophragmina (Proporocyclina) cedarkeyensis* Cole
Paleocene Series	
P-1	*Globorotalia pseudomenardii* Bolli
P-2	*Borelis floridanus* Cole
P-3	*Borelis gunteri* Cole
P-4	*Valvulammina nassauensis* Applin and Jordan
P-5	*Globorotalia angulata* (White)
P-6	*Globorotalia pseudobulloides* (Plummer)
P-7	*Cythereis reticulodacyi* Swain
P-8	*Krithe perattica* Alexander
P-9	*Trachylebris prestwichiana* (Jones and Sherborn)
P-10	*Globorotalia velascoensis* (Cushman)

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[1] Locally these species may also occur in rocks of Oligocene age.
[2] Occurs locally in rocks of late early Eocene age.
[3] Occurs locally in the lower part of the middle Eocene.

sandy marine terraces of Pleistocene age has been developed in much of the area. Stringfield (1966) has discussed the physiography of the study area in detail.

Coastal Plain sediments in the project area can be separated into two general facies: (1) predominantly clastic rocks containing minor amounts of limestone that extend southward and eastward toward the Atlantic Ocean and the Gulf of Mexico from the Fall Line that marks the inland limit of the Coastal Plain and (2) a thick, continuous sequence of shallow-water platform carbonate rocks that underlie southeastern Georgia and all of the Florida peninsula. In north-central Florida and in southeastern Georgia, where these clastic and carbonate rocks generally interfinger with one another, facies changes are both rapid and complex. In general, the limestone facies of successively younger units extends progressively farther and farther updip and encroaches to the northwest upon the clastic rocks in an onlap relation, at least until the end of Oligocene time. Miocene and younger rocks comprise a clastic facies that, except where it has been removed by erosion, covers the older carbonate rocks everywhere. The various stratigraphic units within both the clastic- and the carbonate-rock areas are separated by unconformities that represent breaks in sedimentation. As in most regional studies, however, these unconformities are not synchronous surfaces that extend throughout the project area.

Cretaceous rocks generally crop out in a band adjacent to the crystalline rocks and folded strata of the Piedmont and Appalachian provinces. In northeastern Georgia, Eocene and Miocene sediments cover rocks of Cretaceous age in an overlap relation. Figure 2 is a generalized geologic map showing the distribution of rocks of various ages in and adjacent to the project area. Rocks of Tertiary age, whose carbonate facies comprise most of the Floridan aquifer system, crop out in a discontinuous band seaward of the Cretaceous sediments and are also exposed in an area in western peninsular Florida. Still farther seaward, a band of predominantly clastic rocks of Miocene age crops out to form the upper confining unit of the Floridan aquifer system. Miocene rocks generally separate the Floridan from Pliocene and Quaternary strata that are mostly sands and comprise a surficial (unconfined) aquifer.

RELATION OF STRATIGRAPHIC AND HYDROGEOLOGIC UNITS

In the multistate area covered by this study, many formation and aquifer names have been applied to parts of the carbonate rocks that together are called the Floridan aquifer system in this report. To avoid confusion and cumbersome terminology, the stratigraphic units mapped herein are time-rock units that may include all or parts of several formations. The relation between formation (rock-stratigraphic) terminology and the time-rock (chronostratigraphic) units mapped is shown on a correlation chart (pl. 2). Also delineated on this chart are the formations or parts of formations that are included in the Floridan aquifer system.

Just as it is necessary in a regional study to group several geologic formations into regionally extensive units, so must the rocks be grouped according to their general water-bearing properties. Accordingly, the Floridan aquifer system as mapped in this report represents a vertically continuous sequence of carbonate rocks that are in general highly permeable. The aquifer system is everywhere underlain by low-permeability materials that may be clastic, carbonate, or evaporite rocks. Except where the aquifer system is unconfined, it is overlain by clastic or impure carbonate rocks of low permeability.

Within the sequence of generally high permeability carbonate rocks are confining units of local to subregional extent. Over much of the study area, the subregional-scale confining units separate the Floridan aquifer system into upper and lower high-permeability zones, called the Upper and Lower Floridan aquifers, respectively. A discussion of the aquifer-confining unit terminology used in this report and companion chapters of Professional Paper 1403 is given by Johnston and Bush (1985). Locally, there may be several thin to moderately thick low-permeability units of limited areal extent within either of the high-permeability zones (for example, well FLA-FRA-7, cross section E-E', pl. 21; well GA-CHA-8, fig. 12). The amount of low-permeability rock within the aquifer system varies greatly. In the north-central part of the Florida peninsula, much of the aquifer system is highly permeable; in places in southern Florida, as much as 40 percent of the system is low-permeability rock. The confining units may consist of micritic limestone, fine-grained dolomite, or limestone and dolomite that once were permeable but whose pores are now filled with evaporite minerals; in places, the confining units may represent zones of recrystallization.

GEOLOGIC STRUCTURE

The general configuration of Coastal Plain sediments in the study area is a tilted wedge that slopes and thickens seaward from the Fall Line. Superimposed on this prism-shaped mass of sediment are gentle warps of subregional extent. Local to subregional fault systems cut all or parts of the sediment wedge in places. Some of the more prominent features that interrupt the gentle seaward slope of these Coastal Plain sediments and that have been recognized for many years are shown in figure 3. The major features shown in this figure affected Coastal Plain sediment distribution and configuration over long periods of geologic time. The large positive and negative folds in and contiguous to the Florida peninsula fall into this category. Other features, particularly some of the smaller faults shown in figure 3, were active structures for only a relatively short time, and many of them accordingly had little effect (other than local) on sedimentation.

The dominant influence on sedimentation in the study area has been the Peninsular arch, a northwest-trending feature that was continuously positive from early Mesozoic (Jurassic) until Late Cretaceous time and was intermittently positive during Cenozoic time. Southwest of and parallel to the Peninsular arch is the Ocala "uplift," which affects only rocks of middle Eocene age and younger. Although these two features are often confused in the literature, they are, in fact, distinct entities whose origins are not the same (Winston, 1976). The shape of the Peninsular arch and its effect on sedimentation in north-central Florida resemble those of an upwarp produced by compressional tectonics. Because the Ocala "uplift," does not warp or otherwise affect sediments older than middle Eocene, it is not a true uplift. This feature was produced by sedimentational processes—either an anomalous buildup of middle Eocene carbonate sediments (Win-

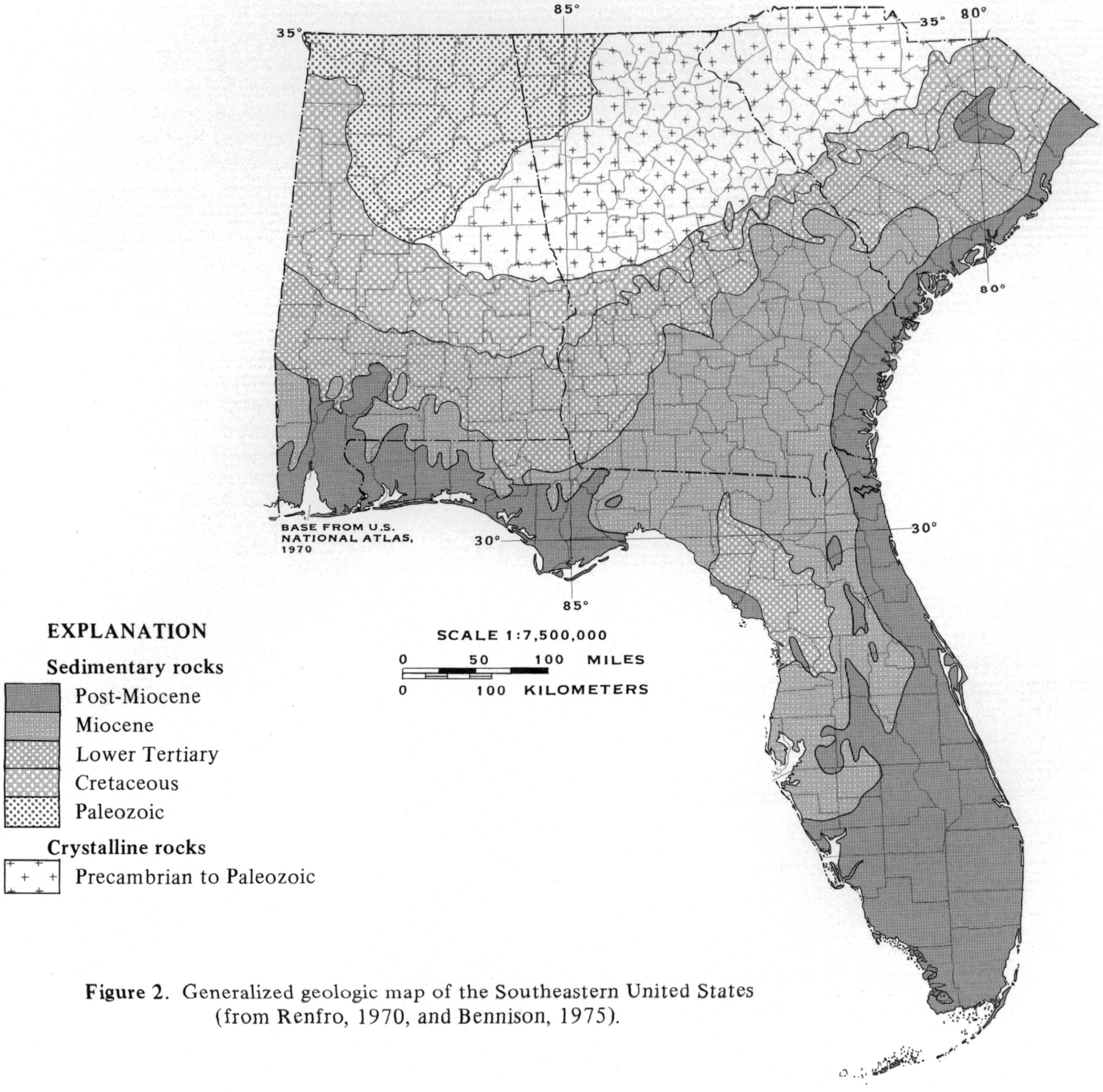


Figure 2. Generalized geologic map of the Southeastern United States (from Renfro, 1970, and Bennison, 1975).

ston, 1976) or, more likely, differential compaction of middle Eocene carbonate material shortly after deposition. Drilling on the "crest" of the Ocala "uplift" shows that the feature is not of deltaic or reefal origin.

A subtle feature that appears at first to be a structural high is located in southeastern Alabama and southwestern Georgia, roughly parallel to the Chattahoochee River. This apparent high has been called the Chattahoochee arch or anticline (Murray, 1961). At places along this feature, outcropping older rocks (Eocene) are surrounded by younger rocks (Oligocene), a situation that would seem to indicate an anticline. However, Patterson and Herrick (1971) thought that such an interpretation was incorrect. A positive structure did, in fact, exist in the general area of the "Chattahoochee arch" during Jurassic time (Miller, 1982g) but there is no evidence that it persisted beyond the end of the Jurassic. No positive feature is shown in the Chattahoochee River area on maps of the tops or thicknesses of the different time-stratigraphic and hydrologic units differentiated in this report. The "Chattahoochee arch" is considered to be an erosional feature rather than a structural one.

The Peninsular arch is flanked on three sides by negative features that have been depocenters since at least Early Cretaceous time (fig. 3). To the south, a thick sequence of platform carbonates was deposited in the South Florida basin. To the northeast, in the

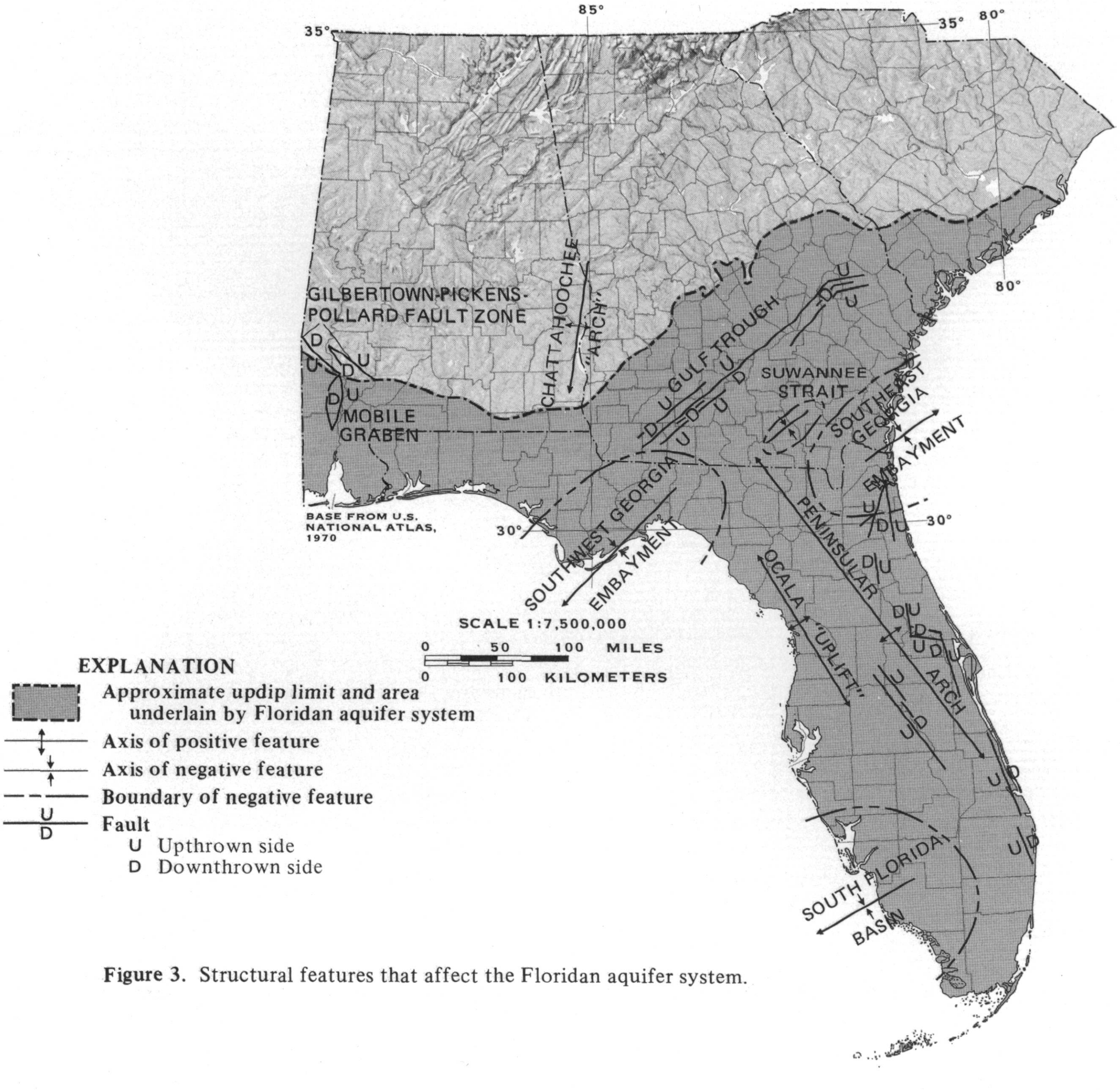


Figure 3. Structural features that affect the Floridan aquifer system.

Southeast Georgia or Savannah embayment, deposition of Lower Cretaceous clastic sediments was followed by deposition of carbonate rocks in the Late Cretaceous and early Cenozoic, which in turn was followed by deposition of Upper Cenozoic clastic rocks. The Southeast Georgia embayment represents a shallow east- to northeast-plunging syncline that subsided at a moderate rate. To the northwest of the Peninsular arch is the Apalachicola or Southwest Georgia embayment, a southwest-plunging syncline where a thick section of predominantly clastic rocks has been deposited, almost continuously, since Late Jurassic time. Rarely, in the Cenozoic, carbonate deposition spilled over westward into the Southwest Georgia embayment from the Florida carbonate platform located to the east. Farther westward, in extreme western panhandle Florida and in southern Alabama, time-stratigraphic units thicken abruptly and their tops slope steeply gulfward, reflections of the influence of the rapidly subsiding Gulf Coast geosyncline. The top and base of the Floridan aquifer system also reflect this steep gulfward slope. The limestone that comprises the Floridan, however, thins gulfward as it is replaced by fine-grained clastic rocks. This facies change continues until the limestone is absent altogether in a well about 60 mi offshore from Mobile Bay, Ala.

A negative feature in southeastern Georgia, just north of the Peninsular arch, has been called the Suwannee strait (Dall and Harris, 1892), channel (Chen, 1965), or saddle (Applin and Applin, 1967). This basin was first called a strait because it was thought to represent a channellike feature, perhaps similar to the modern Straits of Florida, that developed on the sea floor and received little sedimentation because it was swept clean by bottom currents. The feature was also thought to represent the boundary between carbonate sediments to the south and clastic sediments to the north. This carbonate-clastic boundary, however, migrates with time in a general northwest direction and is not always confined to the Suwannee strait area. Well data show a closed depression on the top of Paleocene rocks in southeastern Georgia that may be an arm of the Southeast Georgia embayment but is separated from the main body of the embayment by a sill-like ridge. The absence of such a depression in the top of rocks of lower Eocene age or younger shows that the Suwannee strait ceased to be an actively subsiding basin during the early Eocene. Accordingly, this feature had little effect on the Floridan aquifer system, although the Floridan is slightly thicker within it. Because the Suwannee strait area is a closed basin within which several stratigraphic units are anomalously thin, the exact origin of the basin is not clear. Perhaps "starved-basin" conditions during the time of deposition produced units that are thinner than what would be expected.

Several faults and fault systems are shown in figure 3. In western Alabama, north-trending arcuate faults bound the Mobile Graben, a negative feature that shows much vertical displacement (Murray, 1961). The faults to the north of the Mobile Graben are part of the Gilbertown-Pickens-Pollard fault zone, which is characterized by a series of both isolated and connected grabens. The northeast-trending series of small faults in central Georgia (fig. 3) are the boundary faults for a series of small grabens that, taken together, have been called the Gulf Trough, first described by Herrick and Vorhis (1963) and later by Gelbaum (1978) and Gelbaum and Howell (1982). Within the grabens bounded by the faults shown in figure 3, low-permeability clastic rocks have been downdropped opposite the limestone of the Floridan aquifer system and thus retard the flow of ground water within the system. Several faults shown along Florida's eastern coast (fig. 3) are of limited extent and generally show little vertical displacement. These small faults do not appear to have any effect on ground-water flow in the Floridan aquifer system.

STRATIGRAPHY

GENERAL

Because relief in the study area is generally low, outcrops of Coastal Plain strata are sparse. Accordingly, the stratigraphic units delineated herein, like the major permeability variations mapped, are based primarily on data from wells. Standard techniques of subsurface stratigraphic analysis were used to distinguish and map the separate stratigraphic units. Complex facies variations exist within all rock units throughout the study area; hence, chronostratigraphic units were mapped rather than rock-stratigraphic units. The upper and lower boundaries of the chronostratigraphic units have been made to coincide with rock-stratigraphic (lithologic) boundaries within each well used as a control point. The same rock type may not necessarily mark the boundary of the same chronostratigraphic unit from well to well, however, especially in places where facies change rapidly. Each chronostratigraphic unit may therefore encompass several different rock types. The formations or parts of formations included in the several chronostratigraphic units are shown on plate 2. The chronostratigraphic units are discussed below, from oldest to youngest. Only those units that are part of the Floridan aquifer system or its confining units are mapped and described. Thus, most of the units are not mapped past the updip limit of the aquifer system, even though some are known to continue for a considerable distance updip from the system.

The chronostratigraphic units delineated and mapped represent sequences of rocks judged to have been deposited over a given interval of geologic time. Because exact dating of the rocks is not available, the relative ages of the different units mapped are determined by the fauna (chiefly microfauna) that the rocks contain. The identity of the separate chronostratigraphic units, however, does not depend upon the presence of a certain fauna within them. Many of the "formations" in the subsurface in the area, particularly those in Florida, were originally defined as "a distinct microfaunal unit," or as the sequence of rocks extending between the highest stratographic occurrences of two concurrent species that were judged to be time diagnostic (see, for example, Applin and Applin, 1944). Under the rules of the present North American Stratigraphic Code, a unit defined on the basis of its faunal content is neither a time-stratigraphic unit nor a rock-stratigraphic unit; rather, it is a biostratigraphic unit (North American Commission on Stratigraphic Nomenclature, 1983). Many of the species described in the literature as being diagnostic of a particular "formation" are, in fact, good time markers in the study area and are recognized as such in this report (table 1). The fauna used in this study, however, serve only to support the assignment of strata to a particular chronostratigraphic unit and are nowhere the sole criterion by which any unit mapped herein is recognized. After a given unit's relative age is established, the top and bottom of the unit are adjusted at each well control point to match lithologic changes as shown in core or by a change in electric log pattern.

The external geometry of the different chronostratigraphic units is shown by a series of maps (pls. 3-14) that portray the configuration of the top of a particular unit or its thickness. Variations in the lithology of the units are shown on a series of cross sections (pls. 15-24) that were chosen to also demonstrate the permeability variations within the Floridan aquifer system and its confining units.

CRETACEOUS SYSTEM: GULFIAN SERIES

Rocks of the Gulfian Series of Late Cretaceous age underlie the entire study area and include, in ascending order, units equivalent to the Woodbinian, Eagle Fordian, Austinian, Tayloran, and Navarroan provincial stages of the gulf coast Upper Cretaceous. In the area covered by this study, the Gulfian Series is found only in the subsurface. North of the study area, rocks of the Gulfian Series comprise practically all of the band of outcropping Cretaceous strata found at or near the contact of Coastal Plain sediments and older crystalline rocks (fig. 2). Applin and Applin (1967) mapped and described the Gulfian Series over much of the study area. This report deals only with the rocks that are part of the Tayloran and Navarroan stages because they are the oldest geologic units that comprise either a part of the Floridan aquifer system or its lower confining unit.

ROCKS OF TAYLOR AGE

In the shallow subsurface and in outcrop, Tayloran rocks include parts of the Mooreville and Demopolis Chalks and the Cusseta Sand Member of the Ripley Formation in Alabama, parts of the Cusseta Sand Member of the Ripley Formation and the Blufftown Formation in Georgia; and the upper part of the Black Creek Formation and the lower part of the Peedee Formation of South Carolina (Hazel and others, 1977). Rocks of Taylor age, however, are unnamed in most of the subsurface of the eastern Gulf Coast, including the area covered by this study. Practically all Tayloran strata in the report area consist of low-permeability rocks that range from light-gray, massive, often calcareous clay in southern Alabama, panhandle Florida, and much of central Georgia to chalk or argillaceous chalk in most of peninsular Florida. Thin layers of dolomite are interbedded with the chalk over much of Florida. Beds of fine- to medium-grained glauconitic sand are present in northeastern Georgia and South Carolina, along with carbonaceous material and local shell beds. Clayey beds of Taylor age in northeastern Georgia and South Carolina are usually darker in color and contain less calcareous material than similar beds elsewhere in the study area. The Tayloran chalks of peninsular Florida are part of a thick Upper Cretaceous chalk sequence and can be differentiated only on the basis of their microfauna (Applin and Applin, 1967; Maher, 1971). All Tayloran strata in the study area were deposited in a marine environment. In Florida, southern Alabama, and southwestern Georgia, these rocks represent middle to outer shelf conditions; in northeastern Georgia and South Carolina, they were laid down in marginal marine and inner shelf environments.

Rocks of Taylor age attain a maximum thickness of about 1,300 ft in the study area (Applin and Applin, 1967) and are everywhere underlain by rocks of Austin age. Over much of the area, beds of Navarro age overlie Tayloran rocks. In panhandle Florida, southern Alabama, and southwestern Georgia, however, rocks of Navarro age are thin and discontinuous; here, rocks of Paleocene age may lie directly on rocks of Taylor age (Applin and Applin, 1967). A map showing the configuration of the top of the Cretaceous (fig. 4) is accordingly a composite map representing the tops of several Cretaceous units. Most of the major geologic structures that affect the stratigraphic and permeability units comprising the Floridan aquifer system are shown on this map (compare figs. 3 and 4). The low areas shown in figure 4 in southeastern Georgia and southwestern peninsular Florida represent the Southeast Georgia embayment and the South Florida basin, respectively. The high area in northern Florida is the Peninsular arch. Also shown in figure 4 is the steep, southwest-trending slope of the northern rim of the Gulf Coast geosyncline, and a series of faults in southwestern Alabama that represent the Mobile Graben and the Gilbertown-Pickens-Pollard fault zone.

Fauna considered characteristic of rocks of Taylor age in the eastern Gulf Coast include the foraminifers *Bolivinoides decoratus* Jones, *Stensionina americana* Cushman and Dorsey, *Marsonnella oxycona* (Reuss), *Dorothia glabrella* Cushman, *Globotuncana ventricosa* White, *G. elevata* (Brotzen), and *G. calcarata* Cushman and the ostracod *Brachycythere sphenoides* (Reuss).

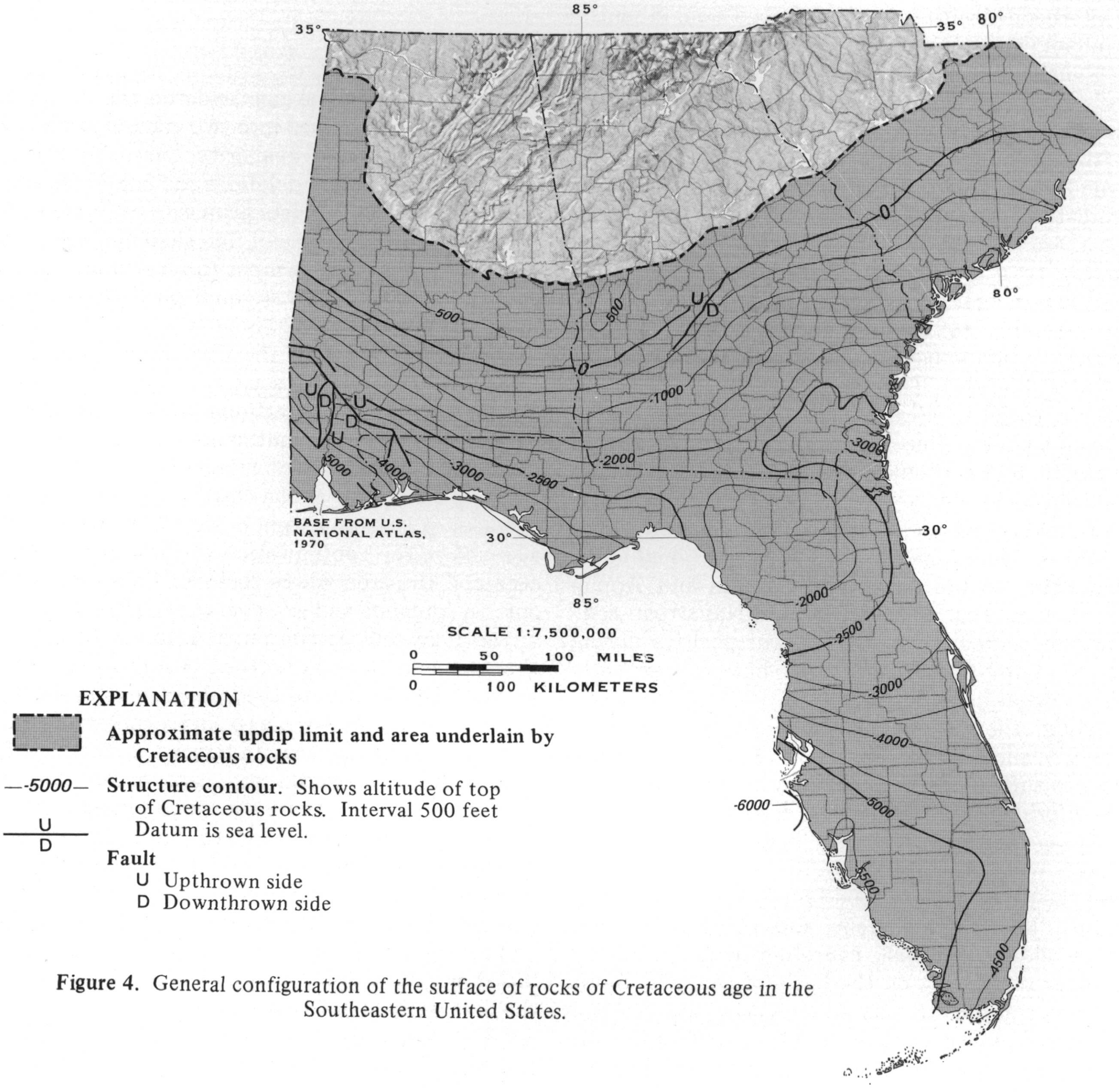


Figure 4. General configuration of the surface of rocks of Cretaceous age in the Southeastern United States.

ROCKS OF NAVARRO AGE

In outcrop and in the shallow subsurface, Navarroan rocks include the Prairie Bluff Chalk, the Ripley Formation (except for the Cussetta Sand Member), and the upper part of the Demopolis Chalk in Alabama; the Ripley Formation (again, excluding the Cusseta Sand Member) and the Providence Sand in Georgia; and the upper part of the Peedee Formation in South Carolina (Hazel and others, 1977). Downdip, rocks of Navarro age are unnamed except for the Lawson Limestone of northern Florida and southeastern Georgia (Applin and Applin, 1944, 1967). As mentioned previously, beds of Navarro age are thin and discontinuous over much of the area, particularly where these strata are clastic. Navarroan rocks in the study area can be grouped into four general facies: (1) calcareous gray shale interbedded with thin, fine-grained sand in southern Alabama and panhandle Florida; (2) light- to dark-gray, glauconitic, locally shelly and calcareous sand, clayey sand, and clay in northeastern Georgia and South Carolina; (3) dominantly tan to white, pelletal, soft, friable, locally gypsiferous dolomitic limestone (Lawson Limestone) that contains the remains of algae and rudistid pelecypods in north-central Florida and southeastern Georgia (the Lawson is locally very porous owing to a decrease in its micrite matrix, and, where it is porous it is included as part of the Floridan aquifer system); (4) white chalk interbedded with light-gray argillaceous micritic limestone in southern peninsular Florida. The transition from clastic to carbonate rocks is abrupt and takes place along a northeast-trending line in southern Georgia, where both clastic and carbonate materials thin drastically. Navarroan rocks thicken to the northwest and southeast of this line, which is located approximately in the area labeled "Suwannee strait" on figure 3, and along its extension to the southwest. Applin and Applin (1967) thought that this area of thin Navarroan sediments represented a flexure that was positive during much of Late Cretaceous time but subsequently became a negative feature.

Although the Lawson Limestone is quite extensive, it is only in and near the Brunswick, Ga., area that the Lawson is sufficiently permeable to be considered part of the Floridan aquifer system. Elsewhere, rocks of Navarro age are of low permeability. The Lawson can be readily recognized because of its distinctive lithology and the rudistid pelecypod fauna that it commonly contains. Micritic limestone and clayey strata of Navarro age, by contrast, can often be distinguished from older rocks only on the basis of the microfauna that they contain. Rocks of Navarro age reach a maximum thickness of about 600 ft in southern peninsular Florida. For the most part, however, they are less than 200 ft thick.

Fauna characteristic of Navarroan rocks include the rudistid pelecypods mentioned earlier and the foraminifers *Vaughanina cubensis* Palmer, *Lepidorbitoides nortoni* (Vaughan), and *Sulcoperculina cosdeni* Applin and Jordan.

Fine-textured Navarroan strata in the study area were deposited in middle to outer shelf environments. The clastic rocks of Navarro age that lie updip from the chalks and micritic limestones were laid down in inner shelf to shoreline environments.

TERTIARY SYSTEM

PALEOCENE SERIES

GENERAL

Rocks of Paleocene age underlie the entire study area and can be grouped into two general facies categories: (1) a carbonate-evaporite facies that consists mostly of interbedded dolomite and anhydrite and (2) a clastic facies that consists primarily of shallow-marine clay and minor amounts of fine sand and impure limestone. The carbonate-evaporite facies underlies all of peninsular Florida and a small part of southeastern Georgia, and the predominantly clastic facies lies to the north and west of the carbonate platform. The demarcation between these two facies is sharp, and they are assumed to interfinger with each other over a narrow transition zone, although no well drilled to date (1983) has shown such interfingering.

The distribution of the clastic and carbonate facies in rocks of Paleocene age is shown on plate 3, which also shows the configuration of the top of the Paleocene and the area where rocks of Paleocene age crop out. In Alabama and extreme western Georgia, the top of the Paleocene is contoured into the outcrop area. From central Georgia northeastward to South Carolina, the updip extent of the Paleocene is based on well control because Paleocene rocks are mostly overlapped there by younger strata. In South Carolina, the Paleocene is known to extend for a considerable distance to the north of the contours shown on plate 3. Paleocene rocks were contoured only to the limit of the well control used to delineate the Floridan aquifer system.

Plate 3 shows that several large-scale structural features affect the shape of the top of Paleocene rocks. In the western third of the study area, the Paleocene top slopes steadily at a rate of about 30 ft/mi toward the axis of the Gulf Coast geosyncline. Farther eastward, a low area of moderate size extending from Franklin County to Leon County, Fla., represents the

Southwest Georgia embayment. In north-central Florida, a northwest-trending high area is the Peninsular arch. The depression contours to the north of this arch represent the Suwannee strait, which is silled to the east by a slight rise in the Paleocene top. East of this sill, the Paleocene top descends into the Southeast Georgia embayment. The depression contours in southern peninsular Florida represent part of the South Florida basin, which was silled to the west by the Charlotte high (Winston, 1971), a local positive feature. The broad negative area that extends northwestward across east-central Georgia and the southeast-plunging positive feature that parallels it to the northeast are both unnamed. The magnitude of these warps on the Paleocene top shows that they are structural rather than erosional in origin.

The maximum measured depth to the top of the Paleocene Series is 4,680 ft below sea level in well ALA-BAL-30 in Baldwin County, Ala. The maximum contoured depth of the top is below 5,000 ft in the same general area. In southern Florida, the Paleocene top reaches a maximum measured depth of about 3,660 ft in eastern Glades County (well FLA-GL-1).

A primary objective of this hydrogeologic investigation was to delineate and map permeability variations within the Floridan aquifer system. As a later section of this report will discuss, evaporite-bearing rocks of Paleocene age comprise the base of the system over much of the Floridan's area of occurrence. Elsewhere, younger rocks make up the base of the system. Neither permeability nor stratigraphy was mapped below the middle part of the Paleocene (except very locally, in the Brunswick, Ga., area, where all of the Paleocene and part of the Upper Cretaceous are included in the aquifer system). No isopach map of Paleocene rocks was constructed because the base of the Paleocene was not mapped. The thickness of clastic Paleocene rocks, however, is known to exceed 1,400 ft in Mobile County, Ala. (well ALA-MOB-16). The Paleocene carbonate-evaporite sequence is known to be slightly more than 2,200 ft thick in southern Florida (well FLA-LEE-3, Lee County).

Paleocene rocks in the study area can be assigned to several formations (pl. 2). Of these units, only the upper part of the Cedar Keys Formation of Florida and southeastern Georgia is part of the Floridan aquifer system. Anhydrite beds in the Cedar Keys, which are areally extensive and usually occur near the base of the upper third of the unit, form the base of the aquifer system over most of peninsular Florida. Updip from the Cedar Keys, clayey Paleocene strata that are equivalent to part of the Clayton Formation locally comprise the base of the system. In eastern Alabama and western Georgia, ground water is obtained from limestone of the Clayton Formation, but this limestone is nowhere connected to the main body of Tertiary limestone mapped as the Floridan aquifer system.

At the time of this writing (1984), the boundary between Paleocene and Eocene strata in the eastern Gulf Coast is being revised. The work of Berggren (1965), as well as more recent work (Oliver and Mancini, 1980; Gibson, 1980, 1982a), has shown that rocks in Alabama that were long thought to be part of the early Eocene are actually of late Paleocene age. Some formations (such as the Tuscahoma) that contain Paleocene index fossils in their lower parts only are mapped herein as part of the Paleocene. Most of the recent stratigraphic revisions of the Paleocene-Eocene boundary have been in the outcrop area of southern Alabama; most of the mapping done during this study, however, was based on deep subsurface data, and the question of the Paleocene-Eocene boundary therefore becomes a problem only as subsurface correlations are projected toward outcrop. Because the boundary is still in a state of revision, it is important to briefly summarize the history of the problem and set forth the rationale used in this report for assigning a Paleocene age to certain rock units.

Beds in the eastern Gulf Coast that are now known to be of Paleocene age were thought to be part of the Eocene Series before the discovery of a Paleocene fossil mammal in a well in Louisiana (Simpson, 1932). Subsequently, these beds were grouped into the provincial Midwayan Stage, a time-stratigraphic unit comprised of formations that could be dated mostly as Paleocene primarily on the basis of their molluscan fauna. Over the years, the term Midway became synonomous with the term Paleocene. In the eastern Gulf Coastal Plain, the Midwayan Stage included the Clayton, Porters Creek, and Naheola Formations (pl. 2), although the Naheola was recognized to be lithologically similar to beds of the overlying Wilcox Group (Toulmin, 1977). The term "Wilcox Group" itself has been controversial (Murray, 1955, 1961), for "Wilcox" has been used in a time-stratigraphic sense (synonomously with Sabinian Stage to designate early Eocene rocks) as well as in a rock-stratigraphic sense (Wilcox Group). In the eastern Gulf Coast, the Nanafalia, Tuscahoma, and Hatchetigbee Formations (pl. 2) traditionally have been considered to comprise the Wilcox Group and to be of early Eocene age.

More recently, the Paleocene and Eocene section of the Gulf Coast has been correlated with the European section by using planktic microfauna (chiefly Foraminifera and calcareous nannoplankton), which are considered to be worldwide stratigraphic markers (Berggren, 1965, 1971, 1977; Oliver and Mancini, 1980; Bybell, 1980; Gibson and others, 1982). The Nanafalia Formation of Alabama, formerly thought to be of early Eocene age, has been shown to consistently contain the planktic foraminifer *Globorotalia pseudomenardii* Bolli, a worldwide Paleocene form. The generic placement of certain planktic species has recently been revised by some authors. For example, *Globorotalia pseudomenardii* is presently considered to belong to the genus *Planorotalites*; *G. subbotinae* and *G. velascoensis* are thought to belong to the genus *Morozovella*. These revisions, however, are not accepted by all micropaleontologists. The taxonomy used for planktic foraminifers in this report and the range of the different species follow Stainforth and others (1975). *Globorotalia pssudomenardii* has been reported (Oliver and Mancini, 1980) from marl beds in the lower part of the Tuscahoma Formation. Higher up in the Tuscahoma, other marl beds contain *G. velascoensis* (Cushman), a form usually shown on foraminiferal zonation charts as ranging into the latest Paleocene. The base of Eocene strata is considered by some authors to be the first occurrence of *G. subbotinae* Morozova (formerly called *G. rex* Martin). However, Oliver and Mancini (1980) recorded *G. subbotinae*, along with *G. velascoensis*, from the same beds in the upper part of the Tuscahoma. Stainforth and others (1975) showed that the range of *G. velascoensis* overlaps the entire range of *G. pseudomenardii* below, and slightly overlaps the range of *G. subbotinae* above.

In the subsurface strata examined during this study, *G. velascoensis* was found to occur commonly in the same beds with *G. pseudomenardii*; accordingly, beds that contain either of these species are considered to be of definite Paleocene age. Beds in the deep subsurface that contain *G. subbotinae* are herein considered to be of early Eocene age. This zonation becomes a problem only in the outcropping Tuscahoma Formation, which, as an earlier discussion pointed out, contains *G. pseudomenardii* in its lower part and *G. subbotinae* in its upper part. Calcareous nannoplankton from marl beds in the Tuscahoma show that these beds are of Paleocene age (Gibson and others, 1982), and sporomorphs from the uppermost Tuscahoma indicate that the entire formation is probably late Paleocene (Frederiksen and others, 1982).

Downdip, all of the Paleocene and lower Eocene formations that are lithologically different in the outcrop area of Alabama grade by facies change into thick marine clay sequences separated by thin sands. The lithology and electric log patterns of these clays are uniform and the strata can be differentiated only on the basis of the microfauna that they contain. Accordingly, the Paleocene in this study was mapped in southern Alabama and western panhandle Florida on the basis of the highest occurrence of *G. velascoensis*. Rocks containing *G. subbotinae* were mapped as part of the early Eocene. As plate 2 shows, rocks of the Tuscahoma Formation or its equivalents are judged to represent the top of the Paleocene. The Hatchetigbee Formation and its equivalents are considered to represent the base of the early Eocene. Plate 2 also shows that neither the units mapped for this study nor the Paleocene-Eocene boundary as determined by Berggren (1971) and Oliver and Mancini (1980) coincides with the traditional concept of the Midwayan and Sabinian provincial stages.

CEDAR KEYS FORMATION

Cole (1944c, p. 28) used the name Cedar Keys Formation for "cream to tan colored, hard limestones which contain *Borelis gunteri* Cole and *Borelis floridanus* Cole in their upper portion." Cole thought that the Cedar Keys was an early Eocene unit and equivalent to the "Midway Formation," which at the time was also considered to be early Eocene. Both the Cedar Keys and the "Midway" are now considered to be Paleocene in age. Cole did not specify a type well section for the Cedar Keys. Applin and Applin (1944) called these rocks the "Cedar Keys Limestone" rather than "Formation," but they, like Cole, neglected to specify a type well. Winston (1976) subsequently designated a well in Levy County, Fla. (Coastal Petroleum Company's #1 Ragland, well FLA-LV-4) as the cotype well for the Cedar Keys and redefined the unit on the basis of lithologic criteria rather than paleontologic criteria. Samples examined by this author confirm the findings of Applin and Applin (1944), Chen (1965), and Winston (1976), all of whom observed that the Cedar Keys is practically everywhere either partially or completely dolomitized and that the unit in most places carries intergranular gypsum that fills much of the pore space in the dolomite. Accordingly, the unit should more properly be designated the "Cedar Keys Formation," the terminology used in this report. The upper part of the Cedar Keys usually consists of gray to cream, coarsely crystalline dolomite that is moderately to highly porous. The species of *Borelis* that characterize much of the Cedar Keys section are not present in this uppermost dolomite, because the dolomitization process obliterated any fauna enclosed in the original limestone.

Approximately the lower two-thirds of the Cedar Keys consists of tan to gray, finely crystalline to microcrystalline dolomite interbedded with white to clear anhydrite that commonly shows an interlithic or "chicken wire" texture—that is, thin, veinlike, contorted partings of dolomite separate large nodular masses of anhydrite. This texture, plus the extensive amounts of anhydrite present in the Cedar Keys, shows that the unit was deposited in a tidal flat type of environment, possibly analagous to but more areally extensive than, a modern sabkha environment. Locally, dolomite strata that are interbedded with the anhydrite contain abundant *Borelis spp.* and the foraminifer *Valvulammina nassauensis* Applin and Jordan, an indication that open marine conditions were reestablished periodically in the tidal flat areas.

