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DEPARTMENT OF NATURAL RESOURCES
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BUREAU OF GEOLOGY
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SPECIAL PUBLICATION NO. 29
KARST IN FLORIDA
by
Ed Lane

Published for the
FLORIDA GEOLOGICAL SURVEY
TALLAHASSEE
1986
DEPARTMENT OF
NATURAL RESOURCES

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LETTER OF TRANSMITTAL

Bureau of Geology
Tallahassee, Florida
August, 1986

Governor Bob Graham, Chairman
Florida Department of Natural Resources
Tallahassee, Florida 32304

Dear Governor Graham:

The Bureau of Geology, Division of Resource Management, Department of Natural Resources, is publishing as its Special Publication No. 29, *Karst In Florida*. This report explains the origins of Florida karst, gives examples of its occurrence throughout the State, and discusses benefits, hazards, and what can be done about it. This publication will be useful to professionals in earth-science related fields, teachers, governmental agencies, and the citizens of Florida.

Respectfully yours,

Walter Schmidt, Chief
Bureau of Geology
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1. Ten of Florida's first-magnitude springs and discharges
2. Calculated rates of surface lowering due to solution
3. The 27 first-magnitude springs of Florida
4. Water quality data for Little Salt and Warm Mineral Springs
Familiar features of surface drainage systems are streams, rivers, and lakes (all interconnected) which cross the land and eventually discharge into an ocean. In contrast, karst terrains have drainage systems that are distinctly different from these surface drainage systems. Karst terrains develop in areas underlain by carbonate rocks, primarily limestone and dolomite, and have drainage which is manifested by sinkholes, springs, caves, disappearing streams and underground drainage channels. Karst topography is usually irregular due to the solution activity of acidic surface and groundwaters, which dissolve the carbonate rocks, forming cavities and allowing surficial sediments to collapse or subside.

Carbonates are a large group of minerals which have as a common constituent the carbonate ion \( \text{CO}_3^{2-} \). When combined with other elements these carbonate ions form various carbonate minerals, of which the three most common are calcite and aragonite \( (\text{CaCO}_3) \), and dolomite \( (\text{CaMg(}\text{CO}_3\text{)}_2) \). Calcite is by far the most abundant carbonate mineral. It occurs as enormous and widespread sedimentary deposits in which it is the predominant mineral. In pure limestones, some of which occur in Florida, calcite makes up 98 to 100 percent of the rock. Practically all carbonate rocks in Florida are limestone or dolomite, with limestone predominant.

It has been estimated that limestones and dolomites constitute about 20 percent of all sedimentary rocks (Gilluly, et al., 1959), and that 5 to 10 percent of earth’s land surface is karstic (Jackson, 1982). Because carbonate rocks comprise such a large proportion of the rocks on or near the earth’s surface, karst terrains occur in many parts of the world.

The classic karst area, from which the name is derived, is the Karst district of Yugoslavia, near the eastern shore of the Adriatic Sea. It is nearly 100-miles wide in places, with the entire district approximating the area of New York State. There, the limestone rocks are honeycombed by tunnels and caverns, so that most of the drainage is underground. Large sinkholes are abundant, some as deep as 600 feet. Streamless valleys are common since streams often disappear into swallow holes (American Geological Institute, 1962, p. 271). Streams tend to have intermittent surface flow for short times after rain or snow melt. The hummocky terrain is characterized by deeply eroded, isolated valleys and steep-sided hills. These geomorphic features are so characteristic of the Yugoslavian Karst district that the generic term karst terrain has been universally applied to them, meaning terrain that has been shaped by dissolution of the underlying carbonate rocks.

Karst regions in the United States include the caves and sinks region of
southern Indiana; central Kentucky and Tennessee, which has the Mammoth Cave system; the Carlsbad Cavern region of southern New Mexico; the Appalachian Mountain's Great Valley limestone belt, which has Natural Bridge and Luray Caverns; and Florida's extensive karst plains, sinkhole lakes and caves.

Why study karst? Figures 1, 2, and 3 show the significance of karst in Florida and why concern is justified. An understanding of karst is important to Floridians because Florida is almost entirely underlain by carbonate rocks. Karst is more than an academic problem when one considers that the surface of much of Florida's bedrock limestone probably resembles Figure 1, if one could strip off all overburden. Florida's karst means special problems which necessitate special considerations and precautions. Planners at all levels need to be familiar with karst, from the private citizen who plans to build a home to architects and engineers who design and site buildings and government officials who issue permits for construction or waste disposal. Florida's rapid population growth results in more construction of roads, houses, and other facilities, increased need for the safe disposal of all kinds of wastes, and increased demands on the State's water resources for consumptive and non-consumptive uses. All of these human activities place continually increasing stresses on the environment, which poses a need to understand Florida's karst. This publication will explore Florida karst: what causes it, specific examples of it, benefits and hazards associated with it, and what can be done about it.

METRIC CONVERSION FACTORS

The Florida Bureau of Geology, in order to prevent duplication of parenthetical conversions, inserts a tabular listing of conversion factors to obtain metric units.

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<th>MULTIPLY</th>
<th>BY</th>
<th>TO OBTAIN</th>
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<td>meters</td>
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<tr>
<td>square feet</td>
<td>0.092</td>
<td>square meters</td>
</tr>
<tr>
<td>miles</td>
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<tr>
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<td>liters</td>
</tr>
<tr>
<td>tons</td>
<td>0.907</td>
<td>metric tons</td>
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POROSITY AND PERMEABILITY

Karst formation involves primarily the chemical weathering and erosion of carbonate rocks. It is appropriate, therefore, to discuss factors relating to and controlling the movement of underground water. The two properties that are common to all rocks, and which control the movement of underground water, are porosity and permeability.

Porosity and permeability are intimately related. A porous rock con-
Figure 1. Karst limestone surface showing honeycomb of round solution pipes. This surface was exposed when the overburden was scraped off and the sands and clays plugging the pipes were removed by water jets. Bedrock is Ocala limestone of Eocene age in the abandoned Buda limerock mine off Route 41 between Newberry and High Springs. Picture taken about 1972 and used by permission of William A. Wisner, geologist, Florida Department of Transportation.
Figure 2. House and car damaged by sinkhole formation. Florida Geological Survey photo.
Figure 3. House going into a sinkhole. Florida Geological Survey photo.
Figure 4. Porosity and permeability as shown by two examples of a well-sorted granular material, such as sand. In Figure A the porous and permeable sand is clean with open, interconnected voids that allow water to move freely. In Figure B the same well-sorted, porous sand is rendered impermeable to water flow due to the retarding effect of the interstitial material, such as clay.
tains voids; clean, well-sorted sand (having all grains approximately the same size) or gravel are good examples. Permeability is a measure of a rock’s ability to allow fluids to move through its pore spaces. By definition, permeability implies that a rock’s pore spaces must be interconnected to allow fluids to move freely. A clean, well-sorted sand is said, therefore, to be permeable; water can migrate through it (Figure 4a). Porous rocks are not always permeable, however. A similar, well-sorted sand may have its interstices filled with clay, small grains of organic matter, or some other fine-grained material, which effectively blocks the free passage of water (Figure 4b). In this case, the sand would be classified as impermeable (if no water could be transmitted) or as having low permeability (if only insignificant quantities of water could pass through it).

Limestone, though usually thought of as being “solid” rock, often has a granular texture and considerable porosity and permeability, either primary (developed when the limestone was deposited) or secondary (developed after deposition). Groundwater flow through granular and porous limestone is, therefore, similar to flow through sand. This is an important concept to keep in mind during the following discussions of aquifers and chemical weathering of limestone.

HYDROLOGIC CYCLE AND AQUIFERS

Only two things are necessary to create karst terrain: carbonate rocks and slightly acidic water to attack them. Florida has an abundance of both. Any discussion of karst revolves around water, its movement and its interaction with carbonate rocks. An explanation of the hydrologic cycle will allow a better understanding of the movement of water above, on, and under the earth’s surface. The hydrologic cycle is the name given to the complex, ever-changing migration of groundwater, atmospheric and surface waters.

