Age and Diagenesis of the Upper Floridan Aquifer and the Intermediate Aquifer System in Southwestern Florida

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By Lucy McCartan, Suzanne D. Weedman, G. Lynn Wingard, and Lucy E. Edwards, U.S. Geological Survey, and Peter J. Sugarman and Mark D. Feigenson, Rutgers University, and Marc L. Buursink and Julie C. Libarkin, U.S. Geological Survey

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Age and Diagenesis of the Upper Floridan Aquifer and the Intermediate Aquifer System in Southwestern Florida

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ABSTRACT

The age and diagenetic alteration of strata that constitute the Upper Floridan aquifer and intermediate aquifer system in southwestern Florida are assessed on the basis of samples taken from 12 cores and 1 set of cuttings from the upper 300 meters. Data were integrated from hand sample analysis; optical and scanning electron microscopy; and X-ray, isotopic, and paleontologic analyses. Diagenetic history is analyzed within a framework of past sea-level oscillations and modern ground-water chemistry. Both age and diagenetic data are integrated for a better understanding of a genetic stratigraphic framework of the aquifer and aquifer system.

Mollusk species and dinocyst assemblage distributions and $^{87}Sr/^{86}Sr$ values indicate that the "Suwannee" Limestone is early Oligocene and the Hawthorn Group ranges from late (possibly early) Oligocene to Pliocene. Within the Hawthorn Group, the Arcadia Formation ranges from late (possibly early) Oligocene to middle to earliest late Miocene; its Nocatee Member is late Oligocene and its Tampa Member ranges from late Oligocene to early Miocene; and the Peace River Formation is Pliocene. Diagenetic textures indicate that much of the alteration was early but that a magnesium mineral diagenetic facies characterized by dolomite, palygorskite, and sepiolite cross-cuts stratigraphy and may obscure stratigraphic correlations. Dolomite textures indicate a complex, multigenerational history; high saturation indices for dolomite in the modern Upper Floridan aquifer ground water suggest that modern dolomite precipitation, though volumetrically small, may be occurring.

Age data reported here indicate extensive deposition in the study area during the late Oligocene, conventionally thought to be a time of subaerial exposure and nondeposition across much of the Florida platform, and an unconformity of ≤10 m.y. between the Arcadia and Peace River Formations. The age data establish a framework that will help delineate a genetic stratigraphy based on depositional units rather than nongenetic lithostratigraphy. Diagenetic analysis indicates that most of the magnesium in the carbonates and clays may have been introduced prior to the establishment of the modern ground-water regime and that the magnesium-rich diagenetic facies cross-cuts stratigraphy and obscures stratigraphic correlations.

INTRODUCTION

The carbonates and siliciclastics of the Tertiary System of the Florida platform host the fresh ground-water supply for the region in three aquifer systems: the Floridan, the intermediate, and the surficial. Currently, this interval is subdivided into lithostratigraphic units on the basis of lithologic properties. Some of those lithologic properties, however, may include diagenetic (postdepositional) alteration, which can obscure stratigraphic boundary identification. Additionally, the ages of the lithostratigraphic units are not well constrained, and their boundaries may cross regional unconformities. The long-range objective of our study in southern Florida is to identify and map depositional, unconformity-bounded units in the subsurface, instead of nongenetic lithostratigraphic units; our focus is on the section that constitutes the upper portion of the Upper Floridan aquifer and the intermediate aquifer system. Delineating this genetic stratigraphy will enhance our ability to calibrate hydrologic models of the ground-water systems of Florida, as well as our understanding of part of the depositional history of the Florida platform. In addition, a genetic stratigraphy will provide the necessary geologic framework to predict hydrologic properties of aquifer rocks in areas that are sparsely drilled.

The results presented in this paper document our initial steps toward a genetic stratigraphy and include constraints on the age and correlation of subsurface strata and an assessment of their diagenetic alteration. Three independent time indicators are used: $^{87}Sr/^{86}Sr$ composition of shells, the distribution of mollusks species, and the distribution of dinocyst assemblages. Diagenetic alteration is examined petrographically with the scanning electron microscope (SEM) and by X-ray diffraction (XRD) and is compared with modern ground-water chemistry. This comparison

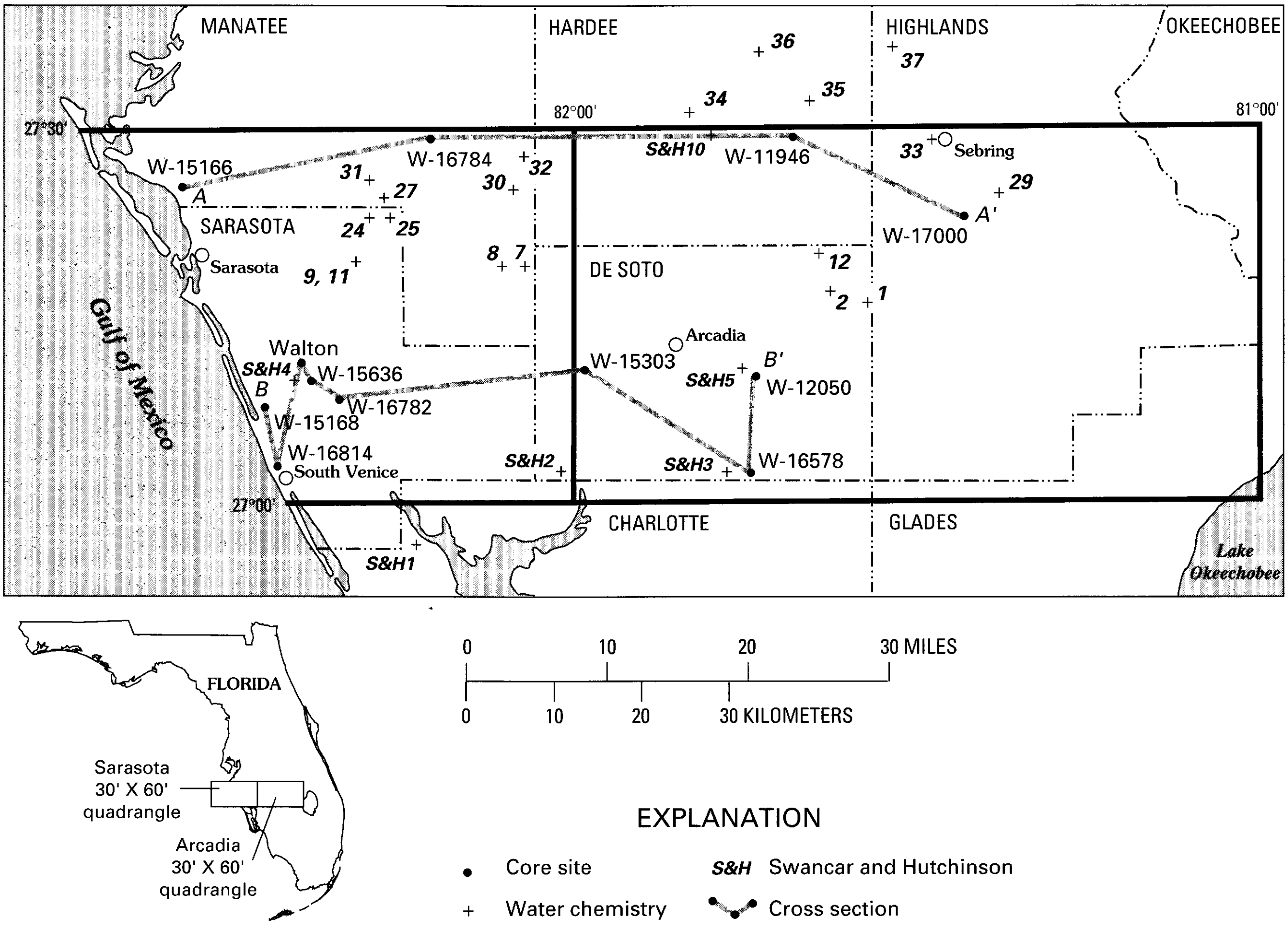

Figure 1. Map showing the location of boreholes in southwest Florida; cuttings only were examined from site W–15636. Cross sections *A–A'* and *B–B'* are discussed in the text and are shown in figures 2*A* and 2*B*; Sarasota and Arcadia quadrangles are outlined in bold lines and indicated on index map, lower left.

allows identification of relict diagenetic features that formed in different water chemistries in the past and enhances our understanding of the freshwater diagenetic environment in the aquifer system.

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GEOLOGIC FRAMEWORK

The study area (fig. 1) is underlain by a sequence of sediment and rocks several kilometers thick, ranging in age from Mesozoic to Holocene; most of the sequence was deposited in nearshore, relatively shallow marine environments (Mansfield, 1937; Petuch, 1982; Tedford and Hunter, 1984; Webb, 1990; and Jones and others, 1991). The upper 300–450 m of this sequence, which includes rocks of Eocene to Pliocene and Pleistocene age, is the subject of this report; we focus on Oligocene and Miocene deposits.

The complex distribution patterns of the lithofacies in the study area are the consequence of paleoshoreline migration and the convergence of coastlines along the Atlantic and the Gulf of Mexico. Shoreline migration has been attributed to eustatic sea-level oscillations (Haq and others, 1987; Dowsett and Cronin, 1990; Krantz, 1991; McCartan and others, 1991; Muhs and others, 1992), tectonic uplift (to the north, beneath the Ocala arch; inferred from distribution of Oligocene and Miocene rocks; Puri and others, 1967; Gohn, 1988) and subsidence (to the south; Herrick and Vorhis, 1963), and subsidence due to dissolution of carbonate rocks (Beck and Sinclair, 1986). The position and configuration of the Florida peninsula also has increased the complexity of the deposits, particularly during and since the late Oligocene. Longshore currents sweep siliciclastic sediment southward from river mouths in northern Florida and Georgia along both sides of the peninsula (Martens, 1928; McCartan and Owens, 1991); in the study area they interfinger with locally produced carbonates and phosphates.

In this paper, we use the lithostratigraphy of the Florida Geological Survey proposed by Scott (1988) as a frame of reference. Scott (1988) subdivided the section we have examined into the Ocala Group, the "Suwannee" Limestone, and the Hawthorn Group (Arcadia and Peace River Formations). The Ocala Group consists largely of very porous limestone, thought to be late Eocene, that forms much of the Floridan aquifer system; it was first described by Dall and Harris (1892) near Ocala in Marion County, Fla., and is subdivided into a locally dolomitized, lower grainstone and an upper packstone/wackestone, typically containing large foraminifers (Miller, 1986). The Ocala Group includes the Crystal River and Williston Formations; few of the cores examined in this study penetrate the Ocala.

Overlying the Ocala Group in the study area is a white to cream, vuggy molluscan and foraminiferal limestone that Scott (1988) refers to as the "Suwannee" Limestone with some uncertainty. Over the years, the age of the Suwannee Limestone has alternately been placed in either the early, the late, or the entire Oligocene. The Suwannee Limestone was originally named by Cooke and Mansfield (1936) for exposures along the Suwannee River from Ellaville to near White Springs, in northern Florida; they stated that the Suwannee "unconformably overlies white limestone containing Vicksburg (Oligocene) fossils" (Cooke and Mansfield, 1936, p. 71), implying that the Suwannee is Vicksburgian age or younger. In the present day, Vicksburgian is restricted to the early Oligocene, but in 1936 the term "Vicksburg Group" was used by the U.S. Geological Survey (USGS) to refer to all Oligocene deposits in the gulf coast region (MacNeil, 1944, p. 1313). Further confusion occurred when MacNeil (1944) revised the concept of the Vicksburg by restricting its use to deposits of middle Oligocene age; in his abstract and throughout his paper, he places the Suwannee Limestone in the upper Oligocene, overlying deposits of the Vicksburg Group. In an easily overlooked footnote, however, MacNeil concluded that the Suwannee may be equivalent in age to the Marianna Limestone and Byram Formation, Vicksburg Group (subsequent studies, for example MacNeil and Dockery, 1984, indicate an early Oligocene age), as well as the late Oligocene Chickasawhay Limestone (MacNeil, 1944, p. 1313–1314, footnote 3). The confusion about whether the Suwannee Limestone is late or early Oligocene or whether it spans the Oligocene continues to this day (see, for example, AAPG, 1988). We agree with Scott (1988): in the study area, the limestone, which commonly has been identified as the Suwannee, may not be correlative with the Suwannee Limestone from the type area. Until a correlation can be demonstrated, or a new assignment made, we will retain Scott's usage of Suwannee in quotation marks.

The Hawthorn Formation was raised to group status by Scott (1988) and includes the Arcadia and Peace River Formations. The Arcadia Formation encompasses the carbonates and associated siliciclastics overlying the "Suwannee" Limestone and is thought to be early early to late early Miocene (Scott, 1988); the type section is in core W–12050 (De Soto County). The Arcadia Formation comprises limestones and dolomites with different amounts of quartz sand, clay, and phosphate grains and in places is subdivided into two members, the Nocatee and the Tampa; the remainder is referred to as undifferentiated Arcadia Formation. The Nocatee Member, named by Scott (1988), is primarily a siliciclastic unit, which comprises quartz sand and clays, with some carbonates and locally abundant phosphate sand and fine gravel, and which occurs at, or near, the base of the Arcadia Formation. The Tampa Member, above or laterally adjacent to the Nocatee Member, is a limestone with different amounts of quartz sand, dolomite, and clays and is distinguished from other Hawthorn Group carbonates by having less than 3 percent phosphate grains. Scott (1988) reduced the Tampa Formation as used by King and Wright (1979) to member status on the basis of its limited spatial extent and suggests that the Tampa Member may straddle the Oligocene–Miocene boundary (Paul Huddelstun, Georgia Geological Survey, personal communication 1984, in Scott, 1988). The Tampa Member in its type area at Tampa and at other places around Tampa Bay (Ballast Point and Six Mile Creek, Tampa Bay, Fla.; Dall and Harris, 1892) differs in appearance from the Tampa Member elsewhere; therefore, a reference core (W–15166) in Manatee County has been proposed (Scott, 1988).