The evaporite-dolomite sequence is characteristic of the Cedar Keys of the Florida peninsula (see pl. 3). A sharp demarcation exists between this facies and the clastic Paleocene beds that are part of the Clayton Formation in southern Georgia and its equivalents in panhandle Florida. The Cedar Keys may either interfinger with or grade into these clastic strata. Well data show that the clastic rocks become calcareous near the point where the clastic-carbonate facies change takes place. No well data available to this author show the Cedar Keys in contact with the clastic Paleocene beds, however. The faunal transition between the Cedar Keys and the clastic Paleocene is equally sharp. The *Borelis* fauna characteristic of the Cedar Keys has not been found as of this writing in any well that contains a planktic foraminiferal fauna of definite Paleocene age. Because of this limitation, no definitive age can be assigned to the Cedar Keys, and the unit is placed in the Paleocene in this study solely on the basis of its stratigraphic position. The thin beds of limestone that occur locally at the top of the clastic Paleocene section in the Florida panhandle do not resemble the Cedar Keys in any way.

The thick anhydrite beds of the Cedar Keys, where they are present, form the lower confining unit of the Floridan aquifer system. Locally, in the Brunswick, Ga., area, well data show that the Cedar Keys is permeable throughout (rather than only in the uppermost dolomite beds), and the entire formation is considered to be part of the Floridan aquifer system there.

CLAYTON FORMATION AND EQUIVALENT ROCKS

The Clayton Formation, at its type area in eastern Alabama, consists mostly of coarse-grained sand and minor amounts of sandy, hard to semi-indurated, mollusk-rich limestone. Downdip for a short distance and eastward into extreme western Georgia, the amount of limestone in the Clayton increases. Still farther downdip, the limestone grades by facies change into a massive calcareous marine clay section that contains a few thin beds of sand. The Clayton thins westward and grades gradually into the sandy, silty Pine Barren Member below and the soft, marly McBryde Limestone Member above (pl. 2). In central and western Alabama, the upper part of the Clayton grades into the massive, dark-colored clay of the Porters Creek Formation (Toulmin, 1977). The Porters Creek is for the most part nonmarine to very shallow marine and is not the same as the marine clay that replaces the Clayton downdip. Scattered well data in central Alabama show that the Porters Creek, like the Clayton, grades laterally downdip into this massive marine clay, but a section of thick-bedded, marine, slightly glauconitic sand and gray to brown subfissile clay intervenes between the two formations. Locally, the uppermost beds of the Porters Creek consist of the thin, abundantly fossiliferous Matthews Landing Marl Member.

Most of the Paleocene strata in Georgia have been placed in the Clayton Formation by Herrick and Vorhis (1963). For the most part, the Clayton in Georgia consists of fine- to medium-grained glauconitic sand and clayey sand and smaller amounts of medium- to dark-gray clay. The top of the Clayton in Georgia is commonly marked by a dark-gray, sandy, glauconitic, hard limestone that usually contains casts and molds of pelecypods and gastropods. This limestone is thickest in western Georgia, where it constitutes an important local source of ground water. In eastern Georgia, near the Savannah River, the amount of dark-colored clay in the Clayton increases and grades laterally into the Black Mingo Formation of South Carolina, which consists mostly of dark-colored, carbonaceous clay and thin beds of fine- to medium-grained sand.

In southeastern Georgia, clastic beds of the Clayton merge along a fairly sharp line (pl. 3) with light-colored dolomite of the Cedar Keys Formation. Locally, in updip areas of the central Georgia Coastal Plain, the Clayton grades into dark-colored clay that has been called the Porters Creek Formation, which in turn grades into sands that may be part of the Huber Formation (Huddlestun, 1981).

UNDIFFERENTIATED PALEOCENE ROCKS

Paleocene rocks in most of panhandle Florida, much of southern Alabama, and a small area in extreme southwestern Georgia consist of massive, gray to greenish-gray, subfissile, calcareous, occasionally sandy and slightly glauconitic marine clay. Eastward, this clay grades into argillaceous limestone, which in turn grades into dolomite and dolomitic limestone of the Cedar Keys Formation. Northward, the clay grades into the sand, clay, and limestone sequence of the Clayton Formation. The massive clay is at present unnamed. Applin and Applin (1944) referred to this unit informally as "the clastic lithofacies of the Paleocene" or as the "Tamesii faunal unit" because these clay beds contain a foraminiferal fauna in their lower part that is similar to the fauna of the lower Paleocene Tamesii (Velasco) Formation of Mexico.

Applin (1964) thought the "Tamesii fauna" represented a span of time roughly equivalent to that during which the Clayton, Porters Creek, and Naheola Formations were deposited. The implication is that the massive clay cannot be differentiated into these three units, as Chen (1965) correctly stated. Chen chose to call the massive clay unit the "Midway Formation." The author prefers the term "undifferentiated Paleocene rocks" because it avoids the implication that the term Midway is synonymous with rocks of Paleocene age.

Microfossils diagnostic of undifferentiated Paleocene strata in the study area include the planktic Foraminifera *Globorotalia pseudomenardii* Bolli, *G. velascoensis* (Cushman), *G. angulata* (White), and *G. pseudobulloides* (Plummer). In shallower water deposits, the Ostracoda *Cythereis reticulodacyi Swain, Krithe perattica* Alexander, and *Trachylebris prestwichiana* (Jones and Sherborn) are characteristic.

NANAFALIA FORMATION

The outcropping Nanafalia Formation in western Alabama can be divided into (1) the lower Gravel Creek Sand Member, a coarse-grained sand, (2) a middle, highly fossiliferous glauconitic sand unit informally called the *"Ostrea thirsae"* beds, and (3) the upper Grampian Hills Member, which consists of dark greenish-gray clay interbedded with minor amounts of glauconitic sand (pl. 2). The Gravel Creek Sand is poorly preserved as local erosional remnants in eastern Alabama. The diagnostic Nanafalia oyster *Odontogryphea thirsae* Gabb, characteristic of the middle part of the Nanafalia, ranges upward into the basal beds of the Grampian Hills Member. The upper and middle parts of the Nanafalia in eastern Alabama and western Georgia grade laterally updip into the Baker Hill Formation (Gibson, 1982a), a sequence of interbedded micaceous sand and kaolinitic, bauxitic, and carbonaceous clay. Nanafalia sediments rapidly become finer grained and more marine in a gulfward direction. In southernmost Alabama and western panhandle Florida, beds that are the equivalent of the Nanafalia are gray to greenish-gray marine clays that are indistinguishable from the underlying clays belonging to undifferentiated Paleocene rocks. The Nanafalia clays can be separated from these older clays only in wells where beds of either limestone or calcareous sand occur between the two thick clay units. The outcropping Nanafalia is known to thin as it loses coarser clastics in a downdip direction (Toulmin, 1977; Reinhardt and Gibson, 1980), and subsurface data still farther downdip show that the Nanafalia (upper) part of the massive marine clay sequence is thin in comparison with the lower part.

TUSCAHOMA FORMATION

The Tuscahoma Formation in outcrop and in the shallow subsurface is chiefly silt and silty clay containing some fine-grained sand beds. Locally, sand is the dominant lithology in outcrop areas. Some sand beds are glauconitic and fossiliferous, and two such beds have been named the Greggs Landing and Bells Landing Marl Members. The Tuscahoma grades downdip into soft, brown to gray, calcareous, slightly glauconitic clay that contains much fine-grained organic material and a few beds of fine-grained glauconitic calcareous sand.

Still farther southward, the Tuscahoma grades into gray to greenish-gray marine clays that are included in the undifferentiated Paleocene rocks. *Globorotalia pseudomenardii* Bolli and *G. velascoensis* (Cushman) characterize the Tuscahoma. *G. subbotinae* Morozova, which is found in the outcropping Tuscahoma, is not considered characteristic of the formation in the subsurface.

LOCAL PALEOCENE UNITS

There are several Paleocene units of local to subregional extent in and contiguous to the study area. One of these is the Ellenton Formation in South Carolina (pl. 2), a thin unit of clay and marl (Siple, 1967) whose extent is poorly known and which is dated in only a few places. Although the Ellenton is possibly equivalent to basal Paleocene deposits in the Charleston, S.C., area (G. S. Gohn, written commun., 1983) that were called Beaufort(?) Formation by Gohn and others (1977), well control is not sufficient to correlate the two units exactly. Faye and Prowell (1982) assigned an early to middle Paleocene age to cored materials in Burke County, Ga., that they thought belonged to the Ellenton Formation. Another such local unit is the Naheola Formation in Alabama, which consists of the lower Oak Hill Member (a laminated dark-colored silt, clay, and sand sequence that is locally fossiliferous) and the upper Coal Bluff Marl Member (a fossiliferous glauconitic sand). The Naheola is not recognized in the subsurface, but its equivalents are possibly part of the massive, unnamed, downdip marine clay of Paleocene age. A third Paleocene unit of minor importance is the Salt Mountain Limestone, a white, massive, dense, microcrystalline to finely crystalline limestone that crops out locally in western Alabama, where it has been upthrown along the Jackson fault zone (Toulmin, 1940; Wind, 1974). The Salt Mountain is thin and discontinuous in the subsurface and occurs as a series of disconnected lenses that typically lie within the upper third of the thick, undifferentiated Paleocene clay sequence.

DEPOSITIONAL ENVIRONMENTS

Rocks of Paleocene age were for the most part deposited in marine or marginal marine environments. In updip areas, the basal sands of the Clayton Formation represent a transgressive marine sand. Their western equivalents, the laminated, fossiliferous silt and sand of the Pine Barren Member of the Clayton, represent a shallow, restricted marine environment such as a bay or an estuary. Both the Pine Barren and the basal Clayton sands were succeeded by soft, micritic (McBryde Limestone Member) to shelly, sandy limestone that represents a shallow, open marine environment. A minor regression of the sea followed deposition of this limestone, during which a shallow marine sand (part of the Clayton) was laid down in eastern Alabama and the blocky, massive, nonmarine to very shallow marine Porters Creek Formation was deposited in western Alabama. The Matthews Landing Marl Member of the Porters Creek was deposited in a restricted marine environment during a minor transgression near the end of Porters Creek time. In middip areas, the Clayton Formation and its equivalents are entirely shallow marine. The laminated silty sands of the Tuscahoma Formation were deposited in a restricted marine environment, probably a tidal flat. Periodically, local transgressions of the sea covered the tidal flat and allowed deposition of the Greggs Landing and Bells Landing Marl Members. Farther downdip, the massive marine clay that is the deeper water equivalent of the Clayton, the Nanafalia, and the Tuscahoma was deposited in quiet open-marine water in a midshelf area.

To the south and east of the clastic Paleocene rocks, the Cedar Keys Formation was deposited in a shallow, warm-water, carbonate bank environment. The extensive evaporite deposits of the Cedar Keys represent tidal flat or sabkha-type conditions that existed over wide areas and for a long time on this carbonate bank.

The basal part of the Naheola Formation in western Alabama (Oak Hill Member) represents a fluvial to very shallow marine (tidal flat accompanied by occasional oyster banks) environment. The succeeding Coal Bluff Marl Member of the Naheola was deposited in a restricted marine to very shallow open marine environment. Downdip, the Naheola probably passes by facies change into part of the massive, open marine clay that forms most of the downdip Paleocene. Well control is not available to show such a transition, however.

The Salt Mountain Limestone was deposited in an open marine, quiet, shallow-water environment. The Salt Mountain is thin and discontinuous, possibly as the result of postdepositional erosion. In wells where the Salt Mountain is absent and the Paleocene sequence consists entirely of marine clay, however, no disconformity is known to exist within the massive clay sequence.

The Gravel Creek Member of the updip Nanafalia Formation in western Alabama is a fluvial sand. It is overlain by the *"Ostrea thirsae"* beds and the Grampian Hills Member, both of which were deposited in a restricted marine environment. The Baker Hill Formation, which is the equivalent of the upper Nanafalia in eastern Alabama and western Georgia, was deposited in fluvial and estuarine environments. Downdip, the Nanafalia Formation grades into and becomes part of the massive, marine, undifferentiated Paleocene clay.

The Ellenton Formation is thought to represent a basal shallow marine transgressive deposit that consists in large part of reworked sediments from the underlying Cretaceous. The Beaufort(?) Formation of Gohn and others (1977) consists mostly of marginal marine beds. The overlying Black Mingo Formation is shallow marine for the most part and reflects a slight regression followed by a transgression.

EOCENE SERIES

GENERAL

The thick sequence of Eocene rocks that is everywhere present in the study area can be readily divided into rocks of early, middle, and late Eocene age. The rocks mapped during this study as middle Eocene and late Eocene correspond to the Claibornian and Jacksonian provincial Gulf Coast stages, respectively. Rocks of early Eocene age as mapped correspond to the upper part of the Sabinian provincial stage. These relationships are shown on the generalized correlation chart (pl. 2). As the section of this report dealing with the Paleocene Series discusses, the traditionally accepted concept that the Sabinian Stage is equivalent to the Wilcox Group and that both terms refer to rocks of early Eocene age is no longer valid. Many of the units formerly assigned to the lower part of the Sabinian Stage are now known to be of Paleocene age, rather than Eocene (Oliver and Mancini, 1980; Gibson, 1980, 1982a). These units are accordingly included in the Paleocene Series as mapped in this report.

Eocene strata in the study area are extensive, thick, and, where they consist of carbonate rocks, generally highly permeable. The major part of the Floridan aquifer system is made up of Eocene rocks, which commonly show highly developed primary (intergranular) and secondary (dissolution) porosity, particularly in their upper parts. Like the Paleocene rocks, carbonate rocks of both early and middle Eocene age grade updip by facies change into calcareous, glauconitic, clastic rocks. This carbonate-clastic transition lies farther to the north and west in lower Eocene strata than it does in the underlying Paleocene and is located still farther north and west in middle Eocene rocks. Upper Eocene rocks retain their carbonate character in many places up to the point where they are truncated by erosion. The overall effect is that of a general regional transgression that began in Paleocene time and persisted through the late Eocene and during which the marine facies of progressively younger rocks extended progressively farther and farther inland. Several minor regressions punctuated this general transgression. These observations are consistent with the sea level curve of Vail and others (1977), which shows that sea level worldwide became progressively higher from early to late Eocene time.

Rocks of early Eocene age

Downdip, a lower Eocene carbonate sequence underlies southeastern Georgia and the Florida peninsula; updip, the remainder of the study area is underlain by clastic lower Eocene rocks. Locally, in South Carolina, the Eocene in the subsurface is an impure limestone. Plate 4 shows the configuration of the top of rocks of early Eocene age and the area where they crop out. Comparison of plate 4 with a map of the structural surface of the Paleocene (pl. 3) shows that, in Alabama and southwestern Georgia, lower Eocene rocks lie to the south and east of Paleocene rocks in offlap relationship. In central Georgia, however, beds of early Eocene age overlap and extend farther to the north than the underlying Paleocene rocks. Lower Eocene rocks are known to extend farther to the north in this overlap area than plate 4 shows, but they have been mapped during this study only to the limits of the well control used to delineate the Floridan aquifer system. In the western part of the study area, the configuration of the top of the early Eocene is contoured up to the limit of outcrop of these rocks (pl. 4).

Many of the large- to intermediate-scale structural features that affect the shape of the Paleocene surface (pl. 3) are recognizable on the early Eocene surface (pl. 4). Those features common to both maps include (1) the Peninsular arch in north-central Florida, (2) the Southeast Georgia embayment, and (3) a steep, steady slope toward the Gulf Coast geosyncline in the western part of the study area. The Southwest Georgia embayment in eastern panhandle Florida is a negative area on both the Paleocene and early Eocene tops, but this feature is deeper and narrower and extends farther to the northeast on the early Eocene surface than it does on the top of the Paleocene. The configuration of the South Florida basin in southwestern peninsular Florida likewise differs on the Paleocene and early Eocene surfaces. This feature was somewhat silled on its gulfward side in Paleocene time (pl. 3) but, at the end of early Eocene time (pl. 4) it was open to the gulf and appears to have been partially filled from the east and northeast. The Suwannee strait, a closed low that appears in southeastern Georgia on the map of the Paleocene surface, was apparently filled with sediments during early Eocene time and thus does not exist on the map of the early Eocene surface.

The maximum measured depth to the top of lower Eocene rocks is about 3,900 ft below sea level in well ALA-BAL-30 in the southern part of Baldwin County, Ala. The maximum contoured depth is below 4,200 ft, in the same general area. Lower Eocene rocks are slightly less than 800 ft below sea level on the crest of the Peninsular arch, from which they deepen in all directions. In the Southwest Georgia embayment and the South Florida basin, the top of lower Eocene rocks is below 2,600 ft.

The thickness of lower Eocene strata is shown on plate 5, along with the distribution of the clastic and carbonate facies within this unit. The clastic-carbonate boundary and much of the contouring shown on this plate are derived from well control. In areas of sparse control, the thickness of the early Eocene has been estimated as the difference between contoured altitudes of the top of the early Eocene (plate 4) and the top of the Paleocene (plate 3). In south Florida, lower Eocene rocks are more than 1,500 ft thick; in parts of panhandle Florida, they are more than 1,100 ft thick. On the crest of the Peninsular arch, these strata are less than 300 ft thick, and they thin to a featheredge in areas of outcrop.

Oldsmar Formation—Except for the Fishburne Formation that occurs locally in South Carolina, all the lower Eocene carbonate rocks in the study area are part of the unit that Applin and Applin (1944) named the Oldsmar Limestone. The Oldsmar, however, contains much dolomite, and thin beds of chert and evaporite deposits occur in the unit from place to place. The Oldsmar is therefore referred to as a "formation" rather than a "limestone."

The Oldsmar Formation consists mostly of off-white to light-gray micritic to finely pelletal limestone thickly to thinly interbedded with gray to tan to light-brown, fine to medium crystalline, commonly vuggy dolomite. The lower part of the formation is usually more extensively dolomitized than the upper part. Pore-filling gypsum and thin beds of anhydrite occur in the lowermost parts of the Oldsmar in places, particularly in a crescent-shaped band extending from Dixie County, Fla., northeast to southern Ware County, Ga

The location of this band, which locally comprises the base of the Floridan aquifer system, is shown on plate 33. In scattered places, the Oldsmar contains trace amounts of glauconite.

Applin and Applin (1944, p. 1699) defined the Oldsmar "to include the interval that is marked at the top by the presence of abundant specimens of *Helicostegina gyralis* Barker and Grimsdale...and that rests on the Cedar Keys limestone." This definition is unsatisfactory because (1) it is based on the microfaunal content of the strata, not on their lithologic characteristics, and (2) it is based on a species whose range is not restricted to the early Eocene. The author has found specimens of *H. gyralis* that show no evidence of reworking 50 to 70 ft above the top of the Oldsmar in rocks that are part of the overlying middle Eocene sequence ("Lake City" Limestone). Cole and Gravell (1952) reported this species from middle Eocene beds in Cuba. The Oldsmar Formation is thus redefined herein as the sequence of white to gray limestone and interbedded tan to light-brown dolomite that lies between the pelletal, predominantly brown limestone and brown dolomite of the middle Eocene and the gray, coarsely crystalline dolomite of the Cedar Keys Formation. *H. gyralis* is commonly found as part of a characteristic Oldsmar fauna that includes several other species of larger foraminifers listed in table 1. None of these species, however, is ubiquitous within the Oldsmar Formation, nor should they be the criterion by which the Oldsmar is defined.

The Oldsmar Formation underlies all of the Florida peninsula and the southeastern corner of Georgia (pl. 5). Westward, in the eastern part of the Florida panhandle, the Oldsmar becomes increasingly argillaceous and interfingers with calcareous clastic rocks. To the north, in south-central Georgia, the Oldsmar grades from limestone through argillaceous limestone and calcareous clay into glauconitic calcareous sand.

In addition to *H. gyralis*, the larger Foraminifera *Miscellanea nassauensis* Applin and Jordan, *Pseudophragmina (Proporocyclina) cedarkeysensis* Cole, and *Lockhartia sp.* are considered characteristic of the Oldsmar Formation.

UNDIFFERENTIATED LOWER EOCENE ROCKS—Lower Eocene rocks in the western part of the Florida panhandle consist of brownish- to greenish-gray, calcareous, slightly glauconitic shale and siltstone that are occasionally micaceous. Thin beds of fine-grained, slightly glauconitic sandstone and off-white sandy glauconitic limestone occur sporadically throughout the predominantly argillaceous section. These rocks are part of the unit that was called the "clastic facies of Wilcox age" by Applin and Applin (1944) and the "Wilcox Formation" by Chen (1965). Both Chen and the Applins included beds that are the downdip equivalents of the Nanafalia Formation, the Tuscahoma Formation, and the Salt Mountain Limestone in their "Wilcox" unit. In this report, the Nanafalia, Tuscahoma, and Salt Mountain are considered to be of Paleocene age and to grade downdip into undifferentiated argillaceous rocks of Paleocene age. The term "undifferentiated early Eocene rocks" is herein applied to the massive, predominantly argillaceous early Eocene section of western panhandle Florida. These strata grade eastward into the Oldsmar Formation and become less marine and slightly coarser grained updip in southern Alabama and southwestern Georgia, where they take on the character of the outcropping Hatchetigbee Formation.

Microfauna considered characteristic of undifferentiated rocks of early Eocene age include the Foraminifera *Globorotalia formosa gracilis* Bolli and *Rotalia trochoidiformis* (Lamarck). The Foraminifera *Globorotalia subbotinae* Morozova and *G. wilcoxensis* (Cushman and Ponton) are also considered characteristic of early Eocene rocks in the study area, even though these species are known to range downward into rocks of late Paleocene age elsewhere (Stainforth and others, 1975). The Ostracoda *Brackhcythere jessupensis* Howe and Garrett and *Haplocytheridea sabinensis* (Howe and Garrett) are also considered characteristic of these beds.

BASHI AND HATCHETIGBEE FORMATIONS—The lithology of the Hatchetigbee Formation in the area where it crops out in western Alabama is very similar to that of the underlying Tuscahoma. In practice, the two are difficult to separate except where the sandy, glauconitic, highly fossiliferous Bashi Formation (Gibson, 1982b) lies between them. The Bashi occurs only as erosional remnants in eastern Alabama and western Georgia. Downdip, the Hatchetigbee consists of interbedded fine sand and gray calcareous clay. The sand is lost in a short distance gulfward, and the argillaceous Hatchetigbee beds merge in middip areas with the underlying clay of the Tuscahoma.

UNNAMED MID-GEORGIA LOWER EOCENE ROCKS—In the west-central part of the Georgia coastal plain, lower Eocene rocks consist of medium-grained, calcareous, often dolomitic, glauconitic sandstone interbedded with soft, light-gray, calcareous, glauconitic clay. The sandstone ranges from unconsolidated to well indurated, depending on the amount of calcareous matrix that binds the sand grains. Although these strata are the probable equivalents of the combined Hatchetigbee Formation of eastern Alabama and southwestern Georgia, they are unnamed at present and are not shown on the correlation chart (pl. 2) because their relation to the Hatchibtigbee is still inexactly known.

These unnamed lower Eocene sand and clay beds become progressively more argillaceous and calcareous downdip to the southeast and grade into an off-white, micritic, glauconitic, argillaceous limestone that commonly contains the foraminifer *Pseudophragmina (Proporocyclina) cedarkeysensis* Cole, a species that is found in the Oldsmar Formation in Florida. This micritic limestone, unnamed at the time of this writing, grades seaward over a short distance into a typical Oldsmar lithology. Updip, the lower Eocene clay beds are lost, and the sands become progressively less marine until they grade into a predominantly fluvial thick sand sequence that may be part of the Huber Formation (Huddlestun, 1981).

In easternmost Georgia, lower Eocene rocks consist mostly of calcareous, glauconitic, argillaceous sand, cream to gray calcareous clay, and sandy, glauconitic limestone. Locally, some of the clayey beds are dark brown and silty and contain much fine-grained organic material. Northeastward, in South Carolina, lower Eocene strata consist of sandy, fossiliferous, glauconitic limestone that has recently been named the Fishburne Formation (Gohn and others, 1983).

DEPOSITIONAL ENVIRONMENTS—Most of the lower Eocene rocks in the study area were deposited in shallow open marine to marginal marine environments. The laminated silty sands of the Hatchetigbee Formation were deposited in a restricted marine area, probably on tidal flats. Periodically, slightly deeper marine waters covered the tidal flats, and the Bashi Formation was deposited during such a local short-lived transgression.

Seaward of this marginal marine area, the undifferentiated thick sequence of fine clastic rocks of early Eocene age was deposited in quiet, shallow to moderately deep, open marine waters in the area that is now western panhandle Florida. Open marine conditions characterized by slightly higher energy levels existed in the central part of the Georgia coastal plain during early Eocene time, and an interbedded sequence of marine sand and clays was deposited there. This sequence, unnamed at present, grades laterally to the northeast into shallow marine sandy limestone that represents the Fishburne Formation of South Carolina.

Both the shallow water, open marine, clastic lower Eocene strata of central Georgia and the deeper water, massive clay sequence of panhandle Florida grade into and interfinger with the Oldsmar Formation. The Oldsmar was deposited in warm, shallow, open marine water and represents a carbonate bank environment. The minor evaporites found occasionally in the lower part of the Oldsmar represent sabkha conditions that were short lived and not areally extensive.

ROCKS OF MIDDLE EOCENE AGE

Middle Eocene strata are present over almost all of the study area and can generally be divided into a downdip platform carbonate facies and an updip facies that is predominantly clastic. The carbonate facies of the middle Eocene extends much farther to the north and west than the carbonate rocks of the underlying early Eocene. Approximately half of the Georgia coastal plain, much of the eastern part of the Florida panhandle, and all of the Florida peninsula are underlain by middle Eocene carbonate rocks. In the remainder of the study area, the middle Eocene consists of marine to marginal marine clastic rocks.

The configuration of the top of the middle Eocene and the area where this unit crops out are shown on plate 6. Middle Eocene rocks in Alabama and southwestern Georgia are located farther gulfward than underlying rocks of early Eocene age. In contrast to this offlap relation, the lower Eocene is overlapped by middle Eocene strata in central Georgia and in South Carolina. The top of the middle Eocene is contoured to the point where the unit pinches out in its outcrop area but only to the limit of well control in eastern Georgia and South Carolina. In these areas, the middle Eocene is mostly overlapped by younger rocks.

The effect of several large-scale structural features is reflected on the middle Eocene surface. Although many of these features are recognizable on maps of the tops of older units (pls. 3, 4), their locations and shapes are different on the middle Eocene map (pl. 6). The Peninsular arch is poorly defined on plate 6, and its surface is highly irregular, probably as a result of erosion and dissolution of the top of the middle Eocene. The top of middle Eocene strata in this area is generally higher than 200 ft below sea level. The Southeast and Southwest Georgia embayments and the South Florida basin are present as low areas on the middle Eocene top, but they are not as pronounced as they are on the maps of older units. These basins were probably relatively quiescent and were being filled during middle Eocene time. The Gulf Coast geosyncline was actively subsiding during the middle Eocene, as the steep, steady gulfward slope of the top of the unit in western panhandle Florida shows. The configurations of the unnamed negative area in east-central Georgia and of the high area parallel to it in southeastern South Carolina are similar on the middle Eocene top to those on older units.

Several faults of small to intermediate throw first occurred during middle Eocene time (pl. 6). Unlike the large-displacement faults in southwestern Alabama that affect the entire column of rocks mapped for this study, most of the faults shown on plate 6 in central

Georgia and peninsular Florida appear to die out downward within the middle Eocene. An exception is the fault in Palm Beach County, Fla., which cuts rocks at least as old as Paleocene (pl. 3). The series of northeast-trending faults in south-central Georgia bounds several small grabens and half grabens that are collectively called the Gulf Trough (Herrick and Vorhis, 1963). Like most of the faults in peninsular Florida, the Gulf Trough faults appear to die out at shallow depths. A seismic profile was obtained across one of the major Gulf Trough faults in northeastern Colquitt County, Ga., as part of this study. The record on this profile is poor down to a depth of approximately 1,200 ft below land surface. Deeper than about 1,300 ft (roughly the middle of rocks of middle Eocene age), however, sharp reflectors can easily be traced on the profile and do not show the graben structure that well data prove to exist at shallower depths.

The maximum measured depth to the top of the middle Eocene is 3,490 ft below sea level in well ALA-BAL-30 in southwestern Baldwin County, Ala. The maximum contoured depth is below 3,700 ft in the same area (pl. 6). The top of the middle Eocene slopes in all directions from the crest of the Peninsular arch and reaches depths of more than 1,800 ft in the Southwest Georgia embayment, more than 1,600 ft in the South Florida basin, and more than 1,000 ft in the Southeast Georgia embayment. Middle Eocene rocks are slightly above sea level at scattered places on the Peninsular arch. They are exposed at the surface in Citrus and Levy Counties, Fla., where they represent the oldest outcropping rocks in the state.

The thickness of middle Eocene rocks is shown on plate 7, which also shows the limits of the unit's clastic and carbonate facies. The position of the interface between these facies is approximate because it is based on well control. The thickness trends shown on plate 7 have been extended in areas where well control is scattered by subtracting the contoured tops of rocks of early and middle Eocene age. From a featheredge in outcrop areas, the middle Eocene thickens seaward to more than 1,200 ft in the Southwest Georgia embayment and to more than 1,000 ft in southeastern Georgia. Along panhandle Florida's Gulf Coast, these strata are more than 900 ft thick. They thin to less than 500 ft over the crest of the Peninsular arch and thicken southward to more than 1,600 ft in east-central peninsular Florida. Although the middle Eocene is between 1,000 and 1,400 ft thick in most of southern Florida, the unit thins to less than 900 ft in part of the South Florida basin, and shows that this basin was not subsiding rapidly during middle Eocene time.

AVON PARK FORMATION—Applin and Applin (1944, p. 1686) applied the name Avon Park Limestone to the upper part of the late middle Eocene section in a well at the Avon Park Bombing Range in the southernmost part of Polk County, Fla. They referred to the Avon Park as "a distinct faunal unit" and described it as "mainly cream-colored, highly microfossiliferous, chalky limestone" that locally contains some gypsum and chert and that is commonly partially dolomitized. Well cuttings examined during this study show that the Avon Park is in many places composed almost entirely of dolomite. The Avon Park is thus referred to in this report as a "formation" rather than a "limestone."

The term Lake City Limestone was introduced by Applin and Applin (1944, p. 1693) for the lower part of rocks of middle Eocene age in a well at Lake City in Columbia County, Fla. The Lake City was described as "alternating layers of dark brown and chalky limestone"; gypsum and chert are present in some wells. Regionally, the lower part of the middle Eocene, like the upper part, contains much dolomite.

In the early 1940's, there were few deep wells in Florida, and the samples from many of these wells were either contaminated or incomplete. Electric logging was a new technique at the time, and those few logs that were in existence were largely unreliable. A common practice in subsurface stratigraphy was to use paleontologic and lithologic units interchangeably. All of these factors led to imprecise definitions for most of the limestone units of Florida. Between some adjacent "formations," lithologic change is subtle; in places, there is no change at all. Stratigraphic breaks in much of the Florida section currently are based upon a change in the benthic microfauna that the rocks contain. Where dolomitization has obliterated the microfauna, or where it is lacking in nondolomitized sections, correlations are inconsistent. Although most workers studying the Florida subsurface recognize the problem, almost all Tertiary limestone correlations are still made on the basis of the microfaunal assemblages that Applin and Applin (1944) and Applin and Jordan (1945) thought were diagnostic. This practice is, of course, not in accordance with the rules of the current North American Stratigraphic Code (North American Commission on Stratigraphic Nomenclature, 1983). Units that are in reality biostratigraphic units have been mapped as if they were rock-stratigraphic units. Fortunately, as Winston (1976), recognized, the paleontologically defined units of Applin and Applin (1944) in many cases coincide with lithologic units. Exceptions to this generalization are the Avon Park and Lake City Limestones.

There are no lithologic criteria that can be used to separate the middle Eocene carbonate rocks in Florida and in southern Georgia. Both the so-called Avon Park and Lake City Limestones consist primarily of cream, tan, or light-brown, soft to well-indurated limestone that is mostly pelletal but is locally micritic. The pellets consist of fine to coarse sand-sized particles of micritic to fine crystalline limestone and small- to medium-sized Foraminifera; they are bound by a micritic to finely crystalline limestone matrix. The limestone is thinly to thickly interbedded with cream or light- to dark-brown, fine to medium crystalline, slightly vuggy dolomite, fractured in some places, whose texture is locally sucrosic to argillaceous. Locally, differences exist between the general lithologic character of the lower part of the middle Eocene and that of its upper part. Unfortunately, two of the limited number of wells available to the Applins (the Avon Park Bombing Range and Lake City wells) showed such contrasts, and it was on the basis of the limited data then available that the Avon Park and Lake City were named and extended regionally. More recent drilling shows conclusively that the rock types that the Applins thought were representative of their "Lake City" are found in many places at the top of the middle Eocene (in their "Avon Park" part) and the reverse is also true.

Paleontologic criteria by which the Avon Park and Lake City can be differentiated are lacking. In the original definition of both the Avon Park and the Lake City, certain faunal zones by which these units could be recognized were listed. The Lake City was thought to extend from the highest occurrence of *Dictyoconus americanus* (Cushman), accompanied by *Fabularia vaughani* Cole and Porter, down to the highest occurrence of *Helicostegina gyralis* Barker and Grimsdale, thought to characterize the Oldsmar. None of these species is restricted to the horizon for which it is supposed to be characteristic. *H. gyralis* commonly occurs several hundred feet above a typical Oldsmar lithology. In this study, *Fabularia vaughani* has been found at or just below the top of the middle Eocene—in the "Avon Park" part. *Dictyoconus americanus* has been reported by Cole (1944, 1945) and by Vernon (1951) from the upper part of the middle Eocene. The author has found several additional species that were listed as diagnostic Lake City Foraminifera by Applin and Jordan (1945) within 20 to 50 feet of the top of the uppermost middle Eocene. These species include *Discorbis inornatus* Cole, *Fabularia gunteri* Applin and Jordan, and *Gunteria floridana* Cushman and Ponton. Cole and Gravell (1952) found several supposedly diagnostic Lake City species in the same beds as supposedly diagnostic Avon Park species in the outcropping middle Eocene of Cuba. The Avon Park was originally defined by Applin and Applin (1944) as extending from the highest occurrence of *Coskinolina floridana* Cole downward to the top of *Dictyoconus americanus*. As Applin and Applin (1944, p. 1687), recognized, however, that *Coskinolina floridana* is abundant in the Oligocene Suwannee Limestone in many places.

The so-called Avon Park and Lake City Limestones cannot be distinguished from each other on the basis of either lithology or fauna, except locally. Therefore, it is here proposed that the term "Lake City" be abandoned and that all of the cream to brown pelletal limestone and interbedded brown to cream dolomite of middle Eocene age in peninsular Florida and southern Georgia be placed in the Avon Park Formation. The term "Avon Park" is retained because (1) it has precedence over the term "Lake City," (although both the Avon Park and the Lake City were named in the same report by Applin and Applin (1944), the Avon Park was described on an earlier page in that paper) and (2) the term has traditionally been applied to rocks whose lithology is different from that of the overlying Ocala Limestone. The Avon Park is more properly called a "formation" rather than a "limestone" because it contains appreciable amounts of rock types other than limestone. The extended definition of the Avon Park Formation proposed here refers to the sequence of predominately brown limestones and dolomites of various textures that lies between the gray, largely micritic limestones and gray dolomites of the Oldsmar Formation and the white foraminiferal coquina or fossiliferous micrite of the Ocala Limestone.

The reference section proposed for the extended Avon Park Formation is the interval from 221 to 1,190 ft below land surface in the Coastal Petroleum Company's No. 1 Ragland well in sec. 16, T. 15 S, R. 13 E, in Levy County, Fla. Cuttings from this well are on file at the Florida Bureau of Geology, Tallahassee, Fla., as well W-1537 or permit number 66. The well is numbered FLA-LV-4 in this report. A lithologic description of the cuttings from the proposed type well is given in the Appendix of this report. The top of the Avon Park is not known in the type well because there is a gap in the cuttings from the basal Ocala at a depth of 110 ft to the uppermost Avon Park sample at 221 ft. Figure 5 shows a representative electric log pattern for the Avon Park Formation (extended) in a nearby well in Levy County, Humble's No. 1 C. E. Robinson (well FLA-LV-5 of this report).

Fauna considered characteristic of the revised Avon Park Formation include the Foraminifera *Spirolina coreyensis* (Cole), *Lituonella floridana* (Cole), *Discorbis inornatus* Cole, *Valvulina cushmani* Applin and Jordan, *V. martii* Cushman and Bermudez, *Fabularia vaughani* Cole and Ponton, *Textularia coreyensis* Cole, *Gunteria floridana* Cushman and Ponton, *Pseudorbitolina cubensis* Cushman and Bermudez, *Amphistegina lopeztrigoni* Palmer, and *Lepidocyclina antillea* Cushman (formerly called *L. gardnerae* Cole). Fragments of the alga *Clypeina infundibuliformia* Morellet and Morellet are also considered characteristic of the Avon Park.

To the north and west, the Avon Park Formation grades into an argillaceous, soft to semi-indurated, micritic, glauconitic limestone that in turn grades updip into calcareous, glauconitic, often shelly sand and clay beds that are parts of the Lisbon and Tallahatta Formations. The middle third of the revised Avon Park Formation in the eastern half of the Florida peninsula and in much of southeastern Georgia is micritic, low-permeability, finely pelletal limestone. Approximately the lower half of the extended Avon Park in west-central peninsular Florida consists of low-permeability dark-colored gypsiferous limestone and dolomite. Both the micritic limestone and the gypsiferous carbonate beds comprise important subregional confining units within the Floridan aquifer system.

TALLAHATTA FORMATION—Where the Tallahatta Formation crops out in western Alabama, it consists largely of greenish-gray, porous, fine-grained siliceous claystone (called buhrstone in older reports) and some interbedded sands that are calcareous and fossiliferous near the top of the unit. In eastern Alabama, the outcropping Tallahatta is mostly poorly sorted, occasionally gravelly sand interbedded with greenish-gray clay and calcareous sand near the top. In southwestern Georgia, the outcropping Tallahatta is somewhat more marine than it is in Alabama and consists of fine- to coarse-grained slightly fossiliferous sand interbedded with dark-brown, silty, micaceous, occasionally glauconitic limestone. Chert is common near the base of the Tallahatta in updip areas in Georgia.

Downdip, in both Alabama and Georgia, the Tallahatta consists largely of interbedded gray to greenish-gray glauconitic sand and greenish-gray to brownish-gray shale; light- to dark-brown glauconitic fossiliferous limestone is common. Farther seaward in Georgia, the Tallahatta grades into cream to light-gray glauconitic, argillaceous, somewhat sandy limestone that in turn grades into the revised Avon Park Formation. Along and just to the north of the Gulf Coast of Alabama and western panhandle Florida, the Tallahatta consists mostly of gray to greenish-gray clay and thin to moderately thick interbeds of fine-grained, glauconitic, calcareous sand. Neither the limestone facies nor the calcareous clay and sand of western Florida and southern Alabama can be distinguished from similar overlying strata that are considered to be the Lisbon Formation in this study. In northeastern Georgia, the Tallahatta is mostly gray, calcareous, fossiliferous clay and has a thin sequence of calcareous sand and glauconitic limestone at the base. These strata grade northeastward into calcareous shelly sand

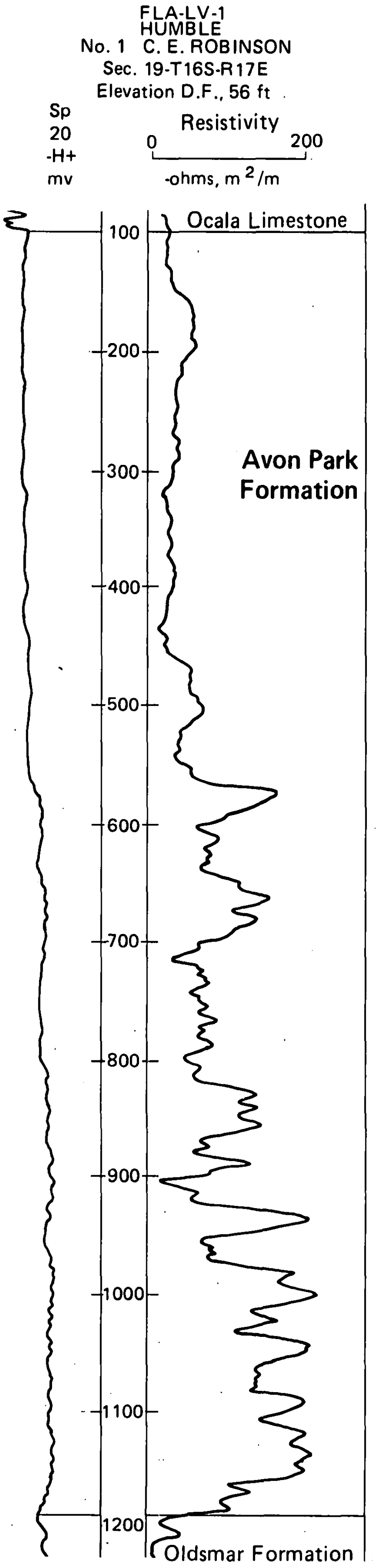


Figure 5. Representative electric log pattern for the Avon Park Formation.

and clay beds that are parts of the Congaree Formation and the Warley Hill Marl of South Carolina.

LISBON FORMATION—In its outcrop area in southwestern Alabama, the Lisbon Formation consists of interbedded calcareous, glauconitic sand, sandy clay, and clay, all of which are dark green to greenish gray and fossiliferous. Carbonaceous clays commonly occur near the middle of the Lisbon in this area. In central Alabama, the outcropping Lisbon is mostly sand. Farther eastward, in southeastern Alabama and southwestern Georgia, the composition and appearance of Lisbon in outcrop are similar to those of the Lisbon in southwestern Alabama, except that the strata are somewhat lighter in color. Downdip, in southern Alabama and panhandle Florida, the Lisbon grades into gray, greenish-gray, or light-brown calcareous, glauconitic clay that contains thin to thick beds of fine-grained, calcareous, glauconitic sand and hard, sandy, glauconitic limestone. In this area contiguous to the Gulf Coast, the Lisbon cannot be differentiated from the Tallahatta.

To the east, the undifferentiated Lisbon-Tallahatta sequence grades into light-gray, glauconitic, argillaceous, somewhat sandy limestone that in turn grades into the Avon Park Formation. This light-colored, fine-grained limestone is also found throughout Georgia in a middip position between the calcareous clastic rocks of the outcropping or updip Lisbon and the pelletal Avon Park Formation. Like the Lisbon-Tallahatta sequence along the Gulf Coast, this limestone facies cannot be split into "Tallahatta" and "Lisbon" components.

In northeastern Georgia, the Lisbon consists mostly of light-gray argillaceous limestone and is underlain by clastic strata that are Tallahatta equivalents. To the northeast, the lower part of the argillaceous limestone becomes sandy, fossiliferous, and glauconitic and grades into the Warley Hill Marl of South Carolina. The upper part of the argillaceous limestone grades into the Santee Limestone of South Carolina, a slightly coarser, soft, cream to yellow, fossiliferous limestone that contains minor beds of glauconitic sand and clay.