The hydrologic cycle is driven by the elemental forces of sunshine and gravity. Figure 5 shows the paths water may take as it moves through the hydrologic cycle. Starting at the ocean, the sun’s radiation heats the ocean’s surface and evaporates water, which is carried aloft by rising convection currents of air, eventually forming clouds of water vapor. The clouds are carried over the land by winds, where they drop their moisture as rain, snow, or hail. Under usual atmospheric conditions some of the precipitation evaporates before it reaches the ground. After precipitation reaches the ground, three things can happen to it: some will evaporate directly from soil, plants, and free bodies of water; some may infiltrate the soil or rocks; and some may run off across the land surface. The runoff may contribute to normal surface drainage in the form of streams or lakes, eventually returning to the ocean to begin the hydrologic cycle anew.

Water that finds its way underground, however, will have a more circuitous route before it returns to the sea. Some water may percolate down-
Figure 5. Hydrologic cycle: the constant movement of groundwater, surface and atmospheric waters. The diagram is highly simplified.
ward to recharge groundwater aquifers, then move laterally until being discharged to stream beds or in surface or submarine springs. Some underground water may be taken up by plants and evapotranspired to the atmosphere; some may be withdrawn by wells for human use.

All groundwater occurs in open spaces within the rock materials of the earth's crust. Aquifers are subsurface zones of rocks or sediments that yield water in sufficient quantities to be economically useful for man's activities. Aquifers are classified as either unconfined, semi-confined, or confined. Figure 6 illustrates several situations commonly encountered in Florida sediments and rocks.

Water that is in direct contact with the atmosphere through the pores or voids in sands, gravels, or rocks is called unconfined water, and the zone of sediments or rocks saturated with water is an unconfined aquifer, sometimes referred to as the surficial or watertable aquifer. The top of the watertable can be visualized as being the upper surface of the zone of saturation. The elevation of the watertable is also represented by the water level in wells. The watertable surface is usually a subdued replica of surface topography, with the watertable lying at shallow depths in much of Florida.

Semi-confined or confined water is separated from direct contact with the atmosphere by impermeable materials, such as clay beds or consolidated rocks. Confinement may impose pressures on the contained water that are higher than atmospheric, creating artesian conditions. Artesian conditions originally meant that a well produced flowing water at the surface because of the pressure in the penetrated aquifer. The term now refers to any condition where water is under greater-than-atmospheric pressure and will rise some distance up a well that penetrates a confined aquifer; however, the well need not flow at land surface.

In nature, the distinction between unconfined and confined groundwater is not so clear-cut, but is usually gradational due to the physical characteristics of most rocks. At one extreme are loose materials, such as sand, gravel, and many soils, which have relatively high permeabilities. At the other extreme are so-called tight, solid, or impermeable rocks. While most clays, or sediments with significant amounts of clay, do have some permeability, it is usually so low that, for water-yielding purposes, they are classified as being "impermeable" and are considered to act as confining beds to more permeable rocks. Somewhere between these extremes lie countless combinations of rock types with varying degrees of permeability which are classified as semipermeable, i.e., they may transmit enough water to allow recharge to contiguous strata, but they cannot provide useful quantities of water to a well. Aquifers bounded by semipermeable units may be classified as semi-confined, depending on the water-yielding abilities of the rocks. Figure 6 illustrates this situation by showing surface water being recharged directly to the confined limestone aquifer through a sinkhole that has breached the confining bed, and indirect recharge of water from the
Figure 6. Unconfined and confined aquifers in a simplified stratigraphic sequence that is common in Florida. All materials below the watertable are saturated. Recharge to the watertable is by rain. Recharge to the confined aquifer is by water moving downward through the confining beds or through karst features that breach confining beds, such as sinkholes.
unconfined watertable aquifer by slow, downward seepage through the semi-permeable clay.

Unconfined and confined groundwaters move in response to gravity, the same as surface water, from higher to lower elevations. Confined groundwater also moves in response to pressure gradients, similar to the movement of water in pressurized pipes. As shown in Figure 6, water will migrate downward through the confining clay if the pressure created by the weight of the water in the overlying watertable aquifer is higher than the pressure in the confined aquifer. Conversely, if pressure in the confined aquifer were high enough to overcome the pressure of the water in the unconfined aquifer, then water would move from the limestone through the clay to the sand. Both of these situations commonly occur in Florida due to inhomogeneities of strata, karst features, and pressure gradients.

Springs are an expression of leakage from a watertable, semi-confined, or confined aquifer. In Figure 6, for example, the surface spring occurs because the watertable aquifer occurs on top of a confining bed that impedes the downward percolation of recharge water. This situation forces the water to move laterally, downslope, and discharge where the permeable sand and the less permeable clay bed intersect land surface. After prolonged periods of no rain the aquifer may become so depleted that the spring ceases to flow. This type of spring is frequently seen in the steep-walled stream valleys of north Florida.

Similarly in Figure 6, the subaqueous spring that discharges into the stream bed from the confined aquifer does so because of higher water pressure in the aquifer. In this situation, however, if the pressure in the aquifer falls too low due to depletion of water, the spring may reverse its flow, taking water back into the aquifer or recharging it. This, too, is a well-documented occurrence in some Florida streams. Ceryak, et al. (1983) found that many sinkholes in the bed of the Alapaha River near Jennings, in northwest Hamilton County, Florida, have recharged as much as 770 cubic feet per second (497,420,000 gallons per day) to the adjacent aquifer. Miller, et al. (1978) found that, at times of high stages of the Suwannee River, river water was recharged to the limestone aquifer through karst features in its channel.

It is these driving forces in the hydrologic cycle that move underground water through Florida’s carbonate rocks. In transit, the water dissolves and carries away in solution the chemical components of the rocks, leaving behind caves, solution pipes, and other voids that result in a karst terrain.

**EVOLUTION OF KARST TERRAIN**

The evolution of any terrain into characteristic landforms involves weathering and erosional processes: wind, water, frost heaving, slumping, or wave activity, to name a few. In most areas, the predominant
Figure 7a. Relatively young karst landscape showing underlying limestone beds and sandy overburden with normal, integrated surface drainage. Solution features are just beginning to develop in the limestone.

Chemical Weathering of Carbonate Rocks

Since the genesis of karst involves the development of underground drainage systems, it is necessary to study such systems to understand the formation of karst. Karst processes tend to be secretive and imperceptible because most development occurs underground over long periods of time. The results of these persistent processes will be manifested, sooner or later, in the subsidence of surficial sediments to form swales, the formation of a new sinkhole, a sudden influx of muddy water in a water-well after a heavy rain, or some other karst phenomenon that may disturb or disrupt man's activities. Figure 7 illustrates the evolution of karst terrain, as described below.

Chemical weathering is the predominant erosive process that forms karst terrain. Chemical weathering of limestone removes rock-mass through solution activity. As rain falls through the atmosphere, some carbon dioxide and nitrogen gases dissolve in it, forming a weak acidic solution. When the water comes into contact with decaying organic matter in the soil, it becomes more acidic. Upon contact with limestone,
Falling rain absorbs gases to become weakly acidic.

Percolating ground water infiltrates limestone, dissolving some and carrying it away in solution.

Chemical weathering is just beginning, with little internal circulation of water through the limestone. Swales, forming incipient sinkholes, act to concentrate recharge.

A chemical reaction takes place that dissolves some of the rock. All rocks and minerals are soluble in water to some extent, but limestone is especially susceptible to dissolution by acidic water. Limestones, by nature, tend to be fractured, jointed, laminated, and to have units of differing texture, all characteristics which, from the standpoint of percolating groundwater, are potential zones of weakness. These zones of weakness in the limestone are avenues of attack that, in time, the acidic waters will enlarge and extend. Given geologic time, conduits will permeate the rock that allow water to flow relatively unimpeded for long distances.

During the chemical process of dissolving the limestone, the water takes into solution some of the minerals. The water containing the dissolved minerals moves to some point of discharge, which may be a spring, a stream bed, the ocean, or a well, and another tiny volume of Florida’s rock substrate has been removed.

Removal of the rock, with the continuing formation or enlargement of cavities, can ultimately lead to the collapse of overlying rocks or sediments. If the collapse is sudden and complete, an open sinkhole will
Figure 7c. Advanced karst landscape. Original surface has been lowered by solution and erosion. Only major streams flow in surface channels and they may cease to flow in dry seasons. Swales and sinkholes capture most of the surface water and shunt it to the underground drainage system. Cavernous zones are well-developed in the limestone.

result, sometimes revealing the cavity in the rock (Figures 8 and 9). More often, though, debris or water covers the entrance to subterranean drainage. Partial subsidence of the overburden into cavities will form swales at the surface, producing hummocky, undulating topography. By this slow, persistent process of dissolution of limestone and subsequent collapse of overburden, the land is worn down to form a karst terrain.

