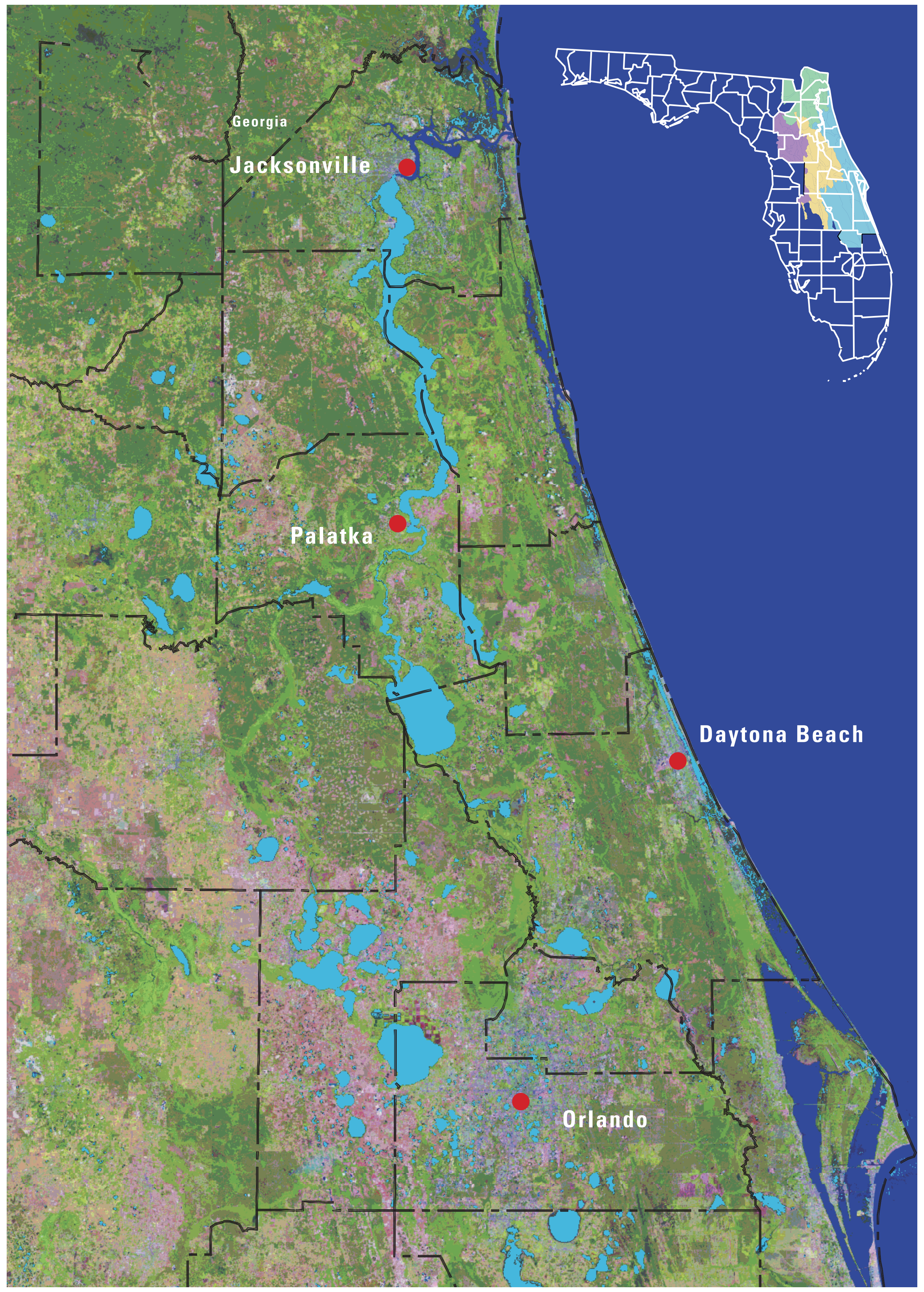
DEPARTMENT OF THE INTERIOR
U. S. GEOLOGICAL SURVEY

SUBSURFACE CHARACTERIZATION OF SELECTED WATER BODIES IN THE ST. JOHNS RIVER WATER MANAGEMENT DISTRICT, NORTHEAST FLORIDA



LANDSAT-TM satellite image, central Florida (courtesy of Florida DEP)

Jack L. Kindinger[1], Jeffrey B. Davis[2], and James G. Flocks[1]
2000

[1] Center for Coastal Geology and
Regional Marine Studies
U.S. Geological Survey
St.. Petersburg, Florida 33701

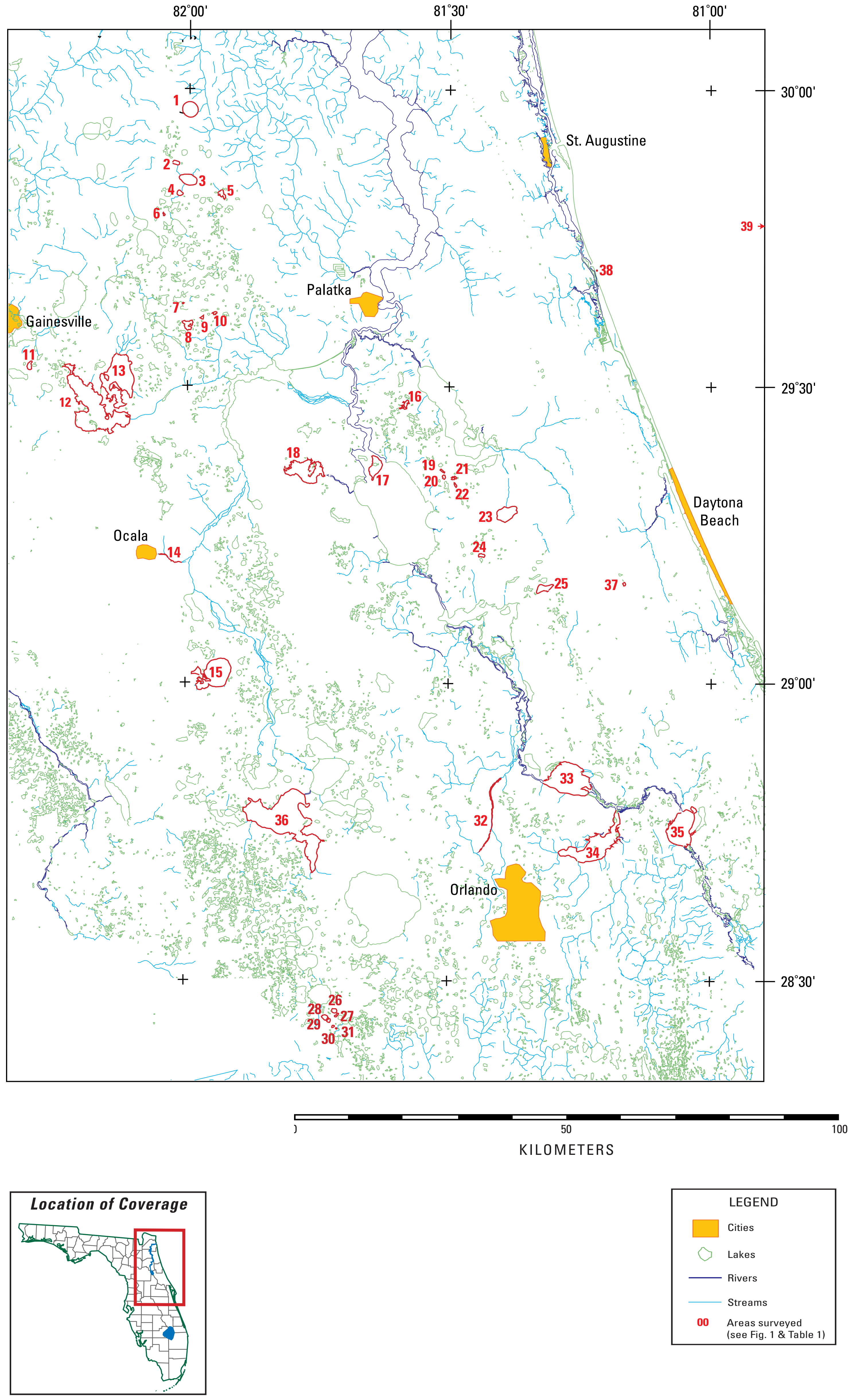
[2] St. Johns River Water
Management District
Palatka, Florida 32178

The U.S. Geological Survey, in cooperation with the St. Johns River Water Management District, prepares this information “as is” for its own purposes and this information may not be suitable for other purposes. This map has not been reviewed for conformity with U.S. Geological Survey editorial standards.

USGS OPEN FILE REPORT 00-180

INTRODUCTION

Figure 1. Location of lakes and rivers in northeast Florida from which high-resolution single channel seismic profile data were collected.



Florida is a karst (limestone) platform with abundant sinkholes, springs, and caverns. Karstic erosion of the land surface is controlled by chemical and mechanical processes occurring in the upper portion of the limestone where the most intense dissolution occurs (Beck, 1988). In Florida, surface features characteristic of karst include dolines (sinkholes), solution pipes, broad flat-bottomed prairies and closed circular depressions that either drain underground or fill with water to form lakes.

The term "sinkhole," or doline, implies a form, a function, and a basic mechanism of origin (Waltham, 1989). The form is a closed basin having no surface drainage outlet. The function is to transmit surface water underground to an aquifer or discharge ground water to the surface as a spring. Sinkhole origin is initiated by solution of the underlying host rock. Sinkholes form primarily on terrain of limestone or dolomite, or where either of these rocks occur near from the surface. They can, however, form over any rock that is soluble.

Sinkholes appear as a variety of structures, including cover collapse, solution and cover subsidence sinkholes, or subsidence over buried sinkholes. Individual sinkholes may be <1 m (3 ft) to >100 m (330 ft), in depth and diameter. Sinkholes may be circular or elongate in plan view can be described in cross section as conical, cylindrical, saucer-shaped or irregular.

Surveys of sinkholes were conducted in part to test the effectiveness of shallow-water marine geophysical techniques in determining the geomorphology of karst features. Investigation of subsurface karst features has proven to be a difficult task. Due to their random, unpredictable distribution, natural cavities or buried sinkholes are notoriously difficult and expensive to locate and assess in site studies. There are several direct and indirect methods of mapping and identifying features associated with karst, all of which have limitations. Waltham (1989) provides a review of the methods used for the detection of cavities. Methods of geophysical applications used in cave and sinkhole detection have been reviewed by Bates (1973), McCann and others (1982), Owen (1983), and McCann and others (1987). These authors, however, report that previously applied geophysical techniques had little reliability for widespread use, but the potential cost savings compared to other methods warrant consideration. High-resolution seismic-reflection profiling (HRSP) been used to detect subsurface features related to karst in lakes and rivers with varying degrees (Missimer and Gardner, 1976; Locker and others, 1988; Snyder and others, 1989; Sacks and others, 1991; Subsurface Detection Inc., 1992; Kindinger and others, 1994, 1996, 1998, 1999) and also offshore in the Atlantic Ocean (Meisburger and Field, 1976; Popenoe and others, 1984; Snyder and others, 1989).

Cooperative investigations of north central Florida lakes and rivers were conducted from 1993 to 1996 by the St. Johns River Water Management District (SJRWMD) and the U.S. Geological Survey (USGS) (Fig. 1). This report presents the data from recently developed digital High Resolution Seismic Profiling (HRSP) and identifies subbottom features from selected lakes in Florida. The objectives were: (1) identify evidence of breaches or discontinuities of the confining units between surficial water bodies and the Floridan aquifer, and (2) identify diagnostic features, structure, and geomorphology of sinkhole lakes.

Table 1. North Central Florida lakes and rivers surveyed during this study between 1994-1996.