Fauna considered characteristic of the undifferentiated clastic Lisbon-Tallahatta sequence in the study area include the Foraminifera *Asterigerina texana* (Stadnichenco), *Ceratobulimina stellata* Bandy, and *Globorotalia bullbrooki* Bolli. The ostracode *Leguminocythereis petersoni* Swain is also commonly found in these clastic middle Eocene strata.

GOSPORT SAND—In western Alabama, the uppermost part of the middle Eocene sequence consists of fine- to coarse-grained, glauconitic, fossiliferous sand and some beds of dark-colored shale. This unit, called the Gosport Sand, is thought to be local because it is not recognizable either in outcrop in central Alabama or in downdip wells. The strata called "Gosport" in the Savannah, Ga., area by Counts and Donsky (1963) are included in the undifferentiated Lisbon-Tallahatta sequence of this report because their lithology is completely unlike that of the Gosport even though their stratigraphic position is the same.

MCBEAN FORMATION—In northeast Georgia and in South Carolina, fine-grained, loose to semiconsolidated, slightly fossiliferous sand of middle Eocene age occurs locally. This sand, called the McBean Formation, grades downward and seaward into calcareous clay that in turn grades into the upper part of the Santee Limestone. Like the Gosport, the McBean is of only local importance in the study area.

DEPOSITIONAL ENVIRONMENTS—The outcropping Tallahatta and Lisbon Formations were deposited in shallow marine to marginal marine environments. Transgression of the sea during the middle Eocene was more extensive than it was during either Paleocene or early Eocene time. Shallow marine Lisbon-Tallahatta rocks extending to the shore of the present Gulf of Mexico show that the middle Eocene sea floor sloped very gently there and that shallow marine waters extended over a wide area.

The Avon Park Formation, like the Oldsmar and Cedar Keys Formations, was deposited on a shallow, warm-water carbonate bank. Some of the evaporites that characterize the lower parts of the revised Avon Park Formation in west-central peninsular Florida may have formed in a tidal flat or sabkha environment.

The Congaree, Warley Hill, and Santee beds of South Carolina were deposited as the result of a single continuous transgression (Pooser, 1965). The Congaree represents basal clastic deposits. The Warley Hill was laid down in very shallow marine waters, and the Santee was deposited in a shallow shelf, open marine environment.

The Gosport Sand represents a regressive shallow marine to marginal marine deposit that was laid down as the middle Eocene sea withdrew. The McBean likewise represents a regressive sand.

ROCKS OF LATE EOCENE AGE

Upper Eocene rocks underlie practically all of the study area, except for local areas in peninsular Florida where they have been removed by erosion. In contrast with older Tertiary units, strata of late Eocene age consist of carbonate rocks throughout all of the study area except (1) in updip outcrop locales where they interfinger with clastic materials or have been weathered into a clayey residuum and (2) in western Alabama and much of the Florida panhandle, where the upper Eocene section consists mostly of fine clastic sediments. The late Eocene represents the most extensive and widespread transgression of Tertiary seas in the Southeastern United States.

The extent, configuration of the top, and area of outcrop of rocks of late Eocene age are shown on plate 8. In Alabama and the southwesternmost corner of Georgia, these rocks are found farther gulfward than the middle Eocene strata that they overlie in offlap relation. From Stewart County, Ga., northeast, however, upper Eocene strata overlap older beds. This onlap relation extends into part of South Carolina.

From an altitude of more than 400 ft above sea level in their area of outcrop in Georgia and South Carolina, upper Eocene beds generally slope gently seaward (pl. 8). This slope is interrupted in northern peninsular Florida by a widespread high area upon which the top of upper Eocene rocks rises to altitudes slightly above sea level. This high area has been called the Ocala uplift, but it is not a true uplift. Even though this feature appears as a high on the upper Eocene top, it is not a structural high on the tops of older units (compare pl. 8 with pls. 3, 4, and 6). The upper Eocene may be high on the Ocala "uplift" because of either (1) deposition of an anomalously thick section of upper Eocene rocks in this area, (2) differential compaction, or (3) postdepositional erosion. The Ocala "uplift," regardless of its origin, is not related to the Peninsular arch. The fact that the effect of the Peninsular arch is not apparent on maps of the top of upper Eocene or younger rock shows that the arch ceased to be an active structure after middle Eocene time.

Some of the major structural lows in the study area, however, continued to actively subside during late Eocene time. Plate 8 shows a steep slope on the upper Eocene top in westernmost panhandle Florida and southern Alabama that reflects the influence of the Gulf Coast geosyncline. The negative area in Gulf and Franklin Counties in panhandle Florida is the Southwest Georgia embayment, and the low centered in Glynn County, Ga., is the Southeast Georgia embayment. The South Florida basin is also shown on plate 8 as a low area in southwestern peninsular Florida. The poor definition of the unnamed low area in east-central Georgia and its contiguous high in South Carolina (pl. 8) indicate that these features were not active "warps" in the late Eocene.

There are a number of small- to medium-sized faults shown on plate 8 that first occur in the late Eocene. Most of these are in central and northern peninsular Florida. Like the Gulf Trough graben system (running northeast across central Georgia on pl. 8), which affects only middle Eocene and younger rocks, these faults in central and northern Florida appear to be shallow features that die out with depth. The locations of the small faults are better known, and the topography shown on plate 8 for the upper Eocene top is more deatailed than that shown for deeper horizons because upper Eocene strata provide a prolific source of ground water and are therefore more intensively drilled than older units.

Upper Eocene rocks crop out more extensively than any other Tertiary unit except the Miocene. In much of their updip outcrop area, they consist largely of calcareous clastic rocks. In southwestern Georgia, easternmost Alabama, and contiguous counties in Florida, uppermost Eocene rocks consist of soft to well-indurated limestone that has a thin to moderately thick (less than 10 to more than 50 ft) clayey residuum developed on it. This residuum masks and subdues the karst topography that drilling shows is developed on the limestone surface there. In western peninsular Florida, upper Eocene sediments consist mostly of highly fossiliferous, soft limestone that shows a highly irregular, karstic, often cavernous surface resulting from extensive dissolution of the rock. Locally, in parts of the Florida peninsula, upper Eocene rocks have been completely removed by erosion, and rocks of middle Eocene age are exposed through the late Eocene surface (pl. 8).

The maximum measured depth to the top of the upper Eocene is about 3,380 ft below sea level in well ALA-BAL-30 in southern Baldwin County, Ala. The maximum contoured depth is about 4,000 ft, just to the southwest of this well. The top of rocks of late Eocene age is more than 1,000 ft below sea level in the Southwest Georgia embayment, more than 700 ft in the Southeast Georgia embayment, and more than 1,200 ft in the South Florida basin. In north-central Florida, the upper Eocene top is at or slightly above mean sea level over a wide area and slopes seaward in all directions from this high. Locally, the upper Eocene top has been vertically displaced as much as 300 ft across some of the small faults that cut the unit.

The thickness of upper Eocene strata is shown on plate 9. In contrast with older Tertiary units, upper Eocene beds are comprised of carbonate rocks almost everywhere. Most of the contouring on plate 9 is based on well-point data. In areas of sparse well control, the thickness of rocks of late Eocene age has been estimated by subtracting contoured structural surfaces of the middle and upper Eocene (pls. 6, 8). The upper Eocene is generally 200 to 400 ft thick, with two major exceptions. In the Southwest Georgia embayment, these rocks are more than 800 ft thick, and in the central part of peninsular Florida, they are less than 100 ft thick in an area that trends east-west across the peninsula. There is much local variation in the thickness of the upper Eocene because of the effects of erosion and (or) dissolution of these rocks, especially in and near the places where they crop out.

OCALA LIMESTONE—Dall and Harris (1892) applied the name Ocala Limestone to the limestone exposed in quarries near Ocala in Marion County, Fla. These rocks were incorrectly correlated with strata in Alabama that were thought then to be Eocene but that are now known to be of Oligocene age. Cooke (1915) was the first to assign the Ocala to its correct upper Eocene stratigraphic position. Applin and Applin (1944) divided the Ocala into upper and lower members. This twofold division of the formation is still used by the U.S. Geological Survey at the time of this writing (1984). However, the Florida Bureau of Geology considers the Ocala to be a group consisting of, in ascending order, the Inglis, Williston, and Crystal River Formations, as Puri (1953b) proposed.

Puri's three formations cannot be recognized lithologically even at their type sections and cannot be differentiated in the subsurface. This author does not consider the Inglis, Williston, and Crystal River Formations to be either readily recognizable nor mappable, and the terms are not used in this report. As Applin and Applin (1944) recognized, the Ocala consists in many places of two different rock types. The upper part of the Ocala is a white, generally soft, somewhat friable, porous coquina composed of large Foraminifera, bryozoan fragments, and whole to broken echinoid remains, all loosely bound by a matrix of micritic limestone. This coquina is the typical Ocala of the literature and comprises much of the formation. The lower part of the Ocala consists of cream to white, generally fine grained, soft to semi-indurated, micritic limestone containing abundant miliolid remains and scattered large foraminifers. Locally, in southern Georgia, the lower part of the Ocala is slightly glauconitic. This lower fine-grained facies of the Ocala is not everywhere present and may locally be dolomitized wholly or in part. In southern Florida, the entire Ocala is composed of micritic to finely pelletal limestone in places. Because the twofold division of the Ocala is not everywhere recognizable and because the lower micritic unit is thin where it occurs, the two members are not differentiated in this report.

The Ocala Limestone is found throughout Florida (except where it has been locally removed by erosion) and underlies much of southeastern Alabama and the Georgia coastal plain. The Ocala is one of the most permeable rock units in the Floridan aquifer system. The surface of the formation is locally very irregular as a result of the dissolution of the limestone and the development of karst topography. Locally, the upper few feet of the Ocala in the subsurface consist of white, soft, clayey residuum. Where the formation is exposed at the surface, such residuum may also be present (as in southwestern Georgia), but the clayey material is ocher to red there owing to the oxidation of the small amounts of iron that it contains.

Fauna considered characteristic of the Ocala Limestone include the Foraminifera *Amphistegina pinarensis cosdeni* Applin and Jordan, *Lepidocyclina ocalana* Cushman, *L. ocalana floridana* Cushman, *Eponides jacksonensis* (Cushman and Applin), *Gyroidina crystalriverensis* Puri, and *Operculina mariannensis* Vaughn. Although the foraminiferal genus *Asterocyclina* is not restricted to the late Eocene, it usually is not found above the top of the Ocala in the study area. The Ostracoda *Cytheretta alexanderi* Howe and Chambers and *Jugosocythereis bicarinata* (Swain) are found in shallower water parts of the Ocala as well as in its clastic equivalents.

MOODYS BRANCH FORMATION—In western panhandle Florida, the Ocala thins and, although the upper part of the formation retains its typical coquinoid character, the lower part grades westward into soft gray clay and minor interbedded fine-grained sand. This lithology is correlative with the outcropping Moodys Branch Formation of western Alabama, which consists of greenish-gray, calcareous, glauconitic sand and clay and a few layers of sandy limestone.

YAZOO CLAY—The upper part of the Ocala in central Alabama grades northward and westward through a white, massive, fine-grained, clayey, glauconitic limestone into the outcropping Yazoo Clay in western Alabama and eastern Mississippi. The Yazoo can be locally divided into four members (Murray, 1947), (from oldest to youngest): (1) the North Twistwood Creek Clay, a bluish-gray, sandy, slightly calcareous, fossiliferous clay; (2) the Cocoa Sand, a yellowish-gray, fine- to medium-grained, massive, fossiliferous sand; (3) the Pachuta Marl, a light greenish-gray, clayey, fossiliferous, calcareous sand or sandy limestone; and (4) the Shubuta, a light-gray to white, calcareous, fossiliferous, sandy clay. These divisions of the Yazoo can be traced in the subsurface for only a short distance downdip from their area of outcrop.

Fauna considered to characterize the Yazoo Clay, its middip equivalents, and the basal clastic part of the Ocala in the Florida panhandle include the Foraminifera *Bulimina jacksonensis* Cushman, *Robulus gutticostatus cocoaensis* (Cushman), and *Globigerina tripartita* Koch. Ostracoda that characterize these beds include *Cytheretta alexanderi* Howe and Chambers, *Clithocytheridea caldwellensis* (Howe and Chambers), *C. garretti* (Howe and Chambers), *Jugosocythereis bicarinata* (Swain), and *Haplocytheridea montgomeryensis* (Howe and Chambers). The latter species ranges downward into middle Eocene beds but does not occur above the top of the upper Eocene.

BARNWELL FORMATION—The lower part of the Ocala Limestone grades laterally into more clastic rocks in northeastern Georgia. In the Savannah area, much of the lower part of the Ocala consists of light-brown, highly sandy, glauconitic, argillaceous limestone. This unit, unnamed at present, grades in turn to the north into the outcropping Barnwell Formation of eastern Georgia and southwestern South Carolina. The updip Barnwell consists of fine- to coarse-grained, gray, yellow, pink, and red arkosic sand and thin beds of light-gray to green, glauconitic, fossiliferous clay.

In parts of eastern Georgia, the Barnwell is divided into (1) a thin and locally occurring basal sand (possibly equivalent to the Clinchfield Sand), (2) a green to gray, sandy, locally glauconitic clay member (Twiggs Clay Member), and (3) an upper, massive, red, medium- to coarse-grained, locally clayey sand (Irwinton Sand Member). The Clinchfield sand and the members of the Barnwell Formation can be traced only a short distance downdip, where they grade into calcareous, argillaceous rocks that in turn grade seaward into the lower part of the Ocala Limestone.

COOPER FORMATION (LOWER MEMBERS) AND EQUIVALENT ROCKS—The upper part of the Ocala grades northward, by the addition of calcareous clay and the loss of large foraminifers, into a soft, white, argillaceous, sandy, slightly glauconitic, bryozoan-rich limestone that is the basal part of the Cooper Formation of South Carolina and northeastern Georgia. In South Carolina, the Cooper is divided into three members (Ward and others, 1979), the lower two of which are of late Eocene age. The uppermost member of the Cooper is of Oligocene age and is discussed in the Oligocene section of this report.

The basal Harleyville Member of the Cooper is a soft, clayey, micritic limestone that contains small amounts of glauconite and pyrite. A phosphate-pebble conglomerate is commonly found at the base of the Harleyville Member. The middle unit of the Cooper is the Parkers Ferry Member, a glauconitic clayey limestone that is highly fossiliferous. The Parkers Ferry Member represents the uppermost part of the late Eocene in South Carolina. The Cooper Formation is not subdivided in Georgia. Most of the Cooper in outcrop and in the shallow subsurface of Georgia is lithologically similar to the Parkers Ferry Member of South Carolina.

The updip equivalent of the Cooper Formation in Georgia is a medium- to coarse-grained, locally argillaceous and pebbly, massive red to reddish-brown sand. This unit, called the Tobacco Road Sand by Huddlestun and Hetrick (1978), is thought to be a marginal marine (lagoonal or estuarine) equivalent of the Cooper Formation. The Tobacco Road is of local importance only and is not recognizable in the subsurface.

Few cores or cuttings from wells that penetrated either the Barnwell Formation or the Cooper Formation and its equivalents were examined during this study. Although these strata are known to contain a sparse to well-developed microfauna in places, no species has been identified during this study as being characteristic of these formations.

DEPOSITIONAL ENVIRONMENTS—Practically all the rocks of late Eocene age in the study area were deposited in shallow, open to marginal marine environments. The Ocala Limestone was deposited in warm, shallow, clear water on a carbonate bank that was probably similar to the modern Bahama Banks. The basal part of the Ocala in western panhandle Florida and the Moodys Branch Formation, which is its updip equivalent, as well as the Yazoo Clay represent marginal marine (lagoon or estuary) to shallow, open-shelf conditions.

The Barnwell Formation and the Tobacco Road Sand were deposited in estuarine, sound, or lagoonal conditions. The Cooper Formation that lies downdip from these units represents shallow water, open marine conditions. The basal phosphate conglomerate of the Harleyville Member of the Cooper was deposited during transgression of the late Eocene sea.

OLIGOCENE SERIES

Rocks of Oligocene age are found over approximately two-thirds of the study area and occur in two separate large bodies. The more extensive area underlain by Oligocene rocks is a wide band that extends seaward from the outcrop of these rocks in Alabama, Georgia, and South Carolina. A second, somewhat smaller area of Oligocene strata covers the southwestern quarter of the Florida peninsula. Plate 10 shows the extent of these two main bodies of Oligocene rocks, the area where Oligocene strata crop out, and the configuration of the Oligocene surface. Throughout the study area, Oligocene rocks are in offlap relation to the upper Eocene and lie seaward of these older beds (compare pls. 8 and 10). Where Oligocene rocks are overlapped by Miocene sediments, the updip limit of the Oligocene is approximate because it is based on available well data; this approximate limit is shown as a dashed line on plate 10. The Oligocene Series consists of carbonate rocks throughout all of the study area except for southwestern Alabama, western panhandle Florida, and parts of northeastern Georgia and southwestern South Carolina, where clastic strata make up an important part of the Oligocene. The few scattered outliers of Oligocene lying between the two main bodies shown on plate 10, indicate that these rocks extended over a much wider area before being removed by erosion. Older rocks are exposed at scattered places within the widespread but generally thin body of the Oligocene in Georgia, where erosion has removed all of the Oligocene locally. The locations of most of the Oligocene outliers and the places where Oligocene rocks have been stripped are based on well data compiled for this study. A few of these features, however, are located from published sources, and thus lie in places where no well control is shown on plate 10. Erosional remnants to the north and west of the general updip limit of the Oligocene show that these rocks once extended over a much wider area.

Both large- and small-scale structural features affect the configuration of the Oligocene top. Large-scale features include (pl. 10) (1) the steep gulfward slope of the unit in southwestern Alabama, which reflects subsidence of the Gulf Coast geosyncline, (2) the low area in southern Gulf County, Fla., that represents the Southwest Georgia embayment, (3) the negative area in Glynn County, Ga., and adjacent counties that is the Southeast Georgia embayment, and (4) a low area in southwestern peninsular Florida that may represent a remnant of the South Florida basin. The northwest-southeast orientation of the axis of the South Florida basin is different from its alinement on the surface of older rock units (compare, for example, pls. 8 and 10). The high area shown on the Oligocene surface along the Gulf of Mexico parallel to the South Florida basin is not present on the upper Eocene top. This high probably acted as a sill or barrier during Oligocene time and partly restricted open circulation between the South Florida basin and the ocean. Smaller structural features shown on plate 10 include the northeast-trending series of small grabens in central Georgia that are collectively called the Gulf Trough and a coast-parallel normal fault that extends from Indian River County southeast through Martin County, Fla. The Oligocene has been eroded from the upthrown side of this fault but is preserved on its downthrown side.

The Oligocene top slopes generally seaward from a high of more than 300 ft above sea level in the unit's outcrop area in central Georgia to slightly more than 600 ft below sea level in both the Southwest and Southeast Georgia embayments. This general seaward slope is interrupted in northern Florida by a high area extending from Leon County eastward to Columbia County, where Oligocene rocks crop out. From a second outcrop area that extends southward from Citrus to Hillsborough Counties, Fla., Oligocene rocks slope into the South Florida basin, where the Oligocene top is more than 900 ft below sea level. The maximum measured depth to the top of the Oligocene is about 2,680 ft below sea level in well ALA-BAL-30 in southern Baldwin County, Ala. The maximum contoured depth is below 3,200 ft, to the southwest of this well. Although the top of the Oligocene is affected locally by erosion and karst topography, it is not as irregular as the top of upper Eocene strata.

The thickness of the Oligocene Series is shown on plate 11. Most of the contouring shown on this plate is based on well data. Where wells are scattered, the thickness of Oligocene rocks has been estimated by subtracting contours that represent the tops of upper Eocene and Oligocene rocks (pls. 8 and 10). Oligocene strata are generally less than 200 ft thick in the study area. Exceptions are southwestern Florida, where these rocks are more than 400 ft thick; southern Gulf and Franklin Counties, Fla., where they are more than 600 ft thick; and the southernmost part of Alabama, where they are more than 800 ft thick. These thick areas represent the South Florida basin, the Southwest Georgia embayment, and the northeastern rim of the Gulf Coast geosyncline, respectively. Throughout most of eastern Georgia and all of South Carolina, the thickness of the Oligocene Series only locally exceeds 100 ft and is generally 50 ft or less.

SUWANNEE LIMESTONE AND EQUIVALENT ROCKS

The name "Suwannee Limestone" was proposed by Cooke and Mansfield (1936, p. 71) for "yellowish limestone typically exposed along the Suwannee River in Florida, from Ellaville...almost to White Springs...." They considered these beds to be of Oligocene (Vicksburgian) age rather than Miocene as previous investigators had postulated. Cores and well cuttings examined during this study show that the Suwannee usually consists of two rock types: (1) cream to tan, crystalline, highly vuggy limestone containing prominent gastropod and pelecypod casts and molds and (2) white to cream, finely pelletal limestone containing small foraminifers and pellets of micrite bound by a micritic to finely crystalline limestone matrix. Although these two rock types are complexly interbedded in places, the pelecypod cast-and-mold limestone is more characteristic of the upper part of the Suwannee and is the lithology most representative of the entire formation in most of Georgia and eastern panhandle Florida. The micritic pelletal limestone that is characteristic of the lower part of the Suwannee is locally found higher in the formation in southwestern Florida. Because the Suwannee, like the Ocala, cannot be divided everywhere, the two facies have not been delineated in this report.

The upper part of the Suwannee has been locally silicified, and this chert-rich horizon was named the Flint River Formation in Georgia. These silicified beds are rarely found in the subsurface and appear to merely represent local diagenetic conditions rather than a widespread mappable variation within the Suwannee. The term Flint River is accordingly not considered to be a valid formational name in this report.

The upper part of the Suwannee in the Georgia subsurface commonly consists of medium to coarsely crystalline, light-brown to honey-colored, saccharoidal, vuggy dolomite. The erosional remnants of Suwannee preserved as outliers several miles distant from the main bodies of Oligocene rocks (pl. 10) and consisting of either limestone or dolomite show that marine Oligocene strata once covered the entire study area. Locally, the cast-and-mold facies of the Suwannee contains fine-grained sand. Very locally, the micritic pelletal facies contains trace amounts of fine- to medium-grained, light- to dark-brown phosphate. In outcrop, the Suwannee locally weathers to a nodular, rubbly surface owing to the removal of layers, lenses, and stringers of soft argillaceous limestone.

The Suwannee grades northward in northeastern Georgia and South Carolina into part of the Cooper Formation by the addition of clay and sand and the loss of limestone. Westward, across panhandle Florida and southern Alabama, the Suwannee appears to grade into the lower part of the Bucatunna Formation. In that area, the Suwannee consists of tan limestone, dolomitic limestone, and light-colored calcareous clay. Some of these beds were called "Byram" or "Glendon" by early workers (Cooke and Mossum, 1929; Cooke, 1945) primarily on the basis of their stratigraphic position. Some faunal aspects of the Suwannee in Florida are Chickasawhayan (late Oligocene); others are Vicksburgian (early Oligocene). The unit is thus interpreted in this report as spanning both ages (pl. 2). The Suwannee in Georgia is thought to be late Oligocene (Huddlestun, 1981).

Microfauna considered characteristic of the Suwannee include the larger Foraminifera *Lepidocyclina leonensis* Cole and *L. parvula* Cole as well as the small Foraminifera *Pararotalia byramensis* Cushman and *P. mexicana mecatepecensis* Nutall, which are closely related. Although the genus *Miogypsina* ranges into younger strata in the central Gulf Coast, it does not occur above the top of the Suwannee in the study area. The larger Foraminifera *Discorinopsis gunteri* Cole, *Dictyoconus cookei* (Moberg), and *Coscinolina floridana* Cole are commonly found in the Suwannee, but these three species are also found lower in the section in the middle Eocene Avon Park Formation. Some authors think that these species have been reworked from the Avon Park into the Suwannee. Others think that they are merely long-ranging species that are "facies seekers." That is, their reappearance in the Suwannee means nothing more than the reestablishment of environmental conditions like those in which the Avon Park was deposited. Most individuals of these three species from the Suwannee examined during this study appeared fresh and unaltered, and the species are widespread throughout the cast-and-mold facies of the formation. In addition, there is no apparent Avon Park source from which these fossils could have been reworked. The isolated patches of Avon Park that are exposed through a cover of upper Eocene sediments (pl. 8) are too small and too scattered to provide a source from which these widely distributed Foraminifera could have been reworked into the Suwannee. This author therefore believes that these are long-ranging species indigenous to the Suwannee Limestone.

BUMPNOSE, RED BLUFF, AND FOREST HILL FORMATIONS

In panhandle Florida, the Oligocene Series thickens considerably (pl. 11) and becomes increasingly clastic westward. In addition, some carbonate units that are older than the Suwannee are present at the base of the Oligocene (pl. 2). One such unit is the Bumpnose Formation, a name applied by Moore (1955) to a soft, white, somewhat glauconitic, highly fossiliferous (pelecypod and gastropod casts and molds and bryozoan and foraminiferal remains) limestone that crops out in central Jackson County, Fla. Moore thought that the Bumpnose represented the uppermost part of the late Eocene but recognized that many of its faunal elements were Oligocene. Subsequent work by Hazel and others (1980) confirmed the findings of MacNeil (1944) and Cooke (quoted by Moore, 1955, p. 38) that the beds that Moore called Bumpnose correlate with the Red Bluff Formation of Alabama of known Oligocene age. The Bumpnose in its type area is very likely a transitional unit between the late Eocene and early Oligocene. The Bumpnose Formation, however, is placed in the Oligocene in this report because carbonate rocks in western Alabama that are in the same stratigraphic position as the Bumpnose and that can be shown to correlate with it are of Oligocene age (Hazel and others, 1980).

The Bumpnose grades northwestward into the Red Bluff Formation, which is mostly dark-gray to brown, fossiliferous, glauconitic clay that contains some iron-rich beds and siderite concretions, and local beds of glauconitic, sandy, fossiliferous limestone. The Red Bluff in turn grades westward into the Forest Hill Formation, a dark-colored silt, sand, and clay sequence that is highly lignitic near its top and base. Gulfward, the Bumpnose merges with the basal part of a thick sequence, unnamed at present, of interbedded pelletal limestone, micritic limestone, and tan, finely crystalline dolomite. To the southwest across the Florida panhandle, the Bumpnose pinches out in western Bay County, Fla. The Red Bluff and Forest Hill Formations are recognizable in the subsurface only a short distance downdip of their outcrop.

Mint Spring and Marianna Formations

The Marianna Formation is a soft, cream to white, highly fossiliferous (mostly large foraminifers), glauconitic limestone that is argillaceous in places. The amount of clay in the Marianna increases northwestward across southern Alabama as the Marianna grades into the Mint Spring Formation, a thin, fossiliferous, glauconitic sand or clayey sand that represents the base of the Vicksburg Group in western Alabama (Hazel and others, 1980). Gulfward from its type area in central Jackson County, Fla., the Marianna becomes part of a thick unnamed sequence of Oligocene limestone and dolomite beds. Like the Bumpnose, the Marianna pinches out to the southwest in western Bay County, Fla. The Mint Spring is not recognizable in the subsurface.

Glendon Formation

The Glendon Formation is a thin, fossiliferous, cream-colored limestone that occurs in the updip Oligocene of western Alabama. The Glendon is not recognizable in the subsurface in downdip areas of southern Alabama and panhandle Florida and is not thought to crop out in Florida. The micritic, pelletal, lower part of the outcropping Suwannee Limestone at its type locality was once thought to be equivalent to either the Glendon (Cooke and Mossum, 1929) or the Byram (Cooke, 1945). This report considers these beds to be part of the Suwannee.

Byram Formation

The Byram Formation in its outcrop area in western Alabama consists of light-colored, sandy, glauconitic, calcareous clay and some beds of sandy, white, fossiliferous limestone. The Byram is thin in outcrop and appears to merge with the Bucatunna Formation in the shallow subsurface by loss of limestone and increase of clay. In some publications, the terms Glendon and Byram appear to have been used somewhat interchangeably.

Bucatunna Formation

To the west of eastern Walton County and western Bay County, Fla., the basal unit of the subsurface Oligocene is a massive, light- to medium-gray, calcareous, fossiliferous clay containing trace amounts of fine sand. This unit, called the Bucatunna Formation, has a distinctive low-resistivity electric log pattern and constitutes one of the most easily recognizable stratigraphic markers in westernmost Florida and southern Alabama. Updip, the Bucatunna is less marine and consists of dark-colored carbonaceous silt, bentonitic clay and thin interbeds of yellow sand. The Bucatunna forms an excellent confining bed, separating permeable limestones of late Eocene age (Ocala) from late Oligocene limestone strata that are also highly permeable. The Bucatunna merges updip with more sandy or calcareous Oligocene beds and passes by facies change eastward into an unnamed thick sequence of limestone and dolomite beds of Oligocene age in eastern panhandle Florida.

Chickasawhay Formation

The uppermost part of the Oligocene Series in southern Alabama and much of panhandle Florida consists of white, micritic to pelletal, hard to semi-indurated, fossiliferous limestone and thin to thick beds of light- to dark-brown, fine to medium crystalline, vuggy dolomite. This unit is thought to be equivalent to the outcropping Chickasawhay Formation of western Alabama. The Chickasawhay in outcrop consists of bluish-gray, soft, glauconitic, calcareous clay and some beds of white fossiliferous limestone. The Chickasawhay can be distinguished in the subsurface as far east as central Bay County, Fla., where it grades into unnamed interbedded Oligocene limestone and dolomite that in turn thin and grade northward and eastward into the upper part of the Suwannee Limestone.

The Paynes Hammock Formation, a thin, calcareous, fossiliferous sand and clay sequence that overlies the Chickasawhay, cannot be distinguished from the Chickasawhay in the subsurface, and the two are thus not separated in this report.

In most of the subsurface of the western third of the study area, Oligocene strata can be divided into the basal Bucatunna Formation and the upper Chickasawhay Formation. Fauna considered to characterize these two units include the Foraminifera *Pulvinulina mariannensis* Cushman, *Robulus vicksburgensis* (Cushman) Ellisor, *Palmula caelata* (Cushman) Israelsky, and *Globigerina selli* (Borsetti). The ostracode *Aurila kniffeni* (Howe and Law) is also considered characteristic of these strata.

COOPER FORMATION (ASHLEY MEMBER)

The uppermost part of the Cooper Formation, called the Ashley Member by Ward and others (1979), is of Oligocene age, in contrast to the late Eocene age of the lower two members of the Cooper. The Ashley Member consists of brown to tan, soft, calcareous, clayey sand that usually contains much phosphate and glauconite and carries a rich microfauna. The thickness of the member is highly variable. To the south and southeast, the Ashley Member grades into the Suwannee Limestone by the addition of impure limestone beds and the loss of clastic strata. The microfauna of the Cooper were not examined in enough detail during this study to determine which species are characteristic of any of the formation's members, including the Ashley. However, the foraminifer *Pararotalia mexicana mecatepcensis* Nutall was identified from the upper part of the Cooper in several wells in northeastern Georgia.

CHANDLER BRIDGE FORMATION

The Chandler Bridge Formation (Sanders and others, 1982) is a thin sequence of clayey phosphatic sand beds that unconformably overlies the Ashley Member of the Cooper Formation. Chandler Bridge beds occur locally and appear to be preserved only in low areas on the Ashley surface. The Chandler Bridge contains no microfauna and is dated Oligocene on the basis of its stratigraphic position and the primitive aspect of its cetacean fauna, which somewhat resembles forms found in the upper Oligocene of Europe.

DEPOSITIONAL ENVIRONMENTS

The Suwannee Limestone and the equivalent thick sequence of unnamed interbedded limestone and dolomite in eastern panhandle Florida were deposited in a carbonate bank environment. The part of the Cooper Formation that is of Oligocene age (Ashley Member) and the Chandler Bridge Formation that overlies it were laid down in a marginal marine environment. All of the Oligocene units in Alabama and those in updip areas of panhandle Florida were deposited in shallow marine to restricted marine (lagoonal or estuarine) environments. The formations that are mostly limestones (Bumpnose, Marianna, and Glendon) formed in shallow, warm, open marine waters. Those units that are highly argillaceous and glauconitic (Red Bluff, Mint Spring, Byram, and Chickasawhay) are estuarine to lagoonal for the most part but may grade into shallow shelf, open marine deposits downdip. The dark-colored clays that are part of the Forest Hill and the updip portion of the Bucatunna are mostly lagoonal but in places may represent deltaic conditions. The Bucatunna and Forest Hill represent local regressive phases of the generally transgressive Oligocene sea.

MIOCENE SERIES

Rocks of Miocene age underlie most of the study area except for a wide band in northwestern peninsular Florida, where they have largely been removed by erosion. These strata are mostly clastic, with the exception of (1) sandy limestone that comprises the Tampa Formation and its equivalents and (2) dolomite beds that commonly make up the lower part of the Hawthorn Formation. Miocene rocks crop out over more of the study area than any other Tertiary unit and are highly dissected in outcrop and shallow subcrop locales. The paleogeography of the eastern Gulf Coast was very different in Miocene time than it had been before. The carbonate bank environment that characterized peninsular Florida and adjacent areas during most of Tertiary time was covered during the Miocene by an influx of clastic sediments. Chemical conditions in parts of the Miocene ocean were also quite different and resulted in the widespread deposition of phosphatic and siliceous sediments, especially during middle Miocene time.

The extent and the configuration of the surface of the Miocene Series is shown on plate 12, along with the area where these rocks crop out. Over more than half of their extent, Miocene rocks are at or above sea level. The contour interval used on plate 12 is smaller than that used on maps of the structural surfaces of older units to better portray the irregular topography developed on the top of the Miocene. The rough surface of the unit and the numerous small outliers preserved as erosional remnants apart from the main body of Miocene rocks show that the Miocene surface has been deeply eroded. At a few scattered places within the main body of Miocene rocks, older units are exposed where the Miocene has locally been completely eroded through.

In outcrop areas in Alabama and Georgia, Miocene rocks are found at altitudes of more than 300 ft above sea level. In south-central peninsular Florida, the Miocene top locally is at an altitude of more than 150 ft above sea level. The maximum measured depth to the top of the Miocene is about 1,360 ft below sea level in well ALA-BAL-30 in southern Baldwin County, Ala., and the maximum contoured depth of the unit is below 1,700 ft to the southwest of this well. Over much of south Florida, the Miocene top is 100 to 200 ft below sea level. Locally, along small faults in extreme southeastern Florida, the top of the unit has been dropped as much as 250 ft on the downthrown side of the faults. The only major structural features shown on plate 12 are a negative area in the southwestern tip of Florida that represents a part of the South Florida basin, and a steep gulfward slope of the Miocene top in southern Alabama produced by subsidence of the Gulf Coast geosyncline.

The thickness of the Miocene Series is shown on plate 13, as are those areas where the Tampa Limestone and its equivalents comprise part of the Miocene. The contours on this map are based primarily on well data. Certain features shown on this map, such as the small fault extending from Martin County to St. Lucie County in southeastern Florida, are taken from published sources. In areas of sparse control, the well-point data have been supplemented by subtracting contoured surfaces of the Miocene and Oligocene. Where Oligocene rocks are absent, the difference in altitude between the Miocene and late Eocene tops was used as a thickness approximation. Miocene strata thicken from a featheredge where they crop out to a thickness of more than 800 ft in southern Florida, more than 500 ft in southeastern Georgia, and more than 1,400 ft in southern Alabama. In a wide area across north-central peninsular Florida, Miocene rocks are very thin on the Atlantic side and absent to patchy on the Gulf side. This area of thinning generally coincides with an area where Oligocene rocks have been stripped (pl. 10) and where upper Eocene rocks are thin (pl. 9). The many local variations in the thickness of the Miocene shown on plate 13 are due to extensive erosion of the unit.

Although the Miocene rocks of the Southeastern United States have been studied in detail for many years, they remain poorly understood. This lack of understanding is due in part to the complexity of facies change within the rocks. For example, in western Florida, detailed work on somewhat scattered exposures of highly variable, shallow marine Miocene beds has resulted in a proliferation of "formations" whose extent and exact stratigraphic relations are poorly defined. Certain economic aspects of the Miocene, such as phosphorites and high-magnesium clays, have been closely scrutinized, but an economic study is likely to be of either local range or narrow focus. It is beyond the scope of this study to address the many problems of Miocene stratigraphy; therefore, the stratigraphic breakdown of the Miocene used herein is a general one (pl. 2). Greater detail on Miocene stratigraphy and various Miocene problems is presented in a collection of papers edited by Scott and Upchurch (1982).

The entire Miocene Series was mapped together as a single unit during this study. Microfauna that are considered characteristic of the undifferentiated Miocene in the study area include the Foraminifera *Amphistegina chipolensis* Cushman and Ponton, *A. lessoni* d'Orbigny, *Bolivina floridana* Cushman, *B. marginata multicostata* Cushman, *Elphidium chipolensis* (Cushman), and *Sorites sp.* Ostracoda considered characteristic of the Miocene include *Aurila conradi* (Howe and McGuirt) and *Hemicythere amygdula* Stephenson.

TAMPA LIMESTONE

The basal part of the Miocene Series in part of west-central peninsular Florida and much of the central and eastern parts of the Florida panhandle consists of the Tampa Limestone. As it is used in this report, the Tampa is a white to light-gray, sandy, hard to soft, locally clayey, fossiliferous (pelecypod and gastropod casts and molds) limestone that contains phosphate and chert in places. The phosphate content of the Tampa is low, however, in comparion with that of the overlying Hawthorn Formation. The mollusk remains in the Tampa vary from trace amounts up to 90 percent of the rock. Except for the sand and phosphate that it contains, the Tampa closely resembles the Suwannee Limestone. Some confusion exists in the literature as to the distinction between these formations, owing in part to the fact the Tampa-Suwannee contact is gradational in the type area of the Tampa (King and Wright, 1979). A difference of opinion also exists concerning the age of the Tampa. Certain mollusks from the unit are also found in the Paynes Hammock Formation of eastern Mississippi, once thought to be of early Miocene age but now known to be part of the Oligocene (Poag, 1972). Foraminifera from the Tampa, however, indicate that the formation is of early Miocene age, and the formation is placed in the early Miocene in this report.

From its type area in and around Tampa Bay, the Tampa Limestone grades southward into white, hard to semi-indurated, finely crystalline to micritic limestone that contains traces of sand, phosphate and scattered pelecypod casts and molds at irregular intervals. The basal part of this fine-textured limestone sequence consists largely of finely pelletal, micritic limestone. To the east and south, all these limestones become silty, clayey, and dolomitic and appear to grade into the lower part of the Hawthorn Formation.

The light-gray, sandy, pelecypod- and gastropod-rich lower Miocene limestone in the eastern and central parts of the Florida panhandle has been called the Tampa Limestone by some workers and the St. Marks Formation by others. This author could not distinguish between the Tampa and the St. Marks either in outcrop or in well cuttings, and all fossiliferous lower Miocene limestones in the study area are therefore called Tampa Limestone in this report. The Tampa in the Florida panhandle appears to pinch out against the Hawthorn Formation where it is overlapped by the latter unit. Marsh (1966) recognized that some limestones in the southern parts of Escambia and Santa Rosa Counties in extreme western Florida contain an early Miocene fauna, but he was unable to separate these strata from underlying limestone beds of the Chickasawhay Formation (Oligocene). This author agrees that a thin sequence of limestone is present near the Gulf Coast in these counties but, like Marsh, cannot consistently differentiate the Oligocene and early Miocene there. The thin carbonate sequence is thus mapped as part of the Oligocene in this report.

The Tampa Formation does not extend into Georgia. The beds that Counts and Donsky (1963) and Herrick and Vorhis (1963) called Tampa are in reality part of the basal Hawthorn, which consists largely of dolomite and dolomitic limestone.

The Catahoula Sandstone, a yellowish-gray sand and sandy clay unit that occurs locally in outcrop and in the shallow subsurface in Alabama, is thought to be a lower Miocene unit and therefore time equivalent to the Tampa. The two formations, however, are not connected. The Catahoula appears to grade into the lower part of the Hawthorn Formation. The Edisto Formation of South Carolina, a yellow-brown, sandy, fossiliferous limestone that occurs as erosional remnants on the top of the Cooper Formation, is also of early Miocene age but, like the Catahoula, is not connected to the Tampa Limestone.

Microfauna identified from the Tampa during this study include the Foraminifera *Amphistegina chipolensis* Cushman and Ponton, *Elphidium chipolensis* (Cushman), and *Sorites* sp. These species are not restricted to the Tampa, however, and are commonly found also in younger Miocene units.

HAWTHORN FORMATION

The Hawthorn Formation is the most widespread and the thickest Miocene unit in the Southeastern United States. East of longitude 85° W, the Hawthorn constitutes most of the entire thickness of the Miocene strata shown on plate 13. The Hawthorn is a complexly interbedded, highly variable sequence that consists mostly of clay, silt, and sand beds, all of which contain scarce to abundant phosphate. Phosphatic dolomite or dolomitic limestone beds are common in the lower part of the formation. The argillaceous beds of the Hawthorn are usually green but locally are cream or gray. Hawthorn sands are light to dark brown where they are highly phosphatic and light green to gray where they carry only trace amounts of phosphate. The dolomite and limestone beds of the Hawthorn are most commonly brown but locally are cream to white. Most of the phosphate that occurs throughout the Hawthorn is fine to medium sand sized, but beds of pebble-sized phosphate are by no means rare, especially in the upper third of the formation.

Locally, the Hawthorn can be roughly divided (Carr and Alverson, 1959; Miller and others, 1978; Scott and Upchurch, 1982). Although the number of zones and their exact lithology vary greatly from place to place, the Hawthorn generally consists of a basal calcareous unit, a middle clastic unit, and an upper unit that is a highly variable mixture of clastic and carbonate rocks. The middle and upper parts of the Hawthorn everywhere contain more phosphate than the lower calcareous unit. Hawthorn phosphorites are mined over a large area in central Florida and are locally exploited in Hamilton County in northern Florida. Although there is some disagreement about the exact environment of deposition and mechanism of concentration of the phosphate minerals in the Hawthorn, the consensus is that the phosphate was deposited from upwelling, cold marine waters (Riggs, 1979; Miller, 1982a).

There is much local variation of rock types within the Hawthorn. Some Hawthorn clay beds contain abundant diatom remains (Miller, 1978). Palygorskite (attapulgite), a magnesium-rich clay that is useful because of its absorptive properties, is mined from the upper part of the Hawthorn in Gadsden County, Fla., and Decatur County, Ga. (Weaver and Beck, 1977). In southwestern Florida, there are thick sequences of light-gray silty to argillaceous limestone in the upper and lower thirds of the formation. In Seminole and Orange Counties, Fla., the Hawthorn is very thin and consists of beds of shell material bound together by light-gray calcareous clay. Southeast of Tampa, Fla., the uppermost part of the Hawthorn consists of brown, orange, and red clayey, slightly phosphatic sand. In northeastern Georgia, Hawthorn beds consist mostly of green silt and clay and interbedded white limestone and fine- to coarse-grained sand.