At some point in this process of dissolution of underground rocks, a normal surface drainage system will begin to be transformed into a dry or disappearing stream system. Continuing dissolution of the limestone will create more swales and sinkholes, which will divert more of the surface water into the underground drainage. Eventually, all of the surface drainage may be diverted underground, leaving dry stream channels that flow only during floods, or disappearing streams that flow down swallow holes (sinkholes in stream beds) and reappear at distant points to flow as springs or resurgent streams.
Figure 7d. Detail of Figure 7c showing advanced stage of karst formation. Limestone has well-developed interconnected passages that form an underground drainage system, which captures much or all of prior surface drainage. Overburden has collapsed into cavities forming swales or sinkholes. Caves may form. Land surface has been lowered due to loss of sand into the limestone’s voids. Wakulla Springs and Silver Springs are examples of cavernous underwater springs.

Lowering of Land Surface

Inherent in the formation of karst terrain is the lowering of land surface on a regional scale, in contrast to the very localized lowering at a sinkhole. Regional lowering of the land surface takes place through the cumulative effects of thousands of individual, localized events, and through the continual removal of carbonate rock by dissolution. Several investigations have been made to determine an "average" rate of surface lowering in Florida, the results of which are discussed below and shown in Tables 1 and 2.

Table 1 gives comparative data for the ten largest first-magnitude springs in Florida. The amounts of solids removed from the land by these springs' flows range from 59 to 541 tons per day. These figures are impressive, but they do not indicate how rapidly the land surface may be being lowered. More meaningful are the amounts of material that are carried off per year per square mile of land surface, which can be calcu-
Figure 8. Karst limestone surface exposed by a flash-flood in the city of Ocala in 1982. Note similarity of karst weathering to that in Figure 1. Florida Geological Survey photo.
Figure 9. Close-up of solution pipes in same area as Figure 8. Pipes are about two feet in diameter. Sinkholes and other karst surface expressions can appear when such pipes become unplugged. Florida Geological Survey photo.
Table 1. Ten first-magnitude springs, ranked according to average discharge for period of record. See Figure 38 for locations. A first-magnitude spring’s average flow must be 100 cubic feet per second (cfs) or more. Data from Rosenau, et al., 1977, p. 7.

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<th>Spring (County)</th>
<th>DISCHARGE (cfs)</th>
<th>Average TOTAL DISSOLVED SOLIDS (mg/L = ppm)</th>
<th>SOLIDS Removed in solution, in tons per day.*</th>
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<td></td>
<td>measurement</td>
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<tr>
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<td></td>
<td></td>
<td>59</td>
</tr>
</tbody>
</table>

*Calculated by: \( \text{cfs X 62.4 lbs/ft}^3 \times \text{86,400 s/day X TDS} \div 2 \times 10^9 \) = tons per day in solution.

** A submarine spring system that may have as many as 14 outlets. Discharge affected by tides, and fresh groundwater is probably being mixed with Gulf water, accounting for high TDS.

*** A system of some 30 springs, which may be tidally affected.
Table 2. Calculated rates of surface lowering due to solution showing possible range of rates depending on variable densities of limestone. Rates of limestone lowering in inches per thousand years.

<table>
<thead>
<tr>
<th>LOCATION</th>
<th>REFERENCE:RATE (inches/1,000 yrs.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Rainbow Springs</td>
<td>Fennell, 1969: 0.5</td>
</tr>
<tr>
<td>2. Itchetucknee Springs</td>
<td>Fennell, 1969: 0.8</td>
</tr>
<tr>
<td>4. central peninsula</td>
<td>Sellards, 1908: 2.0-2.4</td>
</tr>
<tr>
<td>5. Suwannee River drainage basin</td>
<td>Brooks, 1967: 1.2-2.0</td>
</tr>
<tr>
<td>6. near Tampa well field</td>
<td>Sinclair, 1982: approx. 7.0</td>
</tr>
<tr>
<td>7. northern peninsula</td>
<td>Opdyke, et al., 1984: approx. 1.0</td>
</tr>
</tbody>
</table>

lated when the area of a spring’s karst drainage basin is known. The karst drainage basins, which includes surface and underground drainage systems, have been determined for only three of the springs in Table 1: Silver, Rainbow, and Itchetucknee.

Faulkner (1970, Fig. 22), as part of a study of the Cross-Florida Barge Canal, prepared potentiometric maps in the vicinity of Silver and Rainbow springs. The maps delineated the underground drainage areas that supply water to the springs, and showed each spring’s drainage area to be approximately 730 square miles. Using data from Table 1, the amounts of solids carried away in solution by Silver and Rainbow springs were calculated to be 270 and 95 tons per square mile per year, respectively.

Similarly, using potentiometric maps constructed as part of a hydrologic study of the Itchetucknee Springs area, Hunn (1982, personal communication, U.S. Geologic Survey, Tallahassee Subdistrict Office) calculated a drainage area of approximately 400 square miles. These data indicate that Itchetucknee Springs may carry away as much as 155 tons of dissolved rock per square mile per year.

Using the results of two separate studies (Fennell, 1969; Bishop, 1982
personal communication), the author calculated the rates at which Silver, Rainbow, and Itchetucknee springs may be lowering land surface. Fennell (1969, p. 47) analyzed 10 samples of limestone from the Tallahassee area and obtained an average density of 166.6 lbs./cu. ft. Ernest Bishop (personal communication, 1982) analyzed 19 core samples of limestone from three geological formations near Tallahassee and obtained an average density of 111.1 lbs./cu. ft. Within their respective drainage basins Silver, Rainbow, and Itchetucknee springs may be lowering ground surface by solution from 0.5 to 2.1 inches per thousand years, as shown in Table 2.

Using scant data, Sellards (1908, p. 47) calculated the amount of material being carried away in solution by the waters from eight springs in central Florida. The amounts ranged from 29-600 tons per day. Sellards (1908, p. 48) assumed that most of the rock material being removed was limestone, and stated, "From these estimates it would appear that the surface level of the central peninsular section of Florida is being lowered by solution at the rate of a foot in five or six thousand years." These estimates yield a rate of solutional degradation of the surface of 2 to 2.4 inches per thousand years.

In a study of the Suwannee and Waccasassa rivers' drainage basins, Brooks (1967) found in various parts of the basins that the amount of carbonate rock being carried away in solution ranged from 172 to 262 tons per square mile per year. He calculated that the rate of solutional degradation of the karst terrain ranged from 1.2 to 2 inches per thousand years, for an overall rate of 1.5 inches per thousand years.

The above studies were of regional scale and represent the range of land surface lowering that could be expected under long-term natural conditions. Man’s activities, particularly on a local scale, disturb the natural environment, often times drastically within short spans of time. Sinclair (1982), as part of a study on pumpage-induced sinkhole collapse at a municipal well field in the Tampa area, calculated a rate of surface lowering of the limestone of about one foot per 1,700 years (7 inches/1,000 years). This rate of lowering would only be relevant to the area of a few square miles immediately adjacent to the well field that is affected by the pumpage. However, in comparison with the natural rates shown in Table 2, it gives an idea of how man’s activities can affect karst processes.

**KARST FEATURES IN FLORIDA**

A good way to illustrate the variety of physiographic features associated with a karst region is to cite examples. Some of the case histories presented in this section have been selected, admittedly, because of their spectacular nature. In a way, their spectacular nature can be used to advantage to show the evolution of karst terrain which, until now, has been discussed from a theoretical viewpoint. They demonstrate the
cumulative results of millenia of solution activity, which usually operates at microscopic scales on a day-to-day basis.

Selected examples will be discussed in detail to illustrate the generic types of karst features, with other examples noted which are in various parts of Florida. Most of these examples are accessible to the public, so they can be visited, explored, and photographed.

Sinkholes

In any karst terrain, sinkholes are the most common feature, as well as one of the most easily recognized. Figure 10 shows, in a general way, the areas of Florida that are prone to sinkhole development. However, this should not be strictly interpreted as a sinkhole-risk map. Local factors will govern whether sinkholes actually do form; under certain conditions they could form in an area that ordinarily would be at low risk.

Chemical weathering of limestone is the ultimate cause of sinkhole development, but localized stress triggers overburden collapse into pre-existing cavities, which may have taken eons to dissolve out of the limestone. The stress can be natural or a result of man's activities.