Map Loc. No.	Lake Name	Profiles (km)	Date Acquired	Lake[1] Stage (ft. NGVD)	Physio.[2] Region	County	Latitude (Deg.)	Longitude (Deg.)	U.S.G.S. Topo Quad	Area[2] (km)	Perimeter (km)	Roundness (4A.π)/P	Features 1	2	3	4	5	6	Well # (used for gamma log correlation)
1	Kingsley	45.9	Aug-93	176	1C	Clay	29°57'54"	81°59'40"	309	6.30	9.00	0.98	X	X	X			X	C-0478
2	Blue Pond	9.3	Dec-95	130	1C	Clay	29°52'28"	82°01'32"	333	1.30	4.60	0.77	X		X	X			C-0439
3	Lowry (Sand Hill)	12.8	Feb-94	129	4B	Clay	29°50'54"	82°00'29"	333	5.05	8.72	0.83		X				X	C-0439, C-0382
4	Magnolia	10.8	Jan-94	125	4B	Clay	29°49'28"	82°01'07"	333	16.4	16.3	0.78		X	X			X	C-0451
5	Johnson	5.2	Dec-95	95	4B	Clay	29°49'30"	81°56'16"	334	2.00	10.0	0.25	X			X			C-0453, C-0457
6	Paradise	3.8	Dec-95	130	4B	Clay	29°47'16"	82°02'50"	333	0.20	1.90	0.70	X	X		X		X	C-0481
7	Levy's Prairie[†]	2.3	Dec-95	~85	4B	Putnam	29°38'21"	82°00'37"	384	0.05	0.82	0.93							C-0030, P-0797
8	Cowpen	19.4	Dec-95	85	4B	Putnam	29°35'56"	81°59'51"	384	2.80	11.5	0.27	X		X	X			P-0484, P-0038
9	Morris[†]	6.1	Dec-95	~85	4B	Putnam	29°36'54"	81°58'24"	384	x.xx	2.22	x.xx							P-0464, P-0036
10	Galilee[†]	6.3	Dec-95	~85	4B	Putnam	29°37'18"	81°57'00"	384	x.xx	2.90	x.xx							P-0464, P-0036
11	Wauberg	12.7	Dec-95	*67	5H1	Alachua	29°31'50"	82°18'06"	381	1.60	5.20	0.74	X						W-15691, A-0096
12	Orange	85.5	Jan-94	*58	5E4	Alachua	29°27'20"	82°10'20"	407	30.0	44.0	0.19	X	X	X	X	X		See Hillshade Map
13	Lochloosa	14.8	Dec-95	57	5E4	Alachua	29°31'38"	82°08'26"	382	18.0	20.9	0.52	X			?			A-0686
14	Silver River[†]	13.6	Jan-95	~18	5I	Marion	29°12'27"	82°01'17"	484	x.xx	**7	x.xx							M-0416, M-0125
15	Weir	27.0	Jan-95	55	4G	Marion	29°01'24"	81°56'18"	484	30.7	36.3	0.29	X	X	X	X			See Hillshade Map
16	Como	9.3	Aug-95	35	4D	Putnam	29°28'16"	81°34'58"	412	1.40	7.70	0.30	X	X	X			X	P-0114, P-0246
17	Drayton Island	13.8	Feb-94	5	4C	Putnam	29°18'40"	81°35'36"	437	**74	**52	0.34	X		X			X	
18	Kerr	28.1	Aug-95	21	4E	Marion	29°21'30"	81°47'14"	435	17.4	32.5	0.21	X	X		X		X	M-0153, M-0149
19	Davis	11.2	Aug-95	25	4D	Volusia	29°21'29"	81°30'47"	437	1.60	5.00	0.80	X						P-0416, P-0011
20	Upper Louise	9.3	Aug-95	36	4D	Volusia	29°20'55"	81°30'36"	437	1.70	4.90	0.89	X		X	X			P-0416, V-0346
21	Cowpond	6.1	Aug-95	40	4D	Volusia	29°20'48"	81°29'27"	438	0.60	5.00	0.30	X		?			X	V-0184, P-0495
22	Juanita[†]	9.1	Aug-95	35	4D	Volusia	29°20'00"	81°29'15"	438	0.20	2.30	0.48							V-0184
23	Disston	39.6	Feb-96	14	1A6	Flagler	29°17'30"	81°23'30"	438	10.8	15.5	0.56	X	X	X			X	V-0339, F-0296
24	Cain[†]	14.8	Aug-95	11	4D	Volusia	29°13'00"	81°26'00"	438	x.xx	3.50	x.xx							V-0338, V-0339
25	Dias	8.3	Aug-94	35	4D	Volusia	29°09'40"	81°19'06"	464	4.30	8.70	0.71	X		X	X		X	See Hillshade Map
26	Trout	14.7	Dec-95	85	4Q2	Lake	28°26'56"	81°42'44"	611	0.35	2.39	0.77	X		X	X		X	L-0677, L-0188
27	Pike	6.4	Dec-95	85	4Q2	Lake	28°26'30"	81°42'28"	611	0.60	3.20	0.74	X			X		X	L-0677, L-0188
28	Dixie	16.1	Dec-95	109	4L	Lake	29°26'16"	81°43'47"	611	1.10	4.00	0.86	X	X	X	X		X	L-0677, L-0670
29	Hammond	9.9	Apr-96	109	4L	Lake	28°25'53"	81°43'25"	611	0.50	3.00	0.70	X		X	X			L-0677, L-0670
30	Keene	5.7	Dec-95	114	4Q2	Lake	28°24'56"	81°43'15"	611	0.20	2.40	0.44	X		X			X	L-0677, L-0679
31	Smokehouse	4.0	Dec-95	114	4Q2	Lake	28°25'10"	81°45'37"	611	0.78	3.26	0.92	X					X	L-0679
32	Wekiva River	7.6	Feb-96	2	4C	Lake/Orange	28°45'00"	81°25'01"	xxx	x.xx	**8	x.xx	X	X	X	X		X	See Hillshade Map
33	Monroe[†]	n.a.	Jan-95	5	4C	Seminole	28°50'00"	81°34'00"	565	x.xx	22.2	x.xx							V-0375, V-0234, S-1338
34	Jessup	54.7	Jan-95	5	4C	Seminole	28°43'36"	81°12'59"	565	39.7	65.0	0.12	X	X	X	X		X	S-1183, S-0039
35	Harney	23.7	Jan-95	6	1D	Semin/Volus	28°46'10"	81°03'24"	541	27.0	35.0	0.28	X		X	?		X	See Hillshade Map
36	Harris	34.0	Dec-95	63	4G	Lake	28°46'30"	81°49'05"	535	73.8	61.5	0.25	X	X					See Hillshade Map
37	Indian	16.1	Feb-96	37	1C	Volusia	29°10'04"	81°09'51"	465	0.40	2.30	0.95	X		X			X	
38	Crescent Bch. Spring[†]	x.x	Jan-95	0	na	offshore	29°46'05"	81°12'30"	xxx	0.05	0.39	x.xx			X		X		See Hillshade Map
39	Red Snapper Sink	x.x	Jan-95	0	na	offshore	29°44'30"	80°45'00"	xxx	x.xx	x.xx	x.xx							

Notes:
1 -At acquisition date
2 -See Brooks (1981)
* -From SJRWMD database, independent of seismic acquisition date

** -Of area surveyed
X -Type of feature identified from lake profile (see Subsurface Characterization, p. 6, for details)
? -Feature possible

[†] The following sites were surveyed but not included in this report:

Galilee, Morris, Cain, Levy's Prairie, Juanita, Monroe, Red Snapper Sink, Silver River, and Silver Spring.

METHODS

Figure 2. Equipment used to acquire high-resolution single-channel subbottom seismic reflection profiles. Figure includes sound source (A), receiver (B), power supply (C), hard copy output (D) and computer (E) to process, display and store digital signal.

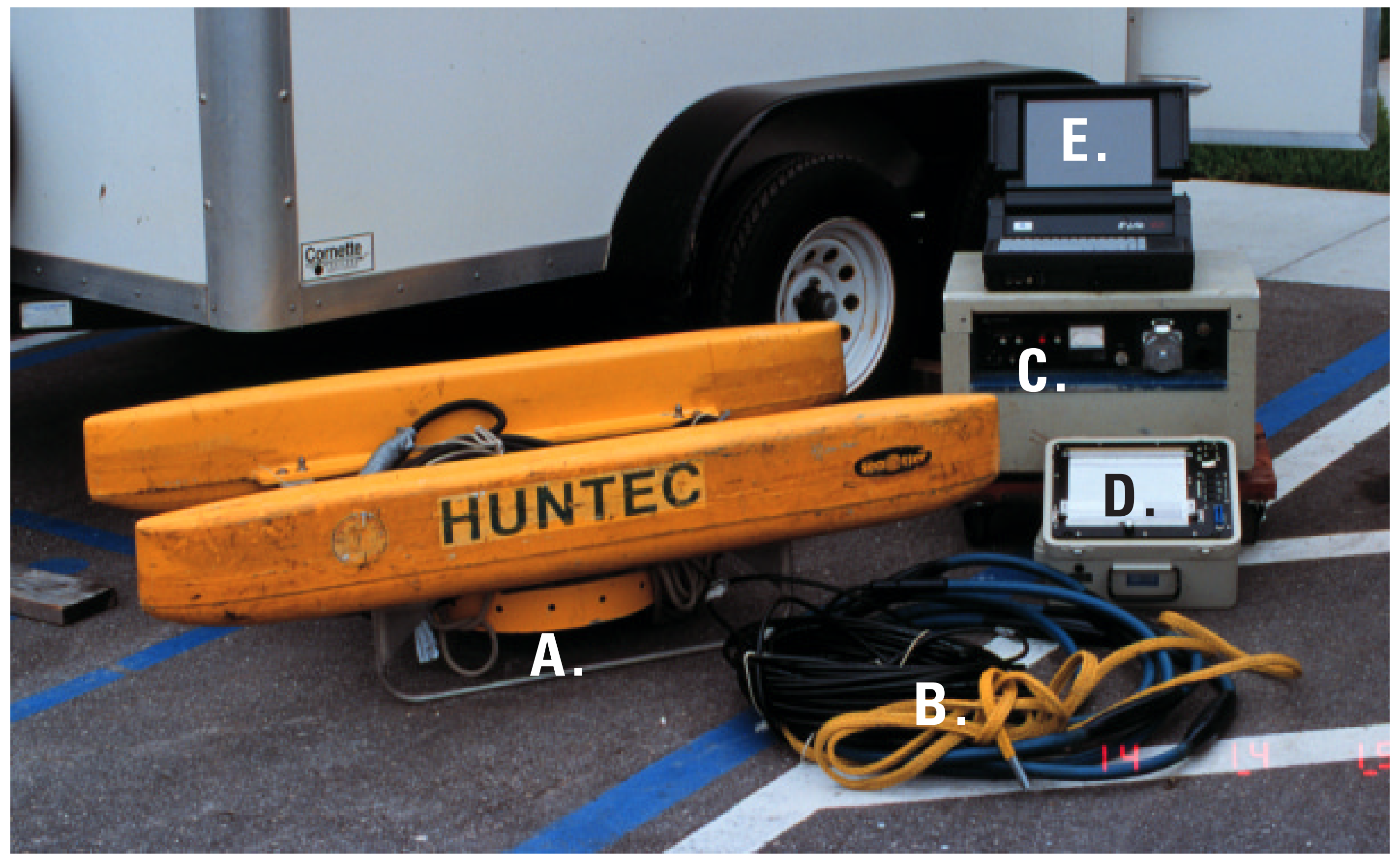
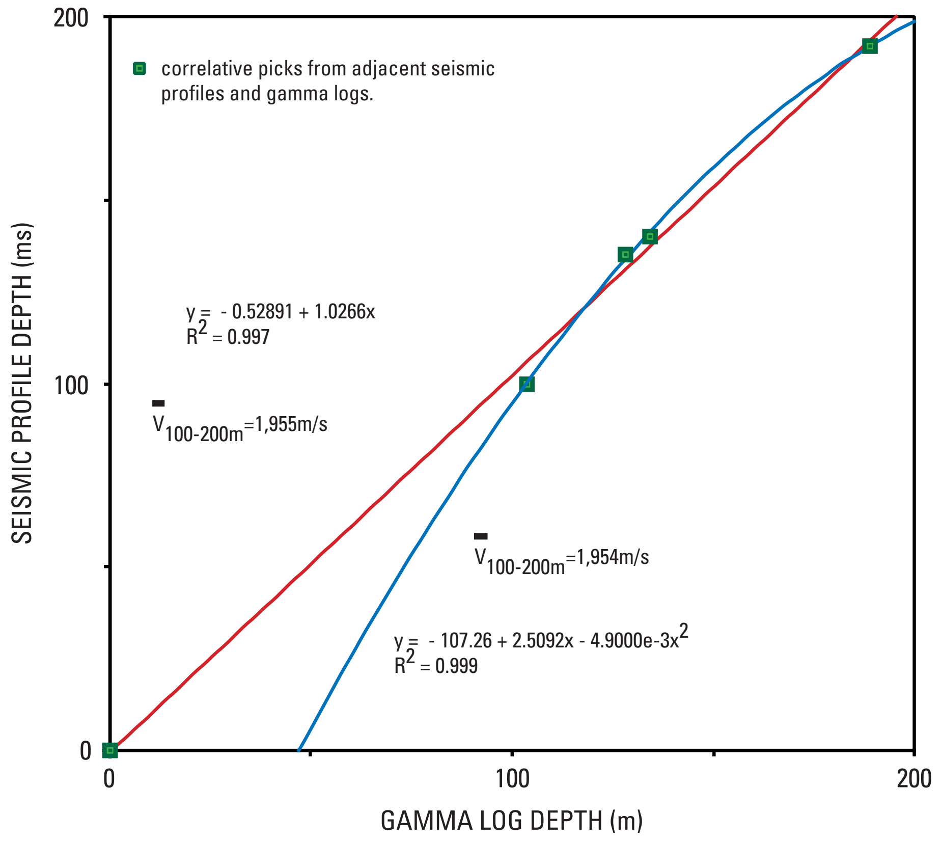


Figure 3. Comparison of depth-to-horizon in milliseconds on seismic profiles to depth-to-peak in meters of a correlative horizon on natural gamma logs. The resulting equations describing the best fit curve (blue) or the best fit curve with zero origin (red) can be used to determine sound velocity for a given depth. Averaged velocity for 100 to 200 meters depth is 1,955 meters per second.



Seismic Profiling

The Elics Delph2* High-Resolution Seismic Profile System (HRSP) was acquired with proprietary hardware and software running in real time on an Industrial Computer Corporation 486/33 PC (Fig. 2). A gray scale thermal plotter was used to display hard-copy data. Digital data were stored on a rewritable magneto-optical compact disk. Navigation data were collected using a Trimble Global Positioning System (GPS) or Rockwell Precision Lightweight GPS Receiver (PLGR) these systems provide navigational accuracies of ±10 m. GeoLink XDS mapping software was used to display navigation. The acoustic source was an electromechanical device, the Huntec Model 4425 Seismic Source Module mounted on a catamaran sled (Fig. 2). Occasionally, an ORE Geopulse power supply was substituted for the Huntec Model 4425 due to operational limitations. Power settings were 60 joules or 135 joules depending upon data quality during acquisition. An Innovative Transducers Inc. ST-5 multi-element hydrophone was used to detect the return acoustical pulse. This pulse was fed directly into the Elics Delph2 system for storage and processing.