Disconformably overlying the Arcadia Formation, in the uppermost Hawthorn Group, is the poorly indurated, siliciclastic Peace River Formation (upper Miocene, according to Scott, 1988). The Peace River Formation consists of interbedded quartz sand, clay, and carbonates (<33 percent) as well as minor amounts of chert. The Bone Valley Formation (Altschuler and others, 1964), a clastic unit of pebble- to cobble-sized phosphate clasts in a matrix of quartz and phosphate sand and clay, originally described by Matson and Clapp (1909) as the Bone Valley gravels, is now considered a member within the Peace River Formation (Scott, 1988) and is not differentiated in this report.

Joyner and Sutcliffe (1976) identified a clay bed (5–7 m thick) at the base of the overlying Tamiami Formation (Pliocene) in central and southwestern Sarasota County. They informally referred to this bed as the Venice clay (Joyner and Sutcliffe, 1976; Sutcliffe and Thompson, 1983). Because of the informal nature of the stratigraphic name and the lack of a rigorous description, some uncertainty persists in stratigraphic placement of this clay bed, and in whether several similar clay beds may be present. Lynn Barr (USGS, oral communication, 1993) mapped the extent of a clay unit (referred to in the field as the "Venice clay") as a confining layer near the top of the intermediate aquifer system.

Deposits stratigraphically younger than the Hawthorn Group are composed of thin, overlapping sheets and lenses of sand and mud, with local concentrations of shells and phosphatic gravel of late Pliocene and Pleistocene age (Jones and others, 1991; McCartan and others, 1991). A few remnants of lower Pliocene deposits are known near the gulf coast (Jones and others, 1991), and Holocene swamp and eolian deposits have been recognized in patches at the surface (Watts, 1980; McCartan and Rubin, 1991). These deposits form the surficial aquifer system, and in this report, we do not differentiate among them.

The complex diagenetic history of Tertiary rocks in west-central Florida has been noted and discussed by Randazzo and Zachos (1984), Randazzo and Cook (1987), Budd and others (1993), and Jones and others (1993). Budd and Jones and their colleagues focus on calcite diagenesis in the "Suwannee" Limestone in approximately the same study area as ours. Our study includes younger strata and places a greater emphasis on dolomite and fibrous magnesian clays, palygorskite and sepiolite, whose coincidence in these rocks has been noted previously (Randazzo and Zachos, 1984; McCartan and others, 1992). The postdepositional roles of magnesium and silica, critical in the formation of sepiolite and palygorskite, have been discussed by Callen (1984), Singer and Galan (1984), and Weaver (1984).

HYDROGEOLOGIC FRAMEWORK

Three major aquifer systems occur in the study area, and the rocks containing these aquifer systems have been classified into formal hydrogeologic units (Southeastern Geological Society 1986); however, it is important to note that the boundaries of the hydrologic systems do not coincide with either lithostratigraphic or chronostratigraphic boundaries. The unconfined surficial aquifer system is found over most of the State and consists of unconsolidated to weakly consolidated siliciclastic deposits. The deeper intermediate aquifer system is found throughout the study area and consists of anastomosing, permeable siliciclastic and carbonate deposits with subregional, clayey upper confining units, and other local zones of low permeability (Duerr and others, 1988). The Floridan aquifer system is typically divided into upper and lower parts; our study does not extend to the base of the Upper Floridan aquifer, so the term "Upper Floridan aquifer" in this report refers to the upper part of that aquifer. The Upper Floridan aquifer consists mainly of limestones and dolomites that underlie the intermediate aquifer system in the study area, and has been studied as part of the USGS's Regional Aquifer System Assessment project by Ryder (1985), Miller (1986), Bush and Johnston (1988), Johnston and Bush (1988), Meyer (1989), and Sprinkle (1989). The configuration of the top of the Upper Floridan aquifer has been mapped in the study area by Buono and Rutledge (1979) and the thickness of the intermediate aquifer system has been mapped by Buono and others (1979). The hydrogeochemistry of Florida has been investigated further by Hanshaw and others (1971), Plummer (1975), Wigley and Plummer (1976), Hanshaw and Back (1979), Katz (1992), and Swancar and Hutchinson (in press).

FIELD AND LABORATORY METHODS

Subsurface samples from 10 cores and from 1 set of cuttings, stored at the Florida Geological Survey, Tallahassee, and also from 1 core at the USGS, Reston, Va., were examined for age determinations, mineralogy, and petrography; geophysical logs were obtained from 9 of those cores from the USGS and the Southwest Florida Water Management District (table 1).

$^{87}Sr/^{86}Sr$ analyses were performed at Rutgers University on 16 mollusk shells and 1 foraminifer from the top 200 m in the study area. Original aragonite or calcite, or slightly recrystallized calcite, shells were cleaned, crushed, and dissolved in a solution of 1.5 N HCl. Ion exchange (Hart and Brooks, 1974) was used to separate strontium for analysis on a mass spectrometer, with an intrarun precision on this instrument of ±0.000008 and an interrun variability of about 0.000026 to 0.000030 (Miller and others, 1991). The National Bureau of Standards strontium sample ratio at Rutgers University is 0.710252 (2 σ standard deviation is 0.000026; n=35) normalized to $^{86}Sr/^{88}Sr$ of 0.1194 (Miller and others, 1991). Numerical ages were estimated using the regression equations of Miller and others (1988, 1991), Hodell and others (1991), and Oslick and others (1992,

Table 1. Core locations and sample information

[Dino=Dinocysts; Moll=Mollusks; Sr=Strontium isotope dating; Xrd=X-ray diffraction; Ts=Microscope and SEM; Litho=Lithologic logs; Geophy=Geophysical logs; *Cuttings only]

Core	Elevation		Core Length		County	Latitude North	Latitude West	Dino	Moll	Sr	XRD	Ts	Litho	Geophy
	(m)	(ft)	(m)	(ft)										
W–15166	2	8	193	634	Manatee	27°25'10"	82°34'57"	—	—	1	—	—	X	X
W–16784	21	70	331	1088	Manatee	27°28'30"	82°12'45"	—	—	—	31	11	X	X
W–11946	20	67	143	470	Hardee	27°27'50"	81°41'45"	—	—	2	32	3	X	—
W–17000	26	85	398	1304	Highlands	27°23'10"	81°27'15"	—	—	2	52	12	X	X
W–15168	4	14	199	654	Sarasota	27°08'08"	82°27'05"	2	—	1	5	—	X	X
Walton site (USGS)	5	16	92	304	Sarasota	27°11'43"	82°24'03"	2	—	—	39	2	X	X
W–15636*	5	15	276	906	Sarasota	27°09'19"	82°23'42"	—	—	1	—	—	X	X
W–16782	3	11	177	580	Sarasota	27°08'04"	82°21'05"	—	1	5	63	13	X	X
W–16814	4	13	213	701	Sarasota	27°02'40"	82°23'57"	3	7	2	86	12	X	X
W–15303	7	22	436	1430	DeSoto	27°10'26"	82°49'30"	—	3	—	24	—	X	X
W–12050	19	62	183	600	DeSoto	27°10'00"	81°43'11"	—	1	4	28	5	X	—
W–16578	13	41	345	1133	DeSoto	27°02'25"	81°44'33"	—	3	—	—	—	X	—

1994); stage boundaries are based on the time scale of Berggren and others (1985).

Dinocysts were separated from fine-grained unlithified samples in hydrochloric and hydrofluoric acids, and their occurrences were compared to published range data for the individual taxa. Emphasis was placed on ranges in the mid-Atlantic region (Stover, 1977; Edwards, 1986, 1991; Verteuil and Norris, 1992), but worldwide compilations also were used (Williams and Bujak, 1985; Haq and others, 1987; Powell, 1992). Mollusks were analyzed primarily from internal and external molds or from latex casts of the molds. The large size of many of the preserved mollusks, relative to the core diameter, limits the investigation to time ranges of individual species rather than assemblages. Within the core studied, *Turritella* species are relatively abundant, easily identifiable and well preserved, even as molds or casts; are fairly widespread geographically; and appear to have evolved rapidly. These characteristics make the turritellids good biostratigraphic indicators.

Samples for XRD were prepared from whole-rock subsamples or from the fraction finer than 2 micrometers that was concentrated by centrifuge-separation (Soller and Owens, 1991). Although these methods do not produce identical peak heights (intensities)—because the first inhibits parallel orientation of planar and fibrous minerals whereas the second enhances orientation—several duplicate test runs produced comparable results. Untreated centrifuge samples that exhibited approximately 15-nanometer peaks were treated with ethylene glycol; a peak shift to approximately 17 nanometers indicates illite/smectite mixed-layer clay, whereas dioctahedral vermiculite peaks do not shift with this treatment. Minerals were identified by matching one or more major peaks with published standards (Joint Commission on Powder Diffraction Standards, 1974, 1981).

Geophysical logs are available for 9 of the 12 boreholes from the Southwest Florida Water Management District and the USGS. Logs from five of the nine boreholes have been included in various previously published reports, but four are presented here for the first time: Walton, W–16782, and W–16814 were logged by the USGS, and W–17000 was logged by Southwest Florida Water Management District. The primary use of geophysical logs in southern Florida is as a tool for correlation of boreholes with and without cores. The electric logs, single point (SP) and resistivity (Res), were run prior to casing the holes and natural gamma radiation logs were run after the hole was cased. The SP logging instrument was not available for W–16814. Electric logging was performed in three increments at W–16782, between drilling and setting casings, to obtain as complete records as possible. On electric logs, electrical conductivity (for SP) and resistance values increase to the right, and natural gamma radiation values increase to the right on gamma logs. In all logs, the geophysical signature, which is the frequency and amplitude of spikes, was a characteristic used in correlation of rock units. Of the three types of logs, gamma logs are considered potentially the most useful for tracking lithologic boundaries, so individual gamma spikes and groups of spikes were compared with lithologic contacts discerned in the cores.

Blue-dyed, epoxy-impregnated thin sections from 58 samples were examined with a petrographic microscope, and selected sample chips and polished thin sections were examined with the SEM. All thin sections were dyed with Alizarine red S to differentiate calcite from dolomite (method of Friedman, 1959).

Unpublished water-chemistry data were obtained from 19 water samples taken from 18 wells (within the study area) that are open in the stratigraphic and hydrologic

Table 2. $^{87}Sr/^{86}Sr$ age estimates[1]

Core	Depth (m)	Depth (ft)	$^{87}Sr/^{86}Sr$	Age (Ma)	Age Epoch
W–12050	25.0–26.5	82.0–87.0	0.708980±6	5.1	Pliocene
W–17000	95.4	313.0	0.708730±7	16.7	Miocene
W–15636	88.4–89.9	290.0–295.0	0.708595±13	18.9	
W–12050	57.3	188.0	0.708534±10	19.7	
W–12050	87.1	286.0	0.708379±4	22.3	
W–15166	87.3	286.4	0.708342±8	22.9	
W–17000	114.0	374.0	0.708216±9	25.3	Late Oligocene
W–16782	70.1	230.0	0.708192±6	26.0	
W–16782	79.2	260.0	0.708182±6	26.3	
W–16814	118.4	388.5	0.708166±5	26.8	
W–16782	96.6	317.1	0.708163±8	26.8	
W–16782	94.7	310.8	0.708153±6	27.1	
W–15168	116.3	381.5	0.708127±5	27.9	
W–11946	55.3	181.5	0.708101±18	28.6	
W–16814	200.9	659.0	0.708042±5	30.3	Early Oligocene
W–12050	178.6	586.0	0.707927±8	33.6	
W–11946	140.2	460.0	0.707853±8	35.8	

[1]Regression curves for age estimates: Pliocene, Hodell and others, 1991; Miocene, Miller and others, 1991; Oslick and others, 1992, 1994; Oligocene, Miller and others, 1988. Time scale for all regression curves from Berggren and others, 1985.

intervals of interest. Saturation indices (SI) for calcite and ordered dolomite were calculated at the USGS, National Center, using a slightly modified version of the WATEQF program of Plummer and others (1978) (Niel Plummer and Eric Prestemon, USGS, written communication, 1993). These data were supplemented by similar SI data from seven wells reported by Swancar and Hutchinson (in press). WATEQF input requirements for a large number of ions and <30 percent error in charge balance eliminated more than 2,500 of the chemical analyses available. The SI for a water sample with respect to a given mineral is defined as the following:

$$SI = \log\ [IAP/K_{sp}]$$

where IAP is the measured ion activity product and K_{sp} is the calculated solubility product at equilibrium for the dissolution reaction of interest. An SI value of 0±0.5 is considered equal to 0, meaning that the water is exactly saturated with a given dissolved mineral species; SI<–0.5 indicates undersaturation and that the mineral is susceptible to dissolution; SI>0.5 indicates supersaturation and, from a thermodynamic point of view, that precipitation of the mineral is possible (Stumm and Morgan, 1981).