Because of its heterogeneity and the predominantly fine textured nature of both the clastic and the carbonate beds within the Hawthorn, the entire formation constitutes a low-permeability rock sequence. Where it is present, the Hawthorn Formation comprises most of the upper confining unit of the Floridan aquifer system.

The Hawthorn Formation is considered by most workers to be of middle Miocene age, and it is so regarded in this report. However, fauna are sparse within the Hawthorn, and the exact relations between this formation and the complex Miocene section of panhandle Florida are unclear at present. Parts of the Hawthorn may be as old as early Miocene or as young as late Miocene. Most of the unit, however, appears to be of middle Miocene age.

Alum Bluff Group

West of longitude 85° W, or approximately at the Apalachicola River in eastern panhandle Florida, the Hawthorn Formation passes by facies change into the lower part of a thinly bedded, complex, finely to coarsely clastic, often highly shelly sequence of strata called the Alum Bluff Group (pl. 2). Several formations have been identified within this group, chiefly on the basis of work done in outcrop areas and in the shallow subsurface. For the most part, these formations are thin and of limited areal extent, and are in many cases not well defined. More detail on the Miocene of panhandle Florida is presented in reports by Puri (1953a), Puri and Vernon (1964) and in a collection of papers edited by Scott and Upchurch (1982).

The Alum Bluff Group as used in this report refers to a sequence of gray to green clay and medium- to coarse-grained sand beds that locally contain much carbonized plant material or mollusk shells. Beds of middle and late Miocene age have been reported from the Alum Bluff Group, but no age separation within the group has been made in this study. Alum Bluff beds grade westward into coarse gravelly sands and thin clay interbeds in westernmost Florida and southwestern Alabama. Alum Bluff Group equivalents in southern Alabama are an undifferentiated sequence of gray clays and fine- to medium-grained sands. Local, patchy erosional remnants of upper Miocene beds that occur at scattered places in parts of peninsular Florida are equivalent to the upper part of the Alum Bluff Group but are undifferentiated in this report.

Depositional environments

The mollusk-rich, cast-and-mold limestone of the Tampa represents a remnant of the carbonate bank environment that characterized the Florida peninsula throughout most of Tertiary time. The Tampa was deposited in warm, shallow, clear, open marine waters in a basin that received little or no clastic supply.

The Hawthorn Formation was deposited under conditions quite different from those that existed in the early Miocene. Hawthorn sediments were laid down in shallow to moderately deep (inner to middle shelf) marine waters in a basin that received copious amounts of clastic material. The highly phosphatic and siliceous (diatom rich) beds of the Hawthorn, as well as some of the microfauna recovered from the formation, show that the waters in the Hawthorn sea were colder than those in which older Cenozoic units were deposited. The considerable local relief on the Hawthorn sea floor (Miller, 1982a) was a factor in the deposition and concentration of some of the Hawthorn phosphorites.

The Alum Bluff Group was deposited in shallow, warm to temperate waters, mostly in a marginal marine environment. Some of the gravelly sands that are part of the Alum Bluff Group in westernmost Florida may be of fluvial origin.

TERTIARY AND QUATERNARY SYSTEM: POST-MIOCENE ROCKS

GENERAL

All beds in the study area that are younger than Miocene are grouped together in this report and mapped as a single unit. Post-Miocene strata can generally be divided into a basal sequence of marginal to shallow marine beds overlain by a series of sandy marine terrace deposits that are in turn capped by a thin layer of fluvial sand and (or) residuum. The basal beds having a marine aspect are mostly of Pliocene age, the terrace deposits were laid down during the Pleistocene, and the fluvial and residual materials are of Holocene age (pl. 2). There are two major exceptions to this general post-Miocene sequence. In southern Florida, practically all post-Miocene strata are of shallow or marginal marine origin and comprise a complex and highly variable sequence of thin formations whose relations are best known along the southeastern coast. In southwestern Alabama and the westernmost part of the Florida panhandle, post-Miocene rocks are mostly a thick sequence of coarse-grained, fluvial, gravelly sands that locally contain interbedded clays, mostly near the base of the sand sequence.

The top of post-Miocene rocks has not been mapped because the surface of the unit obviously is the same as the present-day topographic surface in the study area, and the configuration of this surface is available from other published sources. The general thickness of post-Miocene rocks is shown on plate 14. This map has been contoured on the basis of well data alone, in contrast with the thickness maps of the older units discussed in this report. The purpose of plate 14 is to show the locations of the larger thickness variations in the post-Miocene unit rather than detailed changes. Over most of the study area, post-Miocene sediments are less than 100 ft thick and in many places form a surface veneer that is only 10 to 50 ft thick. In southwestern Alabama, thick Pliocene fluvial deposits make up most of the 1,400-ft-thick sequence of post-Miocene rocks found there.

PLIOCENE SERIES

Pliocene deposits in western panhandle Florida and in southwestern Alabama are assigned in this report to the Citronelle Formation. The Citronelle is a thick, mostly fluvial unit that consists mainly of medium to coarse sand containing many stringers of gravel and a few thin clay beds. There is much iron oxide in the formation, along with minor amounts of organic material. It is possible that the upper part of the Citronelle is Pleistocene in age (Marsh, 1966) but the entire formation is placed in the Pliocene in this report. The Citronelle thins to the north and east, and, if it is present outside southwestern Alabama and western Florida, it cannot be distinguished from younger terrace deposits.

Pliocene rocks in much of central Florida are represented by the Bone Valley Formation, a highly phosphatic sequence of sand and clay beds that locally contains a vertebrate fauna of Pliocene age. The extent and thickness of the Bone Valley are uncertain because the unit is difficult to distinguish from the underlying Hawthorn Formation in places. In southeastern Florida, the Tamiami Formation, a white to cream limestone that contains much sand in pockets and as admixed material, is of Pliocene age. The Tamiami and the Bone Valley are not connected. The Caloosahatchee Formation overlies the Tamiami in southern Florida. In scattered places in central and northern peninsular Florida, thin patches of shallow marine rocks are probably Caloosahatchee equivalents. The Caloosahatchee and its equivalents consist of a thin sequence of interbedded clay, calcareous clay, and sand that locally contains much broken shelly material. The upper part of the Caloosahatchee is of Pleistocene age (pl. 2).

The Raysor Formation of southwestern South Carolina is a bluish-gray, shelly, calcareous sand unit of Pliocene age that extends into northeastern Georgia. Beds now called Raysor were formerly included in the Duplin Formation of northeastern South Carolina, but Blackwelder and Ward (1979) showed that the Raysor is a separate unit. The Goose Creek Limestone (Weems and others, 1982) is a sandy, phosphatic, shelly limestone of Pliocene age that is found locally in South Carolina. The relation between the Goose Creek and the Raysor is not known at present (1984) since the two units have not been found in contact. In southeastern Georgia, the Charlton Formation, a dark brownish-green, soft, fossiliferous, locally micaceous to phosphatic clay, represents the Pliocene Series.

PLEISTOCENE SERIES

Over most of the study area, Pleistocene rocks consist of medium- to coarse-grained, tan, white, and brown sand that locally contains trace amounts of carbonaceous material and broken shell fragments. These sands underlie a series of poorly defined to well-defined terraces that are thought to have formed during the Pleistocene Epoch as seas rose and fell in response to glacial and interglacial episodes (MacNeil, 1950). There is little agreement on the number of these terraces, however, and it is possible that some of the higher ones represent pre-Pleistocene deposits (Healy, 1975). In this report, all the terrace materials are considered to be Pleistocene.

In southwestern South Carolina and northeastern Georgia, the sandy terrace deposits are locally underlain by red and yellow sands that contain thin beds of shell and stringers of phosphate. These strata are equivalent to the Waccamaw Formation of northeastern South Carolina. In southeastern Florida, Pleistocene strata consist of a series of thin and variable marine to marginal marine deposits whose relations are complex. Several highly permeable clastic and carbonate Pleistocene units, taken together, comprise most of the Biscayne aquifer, an important source of water in southeastern Florida. For purposes of this report, separate Pleistocene formations are not delineated in southern Florida. Detailed studies on the Pleistocene of southern Florida include reports by Parker and Cooke (1944), DuBar (1958), and Puri and Vernon (1964).

HOLOCENE SERIES

Holocene deposits in the study area include thin sand and gravel deposits that are mostly adjacent to present-day streams and dune, estuarine, and lagoonal sediments contiguous to the modern coast. Residuum developed from the weathering of older sediments and local windblown materials are also included in the Holocene. Holocene strata are not mapped separately in this report, nor are the different Holocene depositional environments delineated.

DEPOSITIONAL ENVIRONMENTS

Pliocene rocks in southeastern Florida (Tamiami and Caloosahatchee Formations) were deposited in shallow to marginal marine environments. The Bone Valley Formation of central Florida is mostly of fluvial origin and is comprised largely of material reworked from underlying Miocene rocks (Puri and Vernon, 1964). The Citronelle Formation of southern Alabama and westernmost Florida represents a thick sequence of fluvial beds. The Raysor and Charlton Formations of South Carolina and easternmost Georgia were deposited in lagoonal to estuarine conditions. The Goose Creek Limestone was laid down in a shallow marine (inner shelf) environment.

Pleistocene rocks throughout most of the study area represent a series of constructional sandy marine terraces deposited at the shoreline of a fluctuating Pleistocene sea. The Waccamaw Formation equivalents in South Carolina and the complex series of Pleistocene units in southeastern Florida represent marginal marine depositional conditions. All Holocene materials in the study area are either of fluvial origin or derived from the weathering of older rocks.

AQUIFERS AND CONFINING UNITS

GENERAL

The ground-water system beneath the study area generally consists of two major water-bearing units; a surficial aquifer and the Floridan aquifer system. In most places, a low-permeability sequence of rocks herein called the upper confining unit of the Floridan aquifer system separates the Floridan from the surficial aquifer. The Floridan is everywhere underlain by low-permeability rocks that are called the lower confining unit of the Floridan aquifer system in this report.

The surficial aquifer consists mostly of poorly consolidated to unconsolidated clastic rocks (except for southeastern Florida, where it is composed of limestone). Most of the water within the surficial aquifer occurs under unconfined conditions. The Floridan aquifer system's upper confining unit, which lies between the Floridan and the surficial aquifer in many places, consists mostly of low-permeability clastic rocks.

The Floridan aquifer system is a more or less vertically continuous sequence of generally highly permeable carbonate rocks whose degree of vertical hydraulic connection depends largely on the texture and mineralogy of the rocks that comprise the system. The high permeability is only rarely vertically continuous. Flowmeter data from scattered wells show that the aquifer system usually consists of several very highly permeable zones, which generally conform to bedding planes and which commonly are either solution riddled or fractured. These zones, which contribute most of the water to wells, are separated by rocks whose permeability ranges from only slightly less to considerably less than that of the high-yield zones. Because the aquifer system (and its upper and lower confining beds) is defined primarily on the basis of permeability, both the top and the base of the system as mapped in this report are composite surfaces that locally cross formation and age boundaries. Accordingly, the time- and rock-stratigraphic units that make up the aquifer system and its contiguous confining beds vary widely from place to place.

Over much of southern Florida, the aquifer system consists of several relatively thin, highly permeable zones isolated from one another by relatively thick sequences of low-permeability rocks. Differences in the hydraulic heads the several highly permeable zones and differences in the quality of the water that they contain show that the zones behave essentially as separate aquifers.

The Floridan aquifer system's lower confining unit consists of either low-permeability clastic rocks or evaporite deposits. The Floridan is everywhere underlain by these relatively impermeable strata, which separate the high-permeability carbonate rocks from older, deeper aquifers that are mostly of Cretaceous age.

SURFICIAL AQUIFER

A surficial aquifer containing water under mostly unconfined or water-table conditions is present throughout all of the study area except for those places where the Floridan aquifer system or its overlying confining bed is exposed at land surface. The surficial aquifer consists predominantly of sand, but gravel, sandy limestone, and limestone are important constituents in places. Where surficial deposits are thick, highly permeable, and extensively used as sources of ground water, they have been given aquifer names, such as the Biscayne aquifer in southeastern Florida and the sand-and-gravel aquifer in westernmost panhandle Florida. Figure 6 shows the extent of the Biscayne and sand-and-gravel aquifers, which grade laterally into widespread but thin sands that are called simply a surficial aquifer.

The term surficial aquifer as used in this report refers to any permeable material (other than that which is part of the Floridan aquifer system) that is exposed at land surface and that contains water under mostly unconfined conditions. The surficial aquifer may be in direct hydraulic contact with the Floridan or be separated from it by confining beds. Rainfall easily infiltrates the permeable surficial materials and, after percolating downward to the water table, moves either laterally to points where it is discharged into surface streams or vertically downward to recharge either the Floridan or local intermediate aquifers, if the water levels in these deeper aquifers are lower than those in the surficial aquifer. Such downward leakance may be rapid or slow, depending on the presence and character of intervening confining beds (low-permeability rocks) and the head differences between the surficial aquifer and deeper aquifers. Water levels within the surficial aquifer fluctuate widely and rapidly in response to rainfall and other natural stresses such as evapotranspiration or the stages of streams. The general configuration of the water-level surface (water table) of the surficial aquifer is a subdued replica of the configuration of land surface.

The surficial aquifer is important in simulating ground-water flow in the Floridan aquifer system because it serves as a "source-sink" bed for the Floridan. Where the head at the base of the surficial aquifer is higher than the potentiometric surface of the underlying Floridan, the surficial aquifer is the "source" of water that moves downward to recharge the Floridan. Where the potentiometric surface of the Floridan is higher than the head at the base of the surficial aquifer, flow is upward from the Floridan to the surficial

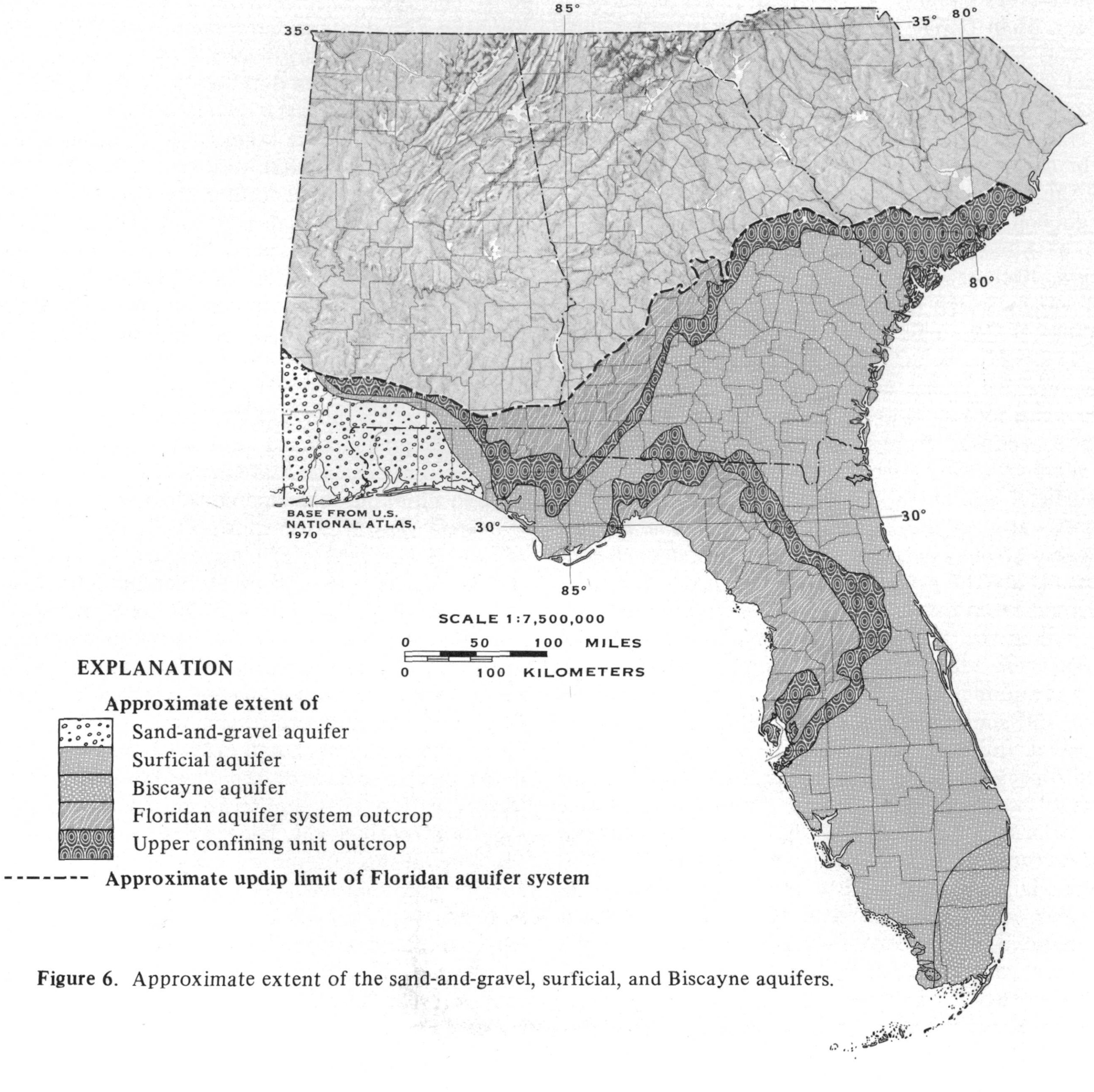


Figure 6. Approximate extent of the sand-and-gravel, surficial, and Biscayne aquifers.

aquifer. In such areas, the surficial aquifer is considered a hydraulic "sink." The thickness and lithologic character of the confining beds that separate the surficial aquifer from the Floridan aquifer system determine the degree of hydraulic interconnection between the two.

The surficial aquifer in the strict sense as mapped on figure 6 consists of all surficial strata containing water under unconfined conditions other than the Biscayne and sand-and-gravel aquifers. Given these restrictions, the surficial aquifer consists mostly of unconsolidated sand and shelly sand deposits that are predominantly of Holocene age but in places include deposits of Pleistocene and Pliocene age. For example, Pleistocene sands that are preserved as ancient beach and shoreline deposits, offshore bars, and the flows of marine terraces (Healy, 1975) are part of the surficial aquifer. Klein (1972) and Hyde (1975) included shell beds and sands of the Anastasia Formation (Pleistocene) and limestones of the Tamiami Formation (Pliocene) in southern Florida in a nonartesian aquifer that they termed the "shallow aquifer"—the equivalent of the surficial aquifer of this report. Callahan (1964) thought that the surficial "sand aquifer" in Georgia consisted of Pliocene to Holocene sands that reach a thickness of about 100 ft in southeastern Georgia. Klein (1972) recorded 130 ft of surficial aquifer in southwestern Florida. The maximum measured thickness of the surficial aquifer recorded during this study is 325 ft in well GA-COF-1 in Coffee County, Ga.

Because the sands designated surficial aquifer on figure 6 are mostly thin and discontinuous in places, water is produced from them primarily for domestic use. Where no other source of ground water exists and the surficial aquifer is sufficiently thick, the aquifer supplies water for industrial or municipal use. Highly permeable strata containing water under nonartesian conditions are the principal source of supply for large municipalities in two areas. These strata are the lateral equivalents of the surficial aquifer. In southeastern Florida, these highly permeable rocks are called the Biscayne aquifer (fig. 6); in extreme western panhandle Florida and south Alabama, they are called the sand-and-gravel aquifer.

The Biscayne aquifer is the source of supply for all municipal water systems in the Palm Beach-Miami area of Florida. Over 500 Mgal/d of water are currently pumped from the Biscayne (Klein and Hull, 1978). The Biscayne is a wedge-shaped body of highly permeable limestone, sandstone, and sand that thickens from a featheredge at its western boundary to more than 200 ft near the Atlantic coast in eastern Broward County (well FLA-BRO-1). The sand content of the aquifer is higher to the north and east; limestone and sandstone are more prominent to the south and west. Included in the Biscayne aquifer are several sand and limestone units of Pleistocene age, the Pliocene and Pleistocene Caloosahatchee Formation, and the upper part of the Pliocene Tamiami Formation (Franks, 1982). Permeability is highest in those areas where the aquifer is mostly limestone, partly because of the development of solution cavities in the limestone. In limestone-rich areas, the transmissivity of the Biscayne aquifer is greater than 1.6×10^6 ft^2/d, but decreases to about 5.4×10^4 ft^2/d where the aquifer is mostly sand (Klein and Hull, 1978). Because of its high permeability and because it is intensively used as a source of water, the Biscayne is subject to contamination by saltwater intrusion from the ocean and by infiltration from an extensive system of canals cut into it that are connected to the ocean. The Biscayne is everywhere separated from the Floridan aquifer system by a thick sequence of low-permeability argillaceous rocks that are mostly of Miocene age. More detailed discussions of the Biscayne aquifer have been given byParker and others (1955), Schroeder and others (1958), Klein and Hull (1978), and Franks (1982).

The sand-and-gravel aquifer (fig. 6) consists primarily of quartz sand that contains much gravel-sized quartz as disseminated particles and as layers. Geologic units included by Franks (1982) in the sand-and-gravel aquifer are, from oldest to youngest, (1) coarse clastics that are probably equivalent to part of the Alum Bluff Group of Miocene age, (2) the Pliocene Citronelle Formation, (3) undifferentiated Pleistocene terrace deposits, and (4) Holocene alluvium. The aquifer thickens southward and westward from a featheredge in southern Alabama and in Walton County, Fla., to a maximum measured thickness of about 1,400 ft in well ALA-MOB-17 in Mobile County, Ala. Locally, layers and lenses of clay within the aquifer form semiconfining beds and create confined conditions in the permeable materials that lie between clay beds. For the most part, however, water in the sand-and-gravel aquifer is unconfined. The aquifer is the primary source of ground water in western panhandle Florida and southwestern Alabama. In places near its updip limit, the sand-and-gravel aquifer is in direct hydraulic contact with the Floridan aquifer system. However, the two aquifers are for the most part separated by thick clay beds. The transmissivity of the sand-and-gravel aquifer is locally as high as about 2×10^4 ft^2/d (Musgrove and others, 1961). Detailed descriptions of the geology and hydrologic characteristics of the sand-and-gravel aquifer have been presented by Musgrove and others (1961), Barraclough and Marsh (1962), Marsh (1966), Trapp (1978), and Franks (1982).

UPPER CONFINING UNIT

Over much of the study area, the Floridan aquifer system is overlain by an upper confining unit that consists mostly of clastic rocks but locally contains much low-permeability limestone and dolomite in its lower parts. In places, the upper confining unit has been removed by erosion, and the Floridan either crops out or is covered by only a thin veneer of permeable sand that is part of the surficial aquifer. Because the lithology and thickness of the upper confining unit are highly variable, the unit retards the vertical movement of water between the surficial aquifer and the Floridan aquifer system in varying degrees. Where the upper confining unit is thick or where it contains much clay, leakance through the unit is much less than where it is thin or highly sandy. In these thick or clay-rich areas, therefore, water in the surficial aquifer moves mostly laterally and is discharged into surface-water bodies rather than moving downward through the upper confining unit (when the head differential is favorable) to recharge the Floridan aquifer system.

The upper confining unit may be breached locally by sinkholes and other openings that serve to connect the Floridan aquifer system directly with the surface. These sinkholes are for the most part found where the thickness of the upper confining unit is 100 ft or less. They appear to result from the collapse of a relatively thin cover of clastic materials into solution features developed in the underlying limestone of the Floridan aquifer system rather than from the solution of limestone beds within the upper confining unit itself. The upper confining unit is generally more sandy where it is less than 100 ft thick because these relatively thin areas represent upbasin depositional sites where coarser clastic rocks were laid down. Plate 25 shows the extent and thickness of the upper confining unit. The maximum measured thickness of the unit is about 1,890 ft in well ALA-BAL-30 in Baldwin County, Ala. The maximum contoured thickness is 1,900 ft. Plate 25 also shows areas where water in the Floridan aquifer system occurs under unconfined, thinly confined (thickness of upper confining unit between 0 and 100 ft), and confined conditions.

The upper confining unit includes all beds of late and middle Miocene age, where such beds are present. Locally, low-permeability beds of post-Miocene age are part of the upper confining unit. Over most of the study area, middle Miocene and younger strata consist of complexly interbedded, locally highly phosphatic sand, clay, and sandy clay beds, all of which are of low permeability in comparison with the underlying limestone of the Floridan aquifer system. Locally, low-permeability carbonate rocks that are part of the lower Miocene Tampa Limestone or of the Oligocene Suwannee Limestone are included in the upper confining unit. Very locally, in the West Palm Beach, Fla., area, the uppermost beds of rocks of late Eocene age are of low permeability and are included in the upper confining unit.

Parker and others (1955) and Stringfield (1966) included basal beds of the Hawthorn Formation in their Floridan and principal artesian aquifers where those beds are permeable. In a few isolated cases (for example, in Brevard County, Fla.), the lowermost Hawthorn strata are indeed somewhat permeable, but their permeability is considerably less than that of the underlying Floridan aquifer system, as Parker and others (1955, p. 84) recognized. Locally, in parts of southwestern Florida (Sutcliffe, 1975; Boggess and O'Donnell, 1982) and west-central peninsular Florida (Ryder, 1982), permeable zones within the Hawthorn Formation are an important source of ground water over a one- or two-county area. Although some of these permeable zones are limestones, their transmissivity is at least an order of magnitude less than that of the Floridan aquifer system, and they are separated from the main body of permeable limestone (Floridan) by thick confining beds. Because of their limited areal extent, relatively low permeability, and vertical separation from the Floridan aquifer system practically everywhere, water-bearing Hawthorn limestones are excluded from the Floridan in this report.

Where the limestone and dolomite of the Floridan crop out, a clayey residuum may form over the carbonate rocks as a result of chemical weathering that dissolves the carbonate minerals and concentrates trace amounts of clay that are in them. Such residumm is particularly well developed in the Dougherty Plain area of southwestern Georgia (Hayes and others, 1983). Although this residuum is a low-permeability material and may very locally form a semiconfining layer above the limestone, it is usually thin and laterally discontinuous. Accordingly, the clayey residuum is not included in this report as part of the upper confining unit of the Floridan aquifer system.

Because the rocks that comprise the upper confining unit vary greatly in lithology, are complexly interbedded, and for the most part are of low permeability, little is known about their hydraulic characteristics. Where clay beds are found in the Hawthorn Formation, they are usually very effective confining beds. Vertical hydraulic conductivity values for Hawthorn clays, as established from core analysis and from aquifer tests, range from 1.5×10^{-2} ft/d (Hayes, 1979) to 7.8×10^{-7} ft/d (Miller and others, 1978). Where sandy beds of the Hawthorn comprise a local aquifer, transmissivity values for the sand range as high as about 13,000 ft^2/d (Ryder, 1982). Hawthorn limestone beds that are local aquifers yield up to 750 gal/min (Boggess, 1974).

FLORIDAN AQUIFER SYSTEM

GENERAL

The Floridan aquifer system is a thick sequence of carbonate rocks generally referred to in the literature as the "Floridan aquifer" in Florida and the "principal artesian aquifer" in Georgia, Alabama, and South Carolina. As defined in this report, the Floridan aquifer system encompasses more of the geologic section and extends over a wider geographic area than either the Floridan or the principal artesian aquifer, as those aquifers have been described in the literature. Figure 7 shows the geologic formations in Florida and southeastern Georgia that were called "principal artesian formations" by Stringfield (1936), those that were included in the "Floridan aquifer" as defined by Parker and others (1955), and those placed in the "principal artesian aquifer" as defined by Stringfield (1966). Subsequent deep drilling and hydraulic testing have shown that highly permeable carbonate rocks extend to deeper stratigraphic horizons than those included in either the "Floridan" or "principal artesian" aquifers as originally described. Accordingly, this author (cited by Franks, 1982) extended the base of the Floridan aquifer downward to include part of the upper Cedar Keys Limestone (fig. 7). Limestone and dolomite beds that commonly occur at the base of the Hawthorn Formation have been included as part of the "Floridan" or "principal artesian" aquifer in most previous reports. However, data collected for the present study show that, except very locally, there are no high-permeability carbonate rocks in the lower part of the Hawthorn Formation that are in direct hydraulic contact with the main body of the Floridan aquifer system.

The Hawthorn Formation was thus excluded from the aquifer system in a report by Miller (1982a) that was one of a series of several interim reports published during the present study. In these interim reports, the aquifer system was called the "Tertiary limestone aquifer system of the Southeastern United States." This cumbersome, albeit more accurate, terminology has subsequently been abandoned, and the aquifer system is referred to in this professional paper as the "Floridan aquifer system" (see Johnston and Bush, 1985 for a more detailed history of the terminology applied to the aquifer system).

The Floridan aquifer system is defined in this report

EPOCH		Stringfield (1936) Formation	Stringfield (1936) Aquifer	Parker and others (1955) Formation	Parker and others (1955) Aquifer	Stringfield (1966) Formation	Stringfield (1966) Aquifer	Miller, in Franks (1982) Formation	Miller, in Franks (1982) Aquifer	Miller (1982 a,c) Formation	Miller (1982 a,c) Aquifer system	This Report Formation	This Report Aquifer system
MIOCENE	Middle	Hawthorn Formation	▨	Hawthorn Formation	▨ Where Permeable	Hawthorn Formation	▨	Hawthorn Formation	▨	Hawthorn Formation	▨	Hawthorn Formation	▨
	Early	Tampa Limestone	Principal artesian formations	Tampa Limestone	Floridan aquifer	Tampa Limestone	Principal artesian aquifer	Tampa Limestone	Where Permeable	Tampa Limestone	Where Permeable	Tampa Limestone	Where Permeable
OLIGOCENE		Oligocene Limestone		Suwannee Limestone		Suwannee Limestone		Suwannee Limestone	Floridan aquifer	Suwannee Limestone	Tertiary limestone aquifer system	Suwannee Limestone	Floridan aquifer system
EOCENE	Late	Ocala Limestone		Ocala Limestone		Ocala Limestone		Ocala Limestone		Ocala Limestone		Ocala Limestone	
	Middle	▨	▨	Avon Park Limestone		Avon Park Limestone		Avon Park-Lake City Limestones		Avon Park-Lake City Limestones		Avon Park Formation	
				Lake City Limestone		Lake City Limestone							
	Early			▨	▨	Oldsmar Limestone		Oldsmar Limestone		Oldsmar Limestone		Oldsmar Formation	
PALEOCENE						▨	▨	Cedar Keys Limestone	▨	Cedar Keys Limestone	▨	Cedar Keys Formation	▨

Figure 7. Comparison of aquifer terminologies.

as a vertically continuous sequence of carbonate rocks of generally high permeability that are mostly of middle and late Tertiary age and hydraulically connected in varying degrees and whose permeability is, in general, an order to several orders of magnitude greater than that of those rocks that bound the system above and below. As plate 2 shows, the Floridan aquifer system includes units of late Paleocene to early Miocene age. Very locally, in the Brunswick, Ga., area, the entire Paleocene section plus a thick sequence of rocks of Late Cretaceous age are part of the aquifer system. In and just downdip of the area where the aquifer system crops out, the entire system consists of one vertically continuous permeable unit. Farther downdip, less permeable carbonate units of subregional extent separate the system into two aquifers, herein called the Upper and Lower Floridan aquifers (fig. 8). These less permeable units may be very leaky to virtually nonleaky, depending on the lithologic character of the rock comprising the unit. Because they lie at considerable depth, the hydrologic character and the importance of the subregional low-permeability units are known from only a few scattered deep test wells. Local low-permeability zones may occur within either the Upper or the Lower Floridan aquifer. In places (for example, southeastern Florida), low-permeability rocks account for slightly more than half of the rocks included in the aquifer system.

Even though the rocks that comprise the base of the Upper Floridan aquifer are not everywhere at the same altitude or geologic horizon or of the same rock type, the presence of a middle confining unit over about two-thirds of the study area has led to a conceptual model for the Floridan aquifer system that consists of two active permeable zones (the Upper and Lower Floridan aquifers) separated by a zone of low permeability (a middle confining unit). Because of this simplified layering scheme, it is necessary to greatly generalize the highly complex sequence of high- and low-permeability rocks that comprise the aquifer system. Local confining beds (see, for example, cross section E-E', pl. 21) are either disregarded because they are regionally unimportant or lumped with one of the major layers. The purpose of the conceptual model, and of the digital computer model derived from it and described by Bush and Johnston (1985) is to portray the major aspects of ground-water flow within the Floridan aquifer system. In like manner, the descrip-

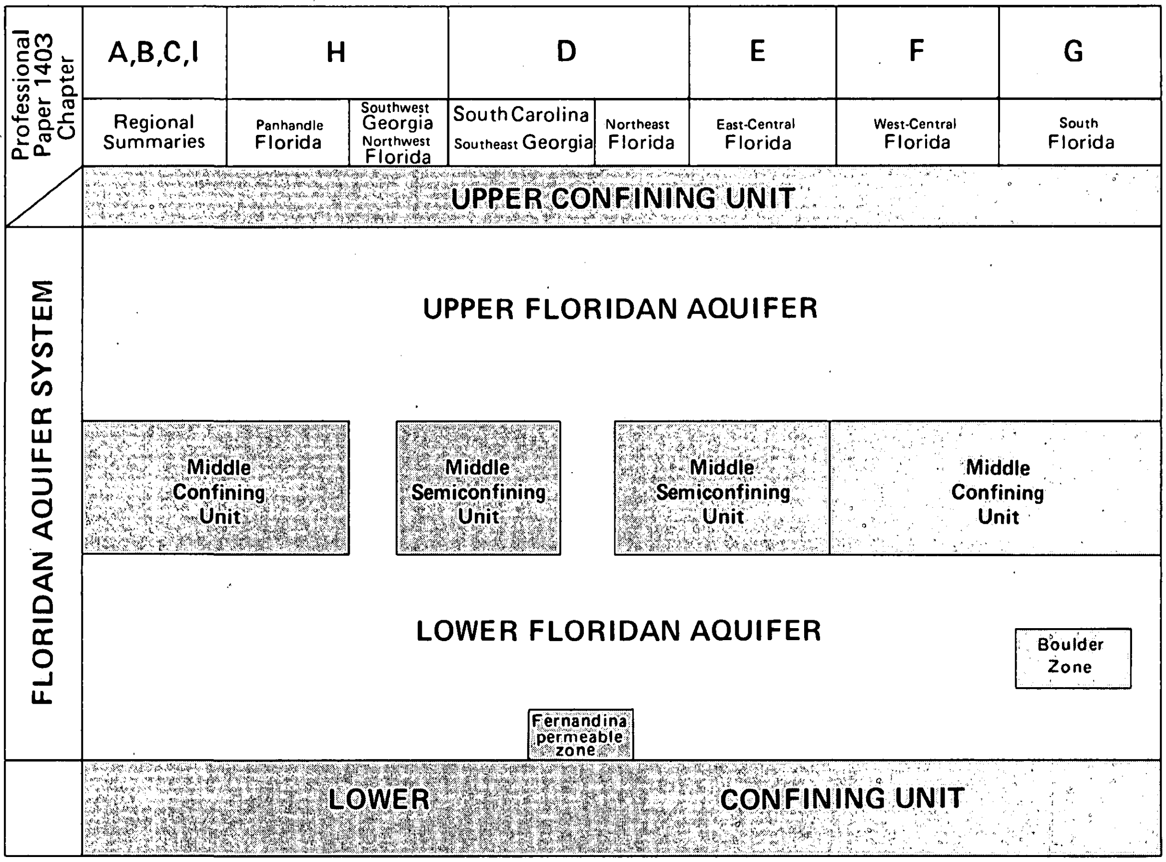


Figure 8. Aquifers and confining units of the Floridan aquifer system.

tion of the aquifer system's geohydrologic framework in this report is intended to show the principal variations in permeability within the aquifer system. In both cases, local anomalies that do not fit with overall (regional) conditions are ignored.

Regionally, the top of the Floridan aquifer system in most places lies at the top of rocks of Oligocene age (Suwannee Limestone) where these strata are preserved. Where Oligocene rocks are absent, the aquifer system's top is generally at the top of upper Eocene rocks (Ocala Limestone). Locally, in eastern panhandle Florida and in west-central peninsular Florida, rocks of early Miocene age (Tampa Limestone) are highly permeable and hydraulically connected to the aquifer system. In places, upper Eocene through lower Miocene rocks are either missing owing to erosion or nondeposition or of low permeability; at these places, rocks of middle Eocene age (Avon Park Formation) mark the top of the aquifer system. It is important to note that there are some places where the upper part of a given formation that comprises the top of the aquifer system consists of low-permeability rocks. At such places, the low-permeability beds are excluded from the aquifer system, and the top of the system is considered to be the top of the uppermost high-permeability carbonate rock. The top of the system, then, may lie within a stratigraphic unit rather than at its top. Because the permeability contrast between the aquifer system and its upper confining unit does not everywhere follow stratigraphic horizons, neither does the top of the aquifer system. Likewise, the top of the aquifer system may locally lie within a limestone unit if the upper part of the limestone consists of low-permeability rock and the lower part is highly permeable.

The time-stratigraphic units or parts of units that mark the top of the Floridan aquifer system at selected localities are shown in figure 9, as well as the time-rock units that comprise the Upper and Lower Floridan aquifers and the units that are considered to represent the aquifer system's base. Figure 9 shows a series of idealized chronostratigraphic columns compiled from well data at several locations in the study area, along with the permeability characteristics of each chronostratigraphic unit at each location. Examination of this figure shows that, in addition to the variations in the top and base of the aquifer system, the degree of complexity varies greatly within the system. Generally speaking (and as figure 9 shows), the aquifer system in most places can be divided into an Upper and Lower Floridan aquifer separated by less-permeable rock. In places, however, no middle confining unit exists (for example, the Baxley, Ga., and Gainesville, Fla., columns on fig. 9), and the aquifer system is highly permeable throughout its vertical extent. In other places, thick sequences of low-permeability rock occur at several levels within the aquifer system (for example, the Savannah, Ga., and West Palm Beach, Fla., areas in fig. 9), and the several discrete permeable zones of the system may be hydraulically separated.

Regionally, and in a fashion similar to the way in which the top is defined, the base of the aquifer system is defined as the level below which there is no high-permeability carbonate rock. The base of the system is generally either (1) glauconitic, calcareous, argillaceous to arenaceous rock that ranges in age from late Eocene to late Paleocene (fig. 9) or (2) massively bedded anhydrite that commonly occurs in the lower two-thirds of the Paleocene Cedar Keys Formation. Locally, near Brunswick, Ga., micritic limestone and argillaceous limestone of Late Cretaceous (Tayloran) age mark the base of the aquifer system. The permeability of the micritic and argillaceous carbonate rocks, the anhydrite beds, and the various clastic rocks that comprise the base of the system is much less than that of the carbonate rocks above. Regardless of its lithologic character, the lower confining unit, whose top is mapped in this report as the base of the aquifer system, everywhere separates the system from deeper, predominantly clastic aquifers of early Tertiary and Late Cretaceous age.

The upper confining unit of the Floridan aquifer system generally consists of rocks of middle and late Miocene age. Where older rocks such as the lower Miocene Tampa or Oligocene Suwannee Limestones are of low permeability, they are also included in the upper confining unit. In parts of the study area, the upper confining unit has been removed by erosion and the aquifer system either: crops out, is covered by only a surficial sand aquifer, or is covered very locally by clayey residuum. Hydraulic conditions within the aquifer system accordingly vary from confined to unconfined. Where thick sequences of less permeable rocks of subregional extent are present within the aquifer system, they divide it into two major aquifers. The uppermost aquifer (Upper Floridan) generally consists of rocks of Oligocene, late Eocene, and late middle Eocene age (fig. 9). The lower aquifer (Lower Floridan) generally consists of rocks of early middle Eocene to late Paleocene age. Where no middle confining unit separates the two aquifers, all the permeable rock comprising the aquifer system is referred to as the Upper Floridan aquifer. The middle confining unit separating the Upper and Lower Floridan aquifers is generally found in the middle part of rocks of middle Eocene age. The less permeable material that comprises the middle confining unit, however, is not everywhere of the same age (fig. 9), nor does it everywhere consist of the same rock type, as a later section of this report discusses in detail.

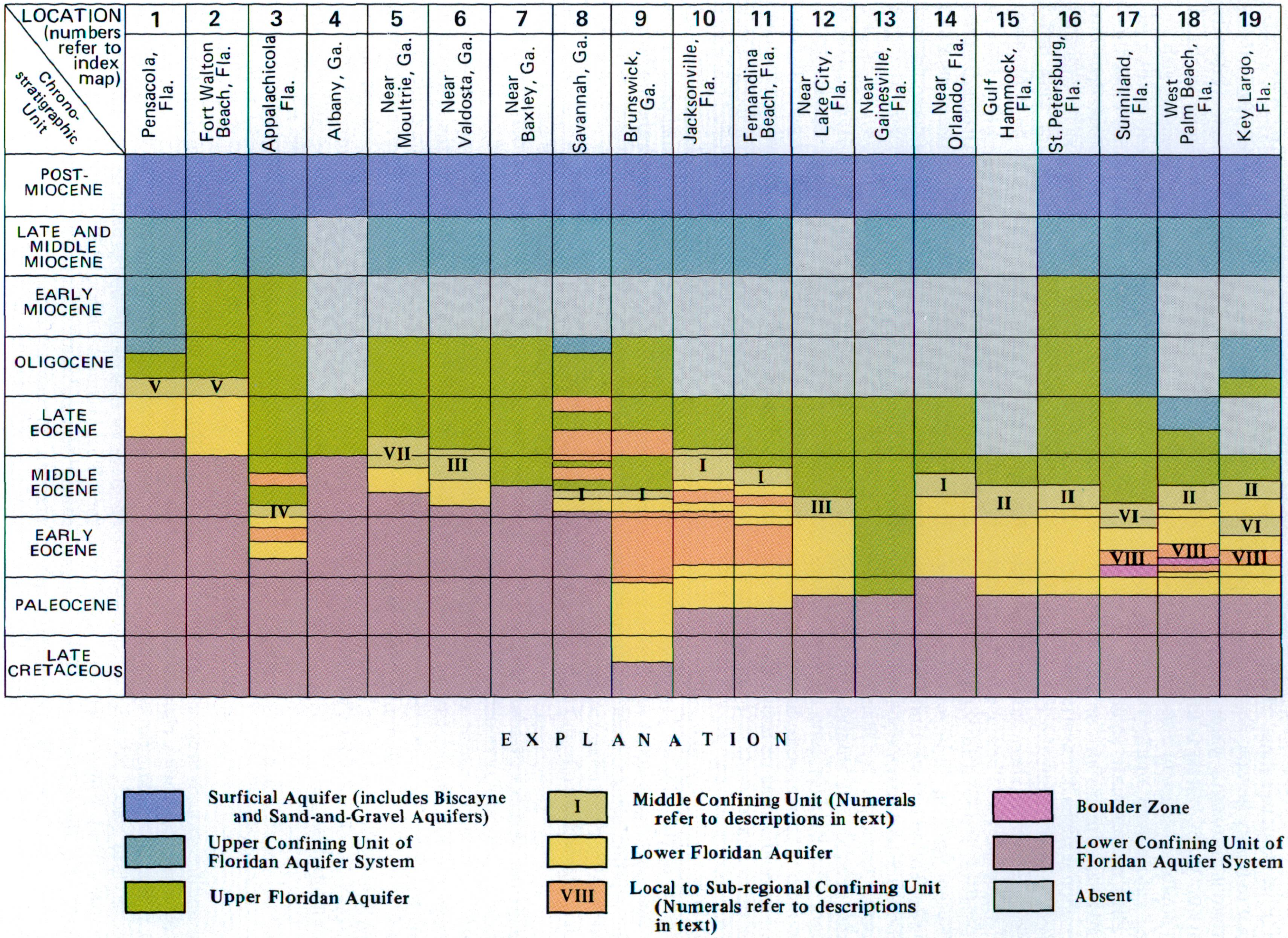


Figure 9. Relation of time-stratigraphic units to the Floridan aquifer system, its component aquifers, and its confining units.