The Elics Delph2 Geophysical system measures and displays two-way travel time (TWTT) of the acoustical pulse in milliseconds (ms). Amplitude and velocity of the signal are affected by variations in lithology of the underlying strata. Laterally consistent amplitude changes (lithologic contacts) are displayed as continuous horizons on the seismic profiles. Depth to horizon is determined from the TWTT, adjusted to the subsurface velocity of the signal. Suggested compressional velocities for Hawthorn Group sediments for the Florida Platform range from 1500 to 1800 meters per second (m/s) (Tihansky, pers. comm.; Sacks and others, 1991). Refraction studies conducted in areas within Alachua County, Florida (Weiner, 1982) yielded velocities of 1707 to 4939 m/s for the Hawthorn Group sediments. Weiner, (1982), reported lower velocities for the sand and clay sediments and higher velocities for the carbonate sediments. To correlate horizons from gamma logs to seismic profiles, best-fit-curve plots were used to determine local velocities (Fig. 3).

More than 750 line-km of data were collected from >40 lakes, rivers and offshore sites, only 34 are presented in this study (Table 1). Best-fit-curves were used to compare well-log depths and seismic depths but an approximate velocity of 1500 m/s was used as a general calculation for depth scales on the HRSP data. Data quality varied from good to poor with different areas and varying conditions. As acquisition techniques improved, data quality in general also improved. The interbedded nature of the lake bottom sediments provides good reflecting surfaces for acoustic signals. These layers appear on the seismic records as convergent, divergent, or parallel bands. Folds, faults and facies changes can be recognized as bands, lateral and vertical discontinuities, and truncations of the bands by other reflections. In some areas, acoustic multiple-reflections masked much of the shallow geologic data. Multiple reflections, an artifact of the acquisition system, are caused by a number of possible factors that reflect the acoustic signal to the water surface and back down more than once.

Geophysical Well Logs

Natural gamma ray logs were used for correlating geologic units to the seismic reflection data. Logs used in this report are part of the St. Johns River Water Management (SJRWMD) geophysical log data base and accessed through GeoSys/4G software version 1.1 developed by Dr. Robert Lindquist and Dr. Daniel Arrington of Gainesville, Florida. Sources of the gamma logs include wells logged using SJRWMD equipment and logs digitized from various agency files or private consultant reports submitted to the SJRWMD.

Gamma logs are scaled in counts per second (cps), which provide a relative indication of gamma ray intensity. Relative gamma ray intensity can be used to identify boundaries between geologic units. The contact between the Miocene Hawthorn Group sediments and the Eocene carbonates is generally identified by low cps (0 to 50) in the Eocene carbonates and higher cps (>50) in the Miocene and younger sediments. Additionally, the Miocene sediments are highly variable and units within the section could vary from 20 to >1000 cps. Many factors influence the absolute values that are recorded (borehole diameter, size of the probe crystal) but a characteristic “signature” can usually be identified. Pliocene and Pleistocene sediments that overlie the Miocene sediments may be identified by a reduction in cps. These sediments are generally sands and sandy clays, commonly reworked Miocene sediments are present and may greatly increase the cps.

Cross sections of the gamma logs available near the surveyed lakes are provided to show the contacts of geologic units that could be readily identified (Fig 4). Elevation of the geologic contacts were interpolated to the sites that were profiled and converted to two-way travel time and correlated to reflections that may represent the contacts. Since the lakes generally represent areas of increased stratigraphic disturbance, the elevation of the contacts are highly variable. Reflections from the least disturbed area within a site were used to correlate to the gamma logs. In some cases, the contact could not be identified but a strong reflector within a geologic unit is identified to show subsurface structure.

Map Generation

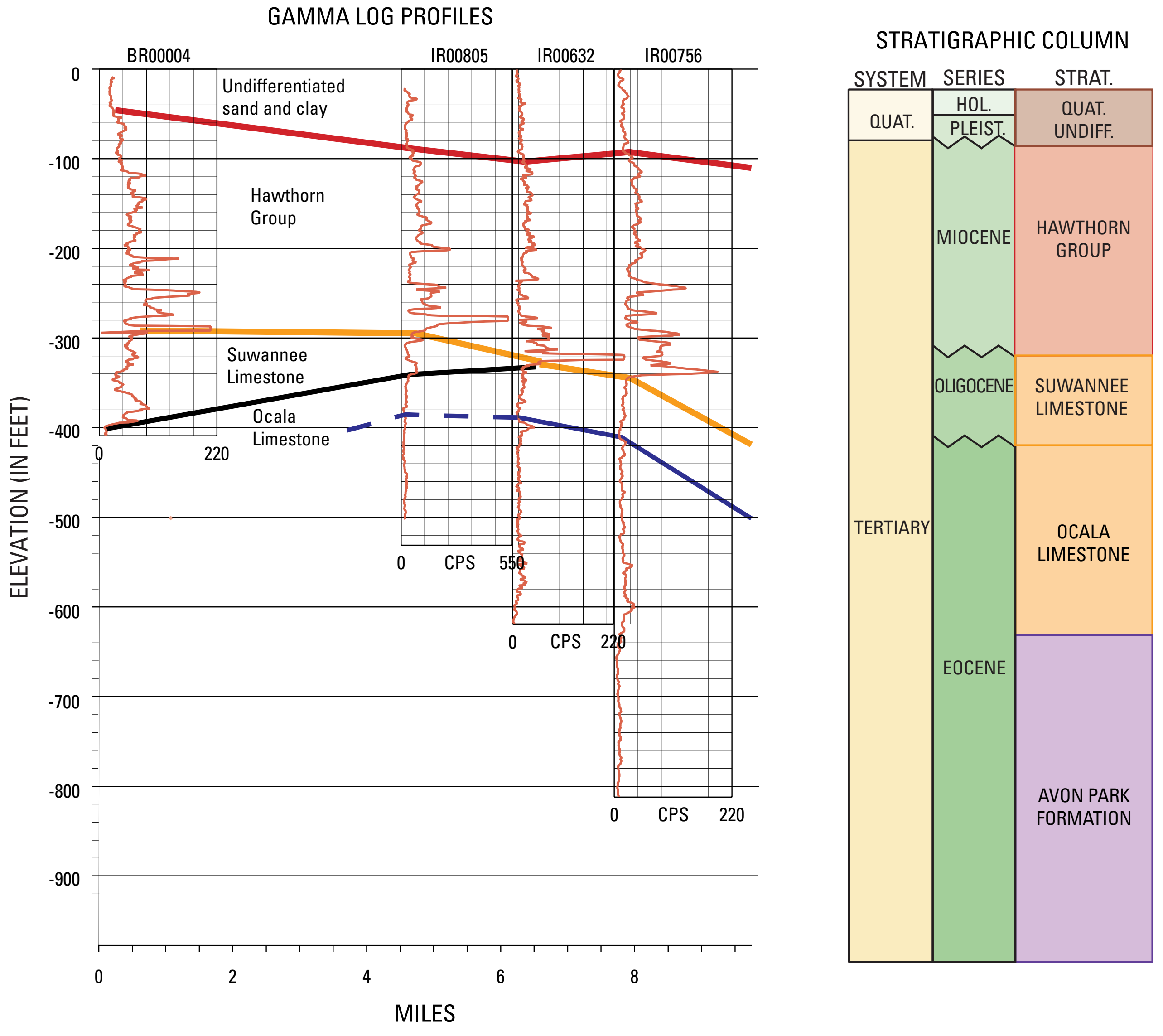
Index maps that show the hydrography of the region and provide background for navigation tracklines were generated from standard USGS Digital Line Graph (DLG) datasets using Qeoquest CPS-3 software products. The hillshade maps showing topographical relief were generated from USGS gridded datasets using ESRI ArcView 3.0. Seismic profiles were scanned from analog copies. All page layout of figures and text was accomplished with the drawing programs Deneba Canvas and to some extent Adobe Illustrator for Macintosh computers.

Reflective horizons from a lake that were laterally continuous and representative of a subsurface feature or the lake bottom were digitized using a standard digitizing table that have been eroded from the areas bordering the lakes have been deposited in the lakes and migrated downward into the space created by dissolution. The elevation of the bottom of these depressions may represent the base level of erosion as constrained by the potentiometric surface of the Floridan aquifer.

The hillshade views commencing the subsections were generated in ArcInfo from a grid of topographic elevations interpolated rom existing five foot contours depicted on USGS topographic maps. Data is projected to UTM, Zone 17, NAD 1983, 1990 correction and copied to double precision. Location of wells used for gamma log cross sections are included to show the proximity of well data to the study sites.

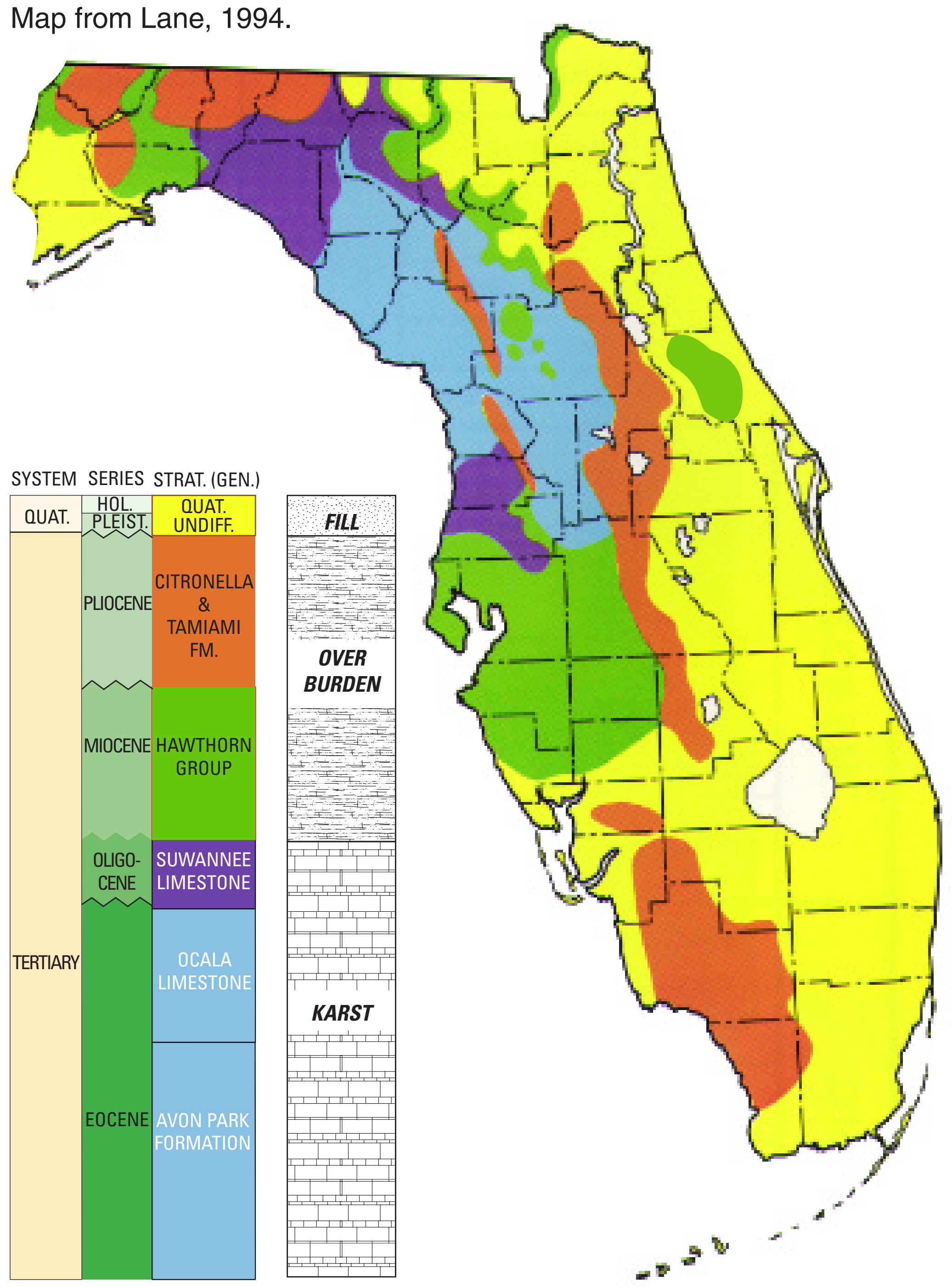
Hillshade views help emphasize the surface characteristics of the physiographic provinces surrounding the sites profiled. Lake distributions varies within high sand ridges to low-lying flood plains of modern and ancient river systems. The hillshade views also show how the topography greatly effects the surface water drainage. Many of the lakes are concentrated within the higher sand ridges and form depressions in the surface. The concentrations of slightly acidic water within the lakes provides a mechanism for enhanced dissolution of the underlying carbonates and other sediments. Many lakes are closed basins with no external drainage. In many cases, sediments eroded from the lake margins have been deposited in the lakes and migrated downward into the space created by dissolution. the elevation of the bottom of these depressions may represent the base level of erosion as constrained by the potentionmetric surface of the Floridan aquifer.

Figure 4. General stratigraphic column for north central Florida. The natural gamma log profiles on the left side of the figure are examples of “signatures” from wells and their regional correlation potential. Modified from Scott (1988) and Miller (1986).



REGIONAL GEOLOGY

Figure 5. Surface stratigraphy of the Floridan Peninsula. Map from Lane, 1994.



In north-central Florida, sinkholes at the surface are generally related to the dissolution of two host limestone units, the Ocala and Suwannee Limestones. The Eocene-age Ocala Limestone was deposited between 40 and 28 million years ago (ma). Over time, sections of the rock have been recrystallized into dolomite, $CaMg(CO_3)_2$. Ocala Limestone is generally tan to cream, highly fossiliferous lime mud preserved as packstone to wackestone (Scott, 1992). Above the Ocala Limestone is the Oligocene age Suwannee Limestone (28 ma-24 ma) only present as scattered deposits in low topographic areas and typically absent on the topographically high areas. Figure 5 shows the surface distribution of these units.