RESULTS

The contributions of this study are age estimates for subsurface lithostratigraphic units and a regional understanding of diagenetic history. Strontium isotope and paleontologic age estimates for rocks in the upper 266 m in the study area constrain the time of deposition of the lithostratigraphic units of Scott (1988). Through investigation of mineralogy and texture, we differentiate primary and diagenetic features, and we use modern water chemistry to identify relict diagenetic alteration. Strontium isotopic age estimates are given in table 2; lithostratigraphy is shown for all cores in two cross-sections in figures 2A and 2B; XRD mineralogy is given for W–16814 in table 3; the effects of diagenetic processes observed in selected thin sections are illustrated in figures 3 and 4 and are summarized for all samples in table 4; the distribution of diagenetic magnesium-rich minerals (from XRD data) is shown in figures 5*A* and 5*B*; and modern ground-water chemistry and SI analyses are given in table 5.

^{87}SR/^{86}SR AND PALEONTOLOGIC AGE ESTIMATES

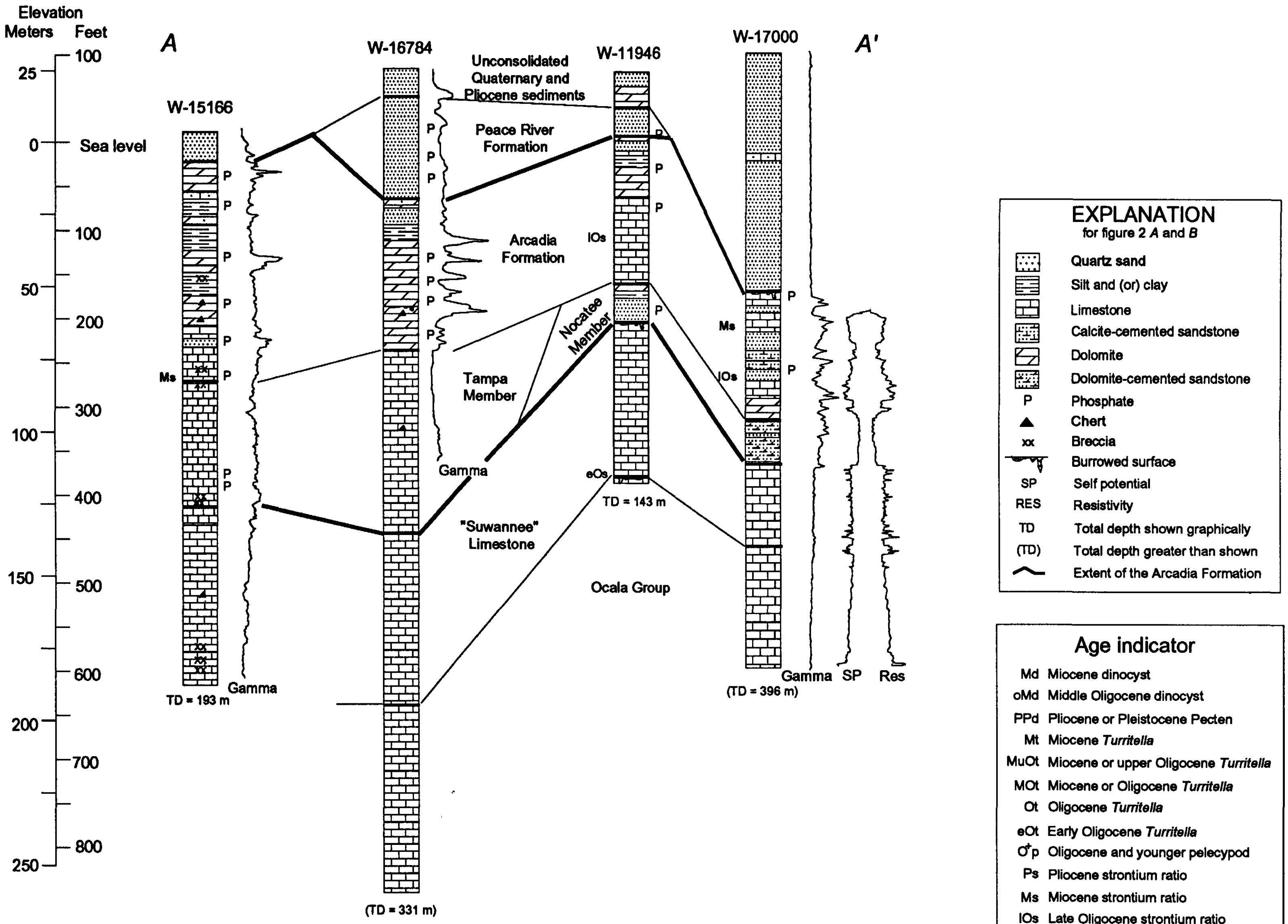
The $^{87}Sr/^{86}Sr$ values of shell samples from the top 200 m in the study area indicate numerical age estimates that range from 5.1 Ma in the Peace River Formation to 36.1 Ma in the "Suwannee" Limestone (table 2). The locations of the molluscan and dinocyst samples and the samples used in the strontium analysis are indicated on the cross-sections (figs. 2*A* and 2*B*).

The core at W–16814 provides our best integration of isotopic and paleontologic data (fig. 2*B*). Analysis of

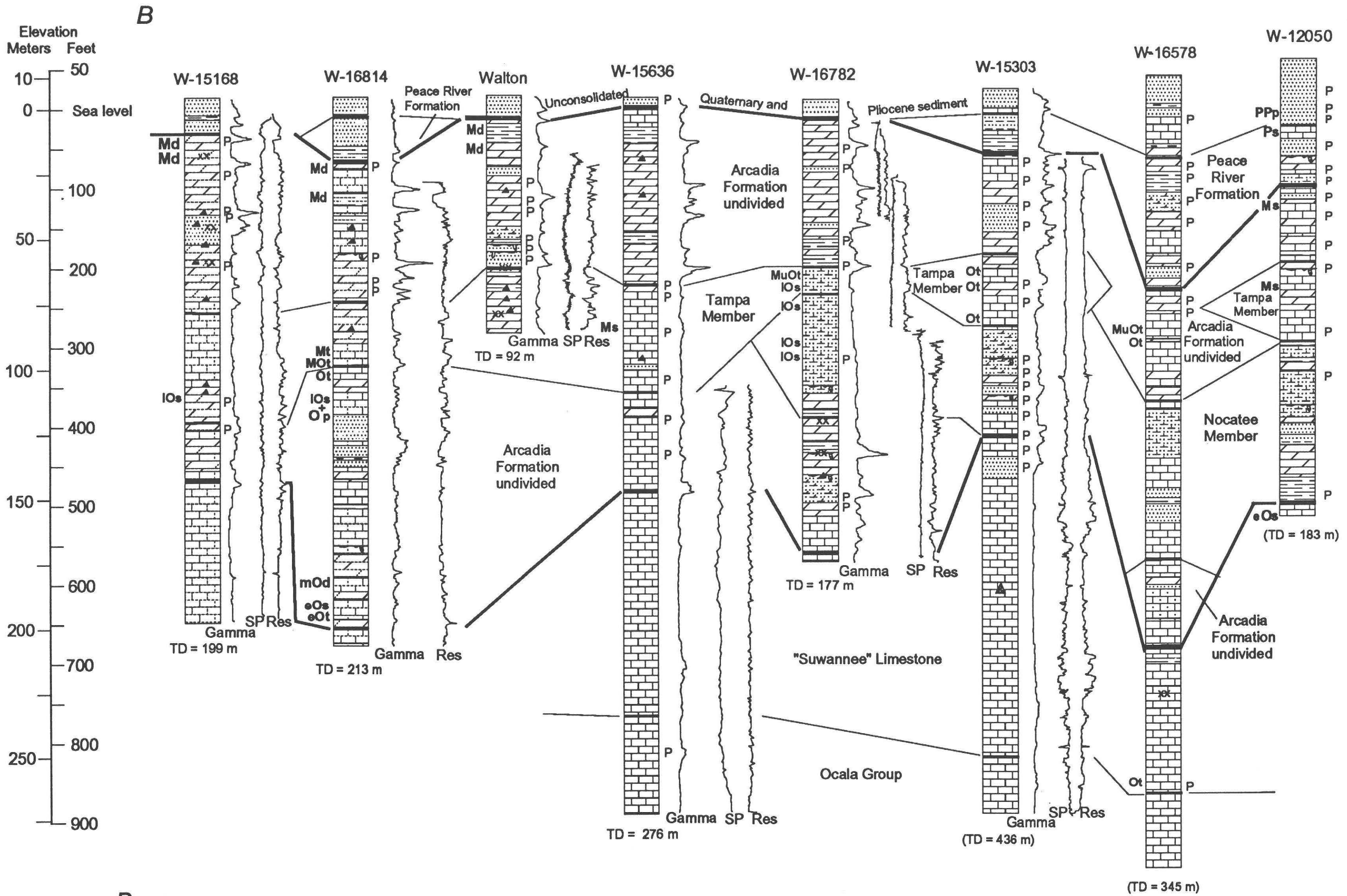
Table 3. Mineralogy of the South Venice core (W–16814). Minerals identified by X-ray diffraction

[I/S, illite smectite mixed-layer clay; Se, sepiolite; P, palygorskite; I, illite; K, kaolinite; ?, possible occurrence; T, trace: ✓, mineral present; ✓✓, dominant XRD peak @, prepared with amyl acetate; cristobalite (opal-CT) is present at 57.2 m; L, light phase; D, dark phase. Empty cells mean mineral not detected. Depth in meters below surface.]

Depth	I/S	Se	P	I	K	Q	C	D
0.3	92			?	8	✓	✓	
1	100					✓✓		
1.5	100					✓		
2.7					T	T		
4.4	100				T			
4.7	T			53	47	✓		
5.2@						✓✓		
5.9					100			
6.6	85				15		✓	
7.0	89				11		✓✓	
7.2							✓	
7.5	100						✓	
8.1	90				10			
12.2	89			10	1	✓		✓
14.5	85	T		14	1	✓		✓
18.6	82			17	1	✓		
21.7	51	42		7	T			T
22.1	46	43		11		✓		
24.7	45	36	T	18		✓		
25.9@						✓		✓✓
28.7@						✓		✓✓
30.2		46	54			✓		✓
31.9@			T			T		✓✓
34.9@			T			✓		✓✓
37.8	35	31	26	8		✓		✓
38.3	39	25	25	11		✓		
40.6	53	16	23	8		✓		
42.5@								✓✓
45.1@			T					✓✓
47.5		32	68			✓		
48.5@		23	77			✓		✓✓
50.3@			T			?		✓✓
51.3@			T					✓✓
55.1@			100					✓✓
55.7@		24	76			✓		✓✓
61.0@			100					✓✓
67.3@		T				T		✓✓
69.5L@			T			?		✓✓
69.5D@			100			✓		✓✓
73.2@			100			T		✓✓
79.3@		25	75			✓		✓✓
82.9@		56	44					✓✓
87.6	22	33	36	9		✓		✓
88.9	15	22	52	11		✓		✓
90.9		31	63	6		✓		✓
92.8	?	36	61	3		✓		
93.9@								✓✓
97.9@							✓✓	T
101.9@							✓✓	
106.0@			T				✓✓	T
108.0@							✓	
109.3@						✓	T	✓✓
112.1@						✓		✓✓
112.9@						✓	✓✓	
113.8		100					✓✓	
118.5@							✓✓	
121.6@			T			✓		✓✓
125.7@						✓		✓✓
136.7@	?					✓✓		✓
139.0@		34	66			✓✓		✓
142.6L		100	T			✓	✓	?
142.6D		100	T			✓	✓	?
146.4@						✓	✓	✓✓
149.7@		T					✓✓	✓
152.1@						✓		✓✓
157.3@		T				✓		✓✓
164.2@							✓✓	T
170.2@						✓	✓	✓✓
173.9@		75	25			✓✓		
174.5@		64	36			✓	✓✓	✓
179.6@		72	28			✓		✓
182.2@			T					✓✓
183.8@		57	43			✓		✓✓
184.9@		72	28					?
188.0@		51	49			✓		✓✓
190.3@		82	18			✓		✓
193.1@							✓✓	
194.2L@		65	35			✓	✓✓	
194.2D@		68	32			✓✓	✓	✓
198.0@						✓	✓✓	✓
201.0@		T				✓	✓	✓✓
202.1@						✓	✓	✓✓
203.2@		100				✓	T	✓✓
205.3@							✓✓	
206.5@							✓✓	
212.3@							✓✓	


Elevation
Meters Feet
25 100
0 Sea level
50
100
150
200
250
200
300
400
500
600
700
800
A
A'
W-15166
W-16784
W-11946
W-17000
Unconsolidated Quaternary and Pliocene sediments
Peace River Formation
Arcadia Formation
Tampa Member
Nocatee Member
"Suwannee" Limestone
Ocala Group
Gamma
SP
Res
Ms
lOs
eOs
TD = 193 m
(TD = 331 m)
TD = 143 m
(TD = 396 m)
EXPLANATION
for figure 2 A and B
Quartz sand
Silt and (or) clay
Limestone
Calcite-cemented sandstone
Dolomite
Dolomite-cemented sandstone
P Phosphate
Chert
xx Breccia
Burrowed surface
SP Self potential
RES Resistivity
TD Total depth shown graphically
(TD) Total depth greater than shown
Extent of the Arcadia Formation
Age indicator
Md Miocene dinocyst
oMd Middle Oligocene dinocyst
PPd Pliocene or Pleistocene Pecten
Mt Miocene Turritella
MuOt Miocene or upper Oligocene Turritella
MOt Miocene or Oligocene Turritella
Ot Oligocene Turritella
eOt Early Oligocene Turritella
O+p Oligocene and younger pelecypod
Ps Pliocene strontium ratio
Ms Miocene strontium ratio
lOs Late Oligocene strontium ratio
eOs Early Oligocene strontium ratio

A



B

Figure 2. Generalized east-west transects of cores showing lithology, geophysical logs, and age indicators. (*A*) Cross section *A–A'*, northern transect; (*B*) cross section *B–B'*, southern transect; symbols used in cross sections are indicated on key.