In Florida, the most common natural sources of stress that trigger sinkhole formation are fluctuations of water levels or water pressures resulting from torrential rains and flooding, or the opposite, severe drought with lowered water levels. Figure 11 illustrates how this can happen. Water, and its relationship to the overburden and bedrock, are the controlling factors under flood or drought conditions. Objects immersed in water weigh less because of the effect of buoyancy. So it is with sand, clay, or limestone beneath the watertable in the zone of saturation. Sand and clay, for example, weigh 40 percent less when immersed in water (Sinclair, 1982). Saturated materials below the watertable, therefore, have significant supportive forces, which tend to forestall collapse of overburden into cavities.

By definition, a karst terrain has underground solution cavities, any one of which may have sinkhole-forming potential under the right conditions. Figure 11a shows normal, stable conditions. In a drought the watertable will fall, decreasing support for the overburden above the cavity (Figure 11b). At some point the overburden will be unable to support its own weight, resulting in surface subsidence or a sinkhole, depending on the degree of collapse.

Under conditions of torrential rains or flooding, the role of water can change—it can become an additional burden to the soil column. Another force comes into play under flood conditions; a downward-acting one that increases the stress on the overburden. The increasing height of the water in the overburden creates an increased flow downward and away from the cavity. This increased downward force may be enough to trigger collapse of overburden into a cavity.

Man's activities also impose stresses on the environment, which, in a karst terrain, pose special concerns. In Florida, two categories account
Bare or thinly covered limestone. Sinkholes are few, generally shallow and broad, and develop gradually. Solution sinkholes dominate.

Cover is 30 to 200 feet thick. Consists mainly of cohesive and permeable sand. Sinkholes are few, shallow, of small diameter, and develop gradually. Cover subsidence sinkholes dominate.

Cover is 30 to 200 feet thick. Consists mainly of cohesive clayey sediments of low permeability. Sinkholes are most numerous, of varying size, and develop abruptly. Cover-collapse sinkholes dominate.

Cover is more than 200 feet thick. Consists of cohesive sediments interlayered with discontinuous carbonate beds. Sinkholes are very few, but several large diameter, deep sinkholes occur. Cover-collapse sinkholes dominate.

Figure 10. Map of Florida showing areas prone to sinkhole development. Modified after Sinclair and Stewart, 1985.
Figure 11. A) Cavity has formed in limestone due to circulation of groundwater. Cavity grows upward by stoping (spalling of material from ceiling of a cavity.)

B) Enough loose sand has been piped into cavities to cause subsidence at surface. The watertable may be lowered due to unrestricted flow into underground drainage. A lowered watertable may be manifested locally by plants stressed for lack of water, or wells may go dry.

C) Continual enlargement of underground drainage and removal of overburden results in the typical, cone-shaped sinkhole. A sudden collapse may swallow trees or buildings. The depression may intersect the watertable, forming a pond.
for most of man-induced sinkhole formation: pumpage from wells and construction activities. The mechanisms responsible for the actual collapse of overburden are the same as explained above; however, man's activities create the instability.

Referring again to Figure 11b, if a well had dewatered the sediments, collapse could have been triggered. This has been a frequent, though unexpected occurrence in Florida. For example, in one documented instance more than 30 small sinkholes occurred near a large-capacity municipal well-field north of Tampa, all within a year after beginning pumpage (Sinclair, 1982).

A related activity, well drilling, can also pose problems—for the driller as well as for the environment. Larger, deeper wells are usually drilled using pressurized, circulating water to lubricate the drill bit and to remove the cuttings from the hole. Visualize a large, heavy drill rig drilling into the cavity in Figure 11a. Simultaneously, the driller has disturbed the
cohesion of the overburden by drilling through it, breached the cavity, and imposed the extra load of the drill rig on the soil. Within seconds, or minutes, the situation goes from 11a to 11c, with the drill rig in the sinkhole. There have been several instances of this in Florida (Figure 12).

Construction activities, such as excavating and dewatering for foundations, heavy equipment traffic, blasting, and altering natural drainage patterns, all can trigger sinkhole collapse. The weight of buildings and loads from reservoirs can also case sinkholes to form.

Although the general notion is that sinkholes collapse suddenly without warning, one or more precursors may occur (from Sinclair, 1982):

1. Slumping or sagging. Canting of fence posts or other objects from vertical, and doors and windows that fail to open or close properly may be early warnings of subsidence.
2. Structural failure. Cracks along mortar joints in walls and in pavements, however small, may be indications of subsidence.
3. Ponding. The ponding of rainfall may serve as a first indication of land subsidence.
4. Vegetative stress. One of the earliest effects at an incipient sinkhole is lowering of the watertable through percolation to the underlying aquifer. The lowered watertable may result in visible stress to a small area of vegetation.
5. Turbidity in well water. Water sometimes becomes turbid during the early stages of development of a nearby sinkhole.

Sinkhole is a word that has acquired bad connotations, such as danger, tragedy, threats to property, people or animals (Figures 2, 3, and 13). There are other aspects of sinkholes, however, that are beneficial. A discussion of a recently formed sinkhole will be useful to illustrate the pros and cons of sinkholes.

Winter Park Sinkhole

The most famous sinkhole in the United States in recent years is the one that formed in May 1981, at Winter Park, near Orlando, Florida. It captured national headlines in all the media with magazine articles still appearing in March, 1982. An aerial view of the sinkhole is shown in Figure 13. It is roughly circular but elongated, approximately 300 feet by 350 feet. The water level in the photograph is about 45 feet below the ground surface. The sinkhole is hydraulically connected to the local aquifers since its water level fluctuates in response to rainfall and changes in the surrounding watertable, sometimes rising to within 15 feet of ground surface.

The following statistics can give an idea of the extent of damage which may be associated with sinkhole formation. The Winter Park sinkhole swallowed: one house and shed, half of the municipal swimming pool, a Porsche sports car, several large oak trees, a section of street that
crossed the sinkhole and part of another street that adjoined it, and an estimated 4-million cubic feet of soil. Additional damages that can be seen in the picture are: three other Porsche sports cars and a pick-up camper which slid into the crater, the rear of an auto-repair shop that cracked open, and various utility lines were exposed or damaged.

As spectacular as this event was, and granted that the total cost of damages was great, it needs to viewed in perspective of the environment in which it formed. Figure 14 is a map of part of the Winter Park-Orlando area that shows all lakes and closed depressions in the vicinity of the new sinkhole. The U.S. Geological Survey has estimated that 95 percent of such features are former sinkholes (Brainard, 1982). It is obvious that sinkhole formation has been common in the past, and, judging from the size of many of the lakes, there probably have been more spectacular collapses. The new sinkhole is one of the smaller karst features of the area.

It is not possible to predict the exact evolutionary course of this or any other particular sinkhole, but some generalizations can be made based on the geological history of the area. This sinkhole may be unstable for an indefinite time. It may become temporarily plugged with debris, organic
Figure 14. Map of the Orlando-Winter Park area in the vicinity of the new sinkhole, showing karst features that hold water some or all of the time.

matter, silt, or clay and thus retain water. The plug may break and drain the water occasionally. During its inactive periods, erosive processes will wear down its sides and fill the sinkhole’s bottom. Eventually, the sinkhole will probably become plugged to such an extent that it will be stabilized, for all practical purposes. At that time it will be just another local lake, which will be considered a community asset.
The foregoing discussion of the possible evolution of the Winter Park sinkhole into a pond or lake is an appropriate introduction to the general subject of lakes, one of Florida’s most ubiquitous natural resources. Lakes occur in a profusion of shapes and sizes throughout Florida. There are more than 7,700 named lakes and ponds that are larger than 10 acres, totalling more than 2,860,000 acres (over 4,400 square miles) (Fla. Bd. of Conservation, 1969). There are probably as many more that are smaller than 10 acres. These thousands of lakes, most formed by karst processes, provide inestimable benefits to Florida citizens and visitors.

Bishop (1967) described several origins for lakes in Florida. Some of the larger lakes occupy depressions that were in the sea bottom when the ocean covered parts of Florida during periods of the Ice Age. These are lakes Okeechobee, Istokpoga, and probably some of the larger lakes in the Kissimmee and St. Johns river valleys. There are also a few lakes formed in low areas between sand dunes; some created by man-made dams, and some as a result of reclamation projects following open-pit phosphate, limestone and dolomite, or sand-gravel mining. However, most of Florida’s lakes are solution-based lakes created by groundwater solution of underlying limestone and subsequent lowering of local land surface, by karst processes already discussed.