Throughout much of the study area, the water in the Lower Floridan is brackish to saline. The Lower Floridan is moderately to highly porous, and digital simulation indicates that it transmits water sluggishly (see Bush and Johnston, 1985). Little is known about the Lower Floridan aquifer because in most places there is no reason to drill into a deep aquifer containing poor-quality water when an adequate shallower source of good-quality water (the Upper Floridan aquifer) exists.

Local to subregional zones of cavernous permeability occur at several levels within the Floridan aquifer system. The best known of these zones, called the "Boulder Zone" (Kohout, 1965) because of its difficult drilling characteristics, is found in the lower part of rocks of early Eocene age (fig. 9) in southern Florida. Borehole televiewer surveys show that this zone consists of a series of thin to moderately thick horizontal openings connected vertically by fractures, some of which have been opened and enlarged into vertical tubes by solution. The Boulder Zone resembles modern cave systems and is presumed to have formed in a similar fashion—by solution at or above an early Eocene paleowater table. As a result, the transmissivity of the Boulder Zone is extremely high (Meyer, 1974). Other shallower, less extensive cavernous zones are found farther north in the Florida peninsula (Miller, 1979). Where these cavernous zones are developed in the parts of the aquifer system that contain saline water, they are used as receiving zones for underground injection of treated sewage and other industrial wastes.

Within the sequence of rocks that is here treated as an upper confining unit are permeable zones that extend over part of a county or over several counties and that are important local sources of water. These localized artesian aquifers are considered in this report to comprise part of the upper confining unit of the Floridan aquifer system because their permeability is low in comparison with that of the Floridan and because they are of limited extent.

EXTENT

The Floridan aquifer system becomes thin in updip areas where it is interbedded with clastic rocks. The limestones that comprise the aquifer system grade in an updip direction into sandy or argillaceous limestone, which in turn grades into calcareous sand or clay. Still farther updip, these calcareous clastic rocks grade into fully clastic sediments that are stratigraphically equivalent to the aquifer system but are much less permeable than their limestone equivalents. The updip facies change from limestone into clastic rocks and the corresponding decrease in the amount of highly permeable rock in an updip direction are shown by geohydrologic cross-sections A-A', B-B', C-C', D-D' and O'-O'' (pl. 15, 16, 18, 19, 20). The updip limit of the Floridan aquifer system (plate 26) has been arbitrarily placed where the thickness of the system is less than 100 ft and where the clastic rocks interbedded with the limestone make up more than 50 percent of the rock column between the uppermost and lowermost limestone beds that can be shown to be connected downdip. To the north and west of the line shown as the approximate updip limit of the aquifer system, thin beds, lenses, and stringers of limestone may be either connected to the main limestone body or isolated from it because of postdepositional erosion. Although these thin beds and outliers locally yield water in small to moderate amounts, they are not considered in this report to be part of the Floridan aquifer system.

The Floridan aquifer system is known to extend offshore from Georgia (McCollum and Herrick, 1964) and peninsular Florida (Rosenau and others, 1977; Schlee, 1977; Johnston and others, 1982). Because offshore geologic and hydrologic data are sparse, however, the aquifer system is not mapped offshore in this report. The Floridan contains fresh to brackish water in some offshore areas (Johnston and others, 1982), but sparse data on water quality mandate mapping of the aquifer system's freshwater-saltwater interface by indirect methods (Bush and Johnston, 1985; Sprinkle, 1985).

In part of the mapped area in South Carolina, the Upper Floridan aquifer has passed by facies change into low-permeability clastic rocks, and only the Lower Floridan aquifer is present. The effect is that of a pinchout of the Upper Floridan. The approximate area of facies change within the Upper Floridan is shown on plate 26 by a dashed northwest-trending line whose location is based on widely scattered well control. Contours to the northeast of the line represent the top of a middle confining unit that is underlain by the Lower Floridan aquifer at an altitude several hundred feet lower. Other water-bearing limestone units in South Carolina are located northeast of the area mapped in this report, but they are either hydraulically separate from the Floridan aquifer system or their permeability is too low to warrant including them in the system.

A series of faults in southwestern Alabama shown on plate 26 marks the updip limit of the aquifer system. These arcuate faults, which are part of the Gilbertown-Pickens-Pollard fault zone, bound a series of grabens. Movement along these faults has juxtaposed low-permeability clastic rocks within the grabens opposite the permeable limestone that comprises the aquifer system. The north-trending, sinuous, fault-bounded feature in Washington and Mobile Counties, Ala., is the Mobile Graben (Murray, 1961). Thin limestone beds within this graben have been downdropped and isolated from the main body of limestone. Farther westward, in southeastern Mississippi, the Floridan aquifer system passes by facies change into clastic rocks. The aquifer system is not mapped in Mississippi because it is insignificant there. Well data offshore from Mobile Bay, Ala., show that the Floridan is absent (again due to facies change) about 60 mi offshore.

CONFIGURATION AND CHARACTER OF TOP

Where the carbonate rocks that are included in the Floridan aquifer system crop out, their extent has been mapped in detail (Bennison, 1975; Copeland, 1968; Georgia Geological Survey, 1976; Vernon and Puri, 1965). The configuration of the surface of the aquifer system and the extent of the different rock units comprising its top are mapped in this report on the basis of the well control shown on plate 26, which is modified from a similar map by Miller (1982a). Detailed contouring in areas of sparse well control is based on data and maps found in published reports. The altitude of the top of the aquifer system may differ locally from the altitudes shown on plate 26 because local irregularities that have been produced by erosion or solution of the limestone may be present on the system's surface.

Plate 26 shows many localized topographic highs and lows on the aquifer system's surface in and adjacent to outcrop areas. These small features result from a combination of topography that developed when the limestone was exposed to subaerial erosion and karst topography that developed by subsurface solution of the limestone either while it was exposed or while it was buried at a shallow depth. If a smaller contour interval had been used on plate 26, many more sinkholes, solution valleys, and other types of karst features would be evident. The purpose of plate 26, however, is to show the regional configuration of the top of the Floridan aquifer system. Many of the references listed in this report contain maps that show the local topography of the aquifer system's surface in greater detail.

Because high permeability is the major criterion used in this report to delineate the top of the Floridan aquifer system, plate 26 differs locally from previously published maps (Vernon, 1973; Kwader and Schmidt, 1978; Buono and Rutledge, 1979; Knapp, 1979; Scott and Hajishafie, 1980) that show the configuration of either the top of vertically continuous limestone or the top of a specific geologic unit without regard to the permeability of the rock. In this report, any low-permeability rocks at the top of the carbonate sequence are excluded from the aquifer system. Within any of the areas where a given time-stratigraphic unit is mapped as the top of the aquifer, one- or two-well anomalies may occur if the particular time-stratigraphic unit is of low permeability throughout. Such isolated anomalies do not affect the general (regional) definition and configuration of the aquifer system and thus are not shown on plate 26.

The top of the aquifer system in most places is comprised of rocks of either Oligocene age (Suwannee Limestone or equivalent) or late Eocene age (Ocala Limestone or equivalent). Rocks of Oligocene age are thought to have once covered the entire area because (1) isolated erosional remnants of Oligocene strata are preserved as outliers surrounded by upper Eocene (Ocala) limestone and (2) a major marine transgression took place in the central and eastern Gulf Coastal Plain during Oligocene time, possibly related to a global rise in sea level (Vail and others, 1977). Post-Oligocene erosion, however, has stripped the Suwannee Limestone and equivalent strata from much of the mapped area, and left upper Eocene rocks widely exposed in outcrop and subcrop. Small patches of middle Eocene rocks that comprise the top of the aquifer system in central and southern peninsular Florida have been likewise exposed by erosion and protrude through a thin veneer of late Eocene strata because the younger rocks that once covered them have been stripped away. The area from which Oligocene rocks have been removed largely coincides with the axis and flanks of the Peninsular arch, and their absence is probably due to a slight rejuvenation or upwarp of this arch. Smaller structural features, such as some of the faults in peninsular Florida, have provided sufficient relief for younger rocks to be stripped and for older sediments to be exposed on the upthrown sides of the faults. By contrast, Oligocene outliers in southeastern Alabama (pl. 26) are not related to structure but reflect present-day topography and erosion.

Throughout most of Georgia and in north-central Florida, all rocks of Oligocene age are highly permeable and are included in the Floridan aquifer system. Accordingly, in these areas, the top of Oligocene strata coincides with the top of the aquifer system. In parts of southern Alabama, panhandle Florida, and the southern part of the Florida peninsula, the upper part of the Oligocene section consists of either low-permeability (commonly micritic) limestone or clastic rocks or both and is therefore not included in the aquifer system. In these places, then, the top of the system lies within rocks of Oligocene age rather than at their top.

Rocks of late Eocene age (Ocala Limestone) are present throughout most of the study area, are highly permeable practically everywhere, and comprise the top of the aquifer system over much of its extent (pl. 26). Upper Eocene rocks are excluded from the system only in South Carolina, where they are highly argillaceous and grade into part of the Cooper Formation, and very locally in southern Florida, where all or part of the Ocala Limestone is micritic and its permeability is accordingly low. With these exceptions, where upper Eocene rocks are present, they yield large quantities of water everywhere. In extreme western panhandle Florida, low-permeability rocks occur in the lower part of the upper Eocene section because upper Eocene limestone there passes into clastic rocks through facies change.

There are a few localities in peninsular Florida where both Oligocene and upper Eocene rocks are absent (pl. 26). In these places, middle Eocene rocks (Avon Park Formation) comprise the top of the Floridan aquifer system. Like upper Eocene rocks, the upper part of the middle Eocene section is generally highly permeable, except in updip areas where there is a transition of middle Eocene limestone into clastic sediments. In much of South Carolina, a thin unit of limestone that lies within the middle Eocene (part of the Santee Limestone) comprises the entire permeable part of the aquifer system; here, younger strata are either clastics or low-permeability carbonates or both. The top of the middle confining unit is mapped here as the top of the aquifer system.

Rocks of early Miocene age (Tampa Limestone and its equivalents) mark the top of the aquifer system in a small area along the central part of peninsular Florida's Gulf Coast and in a larger area in eastern panhandle Florida. Although the area over which lower Miocene rocks are present is considerably wider than that mapped on plate 26, only within the mapped area are they permeable enough to be included as part of the Floridan aquifer system.

Even though plate 26 is a composite of several time-stratigraphic levels, major geologic structures are shown as large-scale features on the map and are generally expressed as a series of broad high and low areas that interrupt the steady, gentle seaward slope of the aquifer system's top. For example, the Southeast Georgia embayment is shown as an east-trending negative area centered near Brunswick, Ga.; the low area in and near Gulf County, Fla., is part of the Southwest Georgia or Apalachicola embayment; the low areas in central Lee County and northern Monroe County, Fla., are arms of the South Florida basin. The influence of the Gulf Coast geosyncline is reflected as a steep, steady gulfward slope of the top of the aquifer system in extreme western panhandle Florida and in southern Alabama.

Parallel to northern peninsular Florida's western coast and extending for a short distance into southwestern Georgia is an elongate, broad, northwest-trending high area. This high, known in the literature as the Ocala uplift, has been thought to represent an arch or an anticline, partly because, like a classic anticline, older rocks are exposed near its "axis." This "axis," although clearly shown on a map of the surface of rocks of late Eocene age (pl. 8), is not present on a map of the top of rocks of middle Eocene age (pl. 6), nor does it occur on maps of older geologic units or on a map of the base of the aquifer system (pl. 33). This author agrees with Winston (1976) that the Ocala uplift is not a structural uplift in the classic sense. The "uplift" may reflect post-Eocene tilting of the Florida peninsula, as Winston proposed, or it may be merely the result of differential compaction of soft carbonate rocks over an irregular depositional surface.

A subtle positive feature in extreme southeastern Alabama and southwestern Georgia (pl. 26) is in the same location as the feature that has been called the Chattahoochee arch or anticline by some authors. This positive area is not shown on maps of the tops or thicknesses of the several time-stratigraphic units that comprise the aquifer system (pls. 3-11), nor is it present on a map of the base of the system (pl. 33). Patterson and Herrick (1971), after reviewing all published evidence, concluded that the Chattahoochee anticline was hypothetical rather than real. This author agrees that there is no evidence for a structural feature where this "anticline" is supposedly located and concludes that the apparent "structure" is in fact an erosional feature, perhaps exaggerated by a change in the strike of the outcropping coastal plain rocks from a northeastern alinement along the Atlantic Coastal Plain to an east-west alinement along the Gulf Coastal Plain.

In addition to the faults in Alabama that form part of the updip limit of the Floridan aquifer system, several small faults concentrated in eastern peninsular Florida and central Georgia are shown on plate 26. The locations of the faults shown in Florida were taken from the literature and changed slightly where it was necessary to conform with well data. Most of the Florida faults are downthrown on the oceanward side, and all appear to be normal or gravity faults. All of the faults shown displace rocks of late Eocene age, and at least one, in southern Florida, which extends from Indian River County southeast to Martin County, is post-Oligocene in age. From Volusia County southward, younger rocks have commonly been eroded from the upthrown sides of these faults, and older strata have thus been exposed in subcrop. None of the Florida faults mapped has a major effect on the flow system of the Floridan, as a comparison of the potentiometric surface (fig. 10) with the fault locations on plate 26 shows. All of the faults are of small displace-

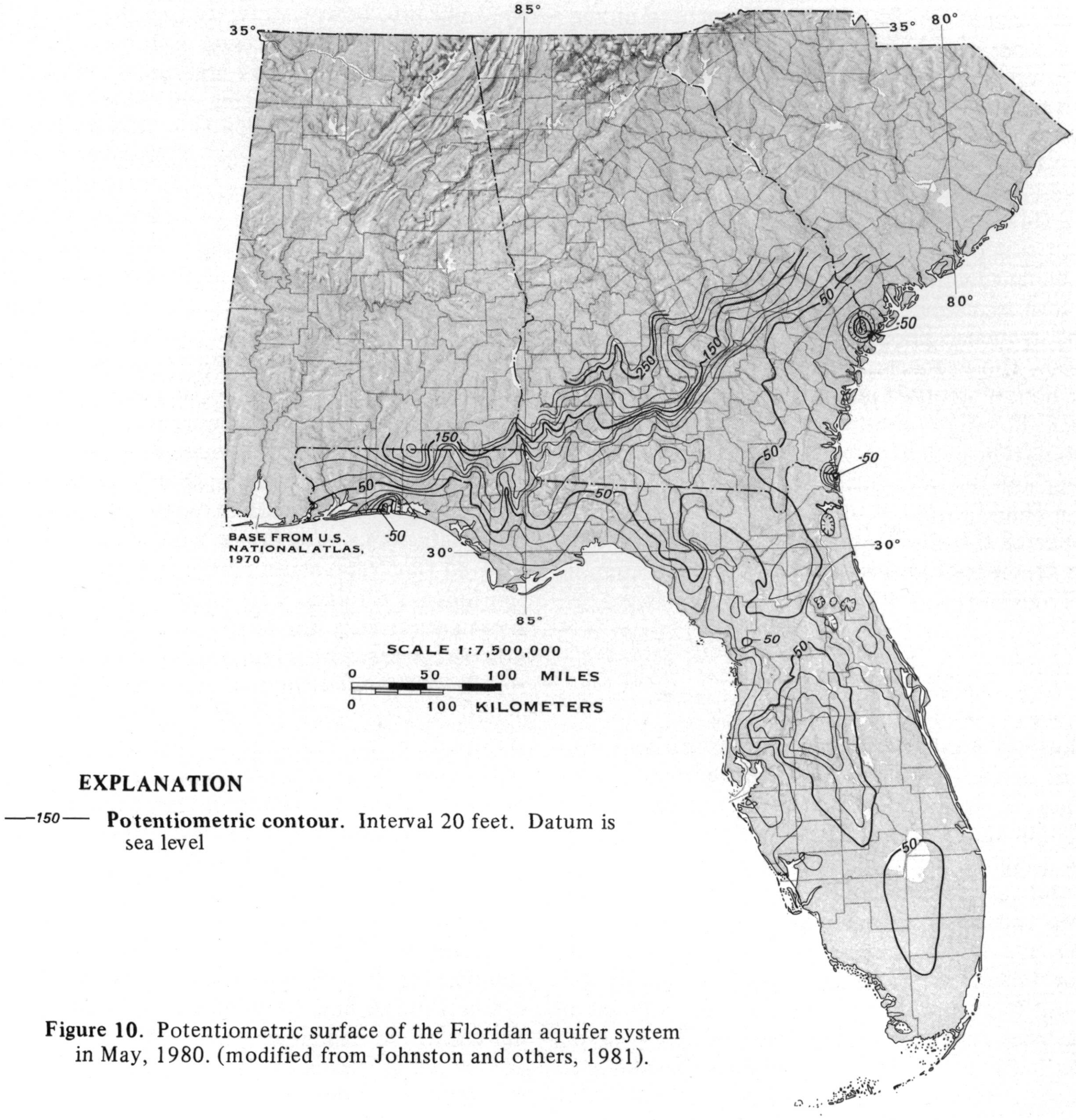


Figure 10. Potentiometric surface of the Floridan aquifer system in May, 1980. (modified from Johnston and others, 1981).

ment, and where they occur, the upper few hundred feet of the aquifer system is highly permeable, regardless of which time-stratigraphic unit it lies within. Fault movement has accordingly juxtaposed rocks of similar permeability and has resulted in only a slight difference in the thickness of the aquifer system. The ground-water flow system is accordingly unaffected.

When the small northeast-trending grabens shown in central Georgia on plate 26 are taken together, they represent a negative feature called by Herrick and Vorhis (1963) the "Gulf Trough of Georgia," a name subsequently shortened to "Gulf Trough" (Hendry and Sproul, 1966). Herrick and Vorhis did not postulate faulting as the cause of the Gulf Trough. Gelbaum (1978) and Gelbaum and Howell (1982), however, indicated that faulting could have formed many if not all of the small elongate basins that constitute the Gulf Trough, an interpretation with which this author agrees. In contrast to the Florida faults discussed above, the faults bounding the Gulf Trough grabens show considerable vertical displacement. The graben system affects the permeability characteristics, the thickness, and the configuration of the top of the Floridan aquifer system, and is also evident on maps of the tops and thicknesses of stratigraphic units ranging in age from middle Eocene to middle Miocene. Limestone units that are part of the aquifer system are less permeable within the Gulf Trough those than on either side (Gelbaum and Howell, 1982), and the system is thin within the trough (pl. 27).

The Gulf Trough coincides with a bunching of contours on a map of the potentiometric surface of the Floridan aquifer system (fig. 10). Such a steep hydraulic gradient can be caused by a decrease in transmissivity. Very low specific capacities for Floridan wells within the trough suggest that the aquifer system is less transmissive there; ground-water modeling tends to confirm this suggestion. The grabens that comprise the trough are bounded by steeply dipping normal faults. Displacement along these faults has downdropped low-permeability Miocene clastic sediments within the grabens opposite the permeable limestone that borders the grabens on both sides (pl. 26). The result is a damming effect at the trough on the generally southeast-flowing ground water within the Floridan. The combination of low-transmissivity limestones in the grabens and the retardation of flow by the juxtaposition of a thick sequence of low-permeability clastic rocks opposite the limestone accounts for the steep hydraulic gradients that exist in the aquifer system in the Gulf Trough area.

THICKNESS

The Floridan aquifer system generally thickens seaward from a thin edge near its approximate updip limit. Plate 27, updated and modified from a map by Miller (1982b), shows the thickness of the entire aquifer system, including the Upper and Lower Floridan aquifers and the middle confining unit that separates them. The thickness mapped includes all strata between the top of the highest vertically continuous permeable limestone sequence (top of the aquifer system) and the top of the low-permeability clastic or evaporitic rocks that form the base of the system. Well point data have been used primarily to construct the thickness map and have been supplemented in areas of sparse well control by thickness estimates obtained by subtracting contoured elevations of the top and base of the aquifer system (pls. 26, 33). Thicknesses may vary locally from those shown, especially where erosion or karst topography has created considerable relief on the aquifer system's surface.

The Floridan aquifer system is composed of all or parts of several different formations and (or) time-stratigraphic units in different combinations at different places. Plate 27 therefore represents a composite thickness that may encompass only a part of a single formation in updip areas or may include several time-stratigraphic units downdip. Because the aquifer system is defined primarily by the occurrence of permeable carbonate rocks, plate 27 cannot be interpreted in exactly the same way as an ordinary isopachous map. Some of the thickening and thinning trends shown on the map are, however, related to depositional conditions and geologic structure. Some of the large-scale structures in the mapped area have maintained their relative positive or negative character over long periods of geologic time. For this reason, and because movement on these features kept pace with depositional rates, basin conditions remained very much the same, and thick sequences of carbonate rocks of similar lithology were deposited. The major structural features in the study area shown on plate 27 are areas of major thickening or thinning of the aquifer system.

The Floridan aquifer system is typically composed of platform carbonate rocks that were deposited in warm, shallow water as limestones of various textures and were subsequently dolomitized in varying degrees. This platform carbonate sequence is best developed to the south and east of the 1,000-ft thickness contour shown on plate 27. North and west of this contour, the carbonate rocks interfinger with clastic sediments in an area that represents spillover of carbonate deposition onto a foreland basin that was receiving clastic sediments from a landmass to the north and west. In upbasin areas, this dual source of sediment supply resulted in complex interbedding and interfingering of clastic and carbonate rocks. As the carbonate rocks thin toward the updip limit of the aquifer, the amount of clastic material admixed with them increases. These factors account for the lower permeability and transmissivity (Bush and Johnston, 1985) of the aquifer system in an upbasin direction.

In north-central peninsular Florida (pl. 27), the limestone units that comprise the aquifer system thin over the crest and flanks of the Peninsular arch. The great thicknesses of carbonate rocks in the eastern panhandle of Florida and in southeastern Georgia have accumulated in the Southwest and Southeast Georgia embayments, respectively. The thick area in Manatee and Sarasota Counties, Fla., is thought to be part of the South Florida basin. The thick area in southern Martin County, Fla., does not correlate with any known structural feature; the aquifer system is thick simply because the anhydrite beds that mark its base in southern Florida are exceptionally deep. The aquifer system does not thicken greatly in a gulfward direction in western panhandle Florida and southern Alabama, as one might expect. The supply of clastic sediments from the north and west was great enough here to preclude the deposition of limestone throughout most of that the time the aquifer system was being formed.

A small graben system in central Georgia cuts through the entire thickness of the aquifer system (section B-B', pl. 16), and was apparently active during as well as after deposition of the limestone that makes up the system. The series of small grabens shown on plate 27 comprises the Gulf Trough discussed earlier.

For the most part, there are more clastic rocks and low-permeability limestone within these grabens than there are to the northwest and southeast of the normal or gravity faults that bound them. Because of the greater amount of clastic material in the grabens, the aquifer system is much thinner within them. For example, near Moultrie in Colquitt County, Ga., the aquifer system is less than 200 ft thick within one of the grabens but is more than 500 ft thick to the northwest, in an upbasin direction where the aquifer system would normally be expected to be thinner.

Movement along the faults of the graben system has downdropped low-permeability clastic rocks within the grabens opposite permeable limestone on either side of them. This juxtaposition has restricted the flow of ground water across the grabens and down the hydraulic gradient from them. Throughout the shaded area shown on plate 27 (southeast of the graben system and extending from Gadsden County, Fla., northeast to Berrien County, Ga.), the aquifer system is thin and consists of only a few hundred feet of permeable limestone underlain by gypsiferous limestone. The ground-water flow across this area, restricted by the grabens to the northwest, has not been sufficient to completely dissolve the gypsum contained in the limestone.

In southwestern Alabama, the arcuate faults shown on plate 27, like those in central Georgia, bound a series of grabens. Gulfward of these grabens (except in southern Mobile County, Ala.), there is very little limestone; thick sequences of clastic rocks in the grabens and seaward of them are the Floridan aquifer system's equivalent.

An oval-shaped northeast-trending thick pod of limestone in Clinch and Echols Counties, Ga., possibly represents the Suwannee Strait, a poorly understood channel-like feature that was once thought to separate predominantly clastic rocks to the northwest from predominantly carbonate rocks to the southeast. Because the feature as mapped on plate 27, is closed to the northeast and southwest, it is obviously not a channel. Its exact origin is not known, however.

There are several local, flat, shelflike features shown on plate 27 in southern Florida. The most prominent are just south of Miami in Dade County, north of Fort Pierce in St. Lucie County, and in Lee County. These shelflike areas are apparent, not real, and are the result of differences in elevation of the evaporite deposits that comprise the base of the aquifer system in southern Florida. These low-permeability evaporites occur at different altitudes in different wells because they interfinger with carbonate rocks as a series of discrete large lenses. Regionally, the lenses are mapped as if they were a single horizon, and their interfingering nature creates the illusion of irregular topography. The anhydrite that represents the base of the Floridan aquifer system is high under all these shelflike areas, and the aquifer system above these high spots is accordingly thin.

MAJOR HYDROLOGIC UNITS WITHIN THE FLORIDAN AQUIFER SYSTEM

The Floridan aquifer system is extremely complex because (1) the rocks that comprise it were originally laid down in highly variable depositional environments, and their texture and mineralogy accordingly vary considerably; (2) diagenesis has produced much change in the original sediments in places, and (3) large- to small-scale karst features are developed at several levels in the aquifer system owing to modern and ancient dissolution of the limestone. These factors, alone or in combination, create much local variability in the aquifer system's lithology and permeability characteristics. It is necessary, therefore, to generalize greatly both the geology and the hydraulic parameters of the aquifer system to present a regional view of each. Also, to simulate regional ground-water flow with a digital computer model, the complexities of local variations in geology and hydraulic properties must be simplified. Regionally, as mentioned earlier (section "Floridan Aquifer System"), the Floridan aquifer system generally consists of an Upper and a Lower Floridan aquifer separated by a middle confining unit. Neither the separate aquifers nor the middle confining unit is everywhere the same thickness or age or necessarily consists of the same type of rock. In places, no middle confining unit exists, and the entire aquifer system is more or less permeable. In other places, such as southern Florida, most of the aquifer system consists of low-permeability rocks separating thin zones of high permeability. Within regionally extensive aquifers or confining units, there may be from one to several local zones of contrasting permeability (see, for example, section E-E', pl. 21); these local zones, however, do not usually affect the overall character of the given aquifer or confining unit, even though a given zone may locally have an important hydraulic influence.

The upper major permeable zone of the aquifer system, herein called the Upper Floridan aquifer, yields large volumes of water nearly everywhere, and the water is usually of good chemical quality. As a result, few water-supply wells penetrate the aquifer system's middle confining unit and the Lower Floridan aquifer, which lie at considerable depth. The hydrologic character of these deeper parts of the aquifer system is therefore known from only a few scattered deep wells, most of which were constructed to test their potential for waste injection. Because all the numerous oil test wells in the study area completely penetrate both the Floridan aquifer system and its lower confining unit, however, the geologic character of the aquifer system's deep zones is better defined. Accordingly, the hydraulic properties of the deeper parts of the aquifer system are inferred in large part from their geologic character. The major high- and low-permeability zones within the aquifer system that are of regional extent are discussed in order from shallowest to deepest.

UPPER FLORIDAN AQUIFER

The configuration and character of the top of the Upper Floridan aquifer are discussed in the section describing the top of the system. The time-stratigraphic units that compose the Upper Floridan aquifer at various places are shown in figure 9. Hydraulic head and water-quality data show that, where the Upper and Lower Floridan aquifers are in contact (that is, where there is no appreciable thickness of low-permeability rock between them), they behave as a single hydraulic unit. Where the aquifer system's middle confining unit is absent, the base of the Upper Floridan aquifer is actually the base of the entire aquifer system, and, likewise, the thickness of the Upper Floridan aquifer equals the thickness of the entire system.

The Upper Floridan aquifer generally consists of all or part of rocks of Oligocene age (mostly the Suwannee Limestone), rocks of late Eocene age (mostly the Ocala Limestone), and rocks of middle Eocene age (mostly the upper part of the middle Eocene). Locally, (for example, near Gainesville, Fla. column 13, fig. 9), all rocks of middle Eocene age, rocks of early Eocene age (mostly the Oldsmar Formation), and the upper part of strata of Paleocene age (mostly the Cedar Keys Formation) are included in the Upper Floridan aquifer in those places where the aquifer system's middle confining unit is not present. At a few locations (for example, column 16, fig. 9), rocks of early Miocene age (Tampa Limestone and equivalents) are permeable enough to be considered part of the Upper Floridan aquifer. Data collected during this study show that the permeability of the rocks included in the Upper Floridan aquifer is much higher than that of those comprising the Lower Floridan aquifer, with the exception of southern Florida's Boulder Zone, a zone of cavernous permeability encompassed within the Lower Floridan.

The thickness of the Upper Floridan aquifer as shown on plate 28 (modified from a map by Miller (1982d)) represents all strata that lie between the top of the highest vertically continuous permeable limestone (top of the Floridan aquifer system) and the base of either the Upper Floridan aquifer, where a regionally extensive middle confining unit exists, or the base of the entire aquifer system, where no appreciable thickness of low-permeability rock is present. This single aquifer condition (no separation of the aquifer system into upper and lower major permeable zones) exists in the patterned area shown on plate 28. The thickness values contoured on plate 28 were obtained primarily from well data, but, in areas of sparse control, the contouring has been supplemented by estimates obtained by subtracting contoured elevations of the top of the aquifer system (pl. 26) and the base of the Upper Floridan aquifer (pl. 29).

It is important to reiterate that the Upper Floridan aquifer, like the other major high- and low-permeability zones within the Floridan aquifer system, is delineated on the basis of permeability characteristics. Thus, neither the top nor the base of the Upper Floridan necessarily conforms to formation or time-stratigraphic boundaries. This situation is particularly true of the base of the Upper Floridan (fig. 9). The lithologic character of the rocks comprising the base of the Upper Floridan varies greatly, and accordingly, the rocks vary in their effectiveness as a confining unit. The vertical hydraulic conductivity of the rocks that comprise the base of the Upper Floridan, however, is everywhere at least two orders of magnitude less than that of the aquifer material itself. Because plate 28 represents the thickness of rocks of similar (high) permeability, interpretation of the map is different from that of the usual isopachous map. For example, thick sequences of rocks shown on plate 28 do not necessarily lie in downbasin positions, the situation commonly encountered on an ordinary thickness map. Rather, because sediments ordinarily become finer grained and correspondingly less permeable in a downbasin direction, greater thicknesses of permeable rock may occur in updip areas.

The altitude of the low-permeability rocks that mark the base of the Upper Floridan aquifer is the major factor affecting the thickness values shown on plate 28. Where the base occurs at shallow depths, the Upper Floridan is thin; where the base is deep, the aquifer is thick. The lines of equal thickness are irregular and, where they are closed, delineate numerous small, isolated thick or thin spots in places where the Upper Floridan as a whole is less than 400 ft thick. These small features are the result of erosion and (or) karst topography developed on the aquifer system's surface.

Plate 28 shows that the Upper Floridan aquifer is thin (1) in and near those places where the aquifer system crops out, (2) throughout roughly the western half of panhandle Florida, and (3) in a wide band parallel to the Atlantic coastline. Near the outcrop area, the limestone that comprises the aquifer thins and grades into clastic rocks in an updip direction. The two other widespread thin areas represent places where the aquifer system's middle confining unit (base of the Upper Floridan aquifer) lies at shallow depths. The greatest thickness of the Upper Floridan is along the north-central part of Florida's Gulf Coast and is part of the area where all of the rocks included in the aquifer system are permeable (the Upper and Lower Floridan aquifers merge). Areas of intermediate thickness adjacent to peninsular Florida's Gulf Coast and straddling the central part of the Florida-Georgia border reflect different altitudes of the aquifer system's middle confining unit.

In some places, the Floridan aquifer system contains two or more regionally extensive middle confining units, which lie at different depths and are separated by permeable rocks. An example of this situation occurs in the central part of peninsular Florida and is shown on plate 28; dashed contact lines show places where a deeper low-permeability zone is overlain by a shallower overlapping confining unit. Here, a band of low-permeability rock parallel to the Atlantic Ocean lies at an altitude several hundred feet higher than that of a western low-permeability zone that extends to the Gulf of Mexico. Where such an overlap occurs. the top of the shallower low-permeability unit is considered to be the base of the Upper Floridan aquifer. Geohydrologic cross section G-G' (pl. 23) shows this overlap in the third dimension. Farther north, the same two confining units are present (cross section F-F', pl. 22) but do not overlap.

Several major structural features are known to exist in the mapped area, but not all of them appear on plate 28. The area in Gilchrist and Lafayette Counties in northern Florida where the Upper Floridan aquifer is thin may represent the Peninsular arch. The thick area in southern Wakulla County, Fla., is probably part of the Southwest Georgia embayment. Aside from these two examples, no other major structures appear to coincide with variations in the Upper Floridan's thickness. Several small faults reflected by local anomalies in regional thickening trends of the Upper Floridan include the Gulf Trough graben system in central Georgia and a small-displacement normal fault in southern peninsular Florida. The faults shown in southwestern Alabama cut, displace, and in part mark the updip limit of the Upper Floridan aquifer.

Preliminary results from a digital model of the aquifer system (Bush, 1982) show that most of the ground-water circulation in the system takes place in the Upper Floridan aquifer. The water in the Upper Floridan is nearly everywhere less mineralized than that from deeper zones in the aquifer system (Sprinkle, 1985), largely because of more vigorous circulation of water in the Upper Floridan. The high permeability that permits this vigorous circulation results from high intergranular or moldic porosity in the Suwannee, Ocala, and Avon Park rocks comprising the Upper Floridan, coupled with much secondary porosity (mostly large dissolution cavities).

MIDDLE CONFINING UNIT

There are eight low-permeability units of subregional extent that lie within the Floridan aquifer system in the study area. Seven of these units separate the Upper Floridan aquifer from the Lower Floridan aquifer. The remaining unit lies within the Lower Floridan aquifer and is discussed in the following section describing that aquifer. Any or all of the subregional low-permeability units may locally contain thin zones of moderate to high permeability. Overall, however, the units act as a single confining unit within the main body of permeable limestone that constitutes the aquifer system. In much of southern Florida, several thick low-permeability units occur within the aquifer system—so many, in fact, that in places the strata that constitute the system are mostly low-permeability rocks containing a few high-permeability zones (see, for example, sections B'-B″ and H-H', pls. 17, 24). These zones show hydraulic head differences, contain water of somewhat different quality, and behave differently in response to natural and pumping (or injection) stresses. In places where two or more of the subregional low-permeability units occur, the base of the shallower low-permeability unit is considered to be the top of the Lower Floridan aquifer.

The areal extent and altitude of the top of each of the seven confining units separating the Upper and Lower Floridan aquifers are shown on plate 29, which was modified from a map by Miller (1982b). Because, by definition, the middle confining unit of the aquifer separates the Upper and Lower Floridan aquifers, the contours shown represent the base of the Upper Floridan aquifer, which varies greatly in altitude from place to place. For convenience and because the confining units are not necessarily a part of the same formation and do not consist of the same rock type everywhere, each confining unit has been designated by a roman numeral on plate 29. Each unit will be referred to by its particular numeral in the text of this report, on a fence diagram (pl. 30) that shows the three-dimensional relations of the various high- and low-permeability units within the aquifer, and in figure 9, which shows the relative ages of each unit. Because none of the low-permeability units mapped on plate 29 crop out, the extent and character of the units have been determined solely on the basis of well control.

Where no middle confining unit is present, the Upper and Lower Floridan aquifers merge vertically and are mapped as part of the Upper Floridan aquifer. In such places, because no low-permeability rocks exist above the base of the aquifer system, that base is synonomous with the bottom of the Upper Floridan aquifer. The white area on plate 29 shows this condition. The contours shown in this area are thus the same as those shown on a map of the base of the aquifer system (pl. 33). Over the northern two-thirds of this area, the base of the Upper Floridan aquifer is marked by calcareous glauconitic sand and clay beds that are the equivalents of the outcropping middle Eocene Lisbon and Tallahatta Formations of Alabama and western Georgia. Farther southeast, the base of the Upper Floridan consists of calcareous clastic rocks that are the equivalent of the lower Eocene Oldsmar Formation of Florida; in north-central Florida, anhydrite beds that are part of the Cedar Keys Formation underlie the Upper Floridan aquifer. The extent of each unit is shown on plate 33, and the units are discussed in more detail in the section of this report that describes the base of the aquifer system. In much of South Carolina (Colleton County and northward), the Upper Floridan aquifer pinches out, and the middle confining unit merges with the upper confining unit of the aquifer system. Accordingly, no middle confining unit is mapped north of the pinchout of the Upper Floridan.

Along the Atlantic Coast, an extensive band of low-permeability rocks (middle confining unit I, pl. 29) extending from southeastern South Carolina to the Florida Keys marks the base of the Upper Floridan aquifer. The strata that comprise unit I lie in the middle and upper parts of rocks of middle Eocene age (fig. 9). Very locally (for example, in the Jacksonville, Fla., area), the lower part of rocks of late Eocene age is included in unit I. From the Florida Keys northward to Liberty County, Ga., unit I consists of soft, micritic limestone and fine-grained dolomitic limestone, both of low porosity. North of Liberty County, these carbonate rocks grade laterally by facies change through calcareous sand and clay in northeastern Georgia northward into sandy clay in South Carolina. Figure 11 shows the approximate areal extent of the clastic and carbonate facies and the general configuration of the top of unit I throughout its known extent. Because the Upper Floridan aquifer pinches out in South Carolina, unit I merges with the aquifer system's upper confining unit north of this pinchout (fig. 12); the only permeable limestone in the extreme northeastern part of the mapped area is a thin bed that is part of the Lower Floridan aquifer. The contrast in permeability between the rocks of unit I and the permeable rocks above and below it is less than that for any other middle confining unit mapped. Accordingly, unit I is the leakiest confining unit known in the study area. The lithology of unit I is not much different from that of the permeable zones vertically adjacent to it, and the unit's original porosity has not been greatly affected by pore-filling secondary mineralization. There are minor variations in hydraulic head (Lichtler and others, 1968; Snell and Anderson, 1970) and water quality across unit I; these variations, together with flowmeter data (see, for example, Leve, 1970) from scattered wells, show that the unit acts as a confining bed. Unit I separates the Upper and Lower Floridan aquifers everywhere in east-central Florida, the area discussed by Tibbals (1985), and throughout roughly half of the contiguous area to the north that is discussed by Krause and Randolph (1985). In a narrow northwest-trending band in central peninsular Florida (pl. 29), unit I overlaps gypsiferous dolomite that comprises middle confining unit II, described below, and is separated from unit II by a few hundred feet of permeable rock (see cross section G-G', pl. 23). The areal extent of the overlap shown by the dashed contact line on plate 29 is approximate because it is based on well control.

In west-central peninsular Florida, the middle confining unit of the aquifer system consists of low-permeability gypsiferous dolomite and dolomitic limestone. This unit, labeled unit II on plate 29, occurs approximately in the middle of rocks of middle Eocene age. As mentioned earlier, unit II is overlapped by unit I in part of central Florida. The altitude of unit II throughout its known extent, including this area of overlap, is shown in figure 13. The gypsum that is responsible for the low permeability of unit II is largely intergranular and appears to fill preexisting pore spaces in the rock. Lenses, stringers, pods, and thin beds of gypsum are also present, however. The gypsiferous dolomite probably represents an extensive middle Eocene sabkha or tidal flat environment, although some of the intergranular gypsum may have been emplaced by gypsum-rich interstitial waters. Hydraulic data (Guyton and Associates, 1976) show that unit II forms an essentially nonleaky confining bed. Data from oil and deep injection test wells show that permeable rock everywhere underlies unit II. The highly mineralized water contained in this rock, which is part of the Lower Floridan aquifer, suggests poor interconnection with the freshwater of the overlying Upper Floridan. Figure 14 shows the thickness of unit II. Anamolously thick areas, such as those shown in Polk County, Fla., are thought to have been caused by incomplete dissolution of gypsum and anhydrite in places where the deep flow system is very sluggish. Thinner areas represent places where more vigorously circulating waters have dissolved much of unit II's

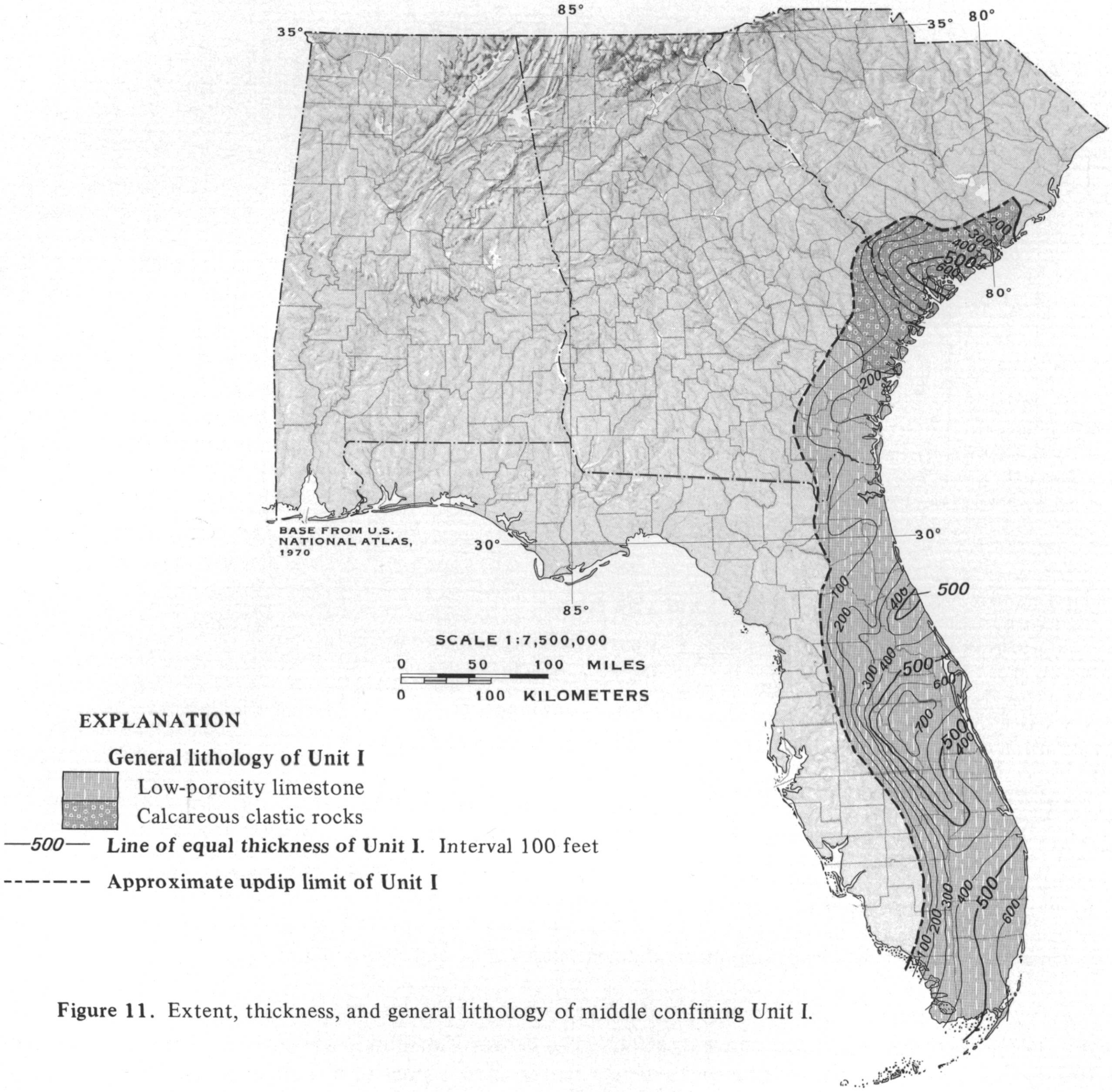


Figure 11. Extent, thickness, and general lithology of middle confining Unit I.

interstitial evaporitic material and thereby increased porosity and permeability. Unit II is treated as the base of the aquifer system in the subregional ground-water flow model discussed in by Ryder (1985) because (1) the unit is present throughout practically the entire area covered by the subregional model, (2) the unit has an extremely low permeability, and (3) the Lower Floridan aquifer below unit II is of relatively low permeability and contains poor-quality water. For the regional simulation described by Bush and Johnston (1985), however, the Lower Floridan aquifer that lies below unit II is treated as a high-permeability zone and is included as part of the ground-water flow system in west-central Florida, as it is elsewhere.