Overlying the Ocala and Suwannee Limestones is the Hawthorn Group (Miocene 24-5.3 ma). This group is composed of massive impermeable clay and dolomite units. Interbedded with these impermeable units are sands, sandy clays and fractured carbonate units (Miller, 1986). Except where thin or breached, the Hawthorn Group is the main semiconfining unit to the Floridan aquifer in north-central Florida. The thickness, stratigraphic position and confining nature of the Hawthorn Group determines the form and function of sinkholes. The Hawthorn Group is absent from the structural highs such as the Ocala Uplift to the east of the study area and the Sanford High (Fig. 6). It maintains a thickness of 9 to 18 m (30-60 ft) across the St. Johns Platform and thickens to over 46 m (150 ft) over the Jacksonville basin (Mallinson and others, 1994). In most of the sites profiled, the potentiometric surface of the Floridan aquifer lies below lake surface. This condition creates a downward gradient which allows water to permeate through the Hawthorn Group sediment from the lake into the limestone units below. Additionally, breaches in the Hawthorn Group allow enhanced surface groundwater interaction. An example of catastrophic breaching occurred in the late 1800s when a sinkhole collapsed and drained the former Alachua Lake, thereby creating Paynes Prairie (Pirkle and Brooks, 1959b).

Quartz sands, clayey sands and clays of Plio-Pleistocene age (5.3 ma-30 ka) overlie the Hawthorn Group and occur as a surface veneer ~10 m (33 ft) thick or as elongate ridges that may be over 30 m (98 ft) thick. The ridges are expressions of relict shorelines created during Pleistocene interglacial periods (Cooke, 1945; White, 1970). These ridges and related features that developed during the Plio-Pleistocene sea-level cycles form the current physiography of the Floridan Peninsula (Fig. 7). This physiography is highly perforated by karst terrain.

Faulting within the deeper sediments of Florida have long been a source of controversy (Scott, 1997). Faulting occurred during the late Oligocene to early Miocene and again through the Pliocene to early Pleistocene. Williams and others (1977) suggest the movement created the Ocala Uplift (Fig. 6). Pirkle and Brooks (1959a) believe the uplift was a pre-Hawthorn Group occurrence. Opdyke and others (1984) suggest uplift was due to isostatic rebound in response to loss of the carbonate load by dissolution processes, they reported that at least 12 x 108 cubic meters (4 x 1010 cubic feet) per year of limestone are lost from peninsular Florida. This loss, over a period of 38 ka years could result in a rebound of 33 m (108 ft). A deeper and older (early Cenozoic, 60 ma) feature, the Peninsular Arch, has also caused faulting and fractures. The associated weakening of the rocks provides optimum conditions for dissolution and formation of karst.

The term "fault" as used in this report refers to vertical displacement or discontinuities occuring at a specific site. Primarily, these are faults resulting from sediment slumping into a sinkhole depression, or tension faults. No large scale faults that can be mapped regionally and reflect a tectonic origin were identified.

From the surface geology and physiographic regions, Scott (1988) delineated physiographic provinces for the peninsula. Provinces included in the study are shown below (Fig. 8).

Figure 6. Approximate limits of the Hawthorn Group, along with structural controls. Contour intervals in feet. Modified from Scott, 1988.

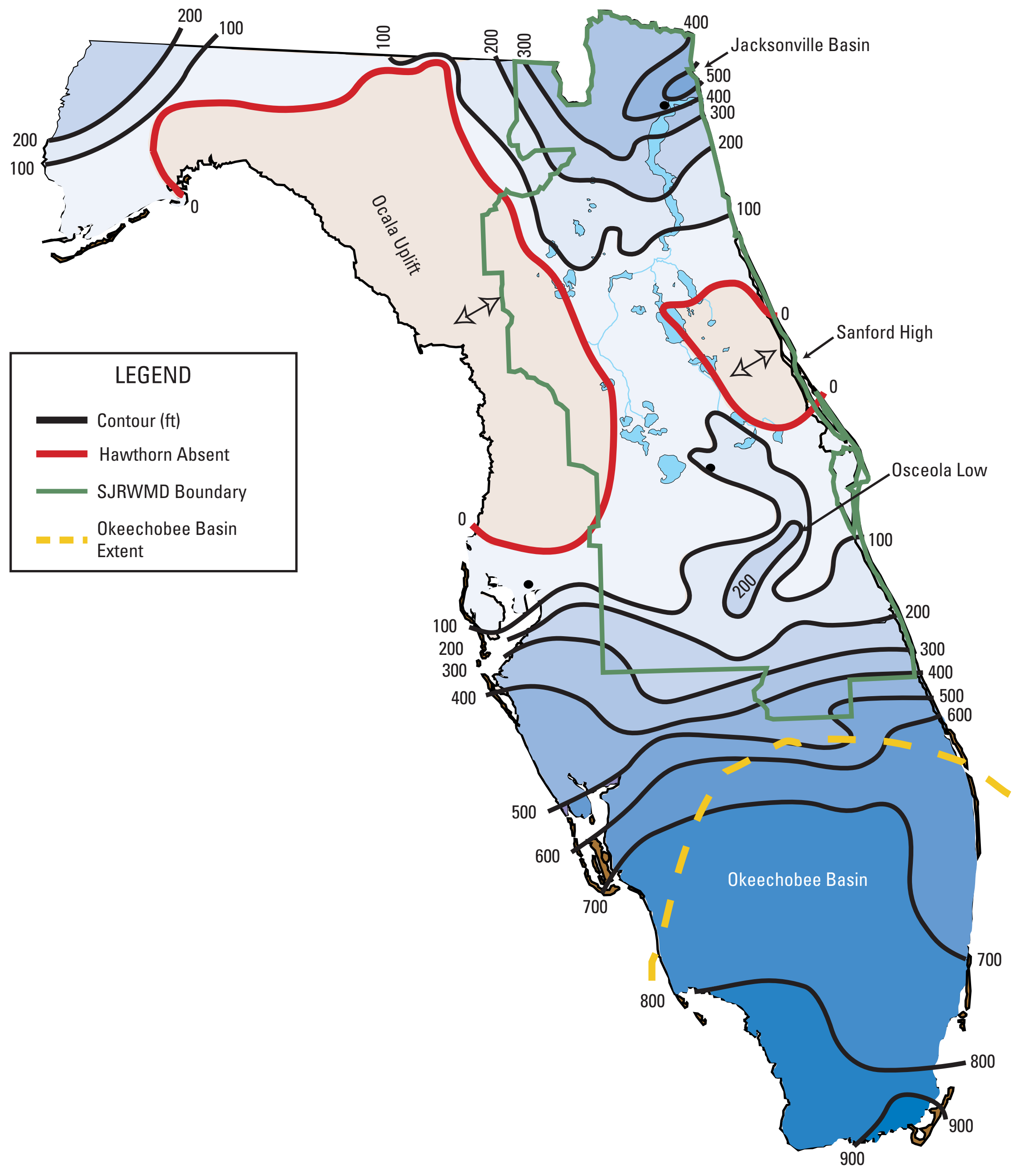


Figure 7. Physiographic regions of Florida. Modified from Randazzo and Jones (eds.), 1997.

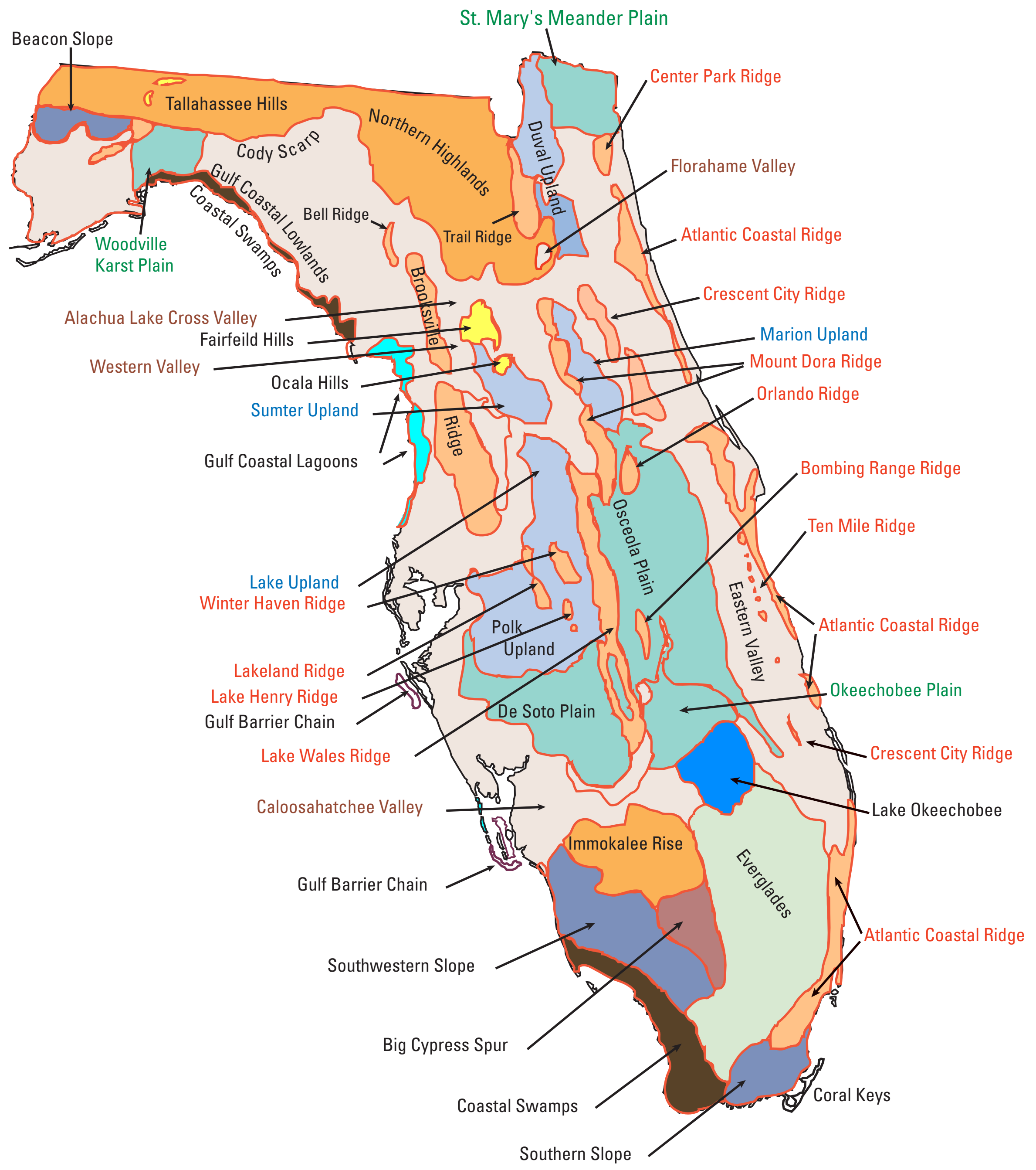
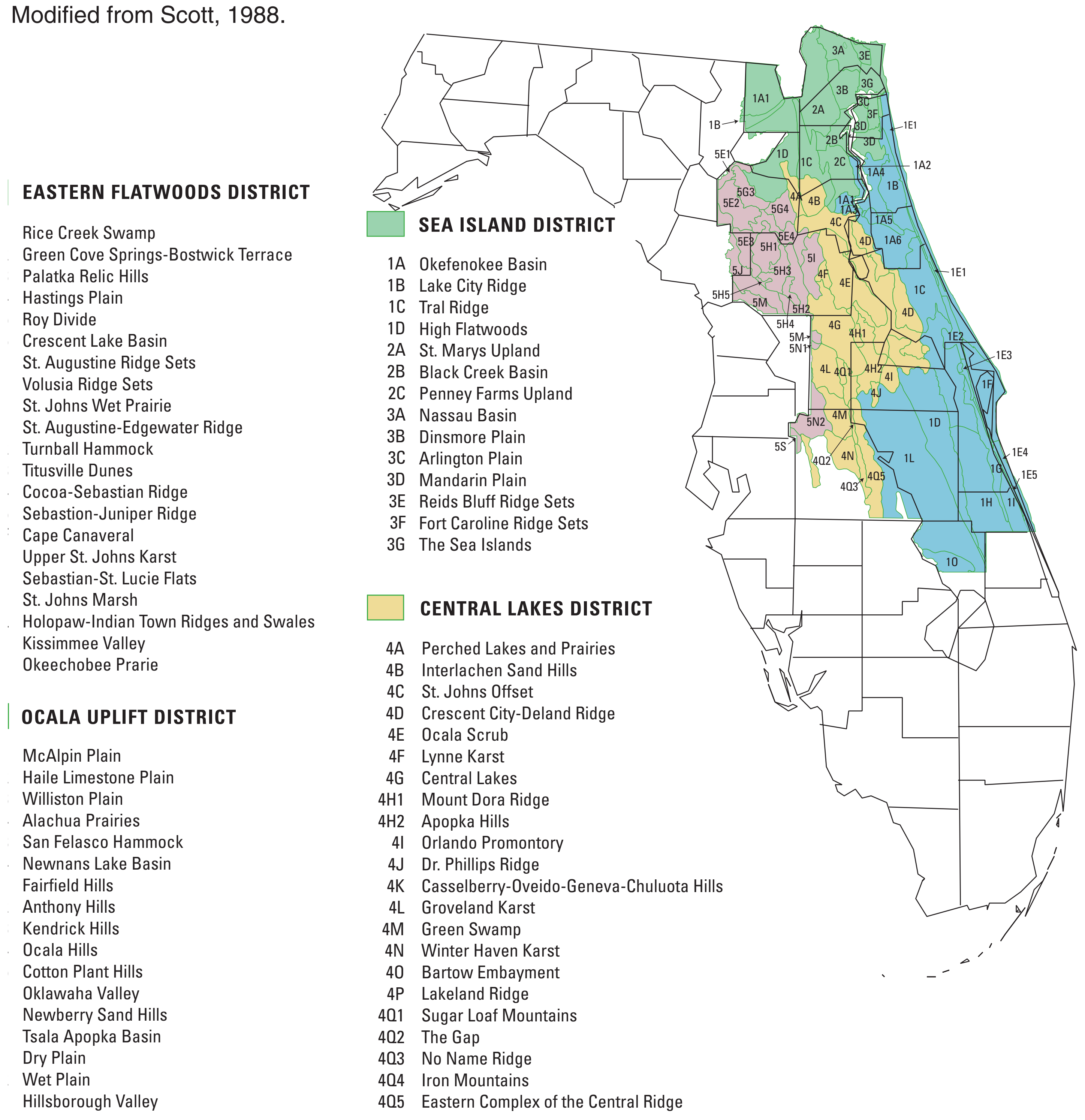
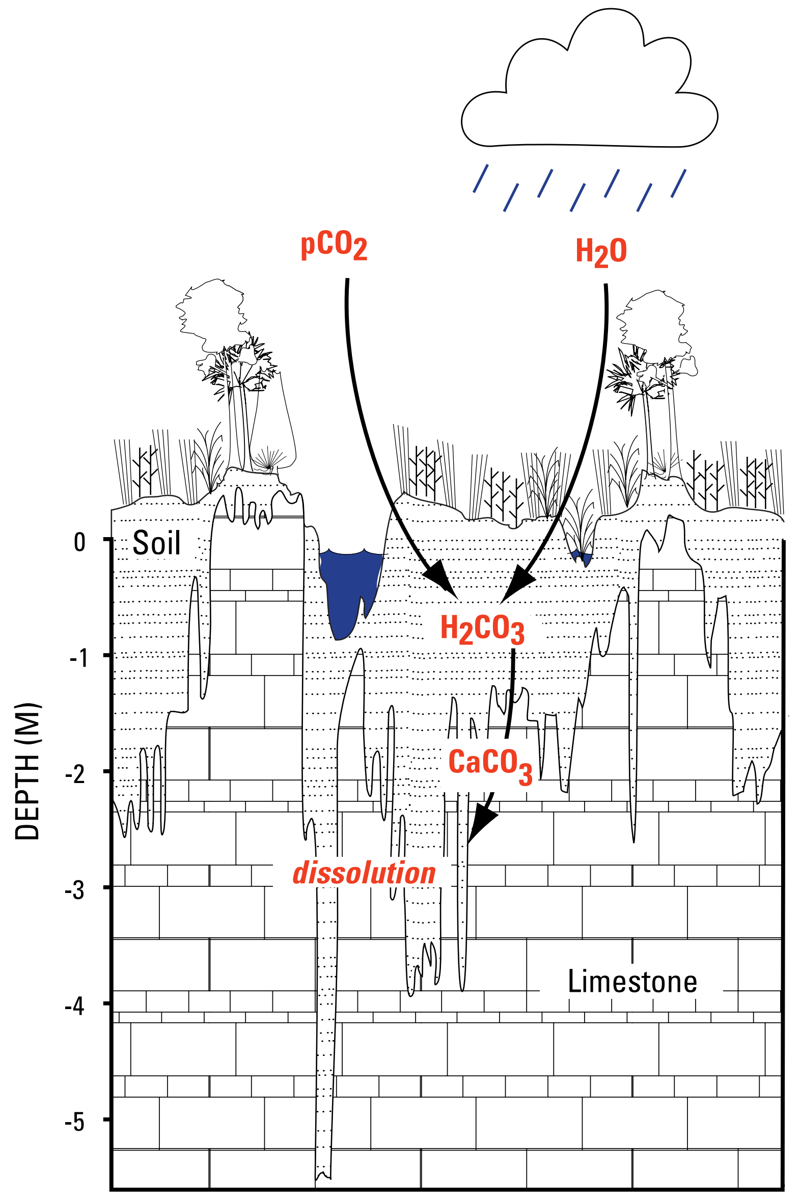