It is not surprising, then, that most of Florida’s karst-origin lakes have physical characteristics of sinkholes, such as relatively steep sloping sides, no surface streams into or out of them, and circular outlines. Many of these lakes are dependent on rain for sustenance and large fluctuations from local average rainfall can cause significant, even drastic effects on water levels. Some have connections with aquifers. A few show a pattern of disappearing when their underground karst drainage systems become “unplugged.” For example, two lakes near Tallahassee, lakes Jackson and Lamonia, drain periodically. Lake Lamonia drained in 1910, 1917, 1934 and 1981 (Figures 15 and 16). Lake Jackson has drained about every 25 years since 1881; its latest disappearance was in 1982. Since then it has refilled.

These two lakes, both quite shallow, are underlain by carbonate rocks, pinnacles of which can be seen in their beds after they drain dry. Severe weather conditions, such as droughts or flooding, impose stresses on the local hydrological regime that can trigger sinkhole collapse. If the material bridging a karst cavity happens to be in the bed of a lake—and hydraulic pressure causes the bridge to collapse—the result is the same as pulling the stopper out of a bathtub drain (Figures 15 and 16).
Figure 15. Dry bed of Lake lamonia, 1981. The main sinkhole drain is near the person at lower left. Limestone is exposed in several circular pits throughout the lake bed, which also act as drains. Florida Geological Survey photo.
Figure 16. Dry bed of Lake Iamonia, 1981. Unconsolidated lake-bed deposits showing bedding. The meandering, incised stream channel is an artifact of many past drainings of the lake; each successive draining etches it deeper. Florida Geological Survey photo.
Woodville Karst Plain

Sinkholes, springs, swales, hummocky terrain, disappearing streams, natural bridges, and cavernous openings, all with their associated underground drainage, are manifestations of karst processes and are prevalent in areas underlain by limestone or other carbonate rocks. The Woodville Karst Plain (Hendry and Sproul, 1966, pp. 25, 29-33), which lies south of Tallahassee in Leon and Wakulla counties (Figure 17), exhibits all of these features.

The Woodville Karst Plain has a flat to gently undulating surface of...
sand that overlies carbonate rocks. The carbonates, which lie at shallow depths of 30 feet or less, have undergone extensive solution by groundwater. This plain exhibits karst features that are still evolving, for example: many old, well developed sinkholes that are either permanently or intermittently flooded (Big Dismal Sink), disappearing streams and natural bridges (Natural Bridge), Wakulla Springs, and new sinkholes reported periodically.

**BIG DISMAL SINK**

Big Dismal Sink is a circular sinkhole located about 10 miles south of Tallahassee and is accessible in good weather by sand trails from State Road 319 (Figure 18). Figures 18, 19, and 20 illustrate its size and shape. The sinkhole intercepts the local water table, and it is about 65 feet to the water surface, which fluctuates according to seasonal rains. Approximately 30 feet of limestone is exposed above the water. The limestone is overlain by a sandy, clayey layer, which in turn is covered by about 20 to 25 feet of loose sand. Springs occur in the clayey sand and limestone of the sinkhole’s walls. The limestone walls form overhangs just above the water. The sides are steep and treacherous, although it is used as a local swimming hole. Divers have not reported an exact depth, but it would not be an unusual configuration if it extended as far below the water as above. One sounding taken from the southeast rim by Florida Geological Survey staff members showed a depth of 61 feet below water level.

In comparison with the 1981 Winter Park sinkhole, Big Dismal Sink has consumed over three-million cubic feet of rock and soil, which places it in the same magnitude. Figure 18 shows that Big Dismal is only one of countless sinks and other karst features that make up the Wakulla Karst Plain.

**LOST LAKE**

Lost Lake is about seven miles south of Tallahassee on State Road 373 and is a designated recreation area in the Apalachicola National Forest (Figures 17 and 21). It is a slightly elongated, circular swale that was created by solution of limestone and subsequent subsidence of sandy soil. Because the swale has subsided enough to intercept the local watertable it contains a perennial lake that is about 600 to 650-feet across and 10 to 12-feet deep. The dimensions and depth of the lake varies in accordance with wetness or dryness of the seasons.

**NATURAL BRIDGE**

Natural Bridge is located about six miles east of Woodville (Figures 17 and 22). For approximately one-half mile along this part of its channel the entire flow of the St. Marks River disappears under limestone “bridges” several times and reappears as springs short distances downstream. The
Figure 18. Map of part of the Woodville Karst Plain showing Big Dismal Sink. This small area of approximately seven square miles has over 100 sinkholes and flooded swales, which are indicated by the irregularly rounded, closed elevation contour lines. From the U.S. Geological Survey 7-1/2 minute Lake Munson quadrangle.
Figure 19. Big Dismal Sink, plan and cross section.
county road uses one of the bridges to cross the stream. The bridges were formed by dissolution of weaker limestone, leaving more resistant portions of the rock in place. The surface stream has been captured by underground drainage for those reaches where it goes under the bridges. About one-half mile south of the bridges the river continues to the Gulf in a well-defined channel in the limestone.

The bridges could eventually collapse if erosion and solution activity persist. However, if the river should create drainage channels at still deeper levels in the bedrock, the bridges could be left isolated and relatively free from the river’s erosion.
Figure 21. Lost Lake, view to west. Stake in right center of picture marks approximate center of lake. Florida Geological Survey photo.

WAKULLA SPRINGS

Wakulla Springs is a major north Florida tourist attraction that is located approximately 14 miles south of Tallahassee on State Road 61 (Figure 17).

Wakulla Springs, with its rich history of local lore, has been commercially developed since 1844. In that year, Mr. P. Randall ran an ad in the Tallahassee newspaper offering lodging to the public and tours of the springs and river in a glass-bottomed boat (personal communication, Charles Daniels, Wakulla Springs, 1984). Present-day visitors to Wakulla Springs can still take entertaining and educational rides on glass-bottomed boats, where they can look down through more than 100 feet of crystal-clear water into the main vent of the springs.

Wakulla Springs is classified as a first magnitude spring. It has an average discharge of about 390 cfs (251 million gallons per day); its maximum measured discharge was 1,910 cfs (1,233 million gallons per day) (Rosenau, et al., 1977). It is the main source of the Wakulla River;
Figure 22. Natural Bridge area, east of Woodville. From the U.S. Geological Survey 7-1/2 minute Woodville quadrangle.
there are several smaller springs near the main spring that contribute to the river.

Figure 23 is a cross section of the spring and 1,000 feet of the main spring's conduit. Divers have explored over 2,000 feet into the cavern, with no end in sight. Visitors to the springs can see a color movie of their exploration of this fascinating natural wonder.

Several sets of mastodon and mammoth bones have been recovered from the springs (Sellards, 1916). In 1930 the Florida Geological Survey recovered a nearly complete mastodon skeleton from the main spring. It is on display in the R. A. Gray State Museum in Tallahassee. Other fossils or artifacts recovered from the main spring include a giant sloth's tooth, bones of tapir, deer, armadillo, and charred wood and more than 600 bone spear points, (Mohr, 1964; Boyles, 1965). These finds indicate that the Spring was probably used as a watering hole by these prehistoric beasts, and possibly as a shelter by early man.

An obvious question is, "How did prehistoric animals or man get into the spring's inner recesses against such a rapidly flowing current?" Reconstruction of a scenario of Wakulla Springs' prehistoric environment will explain the general natural history of the springs and help to resolve the seeming paradoxical question.

One explanation may lie in the possibility that the springs haven't always been "springs." During the Pleistocene (also called the Ice Ages, the period between 2,000,000 and 10,000 years before present) worldwide sea levels were lowered several times by as much as 300 feet. The lowering of the nearby Gulf of Mexico by several hundred feet undoubtedly would have caused a lowering of local inland watertables, such as at Wakulla Springs. Referring to Figure 23, if the water level fell from its present elevation (Point A) to some prehistoric elevation (Point B), then it would be, in fact, Wakulla cave—not spring.