Along the central part of the Georgia-Florida border, the aquifer system's middle confining unit (unit III, pl. 29) consists of low-permeability, dense, fossiliferous, gypsiferous, dolomitic limestone that occurs in the lower or middle parts of rocks of middle Eocene age. The gypsum, like that found in unit II, is mostly intergranular, although it occurs rarely as layers and lenses within the limestone. Although small amounts of water can be obtained from unit III, the water is of poor quality owing to high sulfate concentrations that result from dissolution of the gypsum (see Sprinkle's (1985) map of sulfate concentration.) Concentrations of sulfate as high as 2,600 mg/L have been reported in ground water from unit II in Valdosta, Ga. (Krause,

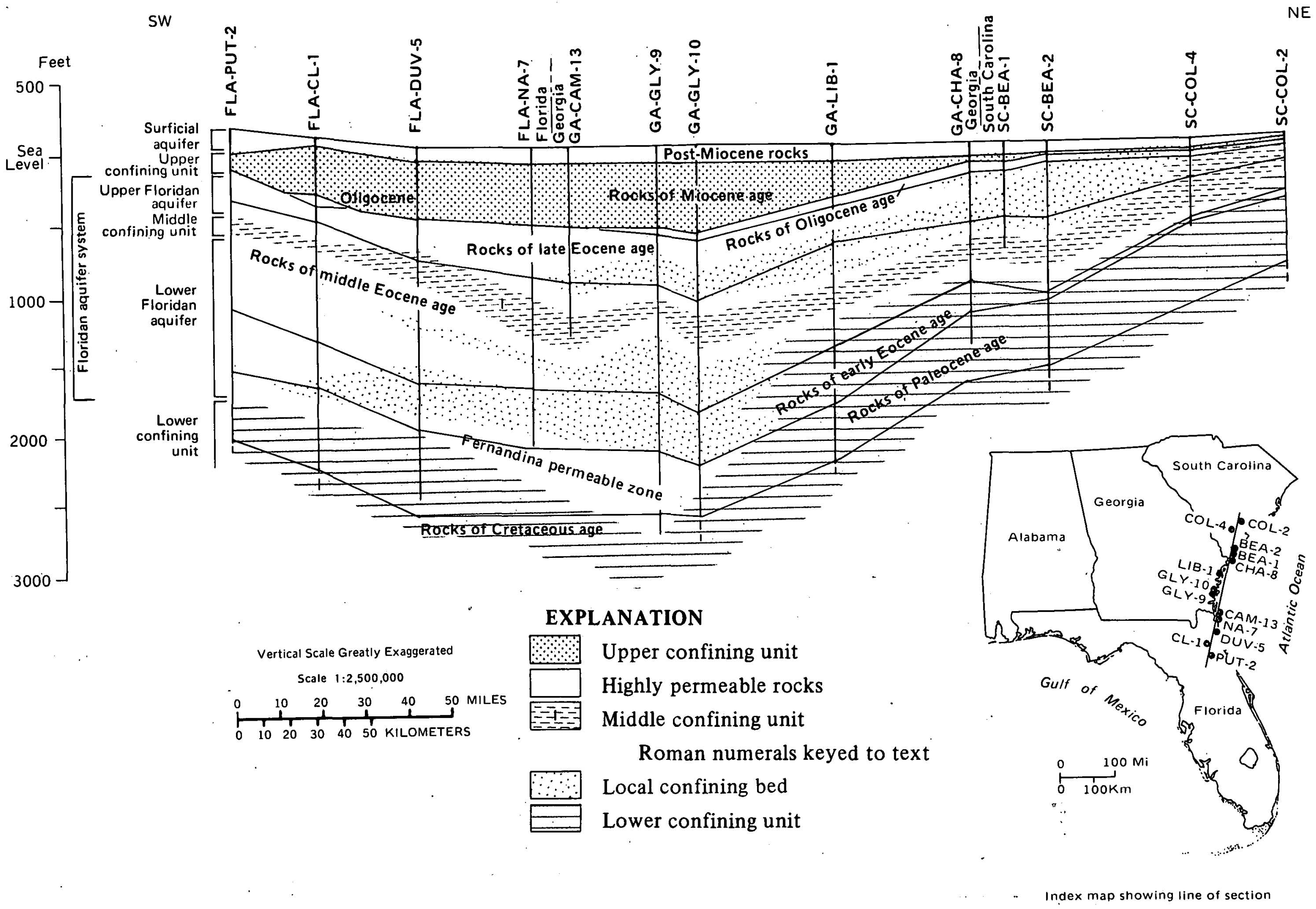


Figure 12. Generalized geohydrologic cross section from Putnam County, Fla. to Colleton County, S.C.

1979). Meyer (1962) recorded a sulfate concentration of about 1,100 mg/L in water from the same rocks near Lake City, Fla. Unit III is considered to be a slightly leaky confining bed. The extent and thickness of unit III are shown in figure 15. Where the thickness values shown in this figure exceed 200 ft, there are no permeable rocks below unit III; the gypsiferous rocks of the unit grade downward, without a break, into low-permeability clastic rocks that are part of the aquifer system's lower confining unit. This gradation is shown in cross section in figure 16. Elsewhere, especially near the edges of unit III, the gypsiferous limestone is underlain by permeable strata that are part of the Lower Floridan aquifer. No hydraulic or water-quality data exist for the Lower Floridan beneath unit III. Because the rock and permeability framework of the area underlain by unit III are similar to those underlain by unit II, the Lower Floridan aquifer under both areas is assumed to be similar: that is, under unit III the Lower Floridan is assumed to contain poor-quality water that is part of a slow-moving flow system. The subregional model that encompasses part of unit III (Krause and Randolph, 1985) does not consider the Lower Floridan aquifer under unit III to be a part of the ground-water flow system, for the same reasons that the Lower Floridan is excluded from the subregional model of Ryder (1985). In the regional simulation, however, the Lower Floridan, where it exists under unit III, is included as part of the flow system.

The rocks designated as middle confining unit IV (pl. 29) are deep-lying calcareous sand and clay, which in part grade northwestward into clastic rocks that are equivalents of the middle Eocene Lisbon and Tallahatta Formations, and the upper part of rocks of early Eocene age. Where unit IV is mapped, the Lower Floridan aquifer is present beneath the unit. Updip, the aquifer system consists of only one permeable zone that is treated as the Upper Floridan aquifer. Unit IV

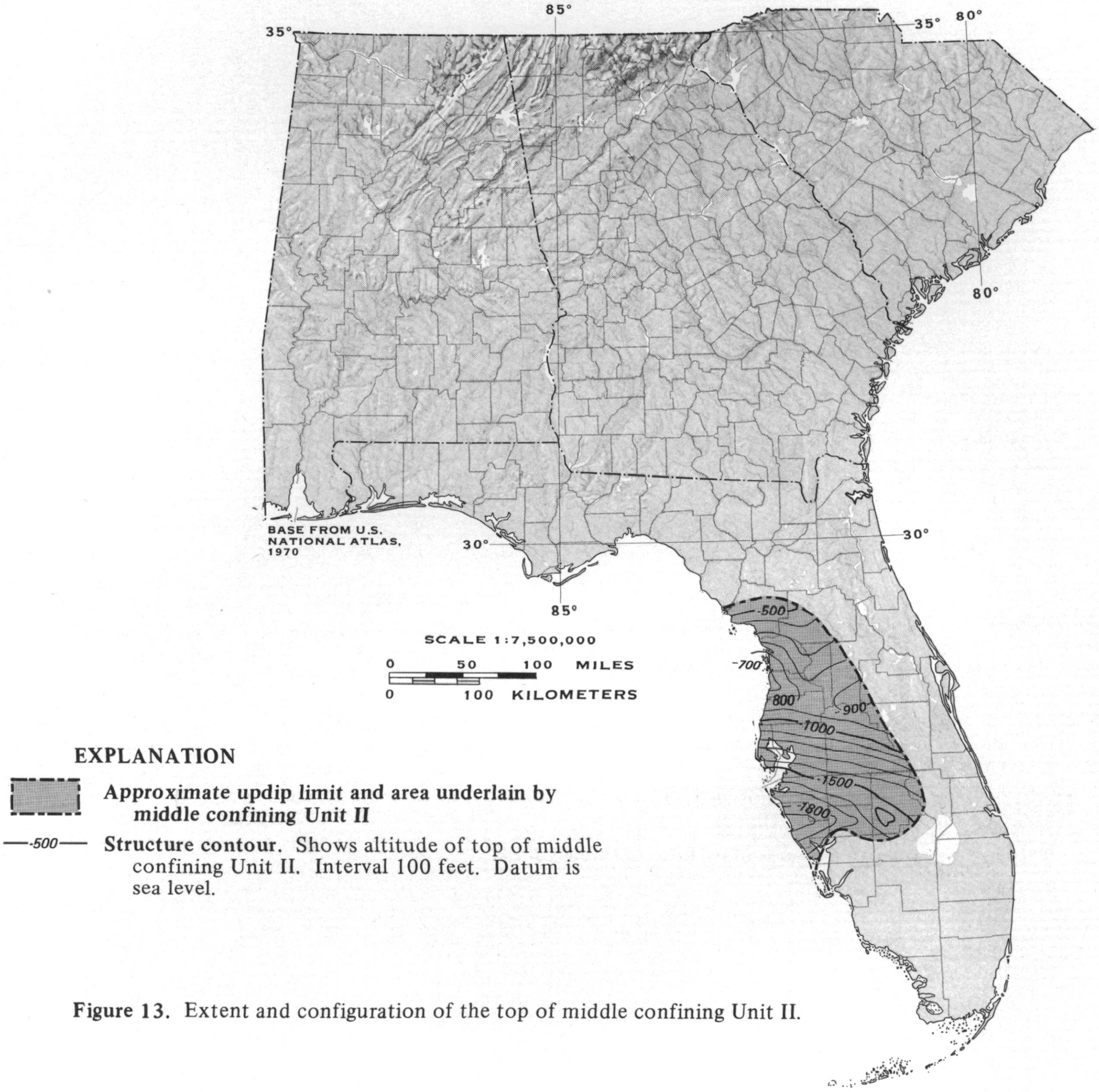


Figure 13. Extent and configuration of the top of middle confining Unit II.

represents a tongue of low-permeability rock extending into the aquifer system's permeable limestone, and locally dividing it into two discrete zones (cross section A-A, pl. 15). As figure 17 shows, the areal extent of unit IV is limited to a few counties in eastern panhandle Florida. There are no hydraulic head data available from which to determine the effectiveness of unit IV as a confining unit. The unit's lithologic character indicates that it is a relatively leaky confining unit whose ability to transmit water vertically is probably exceeded only by that of unit I. The Upper Floridan aquifer is very thick in the area underlain by unit IV (pl. 28). In fact, the greatest measured thickness of the Upper Floridan is from well FLA-GF-8, located in Gulf County, Fla., in this area. The maximum projected thickness of the Upper Floridan, however, is in southwestern Florida in the area underlain by middle confining unit VI.

The Floridan aquifer system is youngest in Florida's western panhandle (fig. 9) and in contiguous parts of southern Alabama. Here, the rocks that make up the Upper Floridan aquifer are mostly Oligocene (Chickasawhay Formation) in age and in places include lower Miocene strata (Tampa Limestone). The middle confining unit in this part of the study area, in contrast with the other units mapped on plate 29, corresponds to a single geologic unit—the Bucatunna Formation of Oligocene age. The Bucatunna Formation, mapped as unit V on plate 29, is a massive, dark gray, calcareous soft clay that contains up to 40 percent sand as dis-

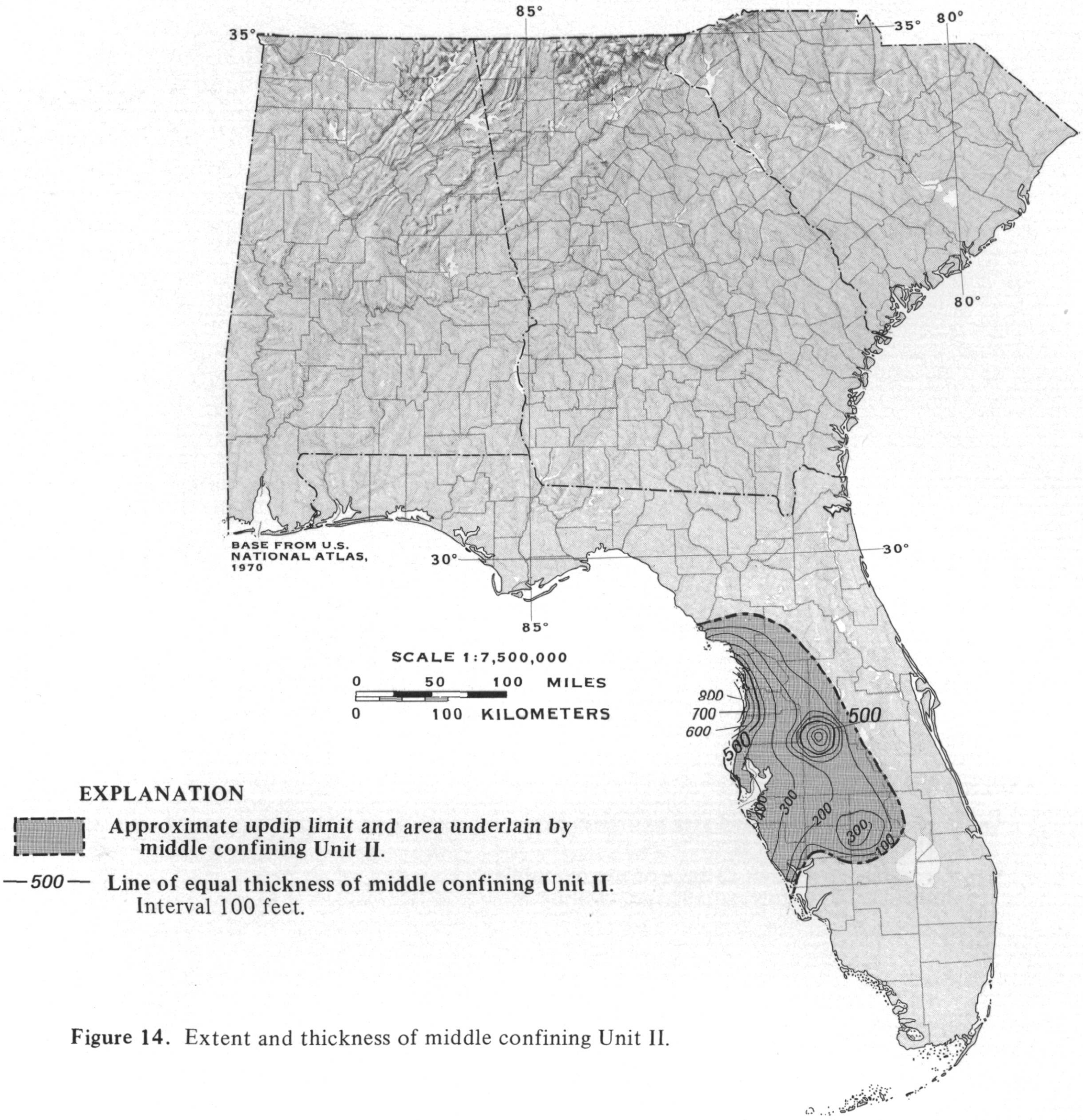


Figure 14. Extent and thickness of middle confining Unit II.

seminated grains and, near its northern and eastern pinchouts, as discrete beds. The thickness of the Bucatunna (fig. 18) is more uniform than that of most of the other middle confining units. The Bucatunna Formation can be readily identified on electric logs because of its extremely low resistivity, and it has been mapped primarily on the basis of this distinctive log pattern. The Lower Floridan aquifer underlies the Bucatunna (unit V) everywhere. Unit V is a virtually nonleaky confining unit. Hydraulic head data from southern Okaloosa County, Fla. (L. R. Hayes, personal commun., 1982), show that the Bucatunna Formation effectively isolates the Upper and Lower Floridan aquifers there. The faults shown in western Alabama on plate 29 disrupt the lateral continuity of unit V in the same manner that they affect the aquifer system's permeable zones—downdropping the grabens bounded by the faults has juxtaposed rocks of contrasting permeability.

The rocks that form the base of the Upper Floridan aquifer in southwestern peninsular Florida (middle confining unit VI, pl. 29) are a sequence of interbedded finely to coarsely crystalline dolomite and finely pelletal, micritic limestone that is commonly argillaceous. The extent of unit VI is shown in figure 19. Over approximately the western half of the area underlain by unit VI, much of the intergranular pore space in the rocks assigned to the unit is filled with gypsum, which also occurs rarely as thin beds and coarse pods. The thickness of unit VI is shown in figure 20. Unit VI is

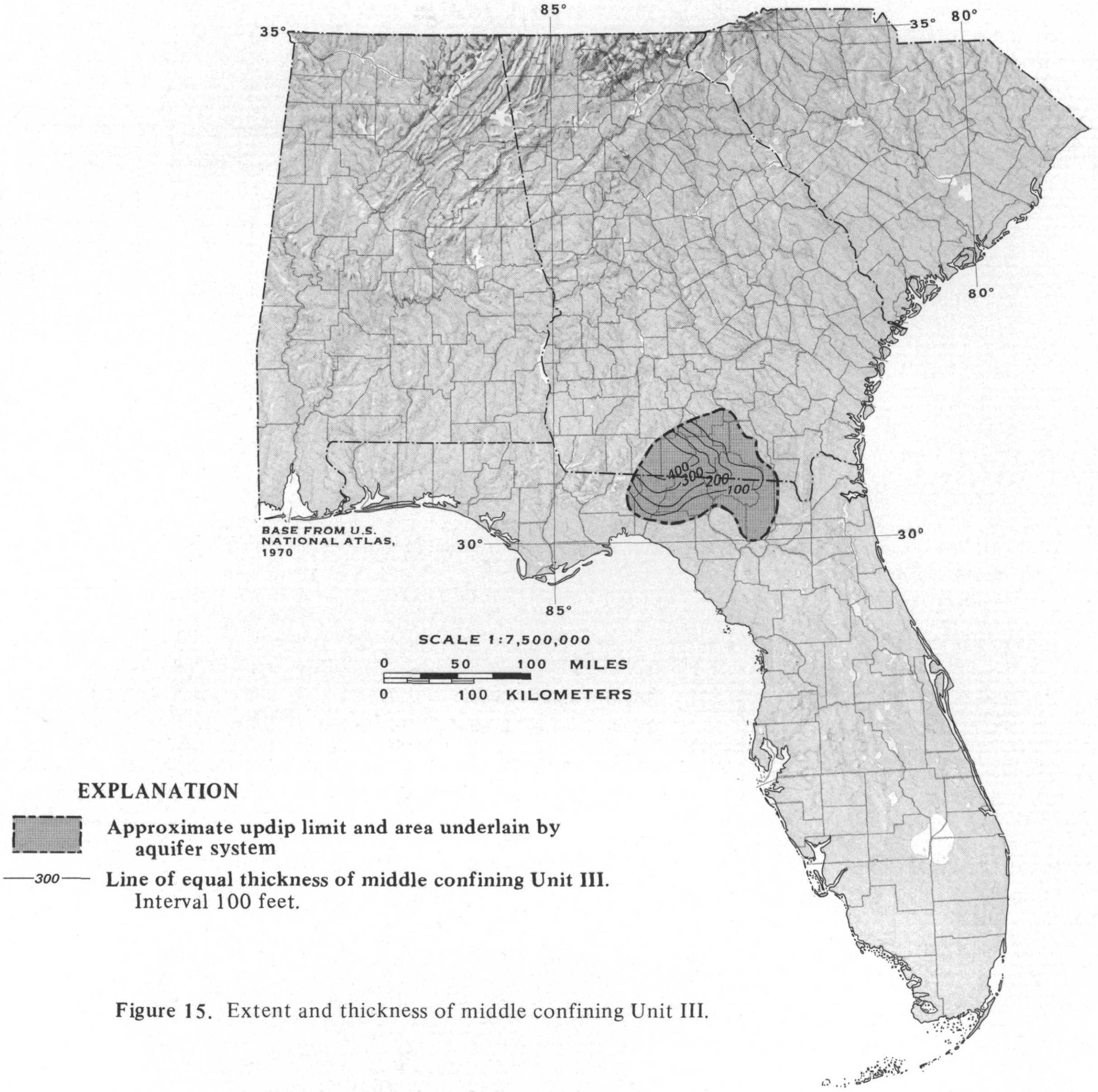


Figure 15. Extent and thickness of middle confining Unit III.

usually found in the lower part of rocks of middle Eocene age, but in places it extends downward to include the upper part of rocks of early Eocene age (see figs. 9, 21). In northern Charlotte County and southern DeSoto and Highlands Counties, Fla., unit VI extends under middle confining unit II, as the dashed contact line on plate 29 shows . Southward, in Dade County and most of Monroe County, Fla., and eastward, in Broward County and part of Palm Beach County, Fla., unit VI is overlapped by unit I (see pl. 29). In both areas, unit VI is separated from the shallower low-permeability unit by a thin to moderately thick sequence of permeable rock. Because of sparse well control, the extent of the overlap shown on plate 29 is approximate. In those places where no shallower confining units overlap unit VI, the Upper Floridan aquifer is considerably thicker than it is where overlap occurs. No hydraulic head data are available across middle confining unit VI, but the unit is considered to be an effective confining bed because of its lithologic character.

A narrow northeast-trending strip of low-permeability rocks in west-central Georgia (middle confining unit VII, pl. 29) marks the base of the Upper Floridan aquifer there. Unit VII partly borders on and in places is gradational into unit III (fig. 16). The rocks that constitute unit VII are micritic to finely crystalline limestone that is often partially dolomitized and contains lenses, pods, beds, and intergranular pore fillings of gypsum. Figure 22 shows the extent and thickness

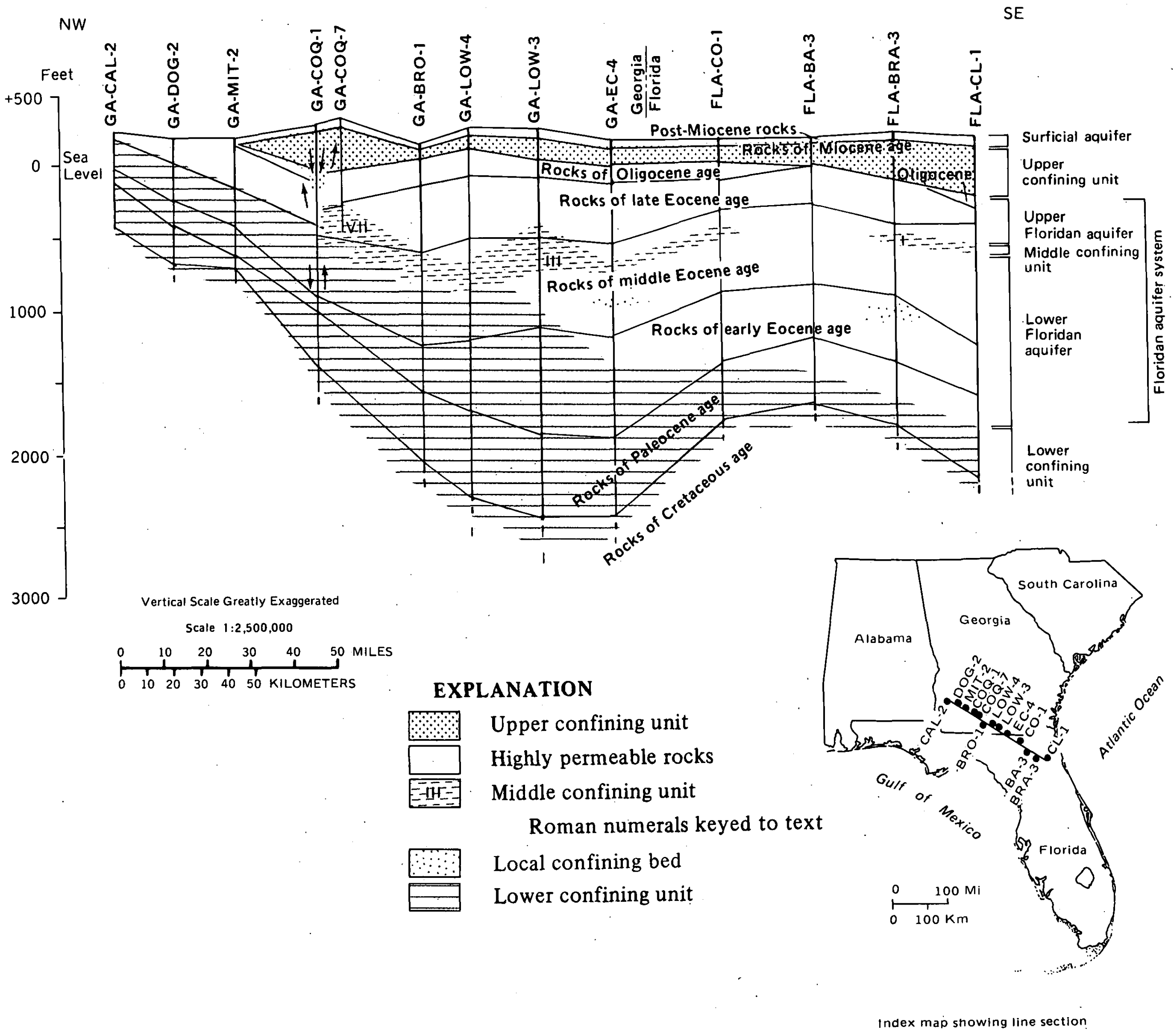


Figure 16. Generalized geohydrologic cross section from Calhoun County, Ga. to Clay County, Fla.

of unit VII. Near its southwestern border, the unit lies in the upper part of rocks of middle Eocene age; in its central part, it is composed of rocks of middle and late Eocene age; toward its northeastern limit, it is restricted to rocks of late Eocene age. Over the southern two-thirds of its extent, middle confining unit VII grades vertically downward into calcareous, glauconitic clastic rocks that are part of the Floridan aquifer system's lower confining unit. In this area, the Lower Floridan aquifer is absent. Farther northward, as the low-permeability rocks of unit VII thin and become younger, the unit is underlain by permeable limestone that is part of the Lower Floridan. The extent of the Lower Floridan aquifer under unit VII is only approximately known because of sparse well control. Unit VII is contiguous with, and just southeast of the Gulf Trough graben system. This author suggests that unit VII exists because it is adjacent to this structural feature. Juxtaposition of low-permeability rocks in the grabens opposite permeable limestone to the northwest (fig. 16) creates a damming effect on groundwater flow through the Floridan aquifer system, as described earlier. The restricted flow downgradient of the Gulf Trough (to the southeast) was not sufficient to dissolve the gypsum from the rocks of unit VII. To the northeast and southwest of the mapped extent of unit VII, either the faults that bound the Gulf Trough are discontinuous or the throw on them is not great. In

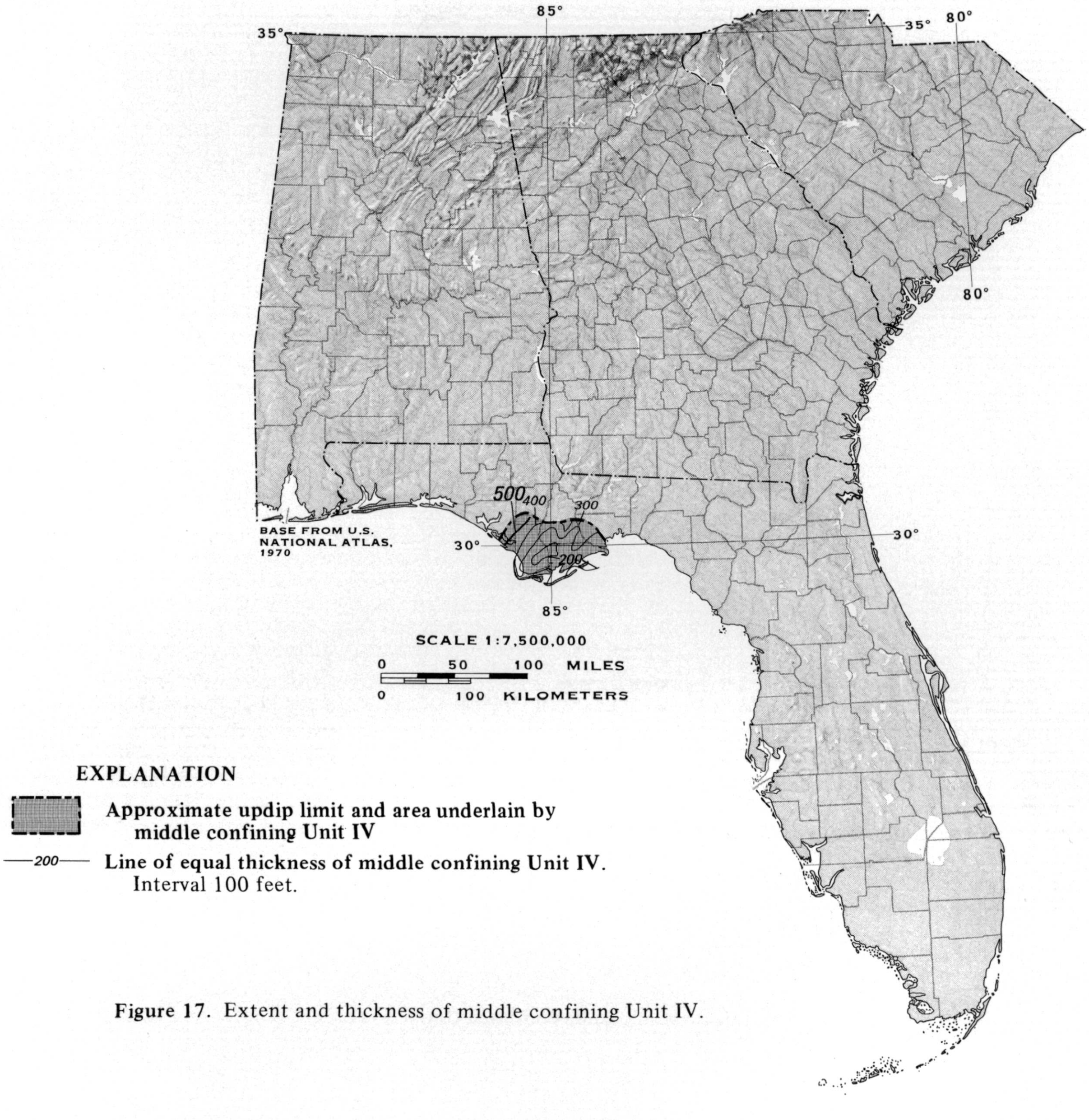


Figure 17. Extent and thickness of middle confining Unit IV.

these places, the rocks equivalent to unit VII are not gypsiferous, possibly because a more vigorous flow system has removed the gypsum by dissolution. On the basis of its lithology, unit VII is thought to be an effective confining unit, but hydraulic head data to quantify its effectiveness are lacking.

Lower Floridan Aquifer

All beds in the Floridan aquifer system that lie below the base of one of the middle confining units and above the base of the aquifer system are included in the Lower Floridan aquifer. Because it is deeply buried and in many places contains poor-quality water, the Lower Floridan has not been intensively drilled or tested, and its hydraulic character is therefore not well known. Scattered hydraulic data show large to small head differences between the Upper and Lower Floridan aquifers. The magnitude of these differences is directly related to the character of the middle confining unit that separates the aquifers; greater differences are found where the confining unit is virtually nonleaky. Ground-water flow in the Lower Floridan aquifer is sluggish except in those places where it is directly connected to the Upper Floridan aquifer. In the regional model discussed by Bush and Johnston (1985), active regional ground-water flow is thought to

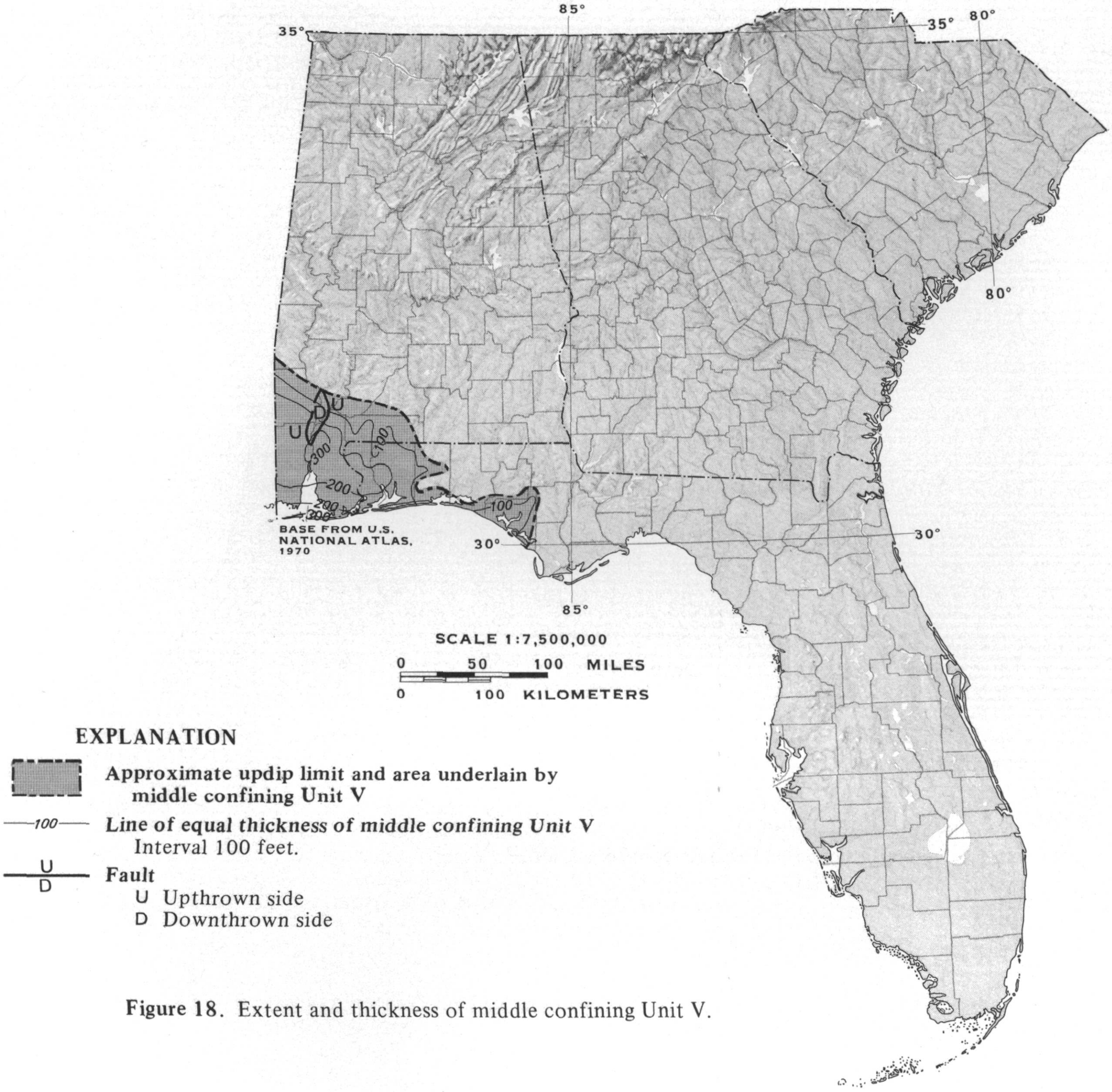


Figure 18. Extent and thickness of middle confining Unit V.

occur in the Lower Floridan aquifer. However, where the Lower Floridan lies below confining beds that are practically nonleaky, it is isolated from the Upper Floridan; and, throughout all of the area treated in the subregional model of Ryder (1985) and part of the area treated by Krause and Randolph (1985), the Lower Floridan is not considered part of the freshwater flow system.

The altitude of the top of the Lower Floridan aquifer is shown on plate 31. Because the top of the Lower Floridan is defined as the base of the highest subregional middle confining unit (units I - III) and because the stratigraphic positions, altitudes, and thicknesses of the confining units vary considerably, the contours shown on plate 31 are drawn on several different horizons. The contact lines shown on the plate mark the approximate limits of the different middle confining units. Where the confining units overlap, as they do in central and southern Florida, the base of the higher unit is contoured, and the extent of the overlap is shown by overlapping contact lines. The Lower Floridan aquifer is not mapped where no middle confining unit exists. In these places, the Lower Floridan merges with and is mapped as part of the Upper Floridan aquifer. The thickness of the Lower Floridan aquifer is mapped on plate 32.

The character of the Lower Floridan aquifer varies from simple (as it is in much of panhandle Florida, where it consists of a thin, fairly uniform sequence of upper Eocene limestone (fig. 9)), to highly complex (as

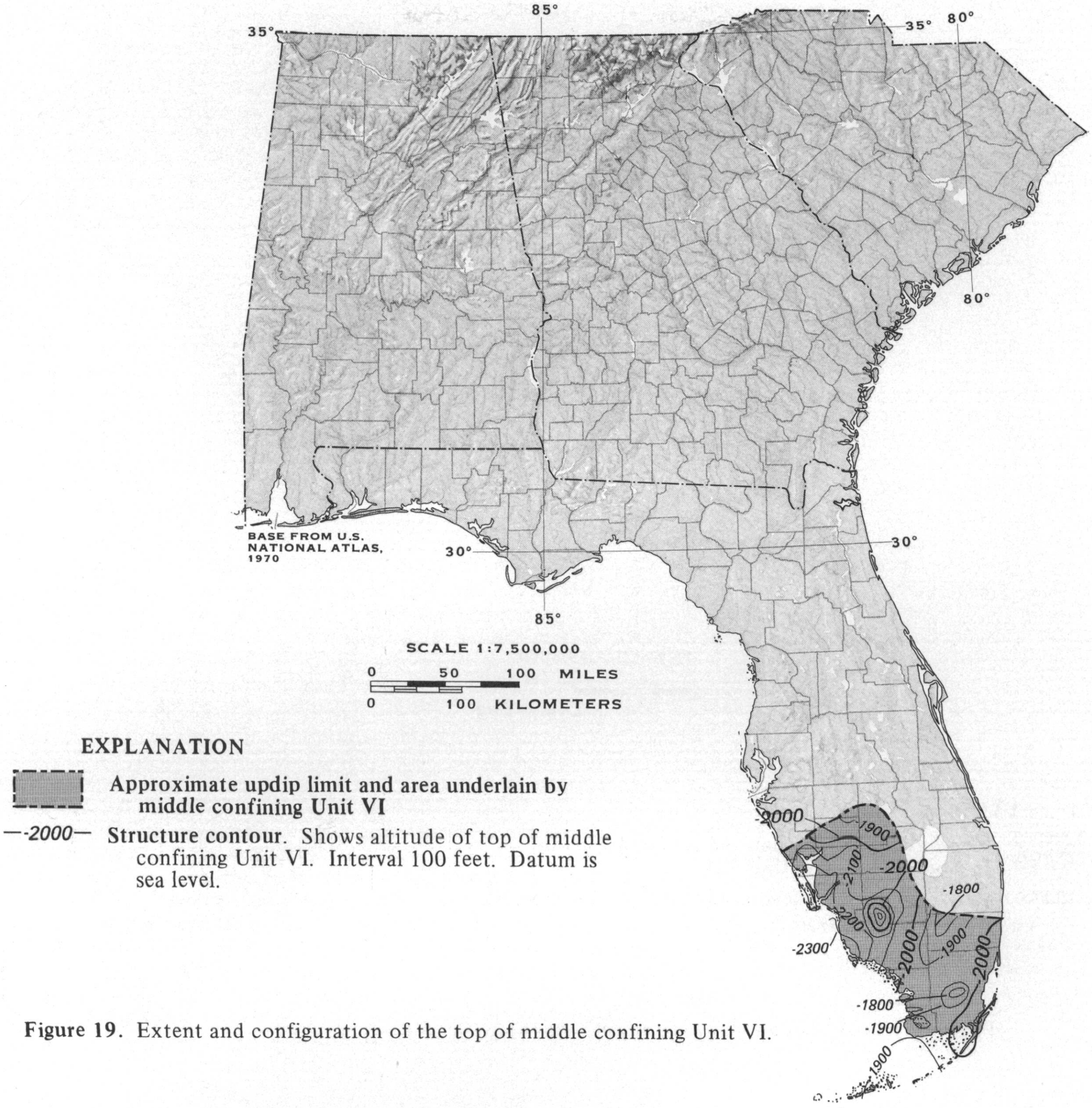


Figure 19. Extent and configuration of the top of middle confining Unit VI.

it is in southern Florida, where it consists of a thick sequence of largely low-permeability rocks separated by relatively thin permeable zones (fig. 21)). For the most part, the rocks comprising the Lower Floridan range from late Paleocene to early middle Eocene age (fig. 9); locally, however, the aquifer may include rocks as young as late Eocene or as old as Late Cretaceous. Some of the thick low- and high-permeability subzones within the Lower Floridan are of subregional extent and have been mapped as a part of this study. These subzones are of interest partly because they represent potential waste-storage receiving or confining beds (southern Florida) and partly because they are in places (for example, extreme northeastern Florida and southeastern Georgia) the source of brackish or saline water that has moved upward and contaminated shallower freshwater-bearing strata (Krause and Randolph, 1985).