Figure 8. Physiographic provinces of Florida. Modified from Scott, 1988.



KARST DEVELOPMENT AND CHARACTERIZATION

Figure 9. Carbonate dissolution process and karst formation.



$CaCO_3 + H_2O + CO_2 \dashrightarrow Ca^{2+} + 2HCO_3$

- Bacterial and root respiration in the soil increase pCO_2
- As pCO_2 increases, so do dissolution rates

Tropical latitudes = high evapotranspiration
+ well developed soil
+ high atm. pCO_2
= KARST

(Yucatan, Caribbean, Florida, South China...)

Karst Development

Karst topography is created by a chemical dissolution process when groundwater circulates through soluble rock (Fig. 9). Carbon dioxide from the atmosphere is fixed or converted in the soil horizon to an aqueous state, where it combines with rainwater to form carbonic acid, which readily dissolves carbonate rock. Root and microbial respiration in the soil further elevates carbon dioxide partial pressure, increasing acidity (lowering pH). In tropical and subtropical regions such as Florida, abundant vegetation, high rainfall and high atmospheric CO_2 values favor the rapid dissolution of the preexisting limestone.

Karst features develop from a self-accelerating process of water flow along well-defined pathways. As the water percolates downward under the force of gravity, it dissolves and enlarges any pore or fracture in the rock through which it flows. These pathways also include bedding planes, joints, and faults (Fig. 10). Enlarging the fracture allows it to carry more water, which increases the dissolution rate. As the fracture gets larger and transmits more water, it begins to pirate drainage from the surrounding rock mass. This process will create areas where the rock is highly eroded with very little dissolution around it, creating a very jagged appearance to the substructure.

Water will continue to percolate downward until it reaches the water table, below which all pore space is occupied by water. Since the rock is saturated with water at this point, water circulation is not as rapid and dissolution rates slow (the dissolution potential of the water is expended over time). However, the water table itself fluctuates up and down as a result of seasonal change, drought conditions and groundwater removal. This movement creates a zone of preferential dissolution along the zone of fluctuation. Over time this process creates pathways in the rock near the water table and provides a very efficient means to transport water.

During wet cycles, the potentiometric surface of the confined aquifer may be higher than the ground surface. This allows water to flow through breaches in the confining unit and flow at the surface as springs.

Water table fluctuations also occur on larger spatial and temporal scales related to sea-level change. Numerous sea-level cycles have occurred with lowstands extensive enough to expose most of the Florida peninsula and create extensive karst environments. These episodes of paleokarst development have been documented (Randazzo, 1972; Randazzo and Zachos, 1984) and can be identified in the rock record as cycles of shallowing-upward sequences. Geologic evidence includes the presence of evaporite deposits which form during the shallow phase of sea-level cycle. A diagenetic end-member of evaporites is hydrogen sulfide which, when oxidized to sulfuric acid, will greatly enhanced the carbonate dissolution process (Hines, 1997). The presence of paleokarst in the subsurface may influence the development of modern day karst.

Types of Sinkholes

Karst topography is the result of sinkholes: funnel, bowl or cylindrical-shaped depressions that form to accommodate loss of material due to dissolution in the underlying carbonate rock. Dissolution creates a subsurface conduit system that leads to collapse and sinkhole formation at the surface (Arrington and Linquist, 1987). In Florida, sinkhole type and lake development depend primarily on three factors: 1) proximity of the limestone rock to the surface; 2) thickness of the overburden (confining unit); and 3) location of the water table and potentiometric surface. Figure 11 shows a classification of sinkholes that has been developed based on these factors. When the water table is deep below the ground surface, dissolution of the rock occurs within the unsaturated rock, creating a conduit system that transports overlying material downward. If overburden is present, it is removed through the conduit system, causing subsidence at the surface (Fig. 11A). If no overburden is present, the self-accelerating process of dissolution eventually removes all the material at the surface and the conduit system develops progressively downward (Fig. 11B). Where the ground is close to the surface, fluctuations in the water table create a void system along the zone of fluctuation. Downward dissolution above the water table directly undermines the surface, eventually causing a collapse. If overburden is present it will slump into the hole, sometimes catastrophically (Fig. 11C). Lack of overburden will create a direct connection between the surface and any underground void or cave system (Fig. 11D). A transitional type of sinkhole (Fig. 11E) straddles the end member classification in that deposition of material in the depression created by dissolution can occur during subsidence or collapse, or after dissolution has ceased. In Florida this type of sinkhole can be found very near the surface with recent infilling, or deep in the subsurface from paleokarst development. Buried sinkholes can also reactivate since they continue to be preferential pathways for groundwater movement.

Figure 12 incorporates near surface geology (factors 1 and 2 mentioned above) with depth to aquifer (factor 3) to map the distribution of sinkhole types in Florida. When compared to the surficial geology map (Fig. 5, Regional Geology Sheet p. 3), it is apparent that in areas where the competent overburden of the Miocene sediments overlie limestone that is in close proximity to the surface, there is the highest likelihood of cover-collapse sinkholes (Lake and eastern Marion counties). Areas of loose Quaternary fill typically experience the slower developing cover-subsidence sinkholes that are most commonly found along the eastern seaboard.

Figure 10. Solution and collapse features of karst and karren topography.

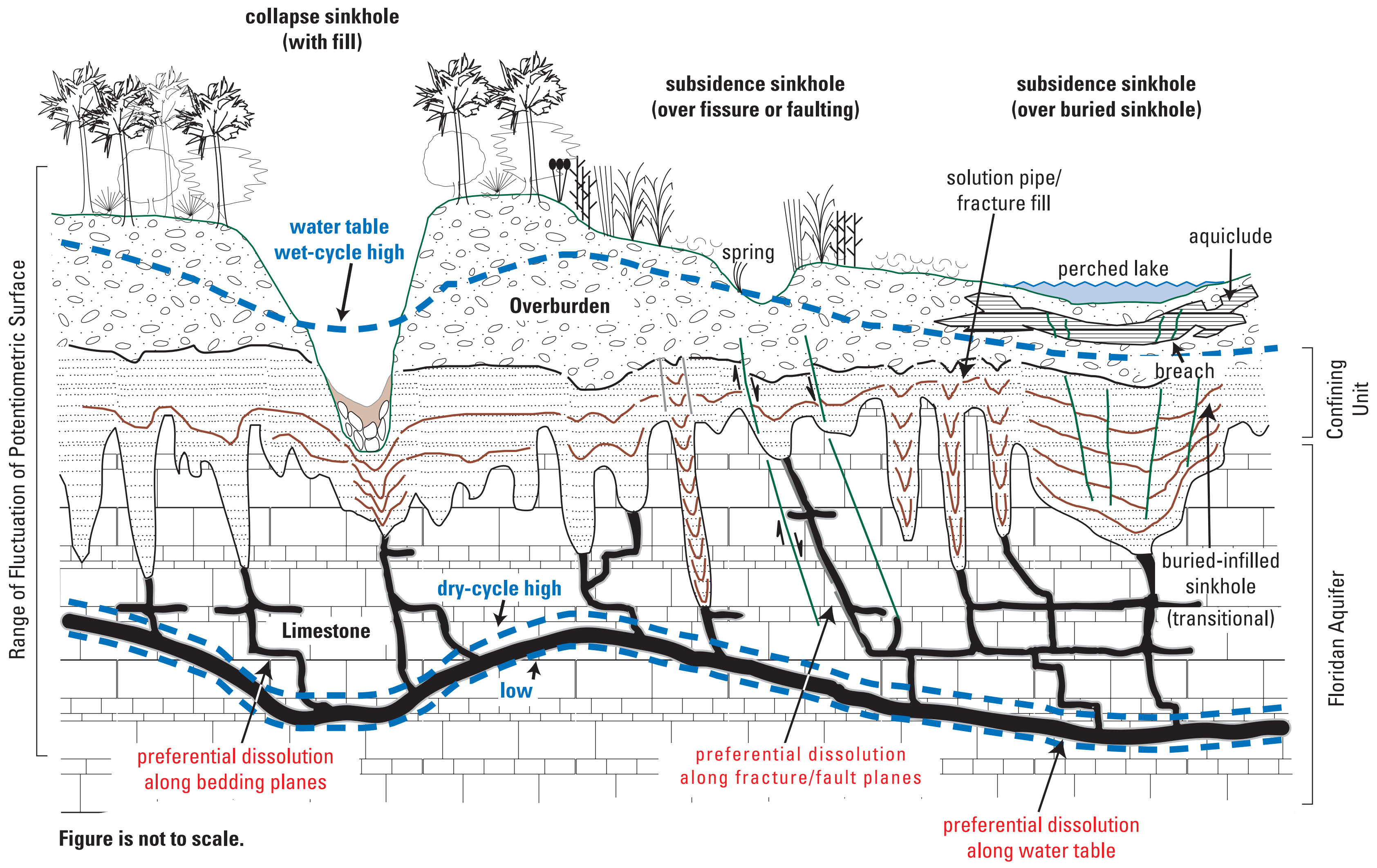


Figure is not to scale.

Figure 11. End-member classification of sinkholes. Modified from Culshaw and Waltham (1987); Ogden (1984). Graph shows distribution relative to potentiometric and overburden controls.