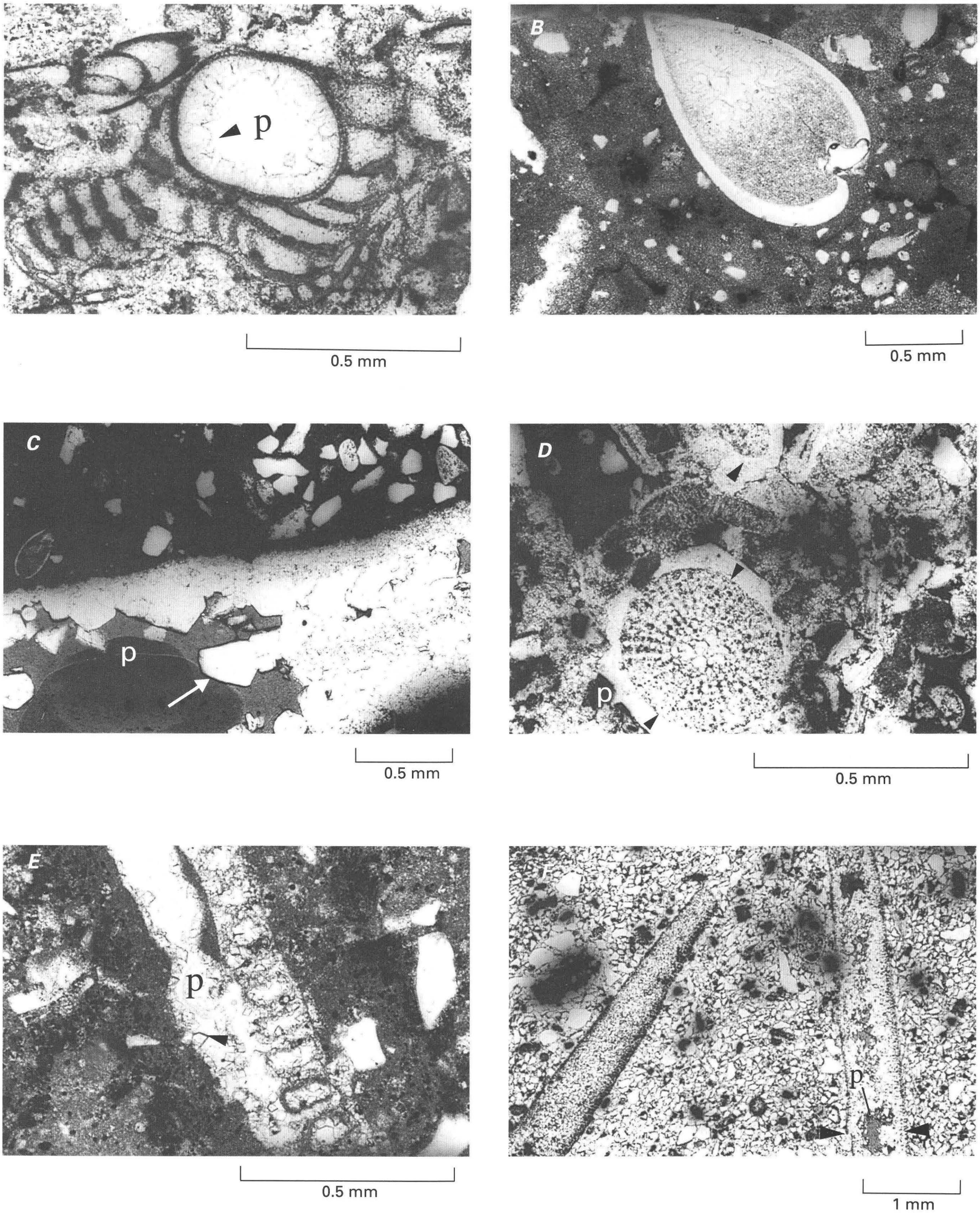


Figure 3. See caption on facing page.

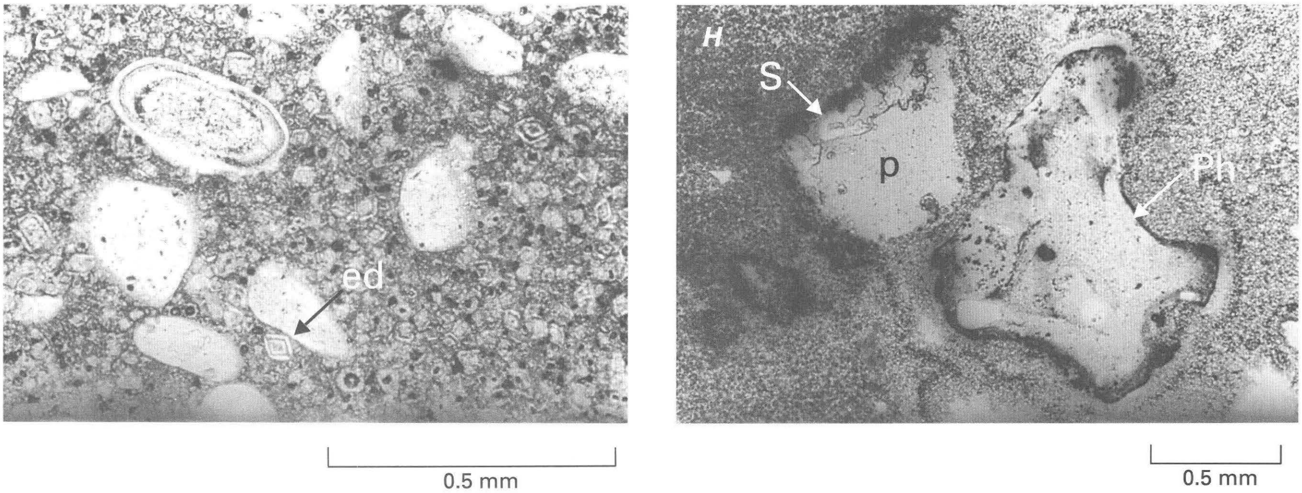


Figure 3. Plane-polarized-light optical photomicrographs of diagenetic textures. (*A*) W–16782, 70.2 m, micritized foraminifer with intraparticle calcite cement (arrow) in porosity (p). (*B*) W–16814, 193.1 m, blocky calcite cement predates shell dissolution and nearly fills primary porosity over geopetal infilling of leached bivalve, matrix is micrite. (*C*) W–11946, 57.1 m, mollusk moldic porosity (p) is partially filled with postdissolution blocky calcite (arrow); dark micrite matrix holds quartz (white) and phosphate (speckled) grains; small dolomite rhombs occur in this sample but are not visible in this view. (*D*) W–12050, 182.9 m, echinoid spine and fragments (arrows) with syntaxial calcite overgrowths into interparticle porosity (p); fine calcite rim cement coats other grains. (*E*) W–16814, 122.6 m, fossil moldic porosity (p), (probably a benthic foraminifer) lined with limpid (inclusion-free) dolomite (arrow), matrix is brown dolomicrite, white grains are fine quartz sand. (*F*) W–17000, 126.4 m, sandy dolostone with partially filled molds of two echinoderm plates and other fossils, dolomite infilling at arrows is in optical continuity, but the echinoid has dissolved leaving a dolmicritic, microporosity filling of the original shell; white grains are quartz sand and silt; gray areas are dyed porosity-filling epoxy (p). (*G*) W–11946, 32.6 m, dyed epoxy-impregnated (forms gray background) claystone of palygorskite (confirmed by XRD) with floating etched dolomite (ed) rhombs; grains are quartz (white) and concentrically layered phosphate grains (speckled); dolomite rhombs show several etched layers (arrow, lower right). (*H*) W–16784, 84.8 m, dolomicrite with leached phosphate grains (Ph, right arrow) that are white in the middle and dark around the margins, dyed porosity-filling epoxy is gray (p), matrix retains shape of the original phosphate clast; white botryoidal silica coats void surface (S, left arrow).

dinocyst assemblages from three depths indicates the following ages: (1) 24.9 m, middle Miocene, or slightly younger; (2) 38.1 m, early to middle Miocene; (3) 187.8–187.9 m, latest early Oligocene or earliest late Oligocene (the *Globoratalia opima opima* zone). The shallowest dinocyst assemblage indicates that the beds referred to in the field as the "Venice clay" (L. Barr, oral communication), is middle Miocene or slightly younger and is a part of the Arcadia Formation. Molluscan data from W–16814 indicate that the Oligocene–Miocene boundary may be crossed between 97.7 and 102.7 m depth. *Turritella* cf. *T. tarponensis* Mansfield, 1937, found at 97.7 m, and *Turritella* aff. *T. pagodaeformis* Heilprin, 1887, found at 97.8 m, resemble species generally considered to be early Miocene (Heilprin, 1887; Mansfield, 1937). *Turritella* cf. *T. tampae* Heilprin, 1887, was found from 100.6 to 101.5 m; *T. tampae* has long been considered early Miocene on the basis of its occurrence in the interval now designated the Tampa Member of the Arcadia Formation (Heilprin, 1887; Dall, 1892; Mansfield, 1937; Cooke, 1945), but a revision in age of the Tampa Member considered herein would lower the range of *Turritella tampae* into the late Oligocene (this agrees with the observations of Ward, 1992, p. 119–120). *Turritella* cf. *T. bowenae* Mansfield, 1937, was found at 103.0 m; *T. bowenae* is typical of the Suwannee Limestone (Mansfield, 1937). A *Trigoniocardia* sp. from 118.4 m brackets that sample as Oligocene or younger (Keen, 1969). The most definitive mollusk was *Turritella caelatura* Conrad, 1848, found in samples from 197.9 to 200.9 m; this species has been reported only from the lower Oligocene (Vicksburgian) Mint Springs Formation of Mississippi (MacNeil and Dockery, 1984). The paleontologic samples analyzed at W–16814 agree with the $^{87}Sr/^{86}Sr$ age estimates of 30.3 Ma (early Oligocene) for samples from 200.9 m and 26.8 Ma (late Oligocene) for samples from 118.4 m.

Dinocyst assemblage data from the core at W–15168 indicate an early to middle Miocene age for samples from both 18.3 m and 21.6 m; samples from 14.8 m and 20.1 m in the Walton core also indicate an early to middle Miocene age. The molluscan species *Turritella* cf. *T. tampae* Heilprin, 1887, was found at 69.2 m in the core at W–16782; at 69 m the $^{87}Sr/^{86}Sr$ age estimate is 26.0 Ma (late Oligocene), an age that is consistent with the revised range for *Turritella tampae*. In the core at W–16578, *Turritella* cf. *T. tampae* Heilprin, 1887, was found at 99.1 m, and *Turritella* cf. *T. bowenae* Mansfield, 1937, was found at 100.6 m. The

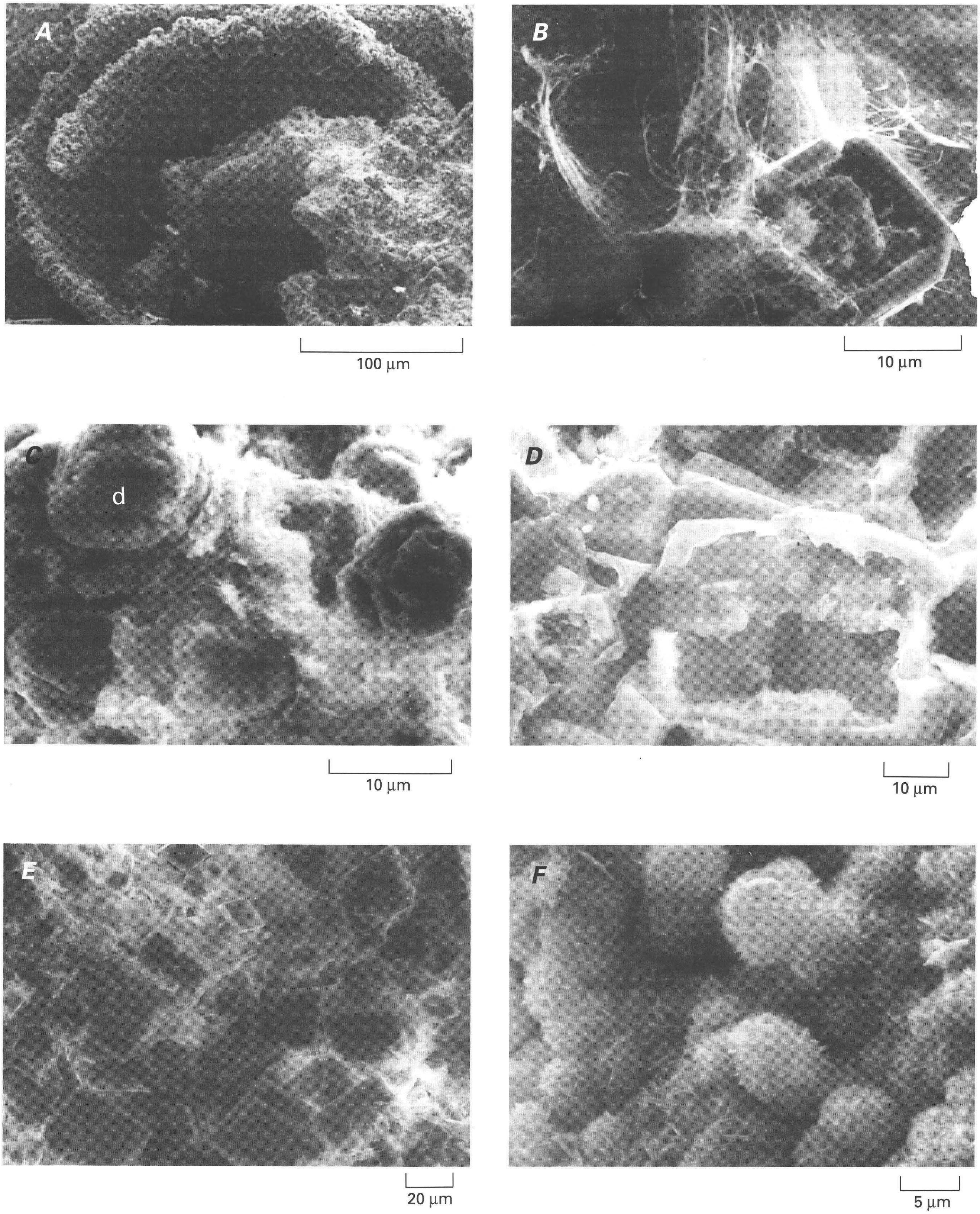


Figure 4. SEM images of selected sample chips. (*A*) W–17000, 156.8 m, micritized foraminifer; sample is all calcite. (*B*) W–11946, 32.6 m, dolomite rhomb with zoned etching and fibrous palygorskite. (*C*) W–16784, 91.3 m, dolomite (d) with etched outer surface in a palygorskite matrix. (*D*) W–16814, 61.0 m, intergrown dolomite rhombs with etched centers, no clays present. (*E*) W–16814, 82.9 m, dolomite rhombs (not etched) and fibrous palygorskite. (*F*) Walton, 80.2 m, opal-CT lepispheres resting on an etched phosphate grain not on image.