A subzone of rocks exhibiting extremely high transmissivity lies deep within the Lower Floridan aquifer in southern Florida. These rocks are mostly massively bedded dolomite within which cavernous permeability is extensively developed. The cavernous and in places fractured nature of the dolomite commonly causes chunks of dolomite to be dislodged during the drilling process, and circulation of drilling fluid is usually lost because of the large-scale porosity and high permeability of the dolomite. The difficult, slow drilling of the dolomite is expressed as a rough bit action, similar to that which occurs in the drilling of boulders. This

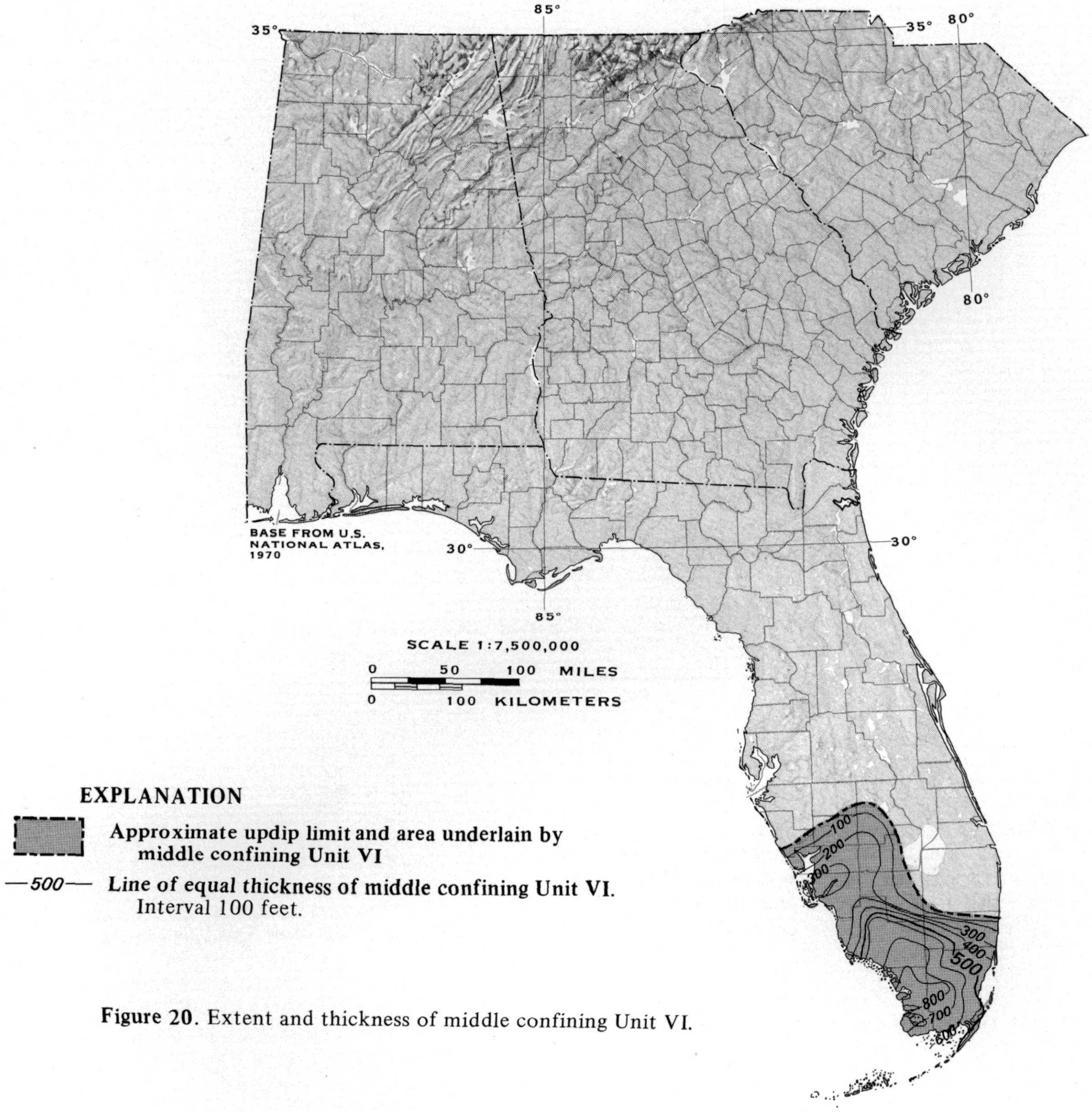


Figure 20. Extent and thickness of middle confining Unit VI.

behavior gave rise to the term "Boulder Zone," first applied to the cavernous dolomite by drillers and subsequently adopted by Kohout (1965) and later authors. The term Boulder Zone is a misnomer because no boulders are present (other than the large chunks occasionally broken off cavern roofs by the drill bit), and the cavernous dolomite is not confined to a single discrete zone. Thus, a "boulder zone" has no stratigraphic significance, because such cavernous conditions can exist at any altitude. The large solution features merely record a period when paleowater tables were at a level that permitted karstification of the upper part of the carbonate rock sequence. Once developed, the karst features can be buried at considerable depth, as they have been in southern Florida's Boulder Zone.

A "boulder zone" does not represent a single cavernous horizon developed over a wide area at the same depth or at the same stratigraphic position. Rather, such a zone represents a fairly thick horizon of large-scale solution-produced openings that are developed, like modern cave systems, primarily parallel to bedding planes at several different levels over a vertical span that may reach several hundred feet. Borehole televiewer surveys show that these levels, separated by intervals of undissolved rock, are commonly connected by vertical fractures. If these fractures are enlarged by dissolution, vertical "pipes" are developed

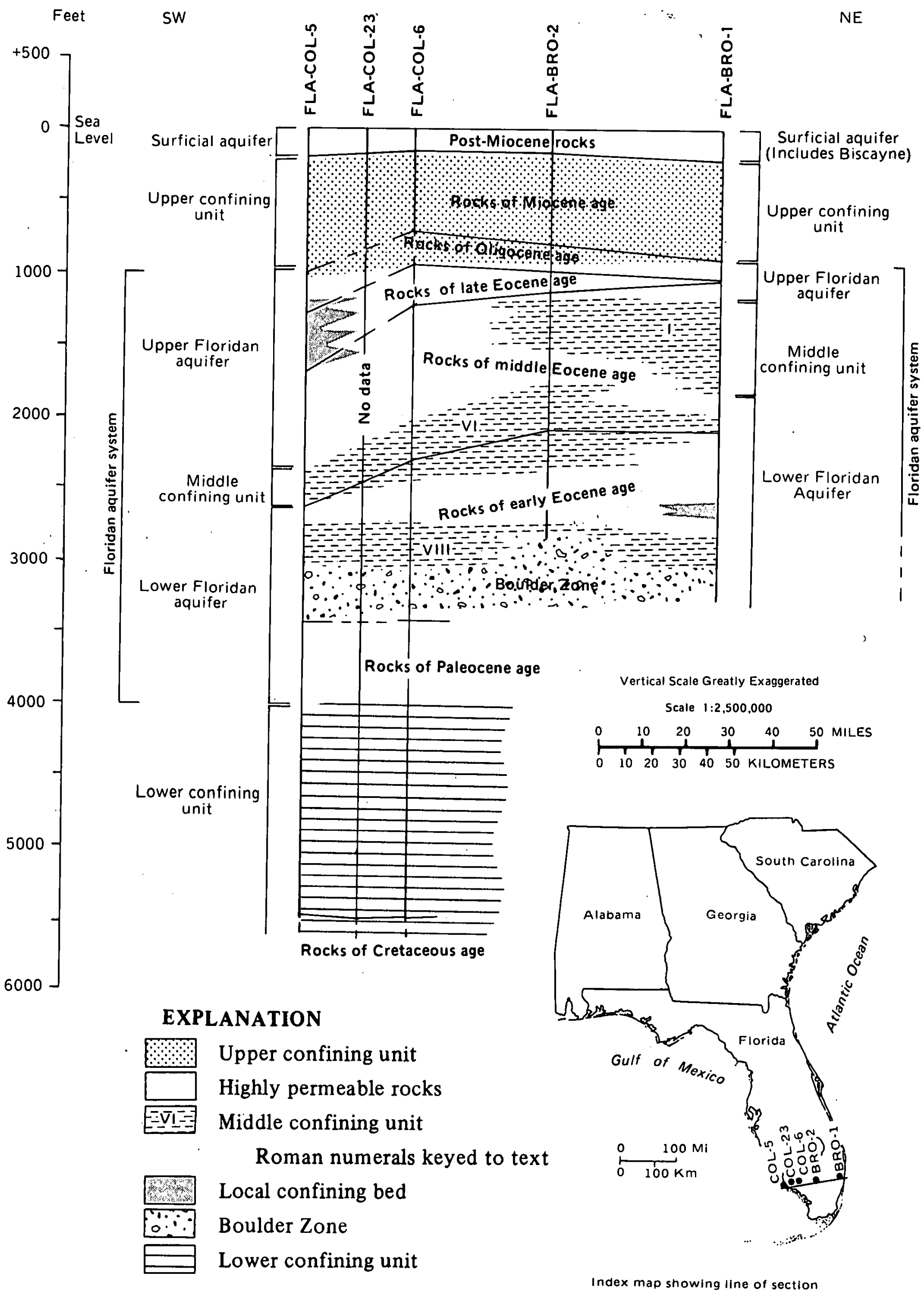


Figure 21. Generalized geohydrologic cross section from western Collier to eastern Broward Counties, Fla.

that connect the horizontal cavernous levels. The 90-ft- high "cavern" reported by Kohout (1965, p. 262) in his discussion of the Boulder Zone is thought by this author to represent such a pipe rather than a large "room" in a cavern system.

Even though a "boulder zone" is not everywhere laterally continuous and may extend vertically across stratigraphic horizons, the zone can be used hydrologically in an informal "operational unit" sense. For example, in southern Florida, one can reasonably ex-

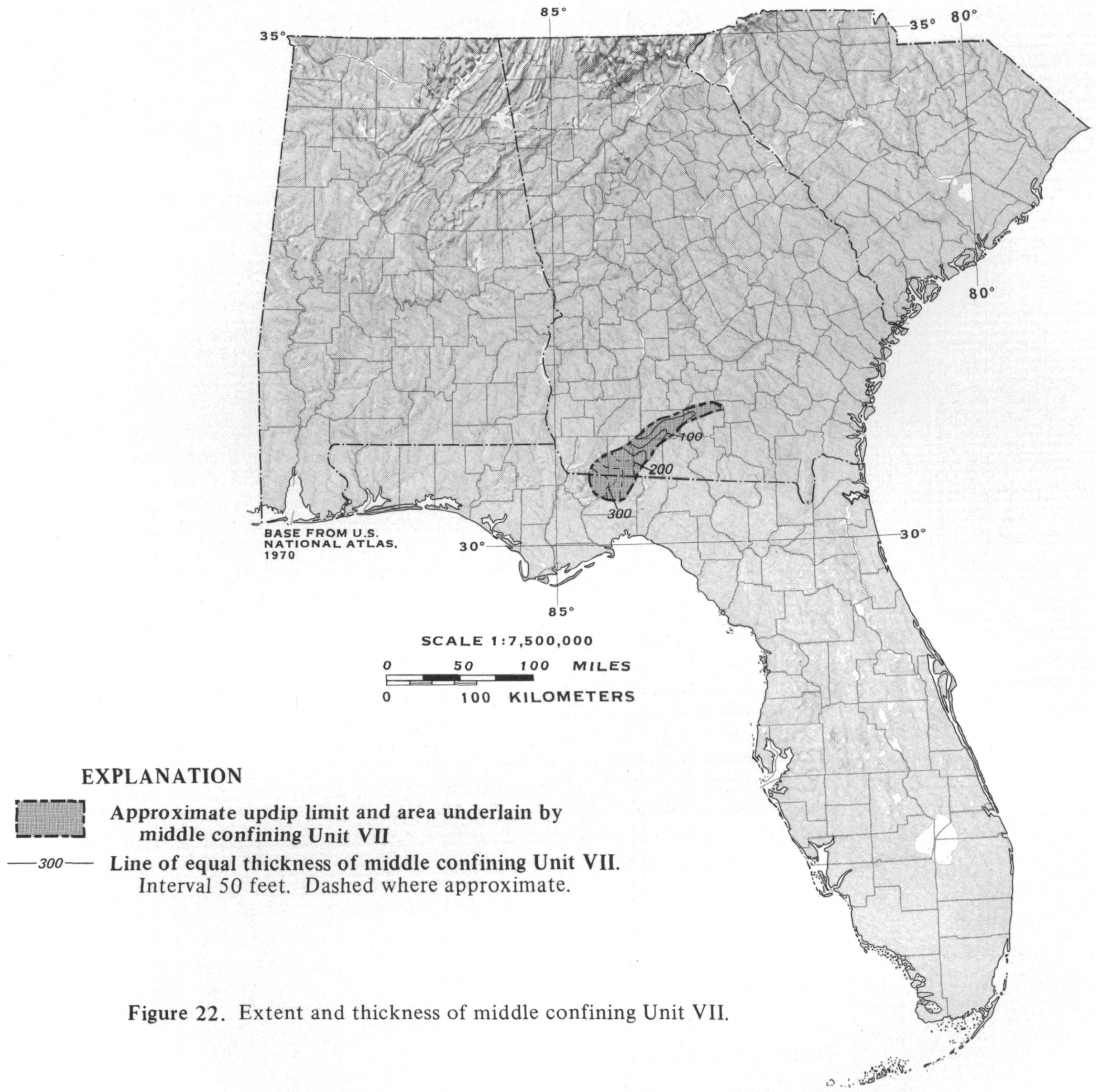
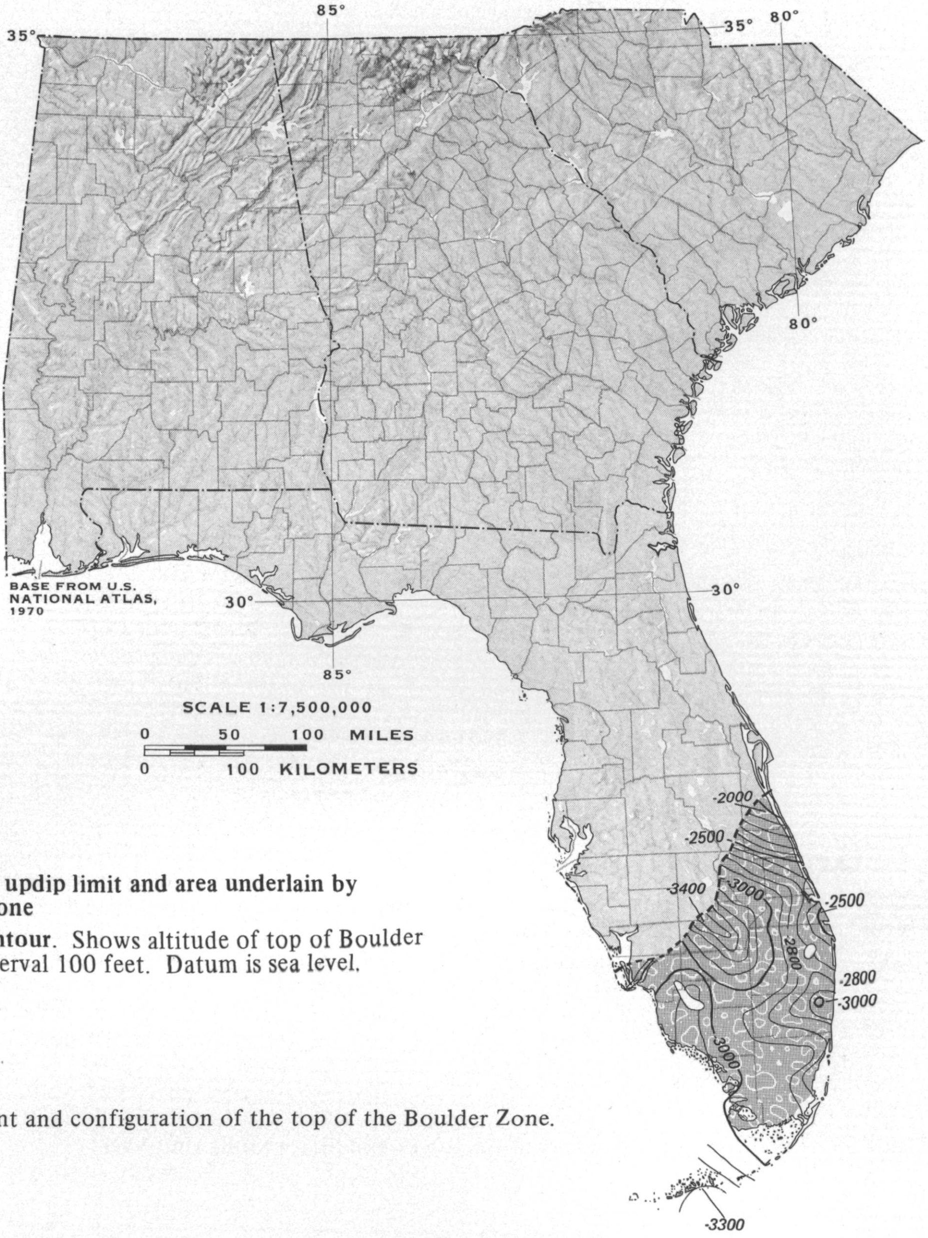


Figure 22. Extent and thickness of middle confining Unit VII.

pect to encounter a high-permeability, commonly cavernous zone at depths of about 2,500 to 3,000 ft. The Boulder Zone of the literature (Kohout, 1965) usually occurs in the bottom third of the lower Eocene Oldsmar Formation, about 100 to 150 ft above the top of Paleocene rocks. Locally, the Boulder Zone may range upward to the middle of the Oldsmar or downward to the top of the Paleocene Cedar Keys Formation. In this report, the Boulder Zone is considered to be a widespread high-permeability unit, and the extent and configuration of the top of the zone are shown in figure 23. The Boulder Zone loses its cavernous character northward and merges with permeable strata that are part of the Lower Floridan aquifer (see pls. 17, 30). Temperature and salinity data from Boulder Zone waters, supplemented by scattered hydraulic head data, indicate that the Boulder Zone is connected to the modern ocean in the Straits of Florida and that there is inland flow of water in the zone (F. W. Meyer, written commun., 1984). The permeability of the Boulder Zone is extremely high owing to its cavernous nature. An analysis of cyclic natural water-level fluctuations in a partially penetrating well (Meyer, 1974) yielded a transmissivity of 3.2×10^6 ft^2/d for only the upper 20 ft of the zone. The transmissivity of the entire thickness of the Boulder Zone probably exceeds 10^7 ft^2/d. The Boulder Zone contains saline water everywhere and is extensively used along Florida's southeastern coast as a receiving zone for treated municipal liquid wastes.



EXPLANATION

▨ **Approximate updip limit and area underlain by Boulder Zone**

—3000— **Structure contour**. Shows altitude of top of Boulder Zone. Interval 100 feet. Datum is sea level.

Figure 23. Extent and configuration of the top of the Boulder Zone.

A second high-permeability zone that is cavernous in part lies above the Boulder Zone and occurs in the lower part of rocks of middle Eocene age. In general, this shallower zone is found north of the Boulder Zone and in places overlaps it (Miller, 1979). Unlike the Boulder Zone, the middle Eocene cavernous interval commonly contains freshwater. Locally, as many as eight separate cavernous levels have been penetrated in the same borehole (Vernon, 1970, p. 10). Only the middle Eocene cavernous interval and the Boulder Zone are areally extensive, however, and only the Boulder Zone has been mapped for this study; the middle Eocene cavernous interval is not separated from the other permeable strata in the Lower Floridan aquifer. Neither cavernous zone appears to be consistently related to rock type or texture, dolomite percentage, thickness of the stratigraphic unit containing the zone, or location of chert, anhydrite, or peat beds. The shallower cavernous interval shows high permeability where middle Eocene rocks are structurally high, as one would expect if the zone were produced by karst activity. The Boulder Zone, however, shows no such relationship.

A thick middle confining unit that is regionally included in the Lower Floridan aquifer overlies and extends beyond the Boulder Zone (pls. 17, 30). This unit occurs in the middle part of rocks of early Eocene age and consists mostly of micritic to finely pelletal limestone and lesser amounts of interbedded, finely crystalline dolomite. The extent and configuration of

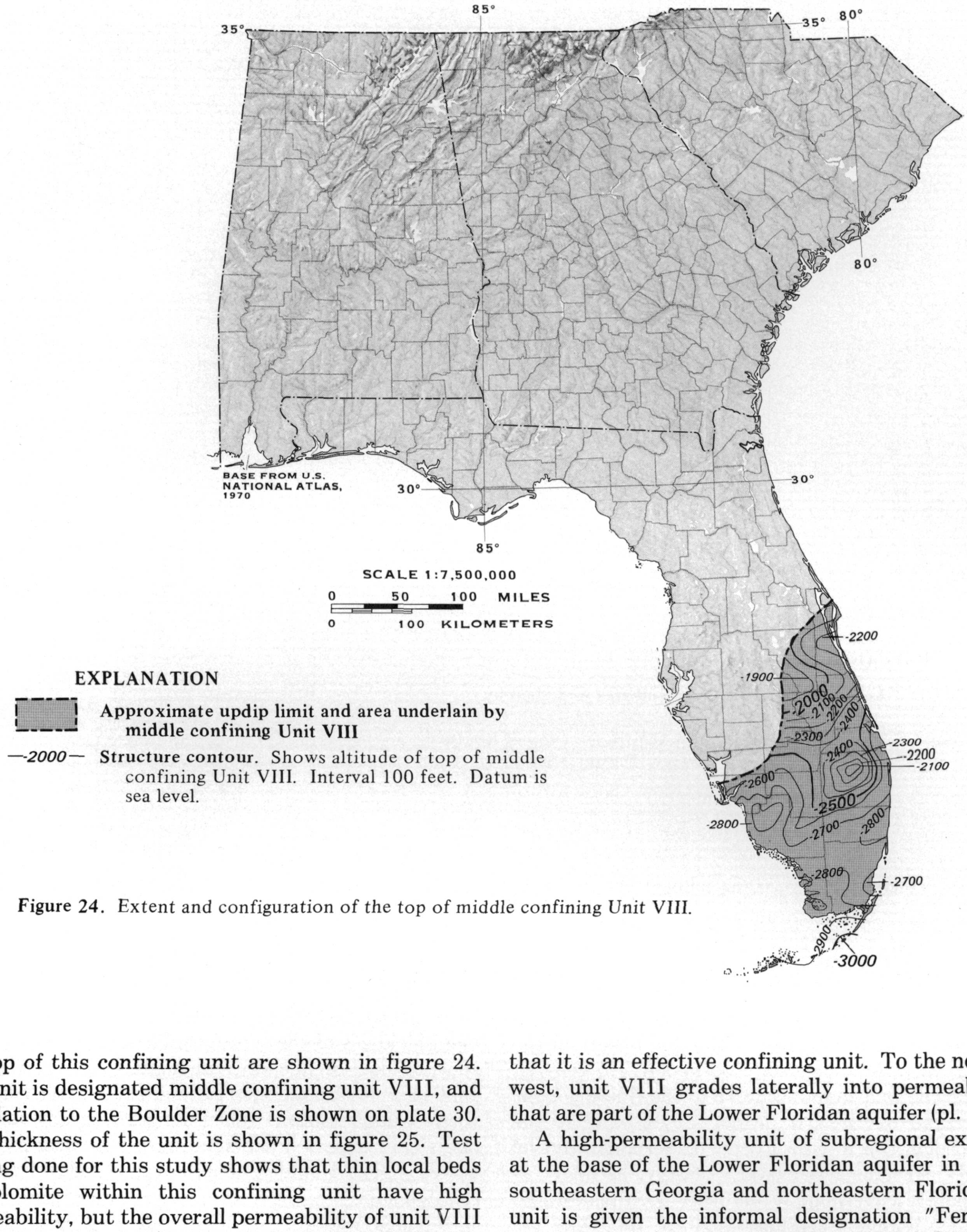


Figure 24. Extent and configuration of the top of middle confining Unit VIII.

the top of this confining unit are shown in figure 24. The unit is designated middle confining unit VIII, and its relation to the Boulder Zone is shown on plate 30. The thickness of the unit is shown in figure 25. Test drilling done for this study shows that thin local beds of dolomite within this confining unit have high permeability, but the overall permeability of unit VIII is low. Data from several deep test and injection wells along Florida's southeastern coast, some areas of which use the Boulder Zone as a receiving zone for treated municipal liquid wastes, show that unit VIII is an effective confining unit there.

Little is known about unit VIII in southwestern Florida, but scattered data from oil test wells indicate that it is an effective confining unit. To the north and west, unit VIII grades laterally into permeable beds that are part of the Lower Floridan aquifer (pl. 17).

A high-permeability unit of subregional extent lies at the base of the Lower Floridan aquifer in parts of southeastern Georgia and northeastern Florida. This unit is given the informal designation "Fernandina permeable zone" in this report because it is best known in the Fernandina Beach area of easternmost Duval County, Fla. The extent and configuration of the top of the Fernandina permeable zone are shown in figure 26. The zone consists of coarsely pelletal, vuggy limestone that is commonly dolomitized and locally cavernous in its upper part. For the most part, the zone is

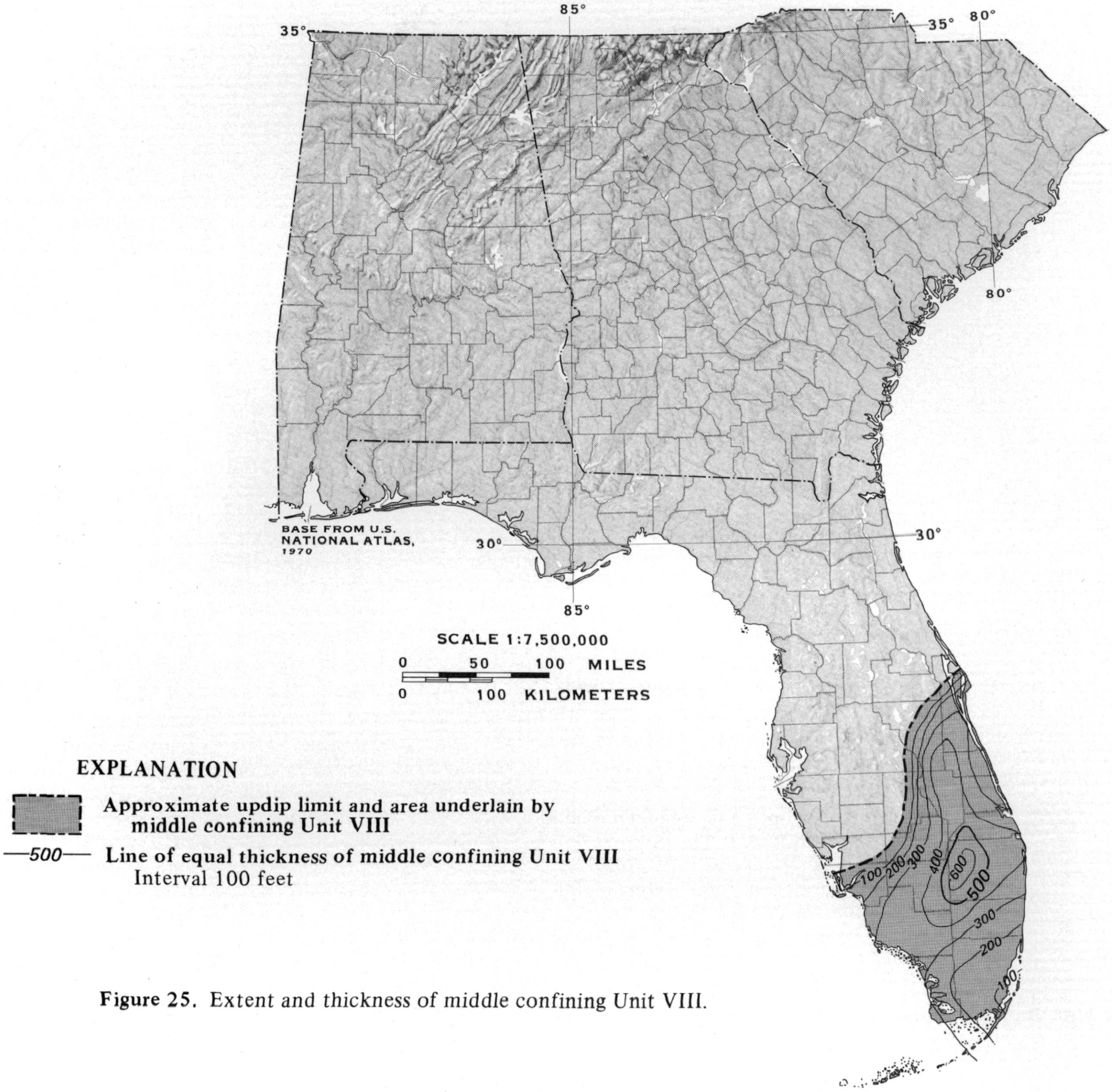


Figure 25. Extent and thickness of middle confining Unit VIII.

restricted to rocks of late Paleocene age, but in places it includes rocks as young as early Eocene or as old as Late Cretaceous (fig. 12). The Fernandina permeable zone is overlain by a confining unit composed of microcrystalline, locally gypsiferous dolomite and finely pelletal micritic limestone that in most places effectively separates the zone from shallower permeable strata. In the Brunswick, Ga., area, however, unpublished data from a deep test well (H. E. Gill, oral commun., 1982) show that this confining unit is fractured and that the fractures provide conduits that have allowed saline water from the Fernandina permeable zone to move upward in response to heavy pumping from the Upper Floridan aquifer and thereby contaminate the shallower permeable zones. The confining unit pinches out in Florida to the south and southwest, and the Fernandina zone merges with shallower permeable strata (fig. 12). To the north and west in Georgia, the confining unit is shown in figure 12 to be a tongue of low-permeability material that extends downdip into permeable strata from the aquifer's lower confining unit. Locally, water in the uppermost part of the Fernandina permeable zone is fresh (Leve and Goolsby, 1967; Brown, 1980), but the high salinity of the water that the zone contains in most places shows that ground-water flow in the zone is very sluggish. Simulation (Krause and Randolph, 1985) shows that the Fernandina zone is part of the Floridan aquifer

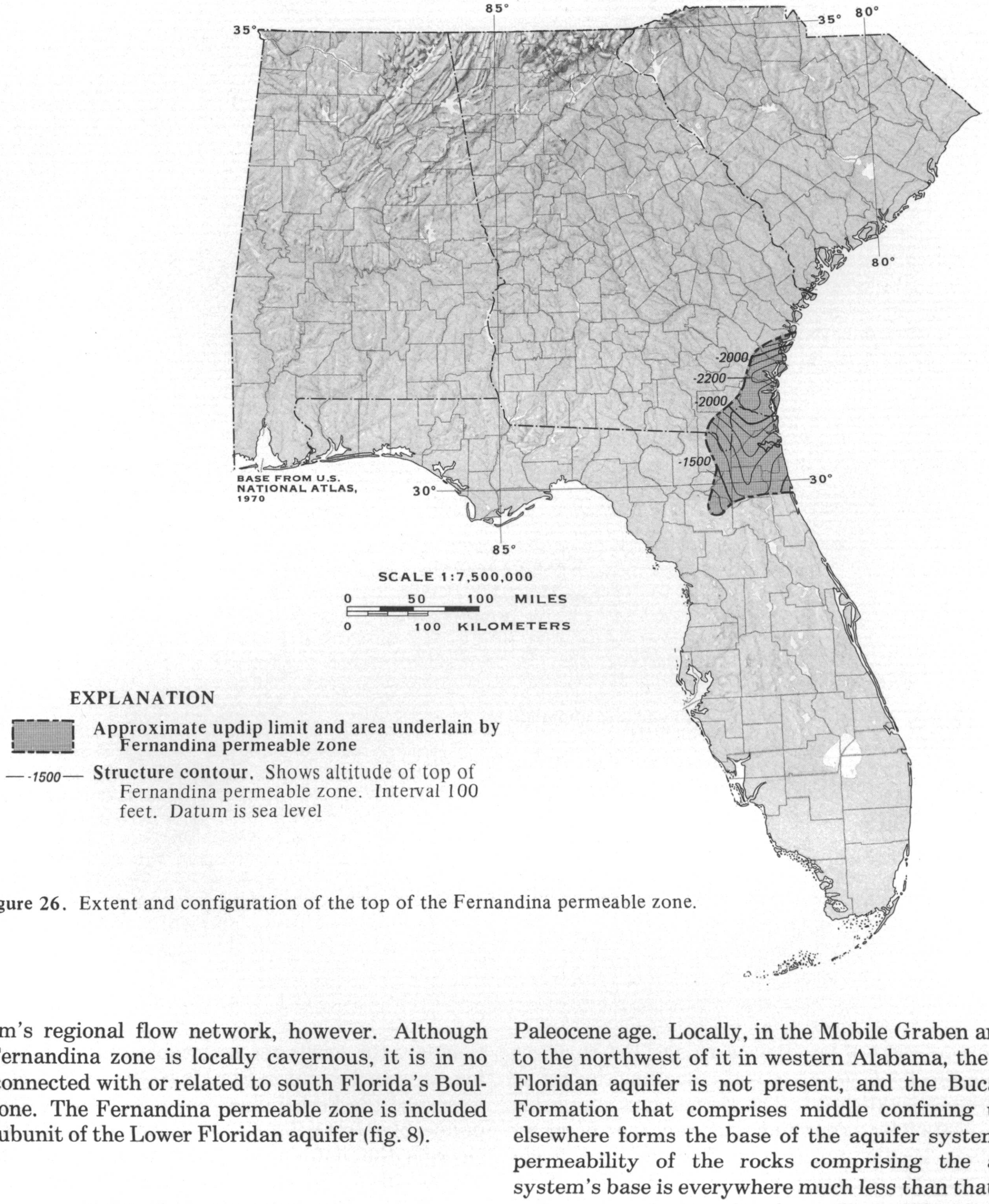


Figure 26. Extent and configuration of the top of the Fernandina permeable zone.

system's regional flow network, however. Although the Fernandina zone is locally cavernous, it is in no way connected with or related to south Florida's Boulder Zone. The Fernandina permeable zone is included as a subunit of the Lower Floridan aquifer (fig. 8).

LOWER CONFINING UNIT

The rocks that comprise the Floridan aquifer system's lower confining unit are generally of two types: either glauconitic, calcareous, argillaceous to arenaceous strata that range in age from late Eocene to late Paleocene or massively bedded anhydrite that usually occurs in the lower two-thirds of rocks of Paleocene age. Locally, in the Mobile Graben and just to the northwest of it in western Alabama, the Lower Floridan aquifer is not present, and the Bucatunna Formation that comprises middle confining unit V elsewhere forms the base of the aquifer system. The permeability of the rocks comprising the aquifer system's base is everywhere much less than that of the carbonate rocks that lie above them. Like the top of the aquifer system, its base is defined in terms of a permeability contrast and does not conform to the same geologic horizon or rock type everywhere. The altitude and configuration of the base of the aquifer system (top of its lower confining unit) as shown on plate 33, modified from a map by Miller (1982c), thus represent a composite surface that crosses formation and time boundaries. The base of the Floridan aquifer system does not crop out, and the areal extent and lithologic character of the different units delineated on plate 33 were determined solely from well control. Low-permeability clastic rocks that are the stratigraphic equivalents of the aquifer system's base do, in fact, crop out updip from the limit of the aquifer system. Where the aquifer system itself is not present, however, it is meaningless to map these low-permeability rocks as the system's base. The altitude of the base of the aquifer system may differ locally from that shown, particularly in areas of sparse well control. Although the different units shown in updip areas extend north and west of the line that marks the aquifer's approximate updip extent, they have not been mapped past the limit of the aquifer. It is important to stress that the contours shown on plate 33 generally do not represent the top of a particular time-stratigraphic unit; rather, they show the top of a permeability contrast that usually occurs within such a unit. Below the altitudes shown, there is no high-permeability carbonate rock. The different time-stratigraphic units that comprise the aquifer system's base, as shown on plate 33, are described in order below, from youngest to oldest. In general, the base of the aquifer system is marked by progressively older rocks in a downdip direction because depositional environments become progressively more marine and thereby more favorable for the accumulation of a thicker sequence of permeable limestone in a seaward direction.

ROCKS OF LATE EOCENE AGE

In western panhandle Florida and southern Alabama, the Floridan aquifer system's lower confining unit consists of interbedded glauconitic, calcareous sand and sandy clay of late Eocene (Jacksonian) age. These rocks lie immediately under the Ocala Limestone. Although detailed correlation has not been done between these calcareous clastic rocks and outcropping upper Eocene rocks, they are thought to be equivalent to the Moodys Branch Formation of western Alabama. In Geneva and Houston Counties in southeastern Alabama (pl. 33), the small area of upper Eocene rocks that comprises the base of the aquifer is also thought to be equivalent to the Moodys Branch. The upper Eocene strata in this small area are glauconitic, calcareous clastic rocks, lithologically similar to the outcropping Moodys Branch. In the northeastern part of the Georgia coastal plain, upper Eocene rocks that consist of fossiliferous, slightly sandy and glauconitic, calcareous clay mark the base of the aquifer system. These rocks are equivalent to the Eocene part of the Cooper Formation (formerly called the Cooper Marl), a low-permeability unit that is in part of late Eocene and in part of Oligocene age (pl. 2). In south-central Georgia, a small, roughly oval patch of upper Eocene rocks makes up the base of the aquifer system (pl. 33). These strata are adjacent to and just down the hydraulic gradient from a series of small faults that bound narrow grabens. The rocks, which are part of the Ocala Limestone, consist primarily of bryozoan particles and whole to broken large Foraminifera loosely bound by a micrite matrix. Here, however, gypsum has filled most of the pore space in the normally highly permeable Ocala. The gypsum has not been dissolved, probably because movement along the faults has downdropped low-permeability clastic rocks that fill the grabens opposite high-permeability limestone to the northwest and thereby created a damming effect on ground-water flow within the Floridan aquifer system. The restricted flow southeast of the faulted area has not been sufficient to remove the pore-filling gypsum from the Ocala. These low-permeability Ocala beds grade downward into glauconitic clastic rocks of middle Eocene age, with no permeable limestone between the clastic and gypsum-rich strata.

ROCKS OF MIDDLE EOCENE AGE

Adjacent to the updip limit of the Floridan aquifer system in southwestern Georgia and much of southeastern Alabama and for a considerable distance downdip of these areas (pl. 33), the aquifer system's lower confining unit consists of fine-grained, calcareous, glauconitic sand interbedded with gray to greenish-gray clay and clayey sand. These clastic strata are of middle Eocene (Claibornian) age and are thought to be equivalent to the outcropping Lisbon Formation (upper part of the middle Eocene). Farther downdip, as the amount of permeable limestone in the Tertiary section increases, the aquifer system thickens rapidly, and its base becomes progressively lower to the southeast with respect to both altitude and stratigraphic position. In a narrow, irregular, northeast-trending strip across the central Georgia coastal plain (pl. 33), the clastic rocks that are Lisbon equivalents grade by facies change into permeable limestone. Here the aquifer system's lower confining unit consists of highly glauconitic, fine-grained, greenish-gray sand interbedded with green to brown clay or clayey sand, all equivalent to the Tallahatta Formation of outcrop (lower part of the middle Eocene). In the central and east-central parts of panhandle Florida, the amount of permeable limestone in the aquifer system thickens toward the Gulf of Mexico, and the system's base becomes stratigraphically lower, as it does in Georgia. In the panhandle area, however, there is no lithologic or paleontologic difference between the upper and lower parts of the middle Eocene section. The glauconitic, calcareous clastic rocks that mark the base of the aquifer system are accordingly mapped on plate 33 as equivalent to the Lisbon Formation; the Tallahatta equivalent cannot be distinguished. In the area of southwestern South Carolina and northeastern Georgia that is adjacent to the Savannah River (pl. 33), the aquifer system's lower confining unit is comprised of highly sandy, greenish-gray, calcareous clay interbedded with soft, sandy to argillaceous limestone and fine-grained calcareous sand. These rocks are thought to be equivalent to parts of the Santee Limestone of South Carolina. The Lisbon and Tallahatta equivalents together grade laterally northeastward into the Santee by facies change.

ROCKS OF EARLY EOCENE AGE

In a narrow band in eastern panhandle Florida and a slightly wider strip in east-central Georgia, clastic rocks of early Eocene (late Sabinian) age form the Floridan aquifer system's lower confining unit (pl. 33). These rocks, which consist of highly glauconitic, silty, often micaceous, fine-grained sand interbedded with brown lignitic clay, are all of low permeability and are thought to represent in part the equivalents of the Hatchitigbee and Tuscahoma Formations that crop out in Alabama. Like the middle Eocene strata in east-central panhandle Florida, they cannot be differentiated into discrete formations in the subsurface and accordingly are mapped on plate 33 as "undifferentiated rocks of early Eocene age." Finely-crystalline, dark-gray, gypsiferous limestone interfingers with these clastic rocks locally, particularly adjacent to places where the Oldsmar Formation forms the aquifer system's base. The Oldsmar represents a carbonate-bank facies of the undifferentiated lower Eocene clastic rocks. The Oldsmar beds that form the aquifer system's lower confining unit in southcentral Georgia and contiguous parts of northern Florida (pl. 33) are glauconitic, micritic to finely crystalline, gypsiferous, cream, brown, and dark-gray limestone interbedded with dark-brown gypsiferous dolomite. In most of southwestern South Carolina (pl. 33), the base of the aquifer system consists of interbedded gray to black clay, red to brown sandy clay, and fine-grained, white, calcareous sand and clayey sand, all of which are equivalent to the upper part of the Black Mingo Formation.

ROCKS OF PALEOCENE AGE

Throughout most of Franklin County and in southern Gulf and Liberty Counties in Florida's eastern panhandle (pl. 33), the base of the Floridan aquifer system consists of hard, cherty, sandy, finely crystalline limestone thickly interbedded with massive brown to black clay. These rocks are of Paleocene age but have no exact corollary in the outcropping Paleocene rocks of either Georgia or Alabama. Their overall lithology resembles that of the Clayton Formation more closely than that of any other described Paleocene unit, and they are accordingly mapped as questionably equivalent to that formation. Eastward, these rocks grade into an interbedded carbonate-evaporite sequence that is part of the Cedar Keys Formation. Cedar Keys rocks, as plate 33 shows, make up the aquifer system's lower confining unit over practically all of peninsular Florida and over a small area in southeastern Georgia. The Cedar Keys consists mostly of thick-bedded dolomite and dolomitic limestone; massive anhydrite beds occur in the lower two-thirds of the formation. These areally extensive, low-permeability evaporites form a very effective confining bed at the aquifer system's base. The permeable dolomite and dolomitic limestone in the upper part of the Cedar Keys are included in the Floridan aquifer system, however. Accordingly, the drastic permeability decrease that marks the aquifer system's base occurs within the Cedar Keys, not at the formation's top. Anhydrite beds occur locally in younger rocks, especially in the lower Eocene Oldsmar Formation and less commonly in the lower part of rocks of middle Eocene age. The evaporite beds do not make up a regional confining unit in any horizon younger than the Paleocene, however. In the central part of western peninsular Florida, a middle Eocene gypsiferous dolomite unit has previously been mapped as the base of the aquifer system (Wolansky and others, 1979). Although this low-permeability dolomite does constitute an effective confining unit (middle confining unit II of this report), deep well data show that it is underlain by permeable limestone considered in this report to be part of the Lower Floridan aquifer. Accordingly, anhydrite beds of the Cedar Keys Formation, which in turn lie beneath the lower major permeable zone, make up the aquifer system's base here, as they do elsewhere in the Florida peninsula.