Reflecting on previous discussions of the Winter Park Sinkhole and Big Dismal Sink, one cannot help but notice striking similarities between them and Wakulla Springs: the sinkholes are 250 to 350-feet across and their visible pits are about 65 to 100-feet deep. From a hydrological viewpoint, the only difference between the Winter Park Sinkhole, and Big Dismal and Wakulla Springs is the direction the local water flows, either into or out of the underground drainage. Another part of an explanation to the question is that geological evidence indicates that Florida was probably semi-arid and savanna-like during periods of the Pleistocene (Simpson, 1929, p. 242). All the parts of the prehistoric scenario are now in place: large cohorts of animals and associated human hunters living on a semi-arid Florida savanna, similar to an African veldt. Watertables are lower than present and water is scarce much of the year. The deep Wakulla cave-sink is a more dependable water hole during dry season, but a steep slope must be negotiated—a feat that some apparently did not successfully complete—their bones attest to their failure. In a similar fashion, prehistoric man could have used the cave for shelter,
Figure 23. Wakulla Springs, cross section. After Boyles, 1965.
possibly bringing killed animals into the cave and leaving their bones for later explorers to find and wonder about.

**Underground Rivers**

The preceding discussion of the Wakulla Springs and its cavernous underground drainage system leads to the subject of so-called underground rivers. The idea of underground rivers is usually put to geologists in the form of a question, "Is it true that underground rivers flow from the mountains of Alabama or Georgia, under Florida, and to the Gulf of Mexico?" The idea of underground rivers that run for hundreds of miles is a fascinating concept that occurs frequently in discussions of groundwater, aquifers, springs, and underground drainage systems. In this context, however, the idea is wrong—underground rivers do not run from the Appalachians to the Gulf.

Because springs obviously are fed by water that is flowing out of the ground, there is a certain logic to the thought that water can flow in underground streams, as it does in surface channels, sometimes for hundreds of miles. There have been rare confirmed cases of underground rivers (more accurately called drainage systems) that flow for tens of miles in other parts of the world (Jackson, 1982). However, no such lengthy underground channel has been documented for any spring's source in Florida. All of the flow of springs of Florida for which measured discharges are available, including the major ones of Wakulla, Silver, Rainbow, and Itchetucknee, can be readily accounted for on the basis of rainfall within relatively small surface drainage basins. It is not necessary to imagine the existence of huge underground rivers to supply their water.

In two hydrologic investigations discussed earlier in the section titled "Lowering of Land Surface," it was shown that the flows for three of Florida's largest springs represented the collection potential for small, local drainage basins. Rainbow and Silver springs each had drainage basins of approximately 730 square miles (Faulkner, 1970), and Itchetucknee Springs had about 400 square miles (Hunn, pers. comm., 1982). On a regional basis, these are relatively small catchment areas; for example, an area of 730 square miles can be visualized as a square that is 27 miles long and wide, while 400 square miles is 20 miles on each side.

This is not to imply, though, that extensive underground drainage systems do not exist in Florida—they do. Discussions in previous sections have shown how they originate. Parts of some systems that have been explored are impressive. Divers have followed the main conduit of Wakulla Springs for over 2,000 feet and have found chambers as large as 100-feet high and 150-feet wide (Figure 23). Fossil skeletons of several Ice Age mastodons found in the recesses of the spring indicates that it has been of large size since prehistoric times.
Florida Caverns State Park, near Marianna, Jackson County, has the best example of a karst cave in Florida (Figures 24 and 25). Karst processes, and how they form caverns, have already been discussed. Up to now, all discussions of karst processes have concerned their corrosive character; that is, groundwater dissolving limestone, carrying it away in solution, and creating voids. Here, at the Caverns, one can see that the chemical processes are reversible—they can be depositional as well as erosive. Visitors can walk through the cave and examine closely the myriad cave deposits formed by karst processes and underground drainage.

Stalactites (Figure 26) grow downward from cracks or tiny openings in a cave's ceiling due to seepage of ground water from the limestone. When the groundwater, which has entrained carbonate ions and carbon dioxide gas, encounters the open air of the cave, some of the water evaporates and some of the gas escapes to the atmosphere. This creates a chemical disequilibrium which causes some calcium carbonate to precipitate and form calcite stalactites.

Usually, some of the excess water then drips from the stalactite to the cave floor, and, in turn, evaporates and precipitates calcite to create a stalagmite, growing upward from the floor (Figure 27). The stalagmite may eventually join the stalactite to form a column (Figure 27), if favorable depositional conditions exist for a long enough time, possibly hundreds of thousands of years. Once joined, columns can become quite thick as the water continues to deposit successive thin layers of calcite. Dripstone and flowstone (Figure 28) are descriptive terms for the decorative deposits that cover or cascade over and around a cave's walls, floor, ceiling, stalactites, stalagmites, columns, and boulders.

Another type of deposit seen in the Caverns is a drapery (Figure 29). This forms similarly to a stalactite, except that the water seeps from a narrow crack in the stone; its precipitate forms a thin, elongated formation, often wavy and color-banded.

Crystalline structures are common in caves or in voids in carbonate rocks. Crystals of calcite, dolomite, or other mineral dissolved into solution by groundwater may be precipitated when the water is released from confinement in the rock. The flat crystal faces reflect light, as do the facets of a cut gemstone, often producing kaleidoscopic sparkles in the dim recesses. Figure 30 shows an example of calcite crystals found in caves and voids in limestones.

The larger caverns that are open to the public represent only a part of this area's underground drainage system. Tantalizing clues to its much larger extent were provided in 1981 and 1984 when some new cave rooms were discovered by following a narrow "squeezeway" from one
Figure 24. Location of Florida Caverns State Park.
Figure 25. Florida Caverns State Park, showing geological features of interest: 1) Caverns entrance and visitor center, 2) Cave tunnel, a walk-through karst feature, 3) Flood plain river bluffs eroded by the Chipola River, 4) Limestone outcrops occur throughout the park, 5) Cave openings are exposed in several places, 6) Sinkholes are present throughout the park, 7) Natural bridge, where the Chipola River goes underground, 8) Blue Hole Spring flows to the surface from depths within the limestone. From Schmidt, 1982.
Figure 26. Thin, straw-like stalactites can be seen on the cave ceiling. Eons of dripping water build them thicker and longer. From Schmidt, 1982.

Figure 27. Columns form when stalactites meet stalagmites. From Schmidt, 1982.
Figure 28. The rock formations take many shapes. Here a dripstone-decorated column appears as a wedding cake in the well-lighted underground trail. From Schmidt, 1982.
Figure 29. A drapery forms when water seeps from a crack in the rock. Prolonged seepage adds more deposits that form a banded drapery. From Schmidt, 1982.
Figure 30. Calcite crystals formed in a cavity in limestone from a Florida quarry. Photo by T. Scott, Florida Geological Survey.

of the older known passages (Figures 31 to 35). Continued exploration by "spelunkers" may discover more caverns.
Figure 31. A pristine cave room—never seen by humans before. Florida State Parks photo.
Figure 32. One of the newly discovered rooms at Florida Caverns has a grotto with a stream. Florida State Parks photo.
Figure 33. A recently discovered cave room at Florida Caverns. Florida State Parks photo.
Figure 34. A large column in one of the new cave rooms. Florida State Parks photo.
Figure 35. A newly discovered cave room at Florida Caverns. Florida State Parks photo.
FALLING WATERS STATE RECREATION AREA

Falling Waters State Recreation Area’s main attraction is a sinkhole with a waterfall (Figure 36). The sinkhole is cylindrical with sheer walls that allows the waterfall to plummet 100 feet to its bottom. Associated with the sink is a cave system which is part of a local underground drainage system, connected to several adjacent sinkholes. Segments of the cave system have been explored and mapped (Figure 37). Most of the underground drainage network consists of a tortuous maze of crawlways and squeezeways only a few inches wide and high, and
Figure 37. Map of cave system associated with waterfall.
Figure 38. Locations of Florida’s 27 first-magnitude springs or groups of springs having average flows of 100 cubic feet per second or more. Modified from Rosenau, et al., 1977, Figure 11, p. 39.
Table 3. The 27 first-magnitude springs and spring groups of Florida with discharges, representative temperatures, and dissolved solids. A first-magnitude spring discharges over 100 cubic feet per second (cfs), or more than 64.6 million gallons per day (mgd). Modified from Rosenau, et al., 1977, Table 2, p. 7).