Table 4. Petrographic observations of diagenetic alteration processes

[1=shell micritization; 2=shell dissolution; 3=equant calcite cement; 4=calcite overgrowths on echinoid pieces; 5=dolomite; 6=dolomite replacement of, or overgrowths on, echinoid pieces; 7=etched dolomite; 8=phosphate grain dissolution; 9=amorphous silica cement]

Sample	1	2	3	4	5	6	7	8	9
W–11946									
32.6	X	X	X		X	X	X	X	
57.1	X	X	X		X			X	
140.3	X	X	X						
W–12050									
64.1	X	X			X	X			
92.7	X	X	X						
135.4	X	X	X	X					
162.0	X	X	X	X				X	
182.9	X	X	X	X					
Walton									
27.5	X	X				X	X	X	
80.2								X	X
W–17000									
88.8					X			X	
94.6	X	X	X		X		X	X	
117.8	X	X	X						
123.0	X	X	X						X
126.5	X	X	X	X	X	X			
146.2	X	X	X	X					
156.8	X	X	X	X					
168.7	X	X	X	X					
175.7	X	X	X	X					
194.7	X		X	X				X	
210.4	X								
W–16782									
30.6					X		X	X	X
39.0		X			X	X	X	X	
57.3	X				X		X	X	X
70.2	X	X	X	X					
74.9	X	X							
87.6	X	X							
W–16782—continued									
97.7	X	X	X						
108.1	X	X							
122.6					X				
126.3					X				
154.3					X				
171.7	X	X	X						
176.4	X								
W–16784									
52.5		X			X		X		
62.7							X		
84.8		X			X	X	X	X	X
91.3					X		X		
95.6					X		X	X	
103.2	X	X	X	X					
114.1	X	X	X						
121.1	X	X	X						
216.1	X	X	X	X					
265.0	X	X							
321.5					X				
W–16814									
24.9	X				X	X	X		
61.0					X	X	X		X
69.5		X			X	X	X	X	
73.2					X	X	X		
82.9					X	X		X	
106.0	X			X	X				
122.6	X	X			X	X			
136.6	X	X			X				
146.4					X				X
149.7	X		X	X	X				
157.3					X				
193.1	X	X	X						X

occurrence of *Turritella* cf. *T. tampae* and *T.* cf. *T. bowenae* within a few meters of each other was seen at W–16814 as well as at W–16578 and may prove to be a significant biostratigraphic marker. *Turritella* cf. *T. halensis* Dall, 1917, was found at 270.4 m in W–16578 and at 70.7 m, 73.2 m, and 87.5 m in W–15303. Dall (1917) found *Turritella halensis* at Hale landing on the Flint River, Georgia; the age of these deposits has been placed from early Oligocene to early Miocene (Dall, 1917; Cooke, 1935; Cooke, 1959). Mansfield identified *Turritella* cf. *T. halensis* from the Suwannee Limestone near the type area.

LITHOLOGY AND MINERALOGY

The cores examined are characterized by carbonate sequences that span several tens of meters, and interbedded carbonates and siliciclastics from less than a meter to tens of meters thick (figs. 2*A* and 2*B*). The limestones are mainly mudstones, wackestones, and packstones (classification of Dunham, 1962), commonly with phosphatic minerals (mainly hydroxyfluorapatite, collectively called "phosphate" in this paper), and quartz sand and silt. Many locally dolomitized limestones retain the original limestone

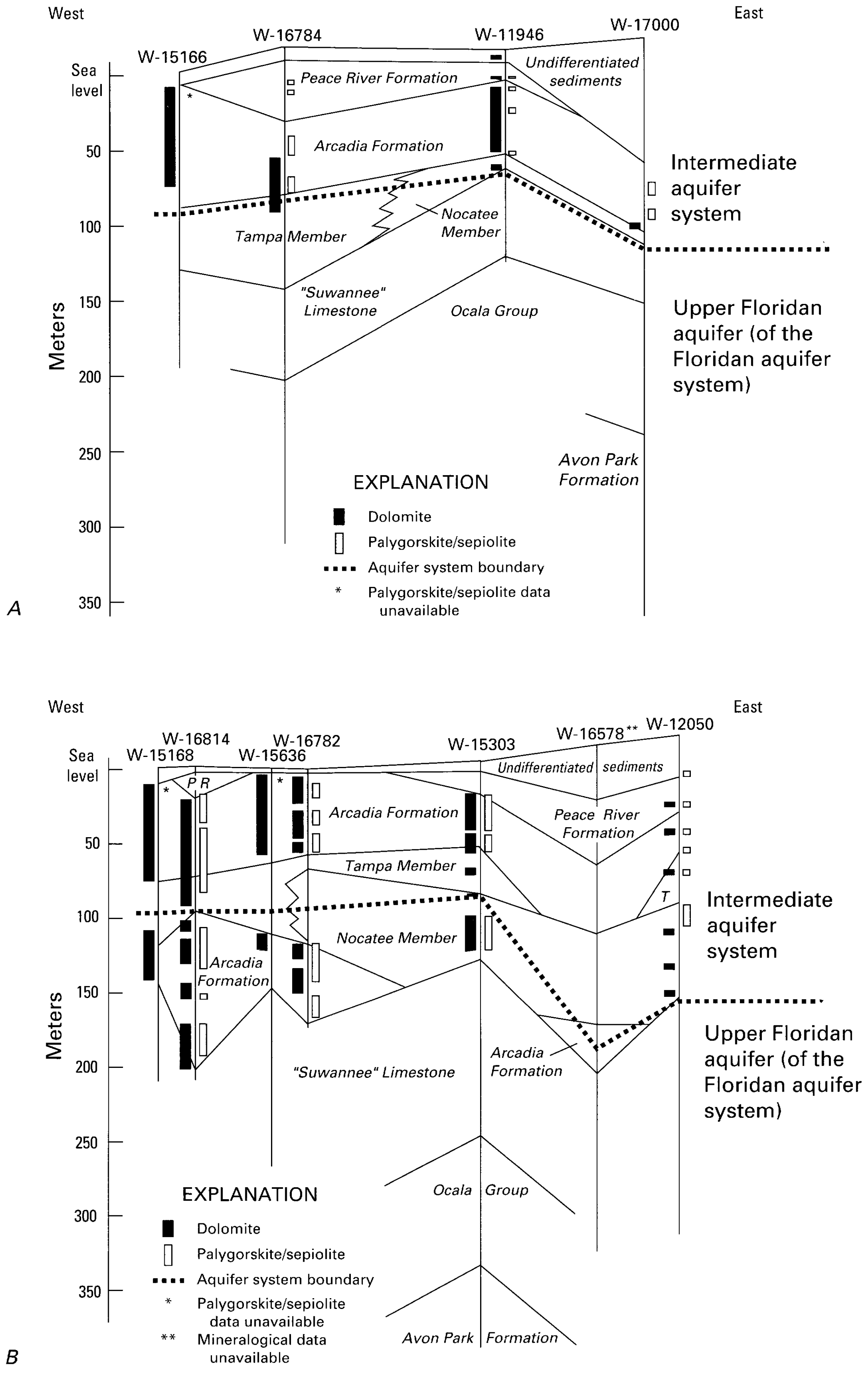

A
West
East
W-15166
W-16784
W-11946
W-17000
Sea level
50
100
150
200
250
300
350
Meters
Peace River Formation
Undifferentiated sediments
Arcadia Formation
Tampa Member
Nocatee Member
"Suwannee" Limestone
Ocala Group
Avon Park Formation
Intermediate aquifer system
Upper Floridan aquifer (of the Floridan aquifer system)
EXPLANATION
Dolomite
Palygorskite/sepiolite
Aquifer system boundary
* Palygorskite/sepiolite data unavailable
B
West
East
W-15168
W-16814
W-15636
W-16782
W-15303
W-16578**
W-12050
Sea level
50
100
150
200
250
300
350
Meters
P R
Undifferentiated sediments
Arcadia Formation
Peace River Formation
Tampa Member
T
Nocatee Member
Arcadia Formation
"Suwannee" Limestone
Arcadia Formation
Ocala Group
Avon Park Formation
Intermediate aquifer system
Upper Floridan aquifer (of the Floridan aquifer system)
EXPLANATION
Dolomite
Palygorskite/sepiolite
Aquifer system boundary
* Palygorskite/sepiolite data unavailable
** Mineralogical data unavailable

Table 5. Water chemistry of the intermediate aquifer system and Upper Floridan aquifer, west-central Florida

[m=meter; ppm=parts per million; IAS=intermediate aquifer system; LIA=lower intermediate aquifer; UIA=upper intermediate aquifer; UFA=Upper Floridan aquifer]

Name	County	Open Interval							Aquifer[2]	Stratigraphic units[3] (Scott, 1988)	Saturation index	
		Latitude North	Longitude West	Elevation (m)	Depth (m)	Field[1] pH	Mg^{++}/Ca^{++}	Cl- (ppm)			Calcite	Dolomite
ID 01 (TRG WELL TB3)	De Soto	27°15'12"	81°34'47"	27.5	28–92	8.20	0.316	148.0	IAS	Arcadia	0.989	1.839
ID 02 (TRG WELL TB1)	De Soto	27°15'20"	81°39'42"	26.2	32–90	8.00	0.686	94.0	IAS	Arcadia	0.432	1.065
ID 07 (GOLDEN RAINBOW)	Manatee	27°18'02"	82°06'27"	22.6	153–467	7.60	0.428	17.0	UFA	"Suwannee"– Avon Park (?)	0.373	0.735
ID 08 (M.J. RANCH)	Manatee	27°18'12"	82°11'12"	16.8	153–244	7.50	0.362	11.0	UFA	"Suwannee"– Ocala (?)	0.310	0.530
ID 09 (ROMP 22)	Sarasota	27°18'13"	82°20'13"	10.7	72–83	7.55	0.627	150.0	L IA	Arcadia	0.245	0.640
ID 11 (ROMP 22)	Sarasota	27°18'13"	82°20'13"	10.7	28–38	7.31	0.394	73.0	U IA	Arcadia	0.130	0.196
ID 12 (AMOCO 1)	De Soto	27°20'15"	81°39'29"	28.7	44–87	7.60	0.562	67.0	IAS	Arcadia	–0.061	–0.015
ID 24 (VERNA #7)	Sarasota	27°23'06"	82°18'27"	23.2	44–146	8.10	0.551	13.0	IAS-UFA(?)	Arcadia	0.712	1.525
ID 25 (VERNA #19)	Sarasota	27°23'07"	82°17'18"	25.0	43–140	7.80	0.750	35.0	IAS-UFA(?)	Arcadia– "Suwannee" (?)	0.332	0.866
ID 27 (VERNA 1A)	Manatee	27°23'56"	82°18'13"	25.0	126–146	7.30	0.500	10.0	IAS-UFA(?)	Arcadia	–0.065	–0.082
ID 29 (COCA COLA)	Highlands	27°24'08"	82°23'25"	38.4	167–182	7.79	0.680	16.0	UFA	"Suwannee"	0.052	0.319
ID 30 (PARKS D. WELL)	Manatee	27°24'23"	82°05'19"	24.4	61–403	7.70	0.444	54.0	IAS-UFA	Arcadia–Avon Park (?)	0.427	0.882
ID 31 (MANLEY FARMS)	Manatee	27°26'43"	82°18'19"	24.7	61–305	7.20	0.569	13.0	IAS-UFA	Arcadia–Ocala	–0.087	0.074
ID 32 (ROMP 032–2)	Manatee	27°28'14"	82°03'48"	31.7	171–183	8.80	0.524	20.0	UFA	"Suwannee"	0.471	1.034
ID 33	Highlands	27°29'20"	81°26'03"	40.3	171–430	8.30	0.325	6.4	UFA	"Suwannee"– Avon Park	0.021	–0.079
ID 34	Hardee	27°32'05"	81°49'20"	28.1	19–70	7.40	0.466	12.0	IAS	Arcadia	–0.372	–0.751
ID 35	Hardee	27°32'12"	81°37'22"	22.9	60–329	7.40	0.445	4.0	IAS-UFA	Arcadia–Avon Park	–0.645	–1.259
ID 36	Hardee	27°35'07"	81°44'47"	30.8	17–33	8.10	0.666	8.0	IAS	Arcadia	0.414	0.979
ID 37 (AVON PARK)	Highlands	27°35'27"	81°31'08"	46.7	153–458	7.60	0.270	9.1	IAS-UFA	Arcadia–Avon Park(?)	–0.539	–1.299
The following data are from Swancar and Hutchinson (in press):												
S&H1 (ROMP TR 3–1)	Charlotte	26°56'38"	82°13'07"	2.1	183–189	7.48	0.718	410.0	UFA	"Suwannee"	0.098	0.437
S&H2 (ROMP 10)	Charlotte	27°01'52"	82°00'28"	6.1	181–280	7.53	0.650	180.0	UFA	"Suwannee"	0.076	0.349
S&H3	De Soto	27°02'56"	81°47'28"	10.7	214–275	7.70	0.560	340.0	UFA	"Suwannee"	0.211	0.580
S&H4 (ROMP TR 5–2)	Sarasota	27°09'19"	82°23'42"	4.6	156–214	7.10	0.292	44.0	UFA	"Suwannee"	0.188	0.234
S&H5 (ROMP 16)	De Soto	27°11'15"	81°46'27"	18.3	231–287	8.60	0.575	39.0	UFA	"Suwannee"	0.995	2.157
S&H6 (ROMP 26)	De Soto	27°17'57"	81°49'30"	22.9	177–403	7.45	0.520	14.0	UFA	"Suwannee"– Avon Park	0.166	0.472
S&H 10 (Zolfo Springs 1)	Hardee	27°29'44"	81°47'40"	19.8	107–305	7.45	0.478	17.0	UFA	"Suwannee"– Avon Park	0.082	0.252