ROCKS OF LATE CRETACEOUS AGE

The Floridan aquifer system is very thick in the Brunswick, Ga., area. Test wells in southern Glynn County, Ga., show that rocks of Oligocene age through the upper part of rocks of Late Cretaceous age are part of the aquifer system there. The base of the system lies several hundred feet below the top of the Late Cretaceous and consists of soft, friable limestone of probable Taylor age (pl. 33). These rocks, which lie entirely in the subsurface, are at present unnamed in both Florida and Georgia. The permeable Cretaceous limestone that overlies the rocks of Taylor age is part of the Lawson Limestone of Navarro age.

CONFIGURATION OF SURFACE

Although the top of the lower confining unit represents a composite of the tops of several low-permeability horizons of different ages and different rock types, some of the large-scale features contoured on plate 33 reflect major structural elements in the eastern Gulf Coast. The east-trending low area centered near Brunswick, Ga., is part of the Southeast Georgia embayment; the negative area in Franklin and Gulf Counties, Fla., represents the Southwest Georgia or Apalachicola embayment; and the low area centered in Lee and Hendry Counties, Fla., is part of the South Florida basin. The steep, steady gulfward slope of the aquifer system's base in western panhandle Florida reflects the influence of the Gulf Coast geosyncline.

The axis of the positive area in northwestern peninsular Florida lies in an intermediate position between the axis of the Peninsular arch and the axis of the "Ocala uplift." This high area probably represents the approximate location of the Peninsular arch or is related to it, even though the axes of the two features do not exactly coincide.

In the broad area in peninsular Florida where anhydrite beds of the Cedar Keys Formation form the base of the aquifer system (pl. 33), the altitude of the highest anhydrite bed has been plotted and then contoured as if the evaporites were everywhere continuous. Actually, they are not. The anhydrite beds probably formed in tidal flat or sabkha environments that were of local extent (P. A. Thayer, personal commun., 1982) and, after burial, now occur as isolated discontinuous lenses that "float" in a mass of carbonate rocks. The lenses are confined, however, to a zone within the middle to lower third of the Cedar Keys, and it is the surface of this evaporite-rich zone that is contoured. Thus, the small, low- to moderate-relief (100 - 300 ft) positive and negative features shown on plate 33 in southern peninsular Florida, rather than being local structural features, represent local evaporite beds that occur at altitudes higher or lower than those of the main body of the Cedar Keys anhydrite-rich zone.

The faults shown in central Georgia on plate 33 are those that bound the series of small grabens called the Gulf Trough. The faults cut the low-permeability rocks that comprise the base of the aquifer system and displace them as shown. Because of the lack of deep well control in and adjacent to the Gulf Trough, the depth to which these faults penetrate is not known. Their geometry, however, indicates that they probably die out at a relatively shallow depth. The faults in southwestern Alabama, which also bound a series of grabens, also cut the base of the aquifer system. Unlike the faults that bound the Gulf Trough, the Alabama faults are known to extend to great depths (Copeland, 1968; Moore, 1971). To the south and west of the Alabama faults, the Floridan aquifer system is very thin and effectively isolated from the main body of limestone because movement along the faults has downdropped relatively impermeable beds opposite the permeable limestone of the aquifer system.

REGIONAL VARIATIONS IN PERMEABILITY

The rocks that make up the Floridan aquifer system are a series of platform carbonate beds that were laid down in warm, shallow water in an environment similar to that of the modern Bahama Banks. The original texture of the limestone ranged from micritic to biosparruditic (textural terms from Folk (1959)) and, like modern carbonates, varied considerably over short lateral distances, depending upon the exact depositional environment at a given place. Slight differences in the depth, temperature, and salinity of ocean waters or in current strength and distribution affect the types and numbers of calcium carbonate-fixing organisms that are present as well as the amount of micrite and the percentage and size of limestone pellets that can accumulate. As the carbonate sediment becomes consolidated, these organic and textural factors determine the primary texture of the limestone formed, which in turn determines the primary porosity and permeability of the rock. For example, the Ocala Limestone, which is part of the Upper Floridan aquifer, was deposited in shallow, warm, clear water and consists in many places of a coquina of bryozoan fragments and large Foraminifera loosely cemented with sparry calcite or a small amount of micrite. The permeability of the Ocala is high nearly everywhere. By contrast, gypsiferous dolomite of middle Eocene age (middle confining unit II) was deposited largely in a series of sabkhas or tidal flats, and has a very low permeability.

Diagenesis subsequent to deposition at any stage of consolidation of the rock can either enhance or decrease limestone permeability. For the Floridan aquifer system, dolomitization has been the chief diagenetic process affecting permeability. Depending upon the original limestone texture, dolomitization can increase or decrease the porosity of the rock. If the original rock is a micrite, it may be recrystallized into a loosely interlocking mosaic of dolomite crystals that is highly porous. On the other hand, if the originally high porosity of a loosely packed, coarsely pelletal limestone is almost completely filled with finely crystalline dolomite, an effective confining unit is created out of a once-permeable rock. The degree to which the original limestone porosity is affected depends also upon whether dolomitization is partial or complete; if the process is incomplete, some of the original porosity may be preserved. The exact mechanism by which dolomitization took place in the study area is unclear. Some of the observed dolomitization is possibly related to paleo or modern ground-water flow systems (Hanshaw and others, 1971; Hanshaw and Back, 1979). Periodic, perhaps repeated exposure of the limestones and flushing of their interstitial saline waters by freshwater is one mechanism by which the amount of magnesium-rich water required to dolomitize the limestone could be moved through the rock. This study, shows the the effect of dolomitization on limestone permeability is very important.

Rapid facies change can occur within a short lateral distance in the Floridan aquifer system, a result of closely spaced but highly variable depositional environments. Such changes may be textural within a limestone bed, such as an increase in the amount of micrite toward a relatively quiet water environment, or they may reflect, usually in an upbasin direction, the mixing of clastic materials with the limestone as one approaches an ancient shoreline. Complex interfingering and intertonguing of rock types and permeability conditions are thus produced, particularly in carbonate-clastic transition areas. The amount of fine-grained carbonate material in the Floridan aquifer system as a whole generally increases in a downbasin direction, so much so that, in parts of southern Florida, the aquifer system consists largely of low-permeability rocks separated by relatively thin, often vuggy, high-permeability zones that are hydraulically isolated from one another.

Geologic structure, like dolomitization, can either increase or decrease the permeability of a limestone. Because most limestones are relatively brittle, they tend to break rather than bend when they are subjected to stress. Joints are thus readily formed in carbonate rocks. In the Floridan aquifer system, borehole televiewer surveys and downhole current meter data show that, in places, joints cut some of the middle confining units and provide conduits along which water is able to move vertically from one permeable unit to another. Enlargement of joints can result from dissolution of limestone by ground water that moves along the joints. Data from wells in Brunswick, Ga. (well GA-GLY-9), and Broward County, Fla. (well FLA-BRO-2), show the effects of jointing on permeability. In contrast to the increase in permeability created by jointing, faults that cut all or part of the aquifer system may effectively decrease the permeability of the system in places and disrupt ground-water flow. The low-permeability materials downfaulted into the aquifer system in a series of grabens in western Alabama and central Georgia are examples of local decreases in permeability created by fault activity.

Most of the gypsum and anhydrite that fill the pore space in some of the confining units within the aquifer system apparently formed in a sabkha or other tidal flat environment. Petrographic examination of evaporite-rich limestone from a test well GA-WA-2 near Waycross, Ga.,however, shows that some of the evaporite minerals that fill the pore spaces in the limestone there were formed by secondary mineralization. Much of the anhydrite near Waycross appears to have been precipitated from ground water that was rich in calcium sulfate. Deposition of anhydrite or other types of pore-filling materials from circulating ground water has effectively decreased the porosity and permeability of the limestone near Waycross.

More commonly, circulating ground water increases the permeability of limestone by dissolution. Secondary porosity, developed as the carbonate rocks are partially dissolved, ranges in scale from pinpoint holes to isolated vugs to caverns tens of feet across. The larger solution conduits, of course, are the more important because they greatly increase the local transmissivity of the Floridan aquifer system. The karst features developed in the aquifer system are best known where the Floridan crops out or is thinly covered (pl. 25), but buried karst horizons, such as southern Florida's Boulder Zone, also occur and are of considerable importance. Stringfield (1966) discussed the near-surface karst features of the study area in detail.

It is obvious from the preceding discussion of the factors influencing the porosity and permeability of limestone that the distribution of permeability within the Floridan aquifer system is extremely complex, depending partly on the environment in which the limestone was deposited and partly on the postdepositional history of the rock. Certain generalizations can be made, however, about the relation between the geologic character of the aquifer system and its hydraulic properties. Figure 27 shows the estimated distribution of transmissivity in the Upper Floridan aquifer. Comparison of this figure with a map showing where the aquifer system is unconfined, thinly confined, and thickly confined (pl. 25) shows that all areas having transmissivity values greater than 1×10^6 ft^2/d, and many of the areas with values between 2.5×10^5 and 1.0×10^6 ft^2/d, occur where the aquifer system is either unconfined or where its upper confining unit is less than 100 ft thick. In these places, the upper part of the aquifer system is riddled with caves, sinkholes, pipes, and other types of solution features. The large-scale secondary porosity developed in and near the Floridan's outcrop area is the reason for the large

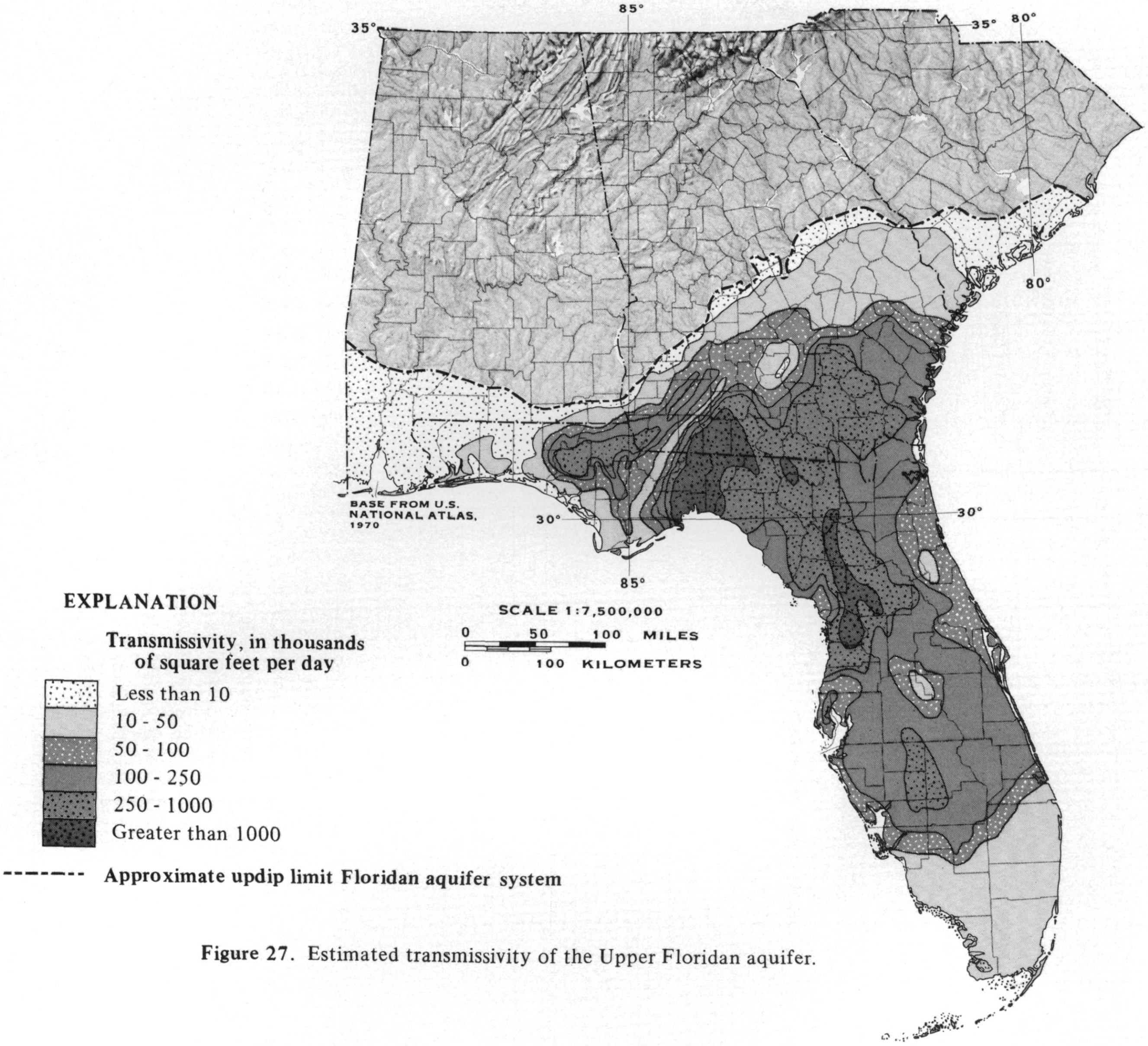


Figure 27. Estimated transmissivity of the Upper Floridan aquifer.

transmissivity values observed there. Where the aquifer system is thickly confined (pl. 25), its transmissivity is generally lower (less than 2.5×10^5 ft^2/d), and the variations that exist are related primarily to textural (facies) changes in the carbonate rocks and secondarily to the thickness of the Upper Floridan aquifer. For example, the mapped transmissivity values of less than 5×10^4ft^2/d in southern Florida result from a decrease in limestone permeability in an area where the aquifer system contains much micrite. Similar values near and just downdip of the aquifer system's updip limit (for example, in western panhandle Florida) are found in places where the Upper Floridan aquifer is thin (pl. 28). A band of low transmissivity extending northeastward across south-central Georgia is related to the small graben system called the Gulf Trough, discussed previously. Generally, then, the transmissivity of the aquifer system is most strongly influenced in and near its outcrop area by thickness and secondary permeability and, where the system is confined, by facies variations. A good example of this relation is shown by the upper Eocene rocks (Ocala Limestone) in figure 28. At Silver Springs, Fla., the Ocala is highly cavernous and forms the vents from which the springs issue (Faulkner, 1973). Downdip, these upper Eocene rocks become increasingly less permeable, chiefly because much of their pore space is filled either with micrite or finely recrystallized material, until, in Glades County, Fla. (well FLA-GL-1, fig. 28), upper Eocene rocks become part of the upper confining unit

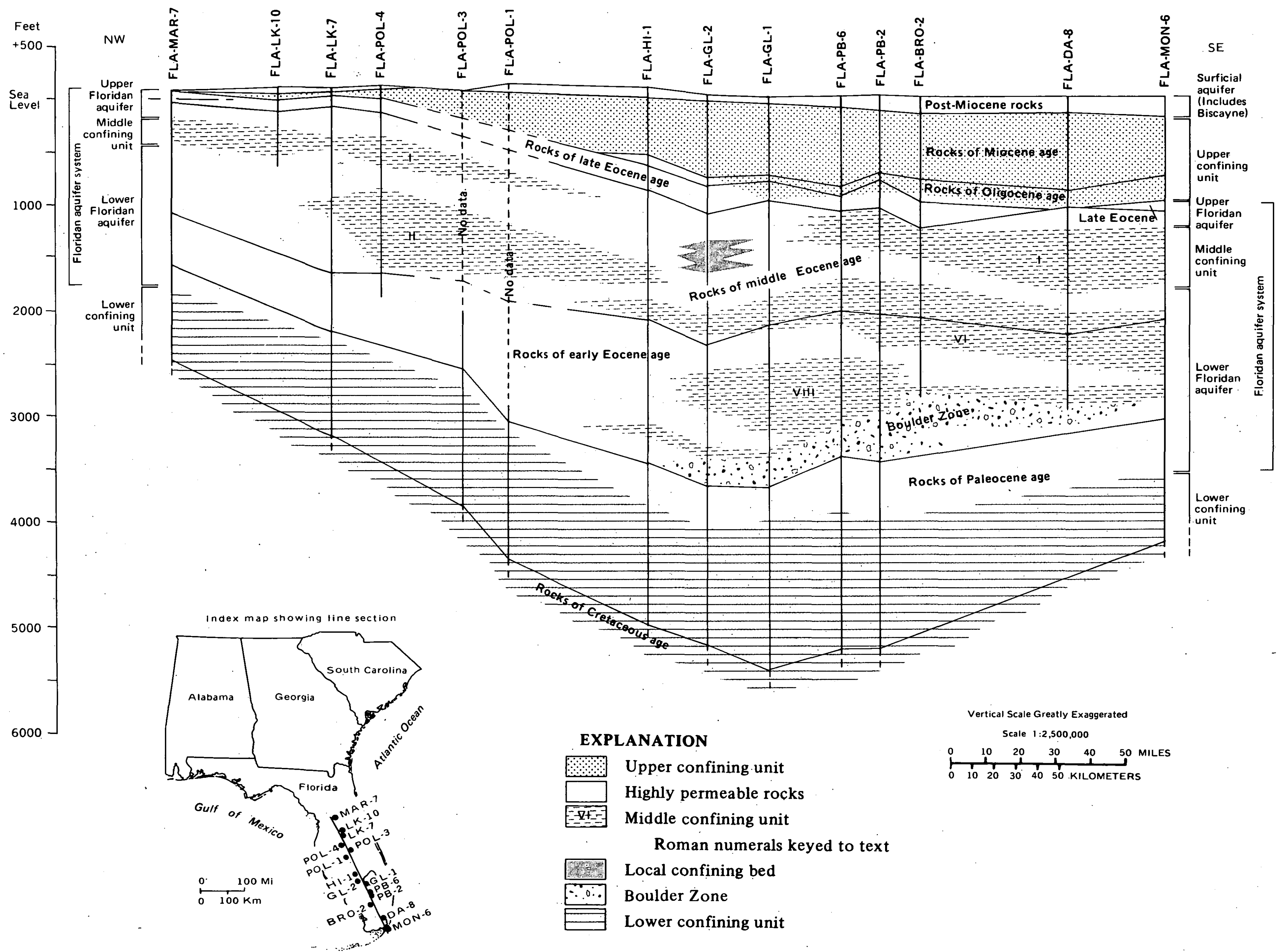


Figure 28. Generalized geohydrologic cross section from central Marion to northern Monroe Counties, Fla.

of the aquifer system. Farther south, as the amount of micrite in the Ocala decreases, upper Eocene rocks are again included as part of the aquifer system because their permeability is higher.

SUMMARY AND CONCLUSIONS

The Floridan aquifer system of the Southeastern United States is comprised of a thick sequence of carbonate rocks that are mostly of Paleocene to early Miocene age and that are hydraulically connected in varying degrees. Locally, the aquifer system includes rocks of Late Cretaceous age. In and near its outcrop area, the system consists of a single vertically continuous permeable unit. Downdip, there are generally two major permeable zones (the Upper and Lower Floridan aquifers) separated by a middle confining unit of subregional extent, whose hydraulic properties vary from very leaky to virtually nonleaky. Neither the vertical boundaries of the aquifer system nor its component major high- and low-permeability zones necessarily conform to either formation boundaries or time-stratigraphic breaks. Commonly, the permeability contrast that distinguishes the Floridan aquifer system from its upper and lower confining units occurs somewhere within a rock or time-rock unit.

The subsurface stratigraphy of the coastal plain rocks that comprise the Floridan aquifer system and its contiguous confining units was delineated and mapped on the basis of data from deep test wells of various types. Chronostratigraphic units were chosen for mapping because such units best portray conditions throughout an entire sedimentary basin when complex facies changes such as those found in the eastern Gulf Coast are present. Each chronostratigraphic unit that was delineated includes all or parts of several surface and subsurface formations. The external geometry of each chronostratigraphic unit is shown by structure contour and isopach maps, and internal variations in the units are shown on a series of cross sections that also portray major variations in permeability.

Coastal plain sediments in the eastern Gulf Coast are predominantly clastic from the Fall Line that marks their inland limit. These clastic rocks merge into and interfinger with a thick sequence of platform carbonate rocks that underlies all of peninsular Florida and much of southeastern Georgia. From Paleocene through Oligocene time, the platform carbonate facies successively encroached on the clastic rocks, the result being that progressively younger Tertiary carbonates extend progressively farther to the north and west. The general gentle seaward thickening of coastal plain rocks is interrupted by large- to small-scale geologic structures. Some of these structures, such as Florida's Peninsular arch, the Southeast and Southwest Georgia embayments, and the South Florida basin, have had a major influence on sedimentation and permeability distribution. The Gulf Trough fault system in central Georgia and the Gilbertown-Pickens-Pollard fault zone in southwestern Alabama both strongly influence ground-water flow within the Floridan aquifer system.

Rocks of Cretaceous age underlie the entire study area and generally consist of low-permeability calcareous clay and fine-textured limestone. Updip, sandy Cretaceous rocks form part of the lower confining unit of the Floridan aquifer system except very locally, in the Brunswick, Ga., area, where the upper Cretaceous Lawson Limestone is part of the system.

Paleocene rocks are generally of low permeability throughout the study area except for the permeable dolomite beds in the upper part of the Paleocene Cedar Keys Formation in peninsular Florida, which are included in the Floridan aquifer system. Thick extensive deposits of Paleocene anhydrite in the Florida peninsula form the base of the aquifer system there. Glauconitic Paleocene clastic rocks to the northwest are part of the aquifer system's lower confining unit. The Paleocene-early Eocene boundary is placed in this report at the highest occurrence of either of the planktic Foraminfera *Globorotalia pseudomenardii* Bolli or *G. Velascoensis* (Cushman).

Lower Eocene rocks in the Florida peninsula are part of the Oldsmar Formation, a sequence of limestone and dolomite beds that is in general highly permeable. Like the Paleocene rocks that underlie them, lower Eocene carbonate rocks grade to the north and west into calcareous, glauconitic clastic rocks that are of low permeability. Middle Eocene carbonate rocks in the Florida peninsula have traditionally been divided into the Lake City Limestone below and the Avon Park Limestone above. Well cuttings and core examined during this study show no consistent lithologic or paleontologic difference between the Lake City and Avon Park Limestones. Accordingly, this report proposes that the term Lake City be abandoned and that all middle Eocene carbonate strata in the Florida peninsula and contiguous areas be included in the Avon Park Formation. A reference well section is suggested for the expanded Avon Park Formation. This report further proposes that the term "formation" rather than "limestone" be applied to the Avon Park, Oldsmar, and Cedar Keys units because all commonly contain rock types other than limestone. Middle Eocene rocks show the same westward carbonate-to-clastic transition as lower Eocene and Paleocene strata. This transition occurs farther northward and westward than that of the lower Eocene, which is in turn north and west of the Paleocene clastic-carbonate transition. Most of the low-permeability zones of subregional extent that occur within the Floridan aquifer system are part of the middle Eocene.

Upper Eocene strata consist mostly of carbonate rocks and represent the most widespread transgression of Tertiary seas in the Southeastern United States. Most upper Eocene beds in the study area are part of the highly permeable Ocala Limestone. The Oligocene strata that overlie the Ocala are also in general highly permeable and consist largely of carbonates. Oligocene rocks, however, are relatively thin throughout the study area and have been completely eroded from large areas in northeastern Florida and southeastern Georgia. In most places, either Oligocene or upper Eocene beds mark the top of the Floridan aquifer system.

Lower Miocene sandy limestones mark the end of carbonate bank depositional conditions in the study area. Beginning with the middle Miocene Hawthorn Formation, clastic rocks covered the eastern Gulf Coast almost everywhere. This clastic influx resulted in rapid and complex changes in rock type in the Hawthorn, and the widespread occurrence of Hawthorn phosphorites and high-silica clays show that the waters in the Hawthorn sea were colder than those in older Tertiary oceans. The marginal marine to fluvial origin of most post-Hawthorn rocks in the study area shows that there was a general regression of the sea after middle Miocene time. The upper confining unit of the Floridan aquifer system consists mostly of Hawthorn rocks but includes younger beds in places.

The term Floridan aquifer system is used in this report in place of the older terms "Floridan aquifer" or "principal artesian aquifer." The base of the Floridan aquifer system has been extended downward to include the upper part of the Cedar Keys Formation. The Hawthorn Formation, whose basal limestones have been included as part of the "Floridan aquifer" in older reports, is entirely excluded from the Floridan aquifer system in this report. The Floridan aquifer system generally consists of an Upper and a Lower Floridan aquifer separated by a low-permeability zone (middle confining unit) of subregional extent. In places, no middle confining unit is present, and the aquifer system is permeable throughout its vertical extent. In such places, the entire aquifer system is included in and mapped with its upper major permeable zone, the Upper Floridan aquifer.

Neither the top or base of the aquifer system nor the top or base of the aquifers and middle confining units within it conforms everywhere to the tops of stratigraphic units. Rather, the permeability contrasts that define the aquifer system and its component parts commonly occur within a formation or within a time-stratigraphic unit. Several stratigraphic units or parts of units may mark the top or base of the aquifer system regionally. Likewise, the subregional middle confining units of the aquifer system may consist of different stratigraphic units from place to place.

Hydraulic conditions within the Floridan aquifer system range from unconfined to confined, depending generally on the presence and integrity of low-permeability clastic rocks of Miocene age above the aquifer system. A sandy surficial aquifer is found throughout the study area and may be separated from the Floridan aquifer system by the system's upper confining unit or may be in direct contact with the system where the upper confining unit has been removed by erosion.

Maps of the top, base, and thickness of the Floridan aquifer system, maps of the top and thickness of the Upper and Lower Floridan aquifers, a series of geohydrologic cross sections, and a fence diagram portray the external and internal geometry of the aquifer system. Locally, there are zones of cavernous permeability developed within the aquifer system, and the larger of these cavernous zones are mapped.

The surficial aquifer that forms the uppermost hydrologic unit in the study area generally can be divided into three major parts: (1) the sand-and-gravel aquifer of southwestern Alabama and westernmost panhandle Florida, a thick sequence of fluvial gravelly sand beds; (2) the Biscayne aquifer of southeastern peninsular Florida, a sequence of sandy limestone and sand beds; and (3) a relatively thin but widespread blanket of fluvial to marine terrace sands that covers most of the study area. Water may leak downward from the surficial aquifer to the Floridan aquifer system or be discharged from the Floridan to the surficial aquifer, depending on the vertical hydraulic gradients at any given place.

The upper confining unit of the Floridan aquifer system is a generally thick sequence of clastic rocks and low-permeability carbonates that in places thins to a featheredge and in places is breached by sinkholes and other solution features. The upper confining unit creates the artesian conditions existing throughout most of the area where the Floridan aquifer system occurs. Where the upper confining unit, which consists mostly of rocks of the Hawthorn Formation, is thin or breached, semiconfined conditions exist in the Floridan aquifer system. The regional extent, character, and thickness of the upper confining unit have been mapped for the first time in this report.

Although the Floridan aquifer system is known to extend offshore, it has been mapped only to the coastline in this report. The top of the aquifer system may consist of different ages and types of rocks and its configuration as mapped is determined in part by large- to small-scale geologic features and in part by karst topography developed on the easily dissolved limestone surface. The system's top in most places lies at the top of or within rocks of Oligocene age; where the Oligocene is absent, the system's top is at the top of or within rocks of late Eocene age. Locally, rocks of early Miocene or middle Eocene age comprise the system's top. Some of the small faults that cut the aquifer system's top in places locally limit the extent of the system, as in southwestern Alabama. Other faults, such as those in Florida, have no apparent effect on the system other than to offset its top by a slight amount. A series of small grabens in the central part of the Georgia coastal plain completely cuts the Floridan aquifer system, and movement along the faults that bound these grabens has juxtaposed low-permeability clastic rocks within the grabens opposite permeable limestone to either side and thereby created a damming effect on ground-water flow across the graben system.

The Floridan aquifer system generally thickens seaward from its outcrop area. This general trend is interrupted by several structural features of subregional scale. The Southeast Georgia embayment, the Southwest Georgia embayment, and the South Florida basin represent depocenters within which thick sequences of the carbonate rocks that comprise the Floridan aquifer system were deposited. The system thins over Florida's Peninsular arch. Although the Gulf Coast geosyncline was also a depocenter during Tertiary time, there was a large supply of clastic sediment to the geosyncline, in contrast to the carbonate bank type of depositional system that existed in peninsular Florida and contiguous areas. Accordingly, the Floridan aquifer system is thin around the northeastern rim of the Gulf Coast geosyncline because conditions were not favorable for carbonate deposition.

Within the Floridan aquifer system, there are subregional to local zones of high and low permeability. The uppermost zone of high permeability within the system, called the Upper Floridan aquifer in this report, nearly everywhere yields large volumes of water. The Upper Floridan generally consists of all or parts of rocks of Oligocene age and late Eocene age and the upper half of rocks of middle Eocene age. The thickness of the Upper Floridan as mapped depends partly on structural and depositional conditions and partly on the depth to one of the aquifer system's middle confining units, which form the base of the Upper Floridan.

Seven of the eight subregional low-permeability units that lie within the Floridan aquifer system act as middle confining units separating the Upper and Lower Floridan aquifers. The remaining confining unit lies within the Lower Floridan aquifer. The stratigraphic positions and the rock types of the different units vary greatly. In places, one of the middle confining units may overlie another. In this case, the higher of the overlapping zones is treated as the base of the Upper Floridan aquifer.

Subregional confining unit I, which extends as a coast-parallel band from the Florida Keys to southeastern South Carolina, consists of micritic limestone of middle Eocene age and is the leakiest middle confining unit identified. Subregional confining unit II, which is located in west-central peninsular Florida, consists of gypsiferous middle Eocene dolomite that forms a very low-permeability confining unit. Unit II is overlapped by unit I over a narrow band in central peninsular Florida. Middle confining unit III, located along the central part of the Georgia-Florida border, is gypsiferous, dolomitic middle Eocene limestone that, like unit II, is virtually nonleaky. Unit IV, in the eastern part of the Florida panhandle, is a glauconitic sandstone that extends tonguelike into the lower part of the Floridan aquifer system. Unit IV is of early middle Eocene age and appears to be a leaky confining unit. Middle confining unit V, located in the western Florida panhandle and in southern Alabama, is a massive, dark-colored, virtually nonleaky Oligocene clay. Unit VI, in southwestern peninsular Florida, is a series of low-permeability argillaceous limestone and coarsely crystalline dolomite beds. Unit VI is partly of middle Eocene age and partly of early Eocene age and is overlapped by parts of units I and II. Middle confining unit VII is a narrow strip of gypsiferous limestone of middle to late Eocene age that lies downgradient of and parallel to a small graben system in central Georgia. Restricted flow of ground water across the graben system has been insufficient to dissolve the gypsum from these rocks.

The Lower Floridan aquifer is that series of mostly permeable carbonate beds that lies beneath one of the middle confining units within the Floridan aquifer system. The Lower Floridan's flow system is sluggish, and its hydraulic characteristics are poorly known. In much of southern Florida, a cavernous zone of extremely high permeability occurs within the Lower Floridan aquifer. This interval, called the Boulder Zone, represents a paleokarst horizon that formed in early Eocene rocks. Other cavernous intervals occur in Florida from shallower depths, but they are not found over as wide an area as the Boulder Zone. The Boulder Zone is extensively used along Florida's southeastern coast as a storage zone for liquid wastes (chiefly treated municipal sewage). The Boulder Zone is overlain by a low-permeability micritic limestone that is mapped as middle confining unit VIII. In northeast Florida and southeast Georgia, another deep permeable zone, informally called the Fernandina permeable zone, occurs within the Lower Floridan aquifer in rocks of early Eocene age. The Fernandina permeable zone, which contains saline water, is separated from shallower permeable zones in the Lower Floridan by a micritic limestone confining unit.

The lower confining unit of the Floridan aquifer consists in most places of either massive bedded anhydrite of Paleocene age (part of the Cedar Keys Formation) or glauconitic, calcareous clayey to sandy strata that range in age from late Paleocene to late Eocene. The base of the aquifer system is thus a composite surface that consists of different types and ages of rocks, all of which are of much lower permeability than the rocks of the overlying aquifer system. Some of the larger structural elements of the eastern gulf coast are recognizable on a map of the aquifer system's base. Variations in permeability within the Floridan aquifer system are complex. The porosity and permeability in the carbonate rocks that comprise the system result from a combination of (1) the original texture of the rock, as determined primarily by depositional environment; (2) the diagenetic processes that have acted on the sediment, such as dolomitization and recrystallization, and that are reflected by changes in mineralogy as well as porosity; (3) the joints, fractures, faults, and other structures that affect the integrity of the brittle carbonate rocks and open channels along which ground-water flow can be concentrated; (4) the dissolution of either the carbonate rocks themselves or pore-filling materials such as evaporites and a resulting increase in porosity; and (5) the precipitation of pore-filling minerals, specifically evaporites, either from seawater or from ground water. That most of the major features seen on a map of the potentiometric surface of the Floridan aquifer system can be explained by one of the above factors or a combination thereof demonstrates the effect of the geologic framework of the aquifer system on ground-water flow patterns within it.

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Appendix: LITHOLOGIC DESCRIPTION OF PROPOSED REFERENCE SECTION FOR THE AVON PARK FORMATION

Description is of cuttings from Coastal Petroleum Company's No. 1 James B. and Julian P. Ragland well, sec. 16, T. 15 S., R. 13 E., Levy County, Fla. Florida Bureau of Geology well no. W-1537, permit no. 66. Elevation of ground level 5 ft. Carbonate rock classification is that of Leighton and Pendexter (1962). Colors are those illustrated in the Geological Society of America's (1951) rock color chart.

Depth (in feet)	*Lithology*
	Tertiary Late Eocene Ocala Limestone
100-110	Limestone (fine- to coarse-grained foraminiferal-micritic limestone), white (N9), consists of 65 percent whole to broken, small to large foraminiferal remains bound by 25 percent finely-crystalline sparry matrix. Echinoid and bryozoan fragments, *Camerina* sp., *Lepidocyclina* sp. prominent.
110-221	No sample.
	Tertiary Middle Eocene Avon Park Formation
221	Dolomite, medium-grained, moderate yellowish-brown (20 YR 5/4), crystalline, consists of well-cemented euhedral to subhedral dolomite crystals. Vuggy porosity prominent, probably a result from selective dissolution of foraminiferal remains in original limestone.
221-410	No sample.
410-420	Dolomitic limestone (medium-grained foraminiferal-micritic limestone), pinkish-gray (5 YR 8/1). 55 percent medium-sized foraminiferal remains (mostly *Quinqueloculina* sp., with *Dictyoconus* sp. prominent) in 45 percent very fine crystalline calcite matrix. Much fine-vug porosity (estimated 25 percent).
420-440	Dolomitic limestone as above.
440-460	Dolomitic limestone as above. Add trace of medium to coarse pellets of pinkish-gray micritic limestone.
460-470	Limestone (microcrystalline limestone), very light gray (N8), consists of very finely crystalline sparry calcite, probably representing recrystallized micrite. Fine-vug porosity estimated at 20 percent.
470-480	Limestone as above.
480-500	Limestone as above, porosity decreased to 10 percent.
500-510	Dolomite, fine-grained, very pale orange (10 YR 8/2), texturally uniform, low porosity, finely crystalline. A few scattered, isolated small vugs. Trace of black organic partings that represent original grassy material.

Depth (in feet)	*Lithology*
510-520	Dolomite as above with trace of large vugs, some lined with very coarsely crystalline clear quartz.
520-530	Dolomite as at 500 to 510 ft. Silt-sized crystals. No open vugs. Trace of scattered white anhydrite as vug fillings.
530-540	Dolomite, medium-grained, pale yellowish-brown (10 YR 6/2), consists of a highly porous (estimated 25 percent intercrystalline porosity) mesh of medium-sized euhedral crystals. Trace of clear selenite as vug fillings.
540-550	Dolomite as above. White gypsum as vug fillings makes up 10 percent of rock.
550-560	Limestone (micrite), pinkish-gray (5 YR 8/1), low porosity, consists of clay- to silt-sized particles of micrite, finely disseminated dark-brown organic material prominent. Trace of organic-rich laminae, *Dictyoconus* sp.
560-570	Limestone (foraminiferal-micritic limestone), pinkish-gray (5 YR 8/1), consists of 60 percent soft micritic limestone matrix enclosing 40 percent large to small *Dictyoconus* sp. Low porosity.
570-580	Dolomitic limestone (micrite), pinkish-gray (5 YR 8/1), texturally uniform, low porosity, consists of silt-sized particles of dolomitic limestone.
580-590	Limestone (micrite), pinkish-gray (5 YR 8/1), texturally uniform, hard, low porosity. Consists of silt-sized limestone particles.
590-600	Dolomite, medium-grained, very pale orange (10 YR 8/2), calcareous, medium crystalline, highly vuggy, most vugs filled with white gypsum.
600-620	Dolomite as above.
620-630	Dolomite, fine-grained, grayish orange pink (5 YR 7/2), texturally uniform, very fine crystalline, low porosity. Trace of scattered small vugs, some filled with medium crystalline euhedral dolomite.
630-640	Dolomite as above.
640-650	Dolomite, coarse-grained, pinkish-gray (5 YR 8/1), medium to coarsely crystalline, low porosity, large isolated vugs common.
650-660	Dolomite as at 590 to 600 ft. Decrease in gypsum to trace.
660-670	Dolomite as at 620 to 630 ft.
670-690	Dolomite as at 590 to 600 ft. No gypsum.
690-710	Dolomite as above. Trace of disseminated dark-brown organic material, clear anhydrite filling a few vugs.
700-720	Dolomite as at 620 to 630 ft.

Depth (in feet)	*Lithology*
720-730	Dolomite as at 690 to 710 ft.
730-740	Dolomite, coarse-grained, pale yellowish-brown (10 YR 6/2), texturally uniform, very coarsely crystalline, low porosity, slightly vuggy. Vugs are large, isolated, filled with clear to white gypsum. Disseminated dark-brown organic material prominent. Trace of pale-brown (5 YR 5/2) clay laminae.
740-770	Dolomite as above, gypsum increased to 10 percent of rock. Gypsum mostly white, very coarsely crystalline.
770-780	Dolomite as at 620 to 630 ft.
780-790	Dolomite as above, disseminated fine-grained white gypsum prominent.
790-820	Dolomite as at 620 to 630 ft.
820-830	Dolomite as above, small-vug porosity prominent. White gypsum fills a few of the vugs.
830-870	Dolomite as above,no gypsum. Very fine grained disseminated dark-brown organic material prominent.
870-880	Dolomite, coarse-grained, pale yellowish-brown (10 YR 6/2), texturally uniform, coarsely crystalline, isolated vuggy porosity common. A few vugs are filled with white gypsum.
880-890	Dolomite as above.
890-900	Limestone (foraminiferal-pellet limestone), pinkish-gray (5 YR 8/1). Consists of 40 percent medium to large Foraminifera and medium-sized pellets of micritic limestone, 40 percent micritic limestone matrix, 20 percent coarse crystalline (recrystallized) calcite as isolated rhombs and aggregates in micritic matrix. Microfauna includes *Lituonella floridana* Cole, *Eponides gunteri* Cole, *Spirolina coreyensis* Cole, *Amphistegina lopeztrigoni* Palmer, *Gyroidina nassauensis* Cole, *Discorbis inornatus* Cole.
900-920	Limestone as above.
920-930	Limestone as above but with most Foraminifera recrystallized. *Dictyoconus* sp. prominent.
930-940	Limestone as above.
940-960	Limestone as above, about half of matrix altered to coarsely crystalline dolomite.
960-970	Dolomite, coarse-grained, pale yellowish-brown (10 YR 6/2), texturally uniform, friable, coarse crystalline, much small-vug and intercrystalline porosity (estimated 15 percent). Dark-brown to dark-gray disseminated organic material prominent.
970-980	Limestone as at 940 to 960 ft. All of micritic matrix dolomitized.

Depth (in feet)	*Lithology*
980-1,000	Dolomite as at 960 to 970 ft. White gypsum prominent as filling
1,000-1,010	Limestone (pelletal-micritic limestone), light-gray (N7), well indurated, low porosity. 60 percent hard, micritic, partially dolomitized limestone matrix. 40 percent fine pellets of micritic limestone and small Foraminifera (mostly *Quinqueloculina* sp.). Very fine-grained dark-green glauconite common, disseminated in micritic matrix.
1,010-1,020	Limestone as above.
1,020-1,050	Dolomite as at 980 to 1,000 ft.
1,050-1,060	Limestone (pelletal-micritic limestone), pinkish-gray (5 YR 8/1), low porosity. 40 percent fine pellets of micritic limestone. 40 percent coarsely crystalline calcite (recrystallized micritic matrix). 20 percent micritic limestone matrix. Fine-grained dark-green weathered glauconite, small Foraminifera, bryozoan fragments prominent.
1,060-1,100	Limestone as above but with 30 percent increase in pellets, and corresponding decrease in coarsely crystalline calcite. Fauna includes *Dictyoconus* sp., and *Cribobulimina floridana* Cole.
1,100-1,110	Limestone (pelletal-foraminiferal limestone), pinkish-gray (5 YR 8/1), low porosity, a few high-porosity intercalations. 85 percent medium-sized pellets of micritic limestone and medium to large Foraminifera. 15 percent hard micritic limestone matrix. White gypsum prominent, disseminated in matrix. Echinoid fragments abundant.
1,110-1,120	Limestone as above.
1,120-1,130	Limestone as above but pellets fine to medium grained and poorly sorted. Microfauna includes *Gunteria floridana* Cushman and Ponton.
1,130-1,140	Limestone as above but texturally uniform, finely pelletal. Pellets are loosely bound with micritic limestone matrix. Much interparticle porosity (estimated 20 percent).
1,140-1,160	Limestone as above, porosity decreased to 10 percent. Most pores are filled with micritic limestone matrix.
1,160-1,170	Limestone (micrite), white (N9), hard, very finely crystalline, micritic, small isolated vugs common. Trace of pelecypod casts and molds. A few vugs filled with white gypsum.
1,170-1,180	Limestone as above, coarsely crystalline calcite (recrystallized) accounts for 30 percent of sample.
1,180-1,190	Limestone as at 1,100 to 1,110 ft. Pellets medium to coarse grained. No gypsum. Fauna includes *Pseudorbitolina cubensis* Cushman and Bermudez.

Depth (in feet)	*Lithology*
	Tertiary
	Early Eocene
	Oldsmar Formation
1,190-1,200	Dolomite, coarse-grained, light-gray (N7), friable, consists of interlocking mesh of coarsely euhedral dolomite crystals. High amount of vuggy and intercrystalline porosity (estimated 30 percent). Trace of white gypsum as vug fillings.

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