<table>
<thead>
<tr>
<th>Spring and number by county (refer to figure 38)</th>
<th>Discharge*</th>
<th>Average</th>
<th>Range</th>
<th>Water temperature</th>
<th>Dissolved solids</th>
</tr>
</thead>
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<tr>
<td>ALACHUA CO. 1. Hornsby Springs</td>
<td>163</td>
<td>76 - 250</td>
<td>22.5</td>
<td>73</td>
<td>230</td>
</tr>
<tr>
<td>BAY CO. 2. Gainer Springs</td>
<td>159</td>
<td>131 - 185</td>
<td>22.0</td>
<td>72</td>
<td>60</td>
</tr>
<tr>
<td>CITRUS CO. 3. Chassahowitzka Springs</td>
<td>139</td>
<td>32 - 197</td>
<td>23.5</td>
<td>74</td>
<td>740</td>
</tr>
<tr>
<td>4. Crystal River Springs</td>
<td>916</td>
<td>**</td>
<td>25.0</td>
<td>75</td>
<td>144</td>
</tr>
<tr>
<td>5. Homosassa Springs</td>
<td>175</td>
<td>125 - 257</td>
<td>23.0</td>
<td>73</td>
<td>1,800</td>
</tr>
<tr>
<td>COLUMBIA CO. 6. Itchetucknee Springs</td>
<td>361</td>
<td>241 - 578</td>
<td>22.5</td>
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<tr>
<td>HAMILTON CO. 7. Alapaha Rise</td>
<td>608</td>
<td>508 - 699</td>
<td>19.0</td>
<td>66</td>
<td>130</td>
</tr>
<tr>
<td>8. Holton Spring</td>
<td>288</td>
<td>69 - 482</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>HERNANDO CO. 9. Weeki Wachee Springs</td>
<td>176</td>
<td>101 - 275</td>
<td>23.5</td>
<td>74</td>
<td>150</td>
</tr>
<tr>
<td>JACKSON CO. 10. Blue Springs</td>
<td>190</td>
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<td>21.0</td>
<td>70</td>
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<td>LAKE CO. 13. Alexander Springs</td>
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<td>LEON CO. 14. Natural Bridge Spring</td>
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<td>79 - 132</td>
<td>20.0</td>
<td>68</td>
<td>138</td>
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<tr>
<td>15. St. Marks Spring</td>
<td>519</td>
<td>310 - 950</td>
<td>20.5</td>
<td>69</td>
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</tr>
<tr>
<td>LEVY CO. 16. Fannin Springs</td>
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<td>64 - 139</td>
<td>22.0</td>
<td>72</td>
<td>194</td>
</tr>
<tr>
<td>17. Manatee Spring</td>
<td>181</td>
<td>110 - 238</td>
<td>22.0</td>
<td>72</td>
<td>215</td>
</tr>
<tr>
<td>MADISON CO. 18. Blue Spring</td>
<td>115</td>
<td>75 - 145</td>
<td>21.0</td>
<td>70</td>
<td>146</td>
</tr>
<tr>
<td>MARION CO. 19. Rainbow Springs</td>
<td>763</td>
<td>487 - 1,230</td>
<td>23.0</td>
<td>73</td>
<td>93</td>
</tr>
<tr>
<td>20. Silver Glen Springs</td>
<td>112</td>
<td>90 - 129</td>
<td>23.0</td>
<td>73</td>
<td>1,200</td>
</tr>
<tr>
<td>21. Silver Springs</td>
<td>820</td>
<td>539 - 1,290</td>
<td>23.0</td>
<td>73</td>
<td>245</td>
</tr>
<tr>
<td>SUWANNEE CO. 22. Falmouth Springs</td>
<td>158</td>
<td>60 - 220***</td>
<td>21.0</td>
<td>70</td>
<td>190</td>
</tr>
</tbody>
</table>
which takes many sharp-angled jogs. The many sharp changes of direction are the result of the preferential manner in which ground water has dissolved the limestone along bedding planes, joints, and fractures in the rock.

Springs

Throughout history humans have been fascinated by springs. And justifiably so, since they are sources of water, the necessity of all life. As such, they also provide predators, including man, with convenient places for stalking and ambushing prey. For primitive hunter-gatherer societies, springs often became the nucleus of communities, a tendency that still occurs today. Because of their importance to primitive people, some springs were imbued with mystical, magical, or sacred status, such as the sacred spring that is the origin of the Seine River. While such superstitions may be scoffed at today, many springs still enjoy favored status as health spas, water recreation and fishing areas, tourist attractions, local water supplies, or just for their serene, idyllic settings. Florida’s karst springs provide all of these benefits.

Florida has 300 known springs: 27 of first magnitude, 70 of second magnitude, and 190 of third magnitude or less (Figure 38 and Table 3). Combined estimated discharge from all 300 known springs is 12,600 cfs or eight billion gallons per day. Although a world-inventory of springs is not available, it appears that the major springs of Florida exceed in both number and in quantity of water discharged those of other states or nations. These springs are invaluable resources and assets. To date, none has been found to be contaminated with pesticides, herbicides, or metals (Rosenau, et al., 1977). Their generic nature, however, makes them extremely susceptible to pollution and care must be exercised in any activities planned near them. Rosenau, et al. (1977) described in
detail, with photos, the known springs of Florida, so only brief descriptions of selected examples will be given here.

Florida owes its national, and possibly world, leadership in spring activity to karst. All of its major springs discharge from solution-riddled limestones associated with the Floridan Aquifer, which underlies the entire State of Florida (Rosenau, et al., 1977).

Springs can occur in any kind of rock. Florida’s surficial and subsurface rocks that contain springs, however, are of four types: sand, clay, limestone, dolomite or some combination of them. Each spring occurs as the result of a favorable combination of geological, hydrological, and topographical factors, and, in the case of limestones, the degree of solutional weathering. Since this report deals with karst and, since all of Florida’s major springs occur in limestone, the small springs in sand or clay sediments will not be discussed.

Geological factors that influence the location and discharge of a spring include the stratigraphy, structure, porosity, and permeability of rocks, which were introduced in earlier sections on the hydrologic cycle, aquifers, and evolution of karst terrains (see Figures 4, 5, 6 and 7). Stratigraphy refers to the layered nature of rocks of differing types. Although Florida stratigraphy is generally as shown in Figure 5, countless variations occur in thicknesses, sequences of layering, areal extent, and lithologic characteristics. Structure refers to the attitude of rock layers, e.g., flat, level, dipping, folded or distorted. Florida’s rock strata are usually relatively flat and level to gently dipping, as shown in Figure 5. Again, deviations from this rule-of-thumb occurs. The structure and stratigraphy of the rocks influences surface drainage which, in turn, erodes the rocks to produce an area’s topography.

Hydrological factors affecting the locations and discharges of springs in Florida are the sizes and types of recharge areas and drainage basins, topography, and rainfall. The most significant influence on a spring’s discharge is its local drainage basin. In those parts of Florida that have little prominent relief, many streams’ surface drainage divides are difficult to define and may not be very meaningful.

The presence of karst can further complicate the delineation of drainage basins. For example, Figure 39 shows the Oklawaha River drainage basin, a tributary of the larger St. Johns River drainage basin. Also shown are the drainage basins for Silver and Rainbow springs, that lie mostly within it. Note, however, that the springs’ basins do not coincide with the river basin’s boundary; both springs’ basins lie partly within and partly outside. This anomalous situation is the result of karst, which is responsible for the springs’ locations and the creation of their underground drainage. The river’s drainage basin boundary was drawn along topographic highs, as is customary. However, the springs’ drainage basin boundaries could only be determined by analyzing surface and groundwater levels throughout the basins (Faulkner, 1970).

This example demonstrates the contradictory problems that can occur when dealing with surface or groundwater in karst terrain. For instance,
if one were trying to trace pollutant travel in surface waters, the drainage system would be accessible to test or monitor. The same problem in karst terrain may be impossible to solve because of a hidden, tortuous maze of underground drainage, which may divert part of the surface water in unknown directions in three dimensions.

Seasonal variations in flow is the norm for Florida springs, as well as for most springs in the world. Each spring exhibits unique flow characteristics, varying between extreme high and low flows, which are controlled by local hydrological factors. Because rain is the ultimate source of all
water for springs, the seasonal rainfall pattern for any area will greatly influence the spring flows of that area.

The extent to which spring flow is dependent on rainfall is shown in Figure 40. For the three years shown, rainfall was greatest from May through August, with marked seasonality. Note the lag-time between peak rainfall and peak spring flow, indicated by the vertical dashed lines. From its seasonal low flow, Silver Springs’ discharge only begins to gradually increase after one or more months of high rainfall; the springs’ high flow occurs after the wet season has waned. Also note that the configuration of the graph showing water level in the Floridan Aquifer well closely duplicates the spring’s flow graph; both gradually rise, peak, then gradually decline. This demonstrates another point—the springs’s water is released slowly from storage in the limestone aquifer’s voids.