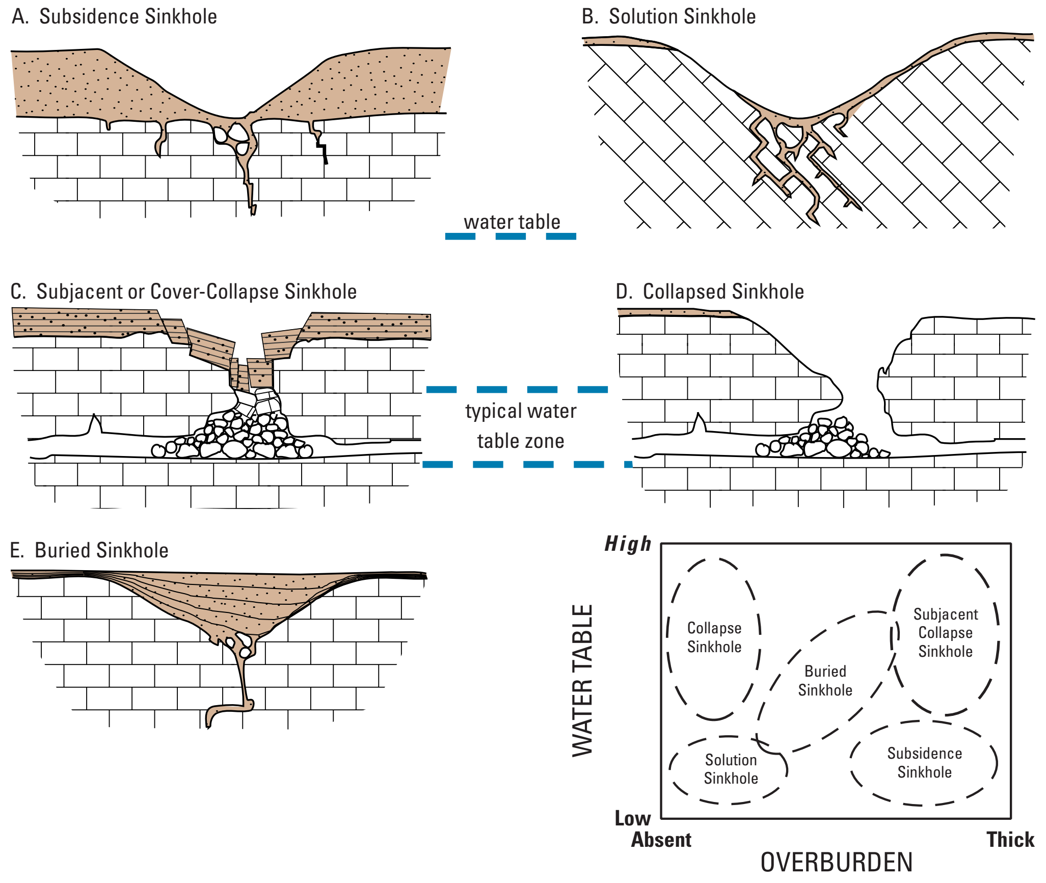
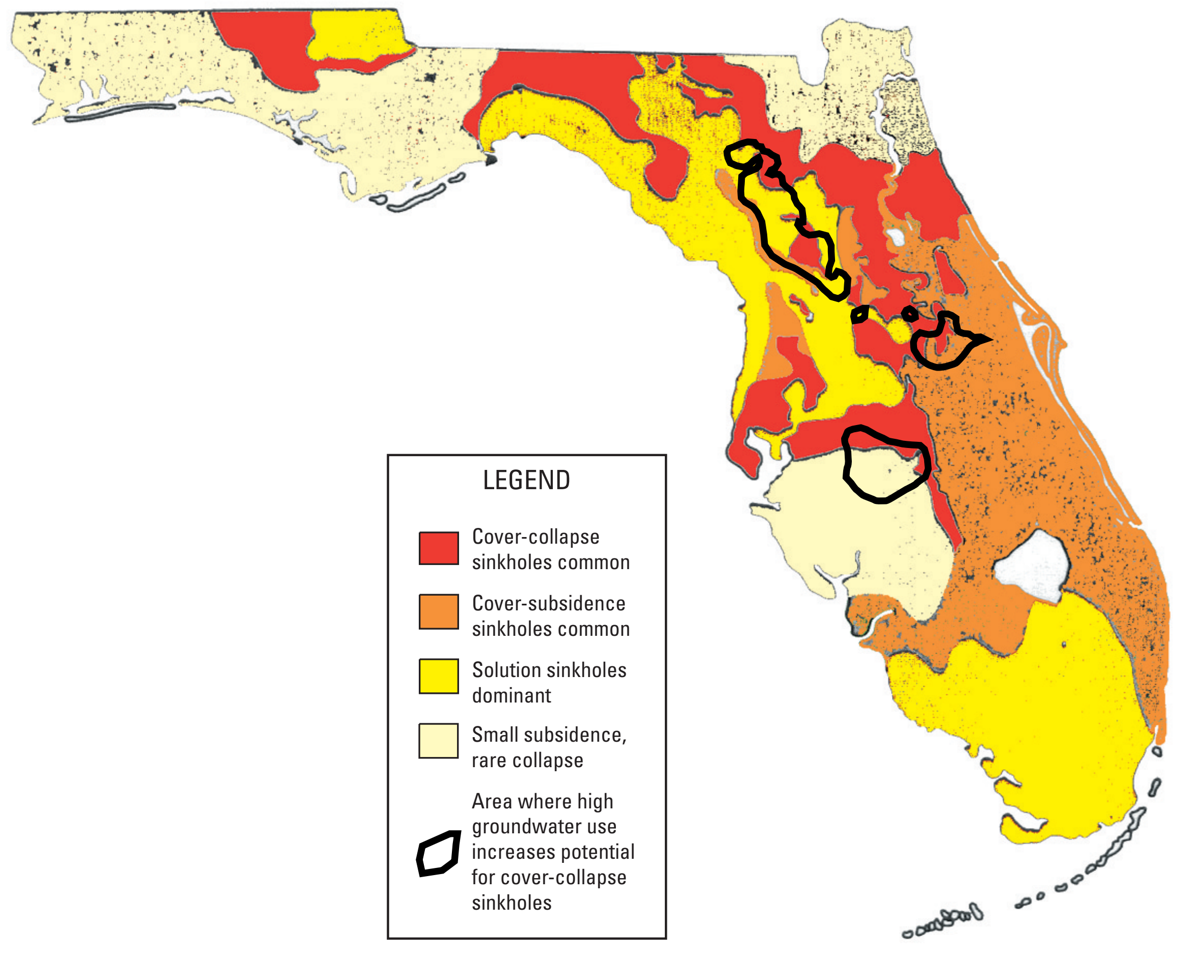
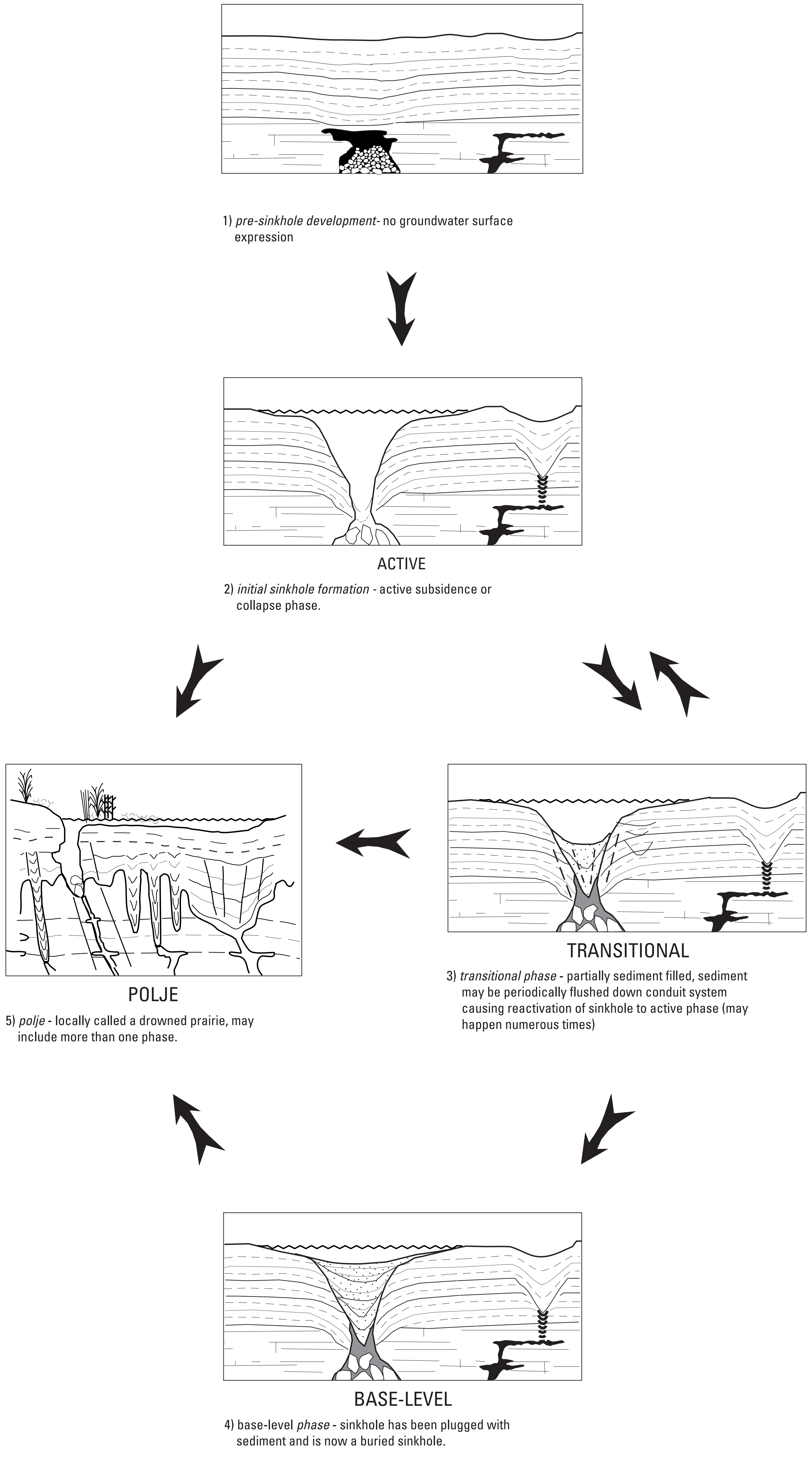


Figure 12. Predicted sinkhole type in Florida. Modified from Randazzo and Jones (eds.), 1997.



SINKHOLE LAKE EVOLUTION AND EFFECTS OF URBANIZATION

Figure 13. Predicted sinkhole type in Florida. Modified from Randazzo and Jones (eds.), 1997.



1) *pre-sinkhole development*- no groundwater surface expression

ACTIVE

2) *initial sinkhole formation* - active subsidence or collapse phase.

TRANSITIONAL

3) *transitional phase* - partially sediment filled, sediment may be periodically flushed down conduit system causing reactivation of sinkhole to active phase (may happen numerous times)

BASE-LEVEL

4) base-level *phase* - sinkhole has been plugged with sediment and is now a buried sinkhole.

POLJE

5) *polje* - locally called a drowned prairie, may include more than one phase.

Sinkhole Lake Evolution

An estimated 95% of the surface waters in northeastern Florida are sinkholes (Brainard, 1982; Lane, 1986). The lakes originate from the direct result of chemical and/or mechanical processes. The mechanical processes that result in lake development are: 1) slumping or subsidence of underlying clastic or carbonate sediments; 2) clustering of sinkholes; or, 3) a combination of the previous two. Sinkhole lakes in Florida occur in areas of thin overburden, typically less than 61 m (100 ft). In areas with an impermeable confining layer and no breaches, a lake might be a perched lake (the lake level is held above the groundwater level) with no communication with subsurface aquifers. Otherwise a lake will form in conditions where a lack of overburden or permeable confining layer allows for increased karstification of the underlying limestone, producing a depression due to limited fill material.

The seismic profiles indicate that sinkhole lakes can be delineated into a progressive sequence of lake evolution based on geomorphic types (Kindinger and others, 1999) (Fig. 13). In central Florida the progression begins with the subsurface dissolution of the limestone host rock (see Karst Development sheet, p. 4), ultimately leading to surface collapse or subsidence. The depression may be dry or, if a portion is below the water table, it may contain water. Erosion of sediments into the depression may cause the sinkhole to become plugged. Further erosion may eventually bury the sinkhole.