[1] Lab pH used for S&H1, S&H2, S&H6, S&H 10.

[2] Aquifer penetrated is estimated from Buono and Rutledge, 1979.

[3] Stratigraphic unit penetrated is estimated from data in Scott (1988, and written communication, 1993) and Johnson (1986); Arcadia, Arcadia Formation; "Suwannee," "Suwannee" Limestone; Avon Park, Avon Park Limestone; Ocala, Ocala Group.

← **Figure 5.** Distribution of magnesian minerals in cores. Approximate depth intervals of the intermediate aquifer system and the Upper Floridan aquifer of the Floridan aquifer system are indicated on the right. Dolomite occurrence, detected within at least 5 m vertically by XRD, is indicated on the left of cores; sepiolite and palygorskite occurrences are shown on the right of cores. (*A*) Transect *A–A'* from figure 1; (*B*) transect *B–B'* from figure 1; PR, Peace River Formation; T, Tampa Member of the Arcadia Formation. Magnesian minerals are more abundant and are found in more of the section to the west and south.

textures at the macroscopic scale and, in some places, relatively unaltered shell material still exists.

Limestone and dolomite grade vertically and, we assume, laterally in the study area into quartz sandstone and mudstone. The mudstone is composed mainly of quartz silt, illite-smectite mixed layer clay, illite, and the fibrous magnesian clays, sepiolite and palygorskite, and forms beds that are a few centimeters to tens of centimeters thick. In addition, magnesian clays form a significant component of the fine-grained carbonate rocks (see table 4).

Quartz sandstone with variable amounts of phosphate grains is cemented by calcite or dolomite and is present in zones as thick as 60 m (W–16782). Quartz sand that is poorly consolidated or unconsolidated or sandstone that is cemented by silica is found mainly in beds less than 0.3 m thick. Silica-cemented quartz sand generally is accompanied by phosphate grains and a small proportion of detrital carbonate grains. Feldspar is a minor component of most sandstones.

Phosphate is present primarily as shiny sand-size grains or small black, brown, tan, and off-white pebbles; a small portion is present as cement in hardgrounds. The grains include phosphatic bone fragments and teeth, phosphatized fossil invertebrate fragments, phosphate-cemented quartz sandstone, and phosphate-cemented sandstone and siltstone composed mainly of detrital carbonate grains. Thin sections reveal concentric structures in the phosphate grains.

Brecciated zones a few centimeters to over 30 cm thick with veinlike interstitial fillings were observed singly or in groups of several beds on the order of a meter apart vertically. These zones are especially notable in the Arcadia Formation. The broken bed lithologies and angular clasts are siliciclastic mudstone, limestone, or dolomite, and the interstitial filling is detrital quartz and phosphate silt, limestone, or dolomite. In some of the brecciated zones, patches and stringers of black to tan chert are evident. The chert has replaced carbonate and siliciclastic clay and, in places, has filled voids caused by dissolution of carbonates. Chert also occurs as thin beds (0.1–2 cm thick) and irregular patches in nonbrecciated rock.

Geophysical logs are presented here for the first time for four boreholes (Walton, W–16782, W–16814, and W–17000) (figs. 2*A* and 2*B*).

DIAGENESIS

Nine diagenetic processes are tracked in thin sections to determine the timing and regional extent of diagenetic alteration of the rocks in the study area: (1) shell micritization, (2) shell dissolution, (3) precipitation of equant or blocky calcite cement in pore spaces, (4) syntaxial calcite overgrowths on echinoderm fragments, (5) precipitation of dolomite as a replacement of calcite or in pore spaces, (6) syntaxial dolomite replacement of echinoderm fragments and overgrowths, (7) partial dissolution of dolomite rhombohedra, (8) partial dissolution of phosphate grains, and (9) precipitation of amorphous silica in pore linings with local alteration to opal-CT and quartz (figs. 3 and 4; table 4).

Shell micritization is one of the earliest diagenetic processes that affects the skeletal grains in the carbonates examined (figs. 3*A* and 4*A*); the shell structure is destroyed, but the shell shape is preserved. Micritization is observed in foraminifers, bryozoans, and red algae and is rare in echinoids and oysters. An early blocky calcite cement forms a thin rind on grain and fossil surfaces in many samples, filling primary porosity in foraminifer chambers and articulated pelecypods (fig. 3*B*). This generation of calcite cement predates shell dissolution. Moldic porosity, the consequence of the dissolution of aragonitic and calcareous shells, also is common in most of the carbonates examined (fig. 3*B*), especially of the aragonitic mollusks and some soritid foraminifers. Dissolution of bryozoans, other foraminifers, ostracodes, calcitic molluscs (oysters and pectens), and red algae is less common; dissolution of echinoderm fragments is very rare. In many samples, a second generation of blocky calcite cement grows on the void surfaces (that is, on the cemented matrix material that packed around the fossil), rarely filling the void completely (fig. 3*C*). Syntaxial overgrowths of calcite are common on echinoid fragments, especially in packstones and grainstones, and extend into intergranular pore space and, in some cases, into nearby fossil molds (fig. 3*D*), indicating postdissolution precipitation. Shell micritization, shell dissolution, equant calcite cement, and calcite overgrowths on echinoderm fragments are observed at all depths in the cores examined and show no preferred depth or regional distribution (table 4).

Dolomite occurs as pore-lining crystals (figs. 3*E* and 3*F*), as etched and nonetched rhombohedra (figs. 3*G*, 4*B*, 4*C*, 4*E*, and 4*F*), as a replacement of calcareous fossils (red algae, foraminifers, bryozoans, and echinoderms) (see replaced echinoderm in fig. 3*E*), as syntaxial overgrowths on dolomitized echinoderm fragments, and as dolomicrite (fig. 3*H*). Dolomite is observed in three leached conditions: leached centers of rhombs (figs. 4*E*), leached zones (figs. 3*G* and 4*B*), and etched surfaces (fig. 4*C*). Etched dolomite is observed only within the upper 95.8 m in the study area (table 4).

Detrital phosphate grains are common constituents of both the siliciclastic and carbonate rocks examined. In most cases, several concentric zones that differ in color or texture can be seen in each grain (fig. 3*G*), indicating multiple generations of phosphate precipitation. Phosphate coatings are observed on fossil fragments, quartz grains, and cementing horizons or groups of grains. In a few samples, phosphate grains show evidence of leaching (fig. 3*H*); most examples are in the upper part of the undifferentiated Arcadia Formation, except at W–12050 and W–11946 where phosphate dissolution is observed in the Tampa Member. Most occurrences of amorphous silica, observed at the thin section scale, are associated with leached phosphate grains in the upper part of the undifferentiated Arcadia Formation (table 4); however, occurrences are observed at W–17000 in the lower part of the undifferentiated Arcadia Formation and at W–16814 at the same stratigraphic horizon. Alteration of amorphous silica to opal-CT can be detected by XRD and observed only at the SEM scale, where it exhibits a fibrous and bladed spheroidal habit (fig. 4*G*); these lepispheres were found only as cavity linings.

Dolomite, palygorskite, and sepiolite are all magnesium-rich minerals and have very similar spatial distributions in the cores examined, as indicated by XRD analysis (figs. 5*A* and 5*B*). Also, palygorskite and sepiolite typically occur with dolomite (figs. 3*C*, 3*D*, and 3*F*). These two magnesian silicate minerals are wispy and fibrous, and encase both etched and nonetched dolomite rhombs. At site W–16814, the most southwesterly as well as the most pervasively dolomitized core in the study area, the limestones and siliciclastics are dolomitized down to 203 m (see fig. 5*B*). All three minerals are more pervasive and extend through a greater stratigraphic interval in the southern and western parts of the study area than in the north and east. In the intermediate aquifer system, magnesian minerals are common along both cross-sections, but their occurrence declines toward the east. In the Upper Floridan aquifer, magnesian minerals occur near the top of the aquifer in the central and western portion of the southern cross-section only and are nearly absent in the northern cross-section.

MODERN GROUND-WATER CHEMISTRY

Modern ground-water analyses from the files of the USGS, Tampa, from 18 wells are analyzed by WATEQF for calculation of SI values with respect to calcite and dolomite (Plummer and others, 1978) and combined with published data from 7 other wells (Swancar and Hutchinson, 1992; WATEQF was also used in their study) (table 5). Included in the table are well locations, elevation of wellhead, open depth interval below the land surface, stratigraphic interval sampled, assumed regional aquifer sampled, chloride content, magnesium-calcium ratios, field pH, and SI values for calcite and ordered dolomite. In the study, in general, wells open to the Hawthorn Group are in the intermediate aquifer system, and wells open to the "Suwannee" Limestone and Ocala Group are in the Upper Floridan aquifer, with some exceptions.

The pH of the ground water is greater than 7.0 at all sites, a finding that indicates that reaction with the carbonate rocks has raised the pH from meteoric water values that are typically near 5.5. Most water samples are saturated with respect to calcite, indicated by a SI value within the interval –0.5 to +0.5. Exceptions are at sites 35 and 37, where the ground water is undersaturated, and sites 1 and 24 and site S&H5 (Swancar and Hutchinson, in press), where the ground water is slightly supersaturated with respect to calcite. Ground water is supersaturated with respect to dolomite at sites 1, 2, 7, 9, 24, 25, 30, 32, 36, S&H3, and S&H5 and undersaturated at sites 34, 35, and 37.

DISCUSSION

AGE OF THE DEPOSITS

Chronostratigraphic information is critical to this study because of the lateral variation and vertical repetition of rock and sediment types within the subsurface of the study area. Biostratigraphic and isotopic data were gathered independently from lithostratigraphic data and from each other. This integrated method allows independent verification of published age ranges of mollusks, which are frequently tied to the strata in which they occur rather than to other primary chronostratigraphic indicators. The mollusks and dinocysts were initially identified, and ages were assigned based on reports in the published literature; the biostratigraphic data were integrated with age estimates based on $^{87}Sr/^{86}Sr$ values.

We note that good agreement exists between the biostratigraphic and isotopic ages despite the differences in time resolution. In general, the time estimates based on the strontium isotopic composition of unaltered shells are our best numerical time indicators, but they have an error of at least ±1.5 m.y. This error is based on our assessment of the scatter of data reported in Miller and others (1991). Error in assigning age estimates to fossil ranges is more difficult to assess. Dinocyst assemblage data have a greater time resolution than individual species ranges of mollusks because dinocysts evolve more rapidly than mollusks and because assemblages, in general, have narrower time ranges than individual species. In the two places where fossils used for biostratigraphy and for isotopic dating were found close together (W–16814 at 200.9 m, and W–16782 at 69.2–70.1 m) (figs. 2*A* and 2*B*), the ages estimates corroborate each other. It is significant also that multiple age indicators in single cores are in correct sequence with one exception (W–16782 at 94.7 m and 96.7 m); that is, the numerical ages increase with depth. Therefore, we infer that the isotopic ages reflect the time of deposition of the strata from which the samples were taken, but we recognize that our data are sparse and require further corroboration from more closely spaced samples in individual cores.

Age indicators provide us with a new basis for examination of the lithostratigraphy. The $^{87}Sr/^{86}Sr$ analyses from the "Suwannee" Limestone in W–11946 and W–12050 support an early Oligocene age for the "Suwannee" Limestone. At the base of W–16814, both an early Oligocene strontium date and an early Oligocene *Turritella* at were found at 200.9 m, a few meters above the top of the "Suwannee" Limestone but within the lower undifferentiated part of the Arcadia Formation (T.M. Scott, written communication, 1993). An early Oligocene age for the Arcadia Formation is anomalous and may be due to pervasive dolomitization in this core that has obscured the lithostratigraphic contact between the "Suwannee" Limestone and the Arcadia Formation.