Progressive Sequence of Lake Evolution

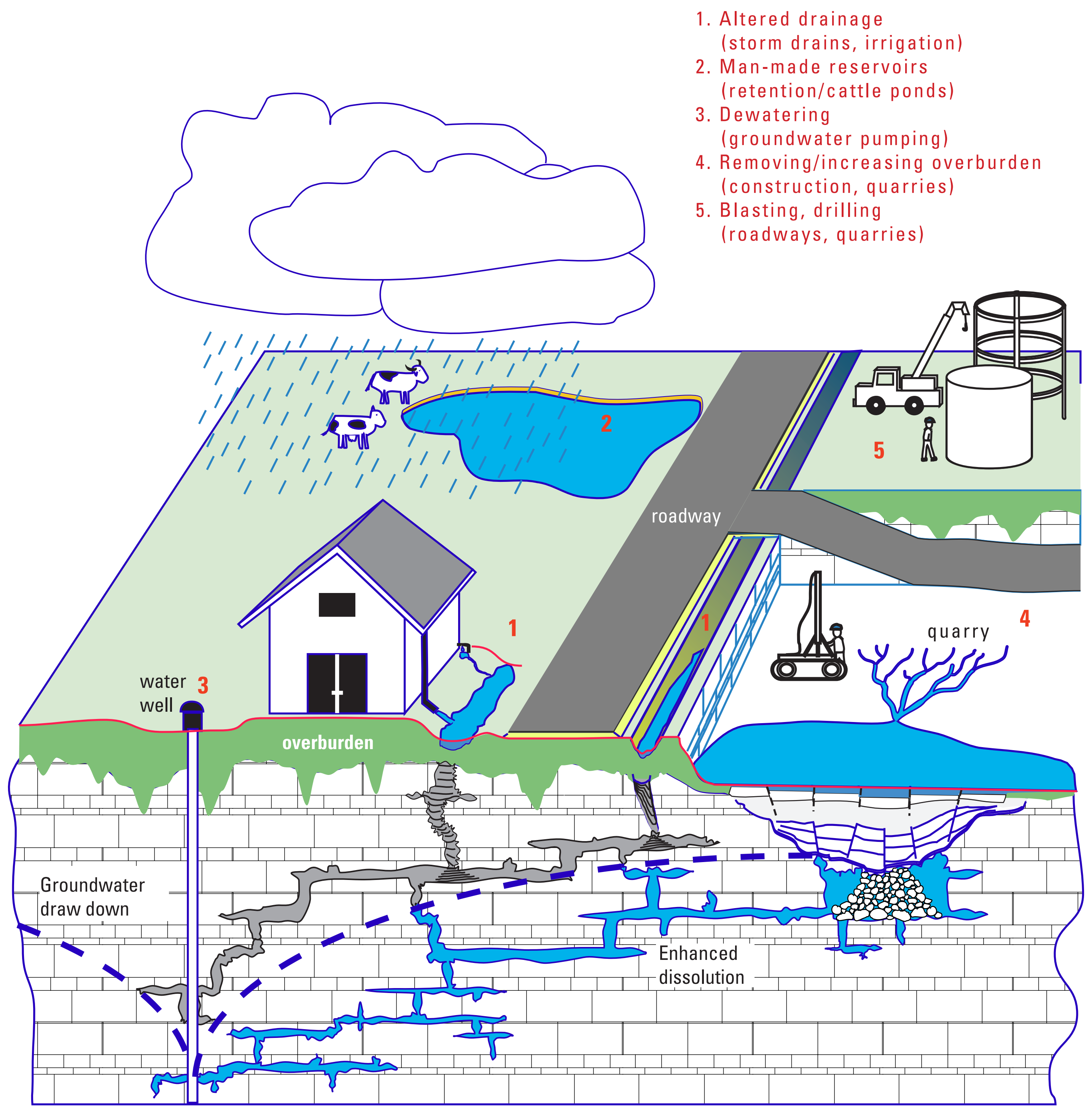
Pre-sinkhole development (no visible expression)- the process begins with subsurface dissolution of limestone below the unconsolidated overburden. Since there is no surficial expression of the dissolution process, predicting areas of sinkhle development is difficult. The process continues, undermining the structural integrity of the overburden, until collapse occurs.

Active subsidence or collapse phase (young) - At the initial surface appearance of a sinkhole, the basin is steep-sided and potentially deep. As surface material is removed by erosion and/or slumping from the expanding perimeter to the center of the sink, the basin walls decrease in angle and the lake basin becomes more extensive. Examples of this phase include sinkholes at Orange Lake, Crescent Beach Spring and Red Snapper Sink (Table 1, Fig. 1).

Transitional phase (middle age) - When the sinkhole becomes partially or completely plugged, the lake begins to develop a shallower and flatter bottom. During this phase the plug may flush through the subsurface conduit system, allowing the sinkhole to reactivate and revert to an active subsidence phase. This may occur several times until sediment accumulates faster than dissolution of the underlying limestone. Many of the lakes in the Interlachen Karst Highlands are in a transitional phase.

Baselevel phase (mature) - Once a transitional phase sink becomes plugged, its growth is limited and the lake becomes shallower. Continual erosion of material into the basin over time will then eventually fill the basin if no reactivation of the sinkhole occurs. The level to which the sinkhole basin erodes is also related to the water table elevation and the potentiometric surface of the Floridan aquifer. Many lakes in the east central study area are in a base-level phase.

Figure 14. Artifically-induced causes for increased karst development.



Polje (drowned prairie) -The lake floor is cut entirely across karst rock (sometimes covered with unconsolidated alluvium) but is located in the epiphreatic zone and is inundated at high stages of the water table. These lakes may have one or all phases of sinkhole development and many karst features. Orange Lake, for example, is a polje and includes active subsidence and transitional features.

The term polje arises from a lowland or depression is flooded by a rising groundwater table -poljes. The Croatian word ‘polje’ means “field”. Gams (1978) identified three criteria for a lake to be classified as a polje: (a) flat floor in rock (which can also be terraced or occur in unconsolidated sediments such as alluvium); (b) a closed basin with a steeply rising marginal slope at least on one side; and (c) karstic drainage. There are three basic poljes -border, structural, and base-level. All poljes have a common hydrologic factor: their development occurred close to the local water table, even though the lake may be perched in some cases (Ford and Williams, 1992). Of the basic types of polje, only the base-level polje (to date) has been identified in north-central Florida and locally described as drowned prairie.

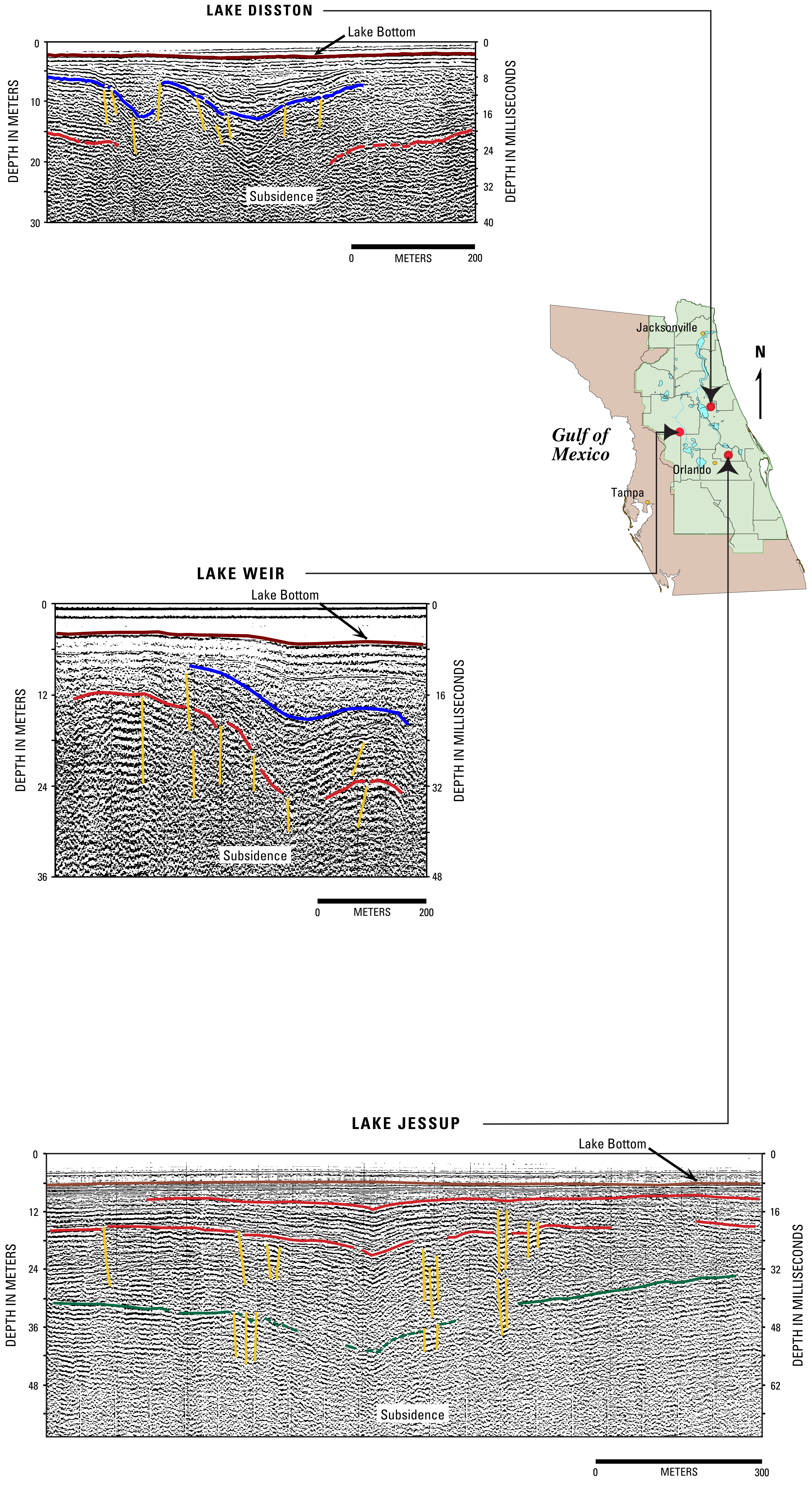
Urbanization and Sinkholes

The process by which sinkholes form in nature is complicated by an additionally important factor: the anthropogenic effect, or urban development in karst areas. As demand for undeveloped land increases, less desirable properties such as karst-prone areas become a target for human construction or development (Ripp and Baker, 1997). Direct contact with an unstable subsurface is the obvious drawback, but not the only geohazard. Other problems related to development of these areas include sources for non-natural sinkhole development. These issues are de-watering, alteration of surface drainage patterns, increase or redistribution of overburden and blasting for quarries and highways (Fig. 14). In Florida, de-watering or aquifer draw down from well field pumping is a major factor (USGS WRI 85-4126), since the potable water supply for metropolitan areas are pumped from aquifers nearby. The magnitude of water removed from the subsurface creates draw down in the aquifer which removes the supporting pressure needed to maintain integrity of the overlying material and land surface. Figure 14 shows typical scenarios where high rates of groundwater withdrawal increase the likelihood of surface collapse. White (1988) estimates that since 1930, artifically-induced collapse has nearly doubled the collapse frequency in karst areas. In the state of Florida, insurance claims for damage from sinkhole collapse have increased from 35 in 1987 to 426 in 1991 (Smith, 1997). Federal Emergency Management Agency (FEMA), 1997 estimates cumulative damage in this state from sinkholes to reach $100 million.

Aside from damage due to surface collapse, sinkholes and related features cannot be considered negative aspects of karst terrain. Many sinkholes, sinkhole lakes and karst-related features in Florida are maintained as state parks for their aesthetic and recreational value (Devil’s Millhopper, Blue Spring, Ichetuknee Springs, etc.). Florida Department of Environmental Protection, Recreation and Parks (FDEPRP) estimates that 14 million people visit Florida parks annually (source: FDEPRP). This, along with privately maintained parks, provides millions of dollars in revenue for the state. But more importantly sinkholes and other karst features provide vital conduits for surface water recharge to the aquifer as breaches through the semi-confining layer. However, as breaches they also become sources of contaminants to the potable water supply. Consequently, sinkholes and sinkhole lakes need to be characterized by their hydraulic connection potential and subsequently maintained and protected if development of this terrain is to continue.

IDENTIFICATION OF KARST FEATURES FROM SEISMIC PROFILES

Figure 15. High-resolution seismic profile examples from three lakes located in separate geomorphologic regions of northeastern Florida. Colors are for interpretive purposes and do not indicate correlation between profiles.



Historically, high-resolution single-channel seismic profiling (HRSP) has been used to determine the regional distribution of stratigraphic units having distinct acoustical characteristics. In this study, the lakes are well distributed and have a relatively small diameter, making stratigraphic correlation difficult. HRSP data has been used primarily here to map the shallow subsurface features found beneath selected lakes of northeastern Florida. Subsurface diagnostic features are used to define the structural history and to locate possible breaches in the confining layer that maintains the perched lakes above the Floridan aquifer. In many cases the acoustical records show fine details of karst (>10 m) and karren (<10 m) features (Ford and Williams, 1992). Compilation of these features from seismic profiles acquired from the lake surveys have shown that certain acoustic patterns reoccur from lake to lake. Figure 14 shows similar acoustic patterns from three lakes located in separate geomorphologic regions. In general, low angle, parallel reflectors are down warped to form a depression. These reflectors are accompanied by discontinuous or segmented reflectors that suggest structural displacement and subsurface subsidence. Horizontal reflectors overlying the subsidence indicate subsequent fill.

The reoccurrence of these features in seismic sections from the more than 39 sites profiled (Fig. 1, Introduction) led to the identification of six acoustical signatures of commonly found karst or geologic features. These features are characterized in Figure 16. Included in the summary are patterns indicative of no acoustic return (Fig. 16 type 1). Negligible or noisy acoustic return unfortunately is common in the lake surveys and are typically the result of various environmental and geomorphologic factors. Such factors include organic material collecting in depressions that disperse the acoustic signal, or a lithologically "hard" lake bottom of packed homogeneous sands. A karst surface near the lake bottom may also disperse the signal or cause ringing (multiples) throughout the record. Side-wall reflections from the shoreline or slope of a depression may further obscure return from subsurface features. Acquisitional deficiencies such as electrical noise or faulty grounding may affect entire surveys, as do lake surface wind, chop or waves.

When the record is not obscured, a number of patterns have been identified that relate to karst features. Types 2 and 3 (Fig. 16) represent depressions that have been subsequently filled to the present lake bottom. The fill is represented by horizontal reflectors that may onlap the depression or completely cover the subsided area. Evidence of stress fractures, slumping, faulting, or dissolution fractures around the depression (Type 3) differentiate the two dolines and may indicate more rapid or continuous subsidence, or a more competent overburden. These breaches within the depression may provide a significant hydraulic connection between surface waters and the underlying aquifer. Most of the sinkholes detected using HRSP are of the buried base-level type (Fig. 13, Sinkhole Evolution sheet) and should be a common occurrence beneath dry land as well. Only when these features develop a transitional phase (Fig. 13.), reactivate and cause a surface subsidence or collapse, do they become evident at the surface.