The age indicators within the Arcadia Formation range from early Oligocene to middle, or earliest late, Miocene. For purposes of this discussion, the Arcadia can be broken into four parts: a lower undifferentiated part, the Nocatee Member, the Tampa Member, and an upper undifferentiated part. Age indicators found in the lower part of the undifferentiated Arcadia are early to late Oligocene (30.3 to 26.8 Ma); age indicators within the Nocatee Member are late Oligocene (27.1 to 26.3 Ma); age indicators within the Tampa Member range from late Oligocene to middle Miocene (27.9 to 18.9 Ma); and age indicators within the upper part of the undifferentiated Arcadia Formation range from late Oligocene to middle Miocene (28.6 to 16.7 Ma). Overlapping age ranges of the Tampa and Nocatee Members with the undifferentiated Arcadia Formation support Scott's (1988) assertion that the Arcadia Formation is composed of several coeval lithofacies, at least at this time resolution.

We think it is significant that tens of meters of rock are late Oligocene in age in southern Florida. Although the rocks in the study area have not been rigorously dated in the past, the assumption often has been made that because of the regional low sea-level stand thought to occur during late Oligocene time (for example, Haq and others, 1987), the duration of the unconformity between the "Suwannee" Limestone and the Hawthorn Group spanned the late Oligocene, from about 30 to 25 Ma.

$^{87}Sr/^{86}Sr$ from a mollusk very near the top of the Peace River Formation at W–12050 yields an age of 5.1 Ma. This age is nearly 10 m.y. younger than the shallowest age indicator within the underlying Arcadia Formation and, if correct, expands the duration of deposition of the Hawthorn Group sediments, as they are now defined, to approximately 25 m.y. No definitive late Miocene fauna are observed or reported in the cores examined nor are there any numerical ages from strontium isotopic analyses between 6 and 16 Ma.

As more numerical and biostratigraphic information becomes available for several of the cores, it may be possible to delineate depositional units separated by shorter term local and longer term regional hiatuses. Mapping of regional hiatuses or unconformities will clarify some of the complex lithostratigraphic relationships.

GEOPHYSICAL LOGS

Geophysical logs, singly or in groups, are widely used for correlating lithologic contacts among boreholes in south Florida, particularly where cores are not available. Electric logs are particularly sensitive to porosity of rocks and composition of pore fluid; gamma logs reflect detrital or diagenetic concentrations of radioactive isotopes (Levine, 1988; Weinberg, 1991). In the study area, thick zones of relatively pure carbonates ("Suwannee" Limestone and Ocala Group) give a flat gamma signature, whereas alternating siliciclastics and carbonates in the Hawthorn Group give an irregular, spiky signature. In the new logs from W–17000, three of the four lithostratigraphic contacts coincide with notable changes in geophysical signature in all three logs, and the fourth contact, at the top of the Arcadia Formation, is just above a change in the gamma log.

REGIONAL DIAGENETIC ALTERATION

The processes observed in thin sections indicate in many samples that the strata have been alternately saturated with a range of water chemistries, such that calcite or dolomite can precipitate in sites where calcareous fossils were previously leached. Also, many samples showed evidence for multiple generations of calcite or dolomite. Several of the processes documented are attributed to early marine and meteoric processes, are observed in nearly all rocks examined, and show no regional distribution, such as shell micritization by boring marine algae and perhaps boring sponges, as well (Bathurst, 1964) (figs. 3*A* and 4*A*). Meteoric water entering the aquifer systems in recharge areas typically has a pH in the 5–6 range and low total dissolved solids; therefore, it has the capacity to dissolve aquifer minerals and enhance porosity and permeability (Sprinkle, 1989). Consequently, with a sea-level drop and exposure to meteoric waters, all carbonate materials near the ground surface, especially the aragonitic mollusks, are susceptible to dissolution, and high-Mg calcite shells (echinoids, foraminifers, and red algae) are converted to low-Mg calcite, often with no loss of the details in shell structure (James and Choquette, 1983). Blocky calcite cements both pre- and postdate shell leaching and are generally attributed to precipitation from fresh water, with some exceptions (Folk, 1974; Moore, 1989) (fig. 3*C*). The precipitation of syntaxial calcite overgrowths on echinoderm fragments, common at depths greater than 70 m in the study area, has been attributed to both shallow-marine phreatic diagenesis (Füchtbauer, 1969) and to meteoric phreatic diagenesis (James and Choquette, 1984).

Textural evidence supports a diagenetic origin for much of the dolomite as either the replacement of micrite and calcareous fossils or as precipitation in moldic porosity. Dolomite precipitation in carbonate and siliciclastic rocks of Florida and the Caribbean has been attributed by several authors to a mixing-zone process (Hanshaw and others, 1971; Land, 1973; Folk, 1974; Folk and Land, 1975; Randazzo and Hickey, 1978; Morrow, 1982a, b). The mixing-zone hypothesis states that the precipitation of slow-growing and well-formed, limpid rhombohedra of dolomite is facilitated in water chemistries with Mg/Ca ratios near 1 and low ionic activity—conditions that are achieved with very dilute sea water in the subsurface mixing zone (Folk and Land, 1975). Commonly, water in the mixing zone is saturated with respect to dolomite and undersaturated with respect to calcite, but the difference and magnitude of saturation indices of both minerals vary with calcium and magnesium concentrations and with CO_2 content (Wigley and Plummer, 1976). A case has been made, however, for dolomite precipitation from water that is closer in composition to sea water (Land, 1985; Cander, 1991). In both hypotheses, the source of magnesium is ultimately sea water; however, they differ in the timing and hydrology of the dolomitization process.

Etched dolomite has been interpreted as a product of mixing-zone precipitation followed by meteoric dissolution of the more soluble, nonstoichiometric dolomite in the core (Randazzo and Cook, 1987). Evidence of dolomite replacement of calcite in our samples includes the growth of dolomite rhombs around calcite grains, dolomite rhombs floating in a calcite micrite matrix, and the replacement of fossils that were originally magnesian calcite, such as echinoderm fragments (fig. 3*E*) and red algae.

The regional and depth distribution of the diagenetic processes shown in table 4 reflects the source and residence time of exposure to waters of different chemistries: meteoric water, marine water, and evolved formation water from both meteoric and marine sources. Early marine diagenetic features (micritization of shells and echinoderm fragment overgrowths) and meteoric diagenetic features (shell dissolution, equant calcite cement precipitation, and perhaps further growth of echinoderm fragment overgrowths) are present at nearly all depths in the sampled cores in both transects shown in figures 2*A* and 2*B*. Dolomite rhomb etching, in contrast, is observed only in the upper 96 m of cores examined, suggesting a surface-down process of dissolution from meteoric water. Whole dolomite rhombs observed at greater depths in the cores may be either healed or may never have been leached.

Age indicators for the entire section suggest at least one large regional unconformity may be at the contact between the Arcadia and Peace River Formations. The duration of the unrecorded interval may be as great as 10 m.y. This long period of exposure could have been responsible for the leaching of dolomite rhombs in the upper 96 m as well as the extremely leached condition of some phosphate grains within the Arcadia (fig. 3*H*).

The diagenetic features that we are attributing to either marine or a mixed marine and meteoric water processes (that is, the precipitation of limpid dolomite and dolomite replacement of echinoderm overgrowths and perhaps precipitation of magnesian clays) have an asymmetric spatial distribution that cross-cuts stratigraphy: they are more pervasive and stratigraphically more extensive in the southern transect and in the western parts of both transects (figs. 5*A* and 5*B*). Limpid dolomite is observed down to the base of the Arcadia Formation in all cores examined in thin section and by SEM in the southern transect (W–16814, W–16782, and W–12050) but diminishes in depth and stratigraphic range, as defined by age indicator or lithostratigraphy, to the north and east.

SOURCES OF DIAGENETIC WATERS

Palygorskite and sepiolite are diagenetic minerals on the basis of their common association with dolomite and their delicate branching form (fig. 4*B*). Although the magnesian clays may have formed by direct precipitation from pore fluids at least in part (Callen, 1984; Esteoule–Choux, 1984), it is unlikely that they formed in a sabkhalike environment; they are not found precipitating with carbonates in modern sabkhas such as Coorong, Australia (Callen, 1984). Much of the clay was probably formed by addition of magnesium to illite/smectite clay (Weaver, 1984).

The large volume of diagenetic dolomite, palygorskite, and sepiolite, in the study area requires a significant source of magnesium. The largest source of nearby magnesium is the sea water of the Gulf of Mexico and the Atlantic Ocean. Water-quality data (table 5) show that both the intermediate aquifer system and the Upper Floridan aquifer, in the depths studied, are saturated with waters that have low chloride concentrations ($<$150 parts per million, except in the far southern part of the study area) and low Mg/Ca ratios ($<$0.75), characteristic of fresh water. Therefore, none of the open intervals in wells for which we have water-quality data is currently in the coastal mixing zone or in saline ground water. The most reasonable mechanism for introducing magnesium into aquifer rocks is raising the sea level.

Sea level has risen eustatically as much as 30.5–40 m above modern sea level since the Miocene (Dowsett and Cronin, 1990), and for at least 10 periods during the last 16 m.y., sea level has been higher than at present. The highest sea level over this time span was probably during the period between 4 and 3 Ma (Webb and others, 1984). These high stands have been documented on the Atlantic Coastal Plain and in Florida by dating the marine deposits and in some cases by estimating the depth of water and the total uplift since deposition (Dowsett and Cronin, 1990; Krantz, 1991; McCartan and others, 1991). Maximum lowstands (drawdowns below modern sea level) since the middle Miocene, based mainly on evidence from $\delta^{18}O$ and on the distribution of vertebrates, were as low as −20 to −60 m (Wardlaw and Quinn, 1991), or possibly −100 to −175 m (Pitman, 1978; Haq and others, 1987; for better fit with data from Florida, see Prentice and Matthews, 1988; Quinn and Matthews, 1990; and Krantz, 1991).

Another source of reactive fluids is upwelling water from the lower part of the Floridan aquifer system, which contains high concentrations of dissolved solids from contact with evaporite beds (Simms, 1984). That source seems unlikely, however, for the rocks of the intermediate aquifer system (primarily the Hawthorn Group) because the "Suwannee" Limestone, theoretically in the pathway of upwelling saline waters in the study area, has very little dolomite.

Magnesium and silica also can be derived through the dissolution of siliceous fossils, detrital clays (Altschuler and others, 1963; Weaver, 1984), and possibly volcanic ash. Diatoms and radiolarians are now rare in the study area rocks, but they are locally abundant in correlative units in northern Florida (Scott, 1983), South Carolina (Abbott and Andrews, 1979), Maryland (Andrews, 1988), and New Jersey (Andrews, 1987) and may have provided a source of silica. In the Yucatan peninsula of Mexico, sepiolite and palygorskite are alteration products of volcanic ash (Isphording, 1984), which also may have been present in Florida; volcanic debris is present in Oligocene and Miocene units in Mississippi and the Virgin Islands (May, 1974; Lidz, 1984).

ROCKS AND WATER CHEMISTRY OF THE INTERMEDIATE AQUIFER SYSTEM

The intermediate aquifer system is locally confined by marine clays and carbonates of the Hawthorn Group and comprises a vertically and horizontally anastomosing network of limestone, dolomite, clay, phosphatic clayey quartz sand, and calcite-cemented quartz sand. These lithologic facies have a wide range of hydraulic conductivities and consequently, an unpredictable hydraulic character (Duerr and others, 1988) that has a significant component of vertical recharge within the study area (Ryder, 1985).

Seven of the wells listed in table 5 are open only in the intermediate aquifer system: 1, 2, 9, 11, 12, 34, and 36; three others, 24, 25, and 27, are open mainly in the intermediate aquifer system. Well locations, approximate flow paths (from potentiometric map of Mularoni, 1992), and SI values of the ground water with respect to calcite and dolomite are shown in figures 6*A* and 6*B*. Core locations from which mineralogical data are available are indicated.

In general, ground-water flow is from the northeast to the southwest from two potentiometric highs just north of Hardee and Manatee Counties. Water from sites 1 and 24 is supersaturated with respect to both calcite and dolomite. Water from sites 2, 9, 25, and 36 is supersaturated with respect to dolomite (though saturated with respect to calcite) and yields three zones where ground water is saturated with respect to dolomite: eastern De Soto County, along the border between Sarasota County and Manatee County, and at well 36 in northern Hardee County. Dolomite is very common in the rocks that constitute the intermediate aquifer system; however, nearly all dolomite observed in that aquifer is etched dolomite (table 4), strongly suggesting that the etched surfaces on dolomite rhombs are relict dissolution features and that the dolomite was probably not precipitated from modern ground water. In fact, etched dolomite is observed only within the intermediate aquifer system and no deeper. The one negative SI calculated from data from site 34, where the well is open from 19 to 62 m depth, suggests rapid infiltration by meteoric water, perhaps by way of sinkholes or other connections with the surficial aquifer.