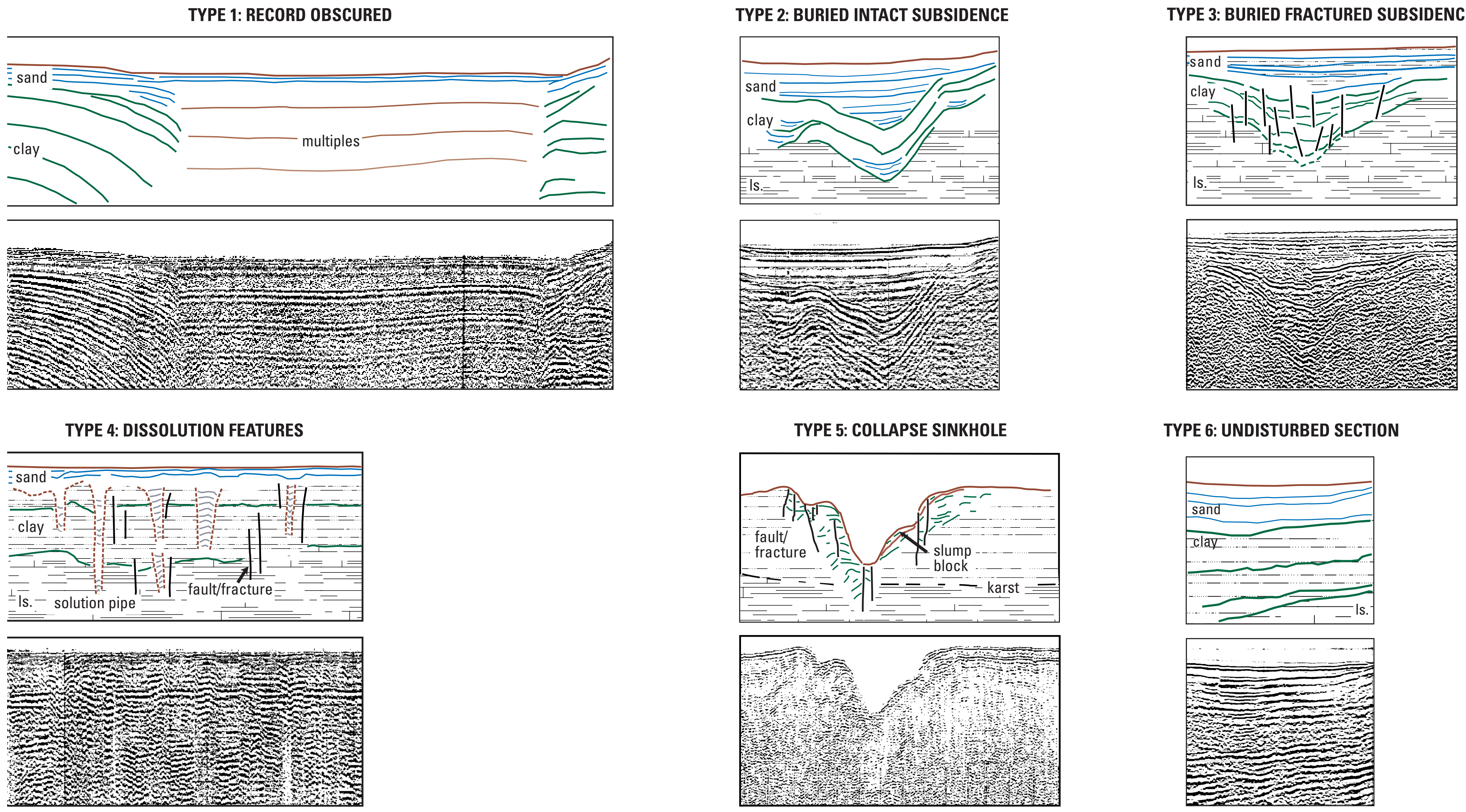
Other common features are high-frequency or chaotic reflections interspersed between horizontal reflections (Type 4). These reflectors indicate a disturbance within a relatively intact stratigraphic sequence and may represent solution pipes or fractures through the overburden. The features may connect to dissolution systems in the underlying limestone and could represent direct hydraulic connection through the semi-confining layer to the underlying aquifer. The disturbed reflections indicate areas of potential subsidence or collapse. These features have a high potential for reactivation since the plugs that fill solution pipes may dislodge during periods of major rainfall variations. There are many examples of this from Marion County (Cain and Hornstine, 1991). Solution pipes and related features commonly occur in areas where cohesive overburden is moderate to thin. Dissolution is focused and material directly over the cavity is washed into the void during the piping process. Type 4 features are widespread throughout the lakes surveyed, they occur in all phases of karst development and are commonly associated with poljes.

The Type 5 feature represents the classic collapse sinkhole, with steep walls that show evidence of slumping and active development along the periphery of the collapse. Freshwater plumes have been imaged emerging from similar collapse features found in marine environments (e. g. Crescent Beach Spring). In seismic profiles, areas of negligible acoustic return below the collapse have been postulated to represent subterranean cavities. These active phase collapse sinkholes are typically evident at the surface without imaging and occur in areas of minimal overburden. They also indicate areas of internal drainage or discharge depending on the location of the potentiometric surface of the Floridan aquifer.

Finally, the Type 6 feature does not necessarily include a karst-related structure but rather represents intact bedding or undisturbed section. A moderate to thick overburden overlies a deeper limestone surface that may not be within the imageable area of the HRSP, in which case depth to limestone is estimated from other methods, such as gamma profiles of well logs. This type of stratigraphy may occur over the entire survey area if there is a thick overburden, or as fill within karst features. Communication between the surface and groundwaters may be minimal in these areas.

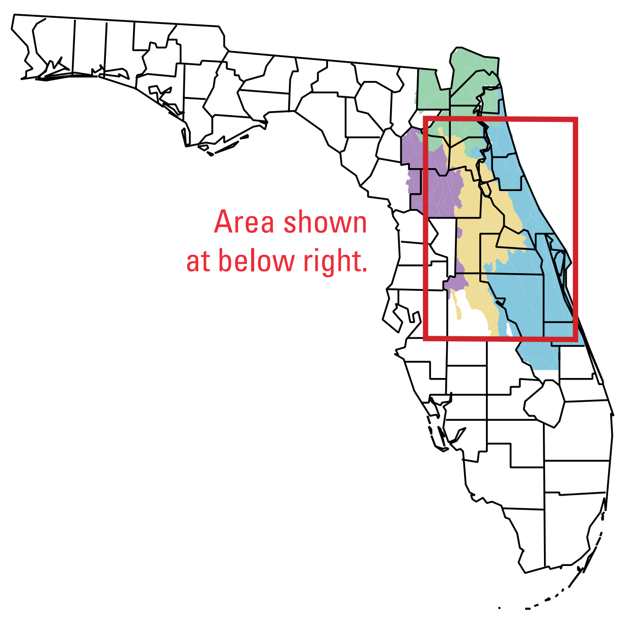
All of the lakes surveyed that have legible seismic profiles show at least one of the features noted in the summary reflections but usually there are multiple features present. Where these features have been identified in the profiles, their corresponding number has been annotated on the index map for each individual lake. The extent of the coverage, along with correlation from other sensing techniques such as gamma logs, and general knowledge of Florida geology, has allowed for some inference as to the type of material associated with the acoustic return. Parallel reflections or "transparent" return infer a stratigraphy of sand and clays. A jagged or noisy return indicates the limestone surface is near the lake bottom. As mentioned earlier, the type of feature present is probably a function of type and amount of overburden, proximity of karst surface to the lake bottom and maturity of karst development. Each of the identified features influence leakage between surface waters and the Floridan aquifer. Studies using seepage meters are being conducted to quantify variations in leakage related to a particular subsurface feature (Hirsch, 1998).

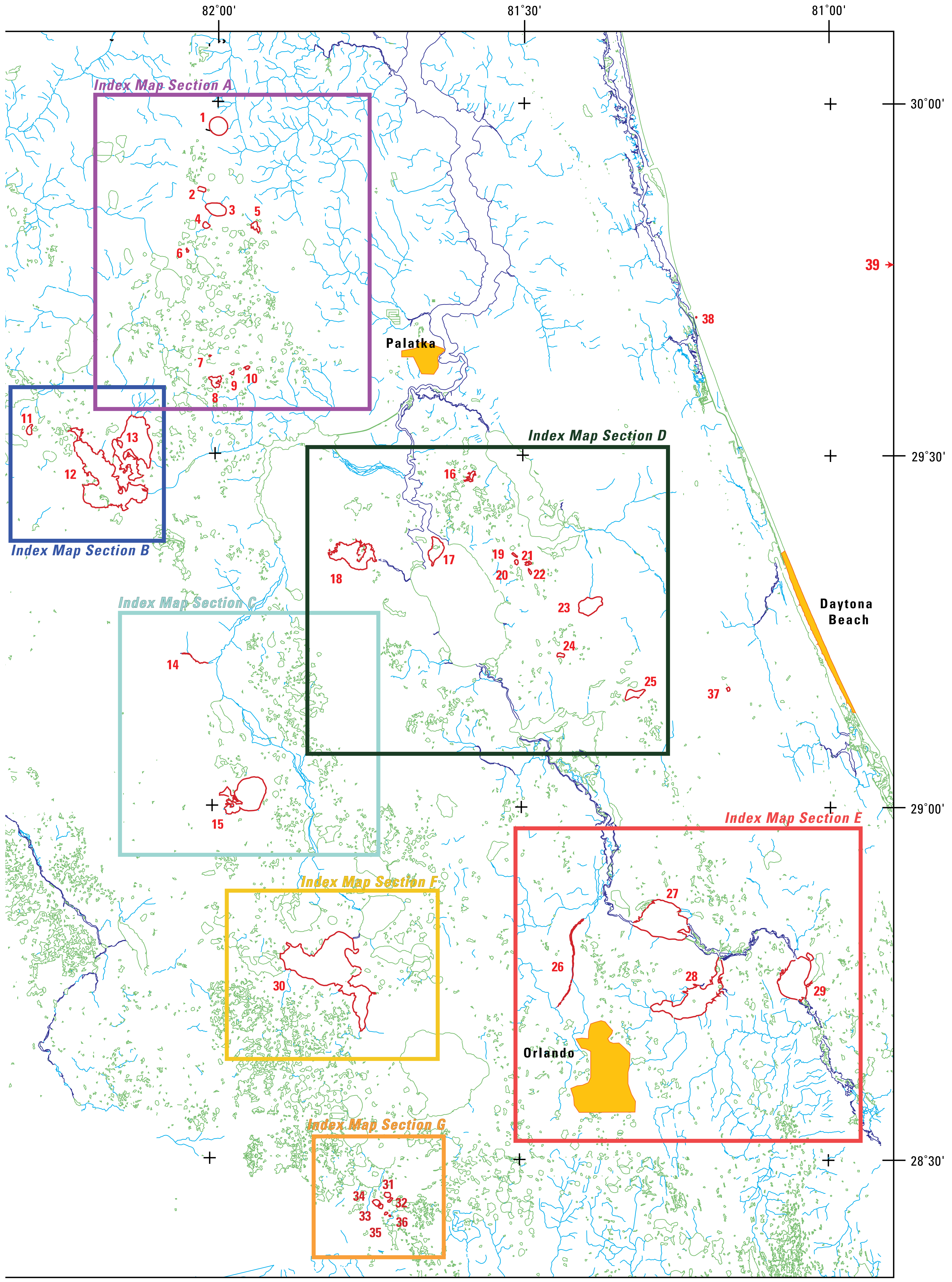
Figure 16. Seismic profiles with line drawing interpretations of six types of features described from the lakes of northeastern Florida.


TYPE 1: RECORD OBSCURED
TYPE 2: BURIED INTACT SUBSIDENCE
TYPE 3: BURIED FRACTURED SUBSIDENCE
TYPE 4: DISSOLUTION FEATURES
TYPE 5: COLLAPSE SINKHOLE
TYPE 6: UNDISTURBED SECTION

INDEX TO COVERAGE

HIGH RESOLUTION, SINGLE CHANNEL SEISMIC PROFILES, NORTHEAST FLORIDA





Surveys conducted by the United States Geological Survey and the St. Johns River Water Management District between August 1993 and April 1996.

Index Number	Index Title	Page Number
Section A	Hillshade & Gamma Logs	8
1	Kingsley Lake	9
2	Blue Pond	10
3	Sand Hill (Lake Lowry)	11
4	Lake Magnolia	12
5	Lake Johnson	13
6	Paradise Lake	*
7	Levys Prairie	*
8	Cowpen Lake	14
9	Morris Lake	*
10	Lake Galillee	*
Section B	Hillshade & Gamma Logs	15
11	Lake Wauberg	16
12	Orange Lake	17 & 18
13	Lake Lochloosa	19
Section C	Hillshade & Gamma Logs	20
14	Silver River	*
15	Lake Weir	21
Section D	Hillshade & Gamma Logs	22
16	Lake Como	23
17	Drayton Island	24
18	Lake Kerr	25
19	Davis Lake	26
20	Upper Lake Louise	27
21	Cow Pond Lake	28
22	Lake Juanita	*
23	Lake Disston	29
24	Lake Cain	*
25	Lake Dias	30
Section E	Hillshade & Gamma Logs	31
26	Wekiva River	32
27	Lake Monroe	*
28	Lake Jessup	33
29	Lake Harney	34
Section F	Hillshade & Gamma Logs	35
30	Lake Harris	36
Section G	Hillshade & Gamma Logs	37
31	LakeTrout	38
32	Lake Pike	38
33	Lake Hammond	39
34	Dixie Lake	40
35	Lake Keene	41
36	Lake Smokehouse	41
Section H	Hillshade & Gamma Logs	42
37	Indian Lake	43
38	Crescent Spring	44
39	Red Snapper Sink	*

Legend

- 00 Shorelines/areas of study
- Shorelines (lakes, coast)
- Rivers (minor)
- Rivers (major)
- Urban areas