The flow directions indicated in figure 6*B* suggest that rocks that form the intermediate aquifer system from cores at W–12050, W–16782, Walton, W–16814, and W–11946 are now in ground water that is supersaturated with respect to dolomite. Samples of the Hawthorn Group from the eastern cores, W–17000, W–12050, and W–11946, however, have much less dolomite than the cores examined from the same stratigraphic units further west (figs. 3*A* and 3*B*). Very little dolomite was detected in samples from W–12050, just down-flow from sites 1 and 2, where ground water has dolomite saturation indices of 1.839 and 1.065, respectively, also suggesting that dolomite may not be precipitating there now despite supersaturation.

ROCKS AND WATER CHEMISTRY OF THE UPPER FLORIDAN AQUIFER

The rocks of the Upper Floridan aquifer are mainly limestone and dolomite (Ocala Group, "Suwannee" Limestone, and some strata in the lower part of the Hawthorn Group in the western part of the study area). Fifteen wells in the study area are open in the upper portion of the Upper Floridan aquifer: Swancar and Hutchinson's (in press) sites (S&H) 1, 2, 3, 4, 5, and 6; and our sites 7, 8, 29, 30, 31, 32, 33, 35, and 37 (table 5). The locations and SI values with respect to calcite and dolomite for these sites are shown in figures 6*C* and 6*D*. Core locations from which thin sections were made are indicated; sites S&H3 and our sites 29, 33, and perhaps 37, are in adjacent ground-water basins and are not considered in this discussion.

Ground water, with the exception of that at site 35, is saturated with respect to calcite; note that site 35 is close to site 34, in the overlying intermediate aquifer system, and has an anomalously negative SI value for calcite. The water chemistry is consistent with the observation that pore-filling, equant calcite cement is common down to depths of more than 213 m in the upper portion of the Floridan aquifer system. Pore-filling calcite examined with SEM is smooth and unetched (fig. 4*A*). Analysis of trace elements and stable isotopes of calcite cements in the Upper Floridan aquifer, however, strongly suggests that they were precipitated very early and are probably not from modern water (Budd and others, 1993).

The saturation indices for dolomite in all wells through the Upper Floridan aquifer, except sites 35 and 37, indicate saturation or supersaturation (fig. 6*D*). The highest values occur in a zone from southeastern Manatee County to central De Soto County; however, the most abundant dolomite observed in XRD data and in thin sections examined is in the west at W–16782, and W–16814, where SI values are

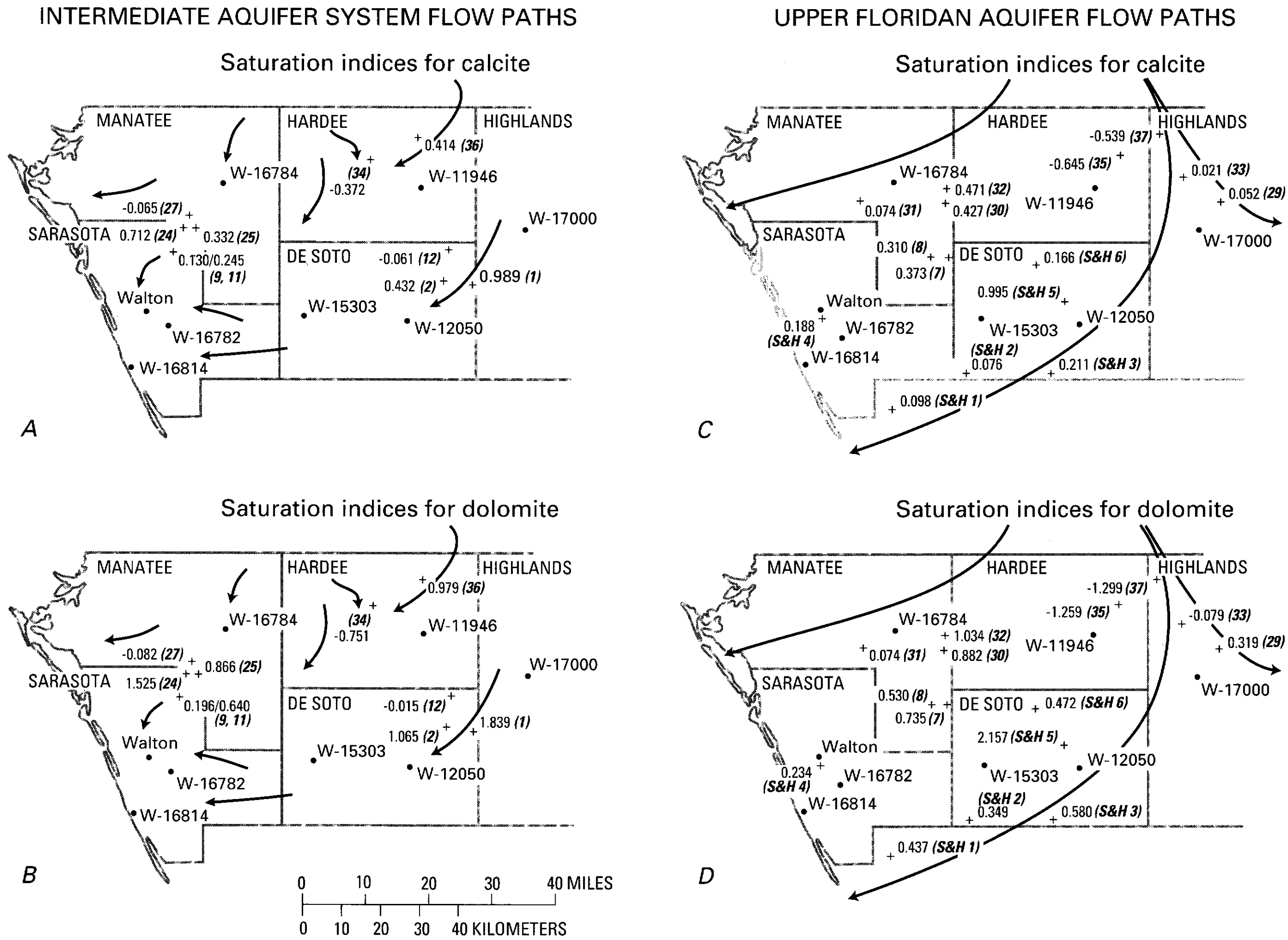


Figure 6. Maps of flow regimes and water chemistry of aquifer systems. (*A*) Flow paths within the intermediate aquifer system and saturated indices (SI) of ground water with respect to calcite; (*B*) Flow paths within the intermediate aquifer system and SI of ground water with respect to dolomite; (*C*) Flow paths within the Upper Floridan aquifer and SI of ground water with respect to calcite; and (*D*) Flow paths within the Upper Floridan aquifer and SI of ground water with respect to ordered dolomite. Flow paths for the intermediate aquifer system are approximated from the potentiometric map of Mularoni (1992); flow paths for the Upper Floridan aquifer are approximated from potentiometric map in (Johnston and others 1980). Water chemistry from Swancar and Hutchinson (in press) indicated in table 5.

near saturation. Dolomite distribution was detected by XRD at core site W–15303 (fig. 1).

Saturation indices often are tracked along ground-water flow paths constrained by potentiometric contours (Plummer, 1977; McCartan and others, 1992). Rising SI values along a flow path are interpreted as either continued dissolution along that path or mixing with water of a different chemistry. A rapid decline along a flow path in SI values indicates precipitation of the mineral in question. A similar line of reasoning can be applied to the data set for dolomite in the study area. If the generalized flow paths are correct, ground water appears to enter study area at or below saturation with respect to dolomite, to increase in SI values within the central part of the study area, and then to drop back down to near saturation near S&H4 in the southwest. The increase followed by decrease of SI for both minerals along the flow path suggests dissolution followed by precipitation, especially of dolomite. The distribution of dolomite within the upper portions of the Upper Floridan aquifer shown in figures 3*A* and 3*B* shows that dolomite does not become abundant along the cross-section from east to west until site W–15303, a short distance "down-flow" from the highest SI values for ground water with respect to dolomite. This observation raises the possibility that dolomite could be precipitating today from modern water approximately in the zone of upward leakage of the Upper Floridan aquifer in southwest Florida (Ryder, 1985), noted also by an increase in magnesium and calcium (table 5).

In summary, most waters in both the intermediate aquifer system and the upper part of the Upper Floridan aquifer are saturated with respect to calcite and dolomite. Rocks examined show evidence for numerous episodes of precipitation and dissolution of both minerals as well as dissolution of aragonite shells, strongly suggesting that many diagenetic alterations, especially dissolution of calcareous fossils and dolomite rhomb surfaces, are relicts of past water chemistries. The etched nature of dolomite in the intermediate aquifer system co-existing with water near saturation with respect to dolomite suggests that the dolomite there is relict also. We think that this diagenetic history is best explained by repeated alternation of meteoric and marine water that occurs with sea-level oscillations, and magnesium-rich mineral diagenetic facies reflects the cumulative residence time of marine or mixed waters in the aquifer rocks. Also, in the western part of the study area, especially in the core at W–16814 where we have fairly good age and X-ray diffraction data, dolomitization is very extensive and may have obscured the lithostratigraphic contact between the "Suwannee" Limestone and the Arcadia Formation. Within the upper portions of the Upper Floridan aquifer, dolomite distribution coincides with declining SI values along presumed flow paths, and the possibility exists of volumetrically small amounts of modern dolomite precipitation. The multigenerational nature of much of the dolomite suggests a complex precipitation history; if dolomite precipitation is going on today, it is probably a small addition to dolomite precipitated at an earlier time.

CONCLUSIONS

Age indicators in the "Suwannee" Limestone in the study area are all early Oligocene. Because of the uncertainty of the age of the type section of the Suwannee Limestone as defined by Cooke and Mansfield (1936) and the lack of rigorous correlation between the rocks of the type section and the study area, we retain the usage of "Suwannee" in quotation marks as suggested by Scott (1988). The Hawthorn Group, previously reported to be Miocene, is shown to range in age from late (possibly early) Oligocene to Pliocene on the basis of strontium isotopic ratios, mollusks, and dinocyst assemblage distributions. Age indicators in the strata suggest the following ages: the Arcadia Formation ranges in age from late (possibly early) Oligocene to middle or earliest late Miocene; the Nocatee Member of the Arcadia Formation is late Oligocene; the Tampa Member of the Arcadia Formation ranges in age from late Oligocene to early Miocene; the Peace River Formation is Pliocene. Extensive carbonate deposition appears to have taken place in the study area during the late Oligocene, conventionally thought to be a time of subaerial exposure and nondeposition across much of the Florida platform.

Much of the diagenetic alteration of the aquifer rocks is early. Early calcite cementation of micrite matrix and internal porosity has preserved the shapes of leached fossils. Some dolomite cement preserves the shape of early leached aragonitic fossils. Dissolution of calcite and dolomite is consistent with dissolution from meteoric water. Modern aquifer water of meteoric origin, however, is saturated with respect to these two minerals. Therefore, dissolution must have occurred soon after deposition when the rocks were at very shallow depths where the ground water pH is closer to that of rain water.

A magnesium-rich diagenetic facies characterized by dolomite, palygorskite, and sepiolite cross-cuts stratigraphy and may obscure stratigraphic boundaries. The magnesium minerals are more pervasive and extend through a greater stratigraphic interval in the western part of the study area. This distribution forms a diagenetic facies and may be due to the longer cumulative residence time of sea water near the coast during past sea-level fluctuations. Much of this dolomite has textures that suggest multiple generations and was probably precipitated prior to the establishment of the modern ground-water regime. High saturation indices for dolomite in the modern Upper Floridan aquifer water suggest, however, that some dolomite precipitation may be occurring now.

We recognize that data presented here are sparse and allow only tentative age determinations. They are sufficient, however, to indicate a need for a reassessment of subsurface stratigraphy. The next phase of this project uses the same integrated approach outlined here but with more closely spaced samples to delineate more accurately the depositional and diagenetic facies of the Upper Floridan aquifer and intermediate aquifer system of southern Florida.

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Professional Papers are mainly comprehensive scientific reports of wide and lasting interest and importance to professional scientists and engineers. Included are reports on the results of resource studies and of topographic, hydrologic, and geologic investigations. They also include collections of related papers addressing different aspects of a single scientific topic.

Bulletins contain significant data and interpretations that are of lasting scientific interest but are generally more limited in scope or geographic coverage than Professional Papers. They include the results of resource studies and of geologic and topographic investigations, as well as collections of short papers related to a specific topic.

Water-Supply Papers are comprehensive reports that present significant interpretive results of hydrologic investigations of wide interest to professional geologists, hydrologists, and engineers. The series covers investigations in all phases of hydrology, including hydrogeology, availability of water, quality of water, and use of water.

Circulars present administrative information or important scientific information of wide popular interest in a format designed for distribution at no cost to the public. Information is usually of short-term interest.

Water-Resources Investigations Reports are papers of an interpretive nature made available to the public outside the formal USGS publications series. Copies are reproduced on request unlike formal USGS publications, and they are also available for public inspection at depositories indicated in USGS catalogs.

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Maps

Geologic Quadrangle Maps are multicolor geologic maps on topographic bases in 7.5- or 15-minute quadrangle formats (scales mainly 1:24,000 or 1:62,500) showing bedrock, surficial, or engineering geology. Maps generally include brief texts; some maps include structure and columnar sections only.

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Miscellaneous Investigations Series Maps are on planimetric or topographic bases of regular and irregular areas at various scales; they present a wide variety of format and subject matter. The series also includes 7.5-minute quadrangle photogeologic maps on planimetric bases that show geology as interpreted from aerial photographs. Series also includes maps of Mars and the Moon.

Coal Investigations Maps are geologic maps on topographic or planimetric bases at various scales showing bedrock or surficial geology, stratigraphy, and structural relations in certain coal-resource areas.

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Catalogs

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