This example illustrates a sequence of events that is important in understanding the groundwater phase of the hydrologic cycle in Florida. To recapitulate: rain percolates downward to replenish the groundwater aquifers, raising their water levels. This takes time, often measured in weeks or months. Increased volume of stored groundwater causes the normal flow through the aquifers to increase. Further delays of weeks or months due to the travel time from recharge areas to points of discharge (a spring in this example) are manifested in the lag-time shown on Figure 40. After the seasonal highs, the spring’s flow gradually decreases as the groundwater reservoir is depleted. Protracted droughts can cause groundwater depletion to the point where springs and surface streams cease to flow.

Some spring flows vary from nothing, or near zero, to flood proportions. For example, Wakulla Springs has been recorded as varying between a low of 25 cubic foot per second (cfs) (a relative trickle) to a flood of 1,910 cfs (16 million to 1,234 million gallons per day) (Table 3). This means the high flow was more than 76 times as large as the low flow. These happen to be the extremes of flow measured between 1904 and 1974; longer periods of record will undoubtedly show an even wider range.

**SUBMARINE SPRINGS**

Florida has 16 known submarine springs, all originating in limestone, some of which have multiple vents (Figure 41). Most are within a mile of shore; some are in bays or tidal stream channels. However, four springs lie farther offshore. Crescent Beach submarine spring lies 2.5 miles offshore in about 55 feet of water; Mud Hole submarine spring lies 13.8 miles south of Sanibel Island lighthouse in 43 feet of water; Bay Hole Spring is about 20 miles offshore in 38 feet of water; Red Snapper Sink is located about 25 miles east of Crescent Beach in water approximately 88-feet deep.

Most of the springs’ waters have been analyzed, and all but one discharge relatively fresh-to-brackish water (Rosenau, et al., 1977). The
Figure 40. Interrelation of rainfall, water levels in the Floridan Aquifer, and discharge of Silver Springs. Note lag-time between maximum rainfall and peak discharge of the springs (dashed lines). Modified after Rosenau, et al., 1977, Figure 10, p. 28.
one exception is Red Snapper Sink. The spring is about 160 feet in diameter at the sea bottom and is probably more than 465-feet deep (Rosenau, et al., 1977). A dye-dispersion test indicated a slight downward velocity of seawater, suggesting that this vent may be a point of seawater intrusion into the Floridan Aquifer (Kohout, et al., 1975).

Similar phenomena from other studies suggest that such karst features on the Floridan Plateau may be common; more of them just haven’t been discovered yet. Benjamin (1970) reported on his scuba exploration of 54 “blue holes” offshore on Andros Island. Andros Island is the largest of the Bahama Islands, lying 140 miles southeast of Miami. It is the emer-
gent portion of the Great Bahama Bank, a carbonate platform of more than 14,000 feet of limestones, that rise precipitously from depths of over 12,000 feet in the Atlantic Ocean. Besides the 54 he explored, Benjamin charted several hundred other locations that he felt might prove to be blue holes. The graphic name "blue hole" describes the appearance of the deep submarine pits when seen from above: dark blue against the crystal clear, light green, shallow water, from three to about 20-feet deep. He explored one hole to 230-feet in depth before his floodlight went out. Flash pictures revealed what appeared to be massive cave stalagmites.

Benjamin (1970) theorized that these blue holes formed in Andros Island's limestone at times of low water, during the last great Ice Age, probably as caves or sinkholes on what was then dry land. The melting glaciers raised sea level, flooding the karst features, forming the blue holes. The island's fresh watertable also rises and falls in cycles through the island's karst drainage.

Benjamin also collaborated with Jacques Cousteau (1971) in exploring blue holes near Andros Island. Dye and current meter tests proved that some of the blue holes, at least, have direct connections with similar karst features on the nearby islands.

Jacques Cousteau (1971) also explored an enormous blue hole that is 1,000 feet in diameter and 412-feet deep, located on Lighthouse Reef, British Honduras. Cousteau's divers encountered vast caves 120 feet below the surface that were filled with large stalactites, some more than 20-feet long. They found caves at the bottom of the blue hole that had small stalactites, indicating that sea level had once been more than 412 feet lower than present, since stalactites can only form in air. A stalactite that had fallen from the ceiling of the caves at the 120-feet depth was laboratory age-dated to be about 12,000 years old, providing evidence that sea level has risen more than 120 feet in 12,000 years.

QUICKSAND

Quicksand is a hydrological phenomenon that may be found where there are springs. Quicksand is, as defined by Webster's New Collegiate Dictionary: "Sand readily yielding to pressure; esp., a deep mass of loose sand mixed with water, into which a person or heavy object sinks."

Quicksand is a phenomenon which, fortunately, many people never encounter. However, when it is encountered it can be an unnerving experience at best, and at worst, potentially dangerous. An examination of the facts will dispel the mystery and the ideas of exaggerated danger that have become synonymous with quicksand.

Quicksand can only occur under certain circumstances. First, there must be loose sand. Sand composed of well-sorted (all grains about the same size), clean, fine-sized, rounded grains tend to become "quick" more easily than coarser types. There must be a source of upward flowing water, such as a spring. These conditions are more usual along
Figure 42a. Under ordinary conditions sand grains are packed against each other, forming a mutually self-supporting structure. Sand in this configuration can support a load.

Figure 42b. Water (blue arrows) moving upward through the sand fills the pores, buoys the grains and tends to "float" them apart. Under these conditions the sand cannot support a load—any heavy object placed on its surface will gradually sink through the sand—it has become "quick." Separation of grains is exaggerated for clarity.
streams and beaches, and it is in these places that most quicksand occurs.

Figure 42a shows sand grains under ordinary conditions, either exposed at the surface level or underwater. The grains form an interlocking structure which can support a load on its surface. Under these conditions, if a load is placed on the sand, such as a person walking, the grains may shift position slightly to accommodate the load, but there will not be any significant change in the density of the sand-column.

If water moves upward through the sand with sufficient velocity, as from an underlying spring, quicksand conditions may be created, Figure 42b. The sand grains may be forced apart, partially suspended, and "floated" or buoyed up. In a sense, the sand column becomes "fluid," and it will not support weight. Any heavy object placed on the sand will sink. The object's sinking speed will be determined by the local conditions, e.g., the quantity and velocity of the water flow, size and shape of the sand grains, and the size, shape, and weight of the object. Generally speaking, though, if a person places their foot upon an area of quicksand, the sand gives way instantly. Most such quicksand occurs as small, shallow pockets, and the plummet is only a few inches before firm bottom is reached. It would be a surprise, but unless the person fell or twisted a leg, it would not be a dangerous experience.

Quicksand is usually restricted to small areas where an underlying spring maintains an upward flow. If the upward flow decreases below a certain critical amount, the "quick" sand will gradually revert to firmness. Local factors will, therefore, control the occurrence, the duration, and the extent of quicksand. For example, during dry seasons springs' discharges and watertables may fall to such low levels that they cannot maintain quicksand conditions at their points of discharge.

Quicksand cannot be detected simply by looking for it. Under ideal quicksand-forming conditions, the upward flow is too slow to disturb the surface or the water may seep into the surrounding sand before reaching ground surface. In either circumstance, the quicksand area is not noticeably different from the surrounding ground—until weight is placed upon it—and it gives way. If upward seepage is too fast, the sand will "boil," or create wash-outs, which will be noticeable.

Figure 43 illustrates two generalized situations that favor the formation of quicksand. It must be emphasized, however, that specialized local factors will determine whether quicksand actually will form.

WINDOWS TO THE PAST

Little Salt Spring and Warm Mineral Springs

Several Florida springs have proven to be windows into the past. Their waters have acted to preserve fossils and archeological artifacts, which continue to provide remarkable clues to the State's natural and cultural histories. One, Wakulla Springs in the north has already been discussed.
Figure 43a. Quicksand may be formed in the bed or along the banks of a stream by the upwelling springs that discharge from the porous limestone or sand. Depending upon local conditions, quicksand may form anywhere in the stream’s bed. Blue arrows denote water moving through the limestone and sand. All material below the watertable is saturated.

Figure 43b. Quicksand may form along a beach due to local conditions that create springs. In a possible situation shown here, groundwater (blue arrows) migrating through loose sand is diverted upward by the denser sand or clay units. If upward seepage is fast enough, areas of quicksand may form in the area with the darker pattern.
Two others lie near the southwest Gulf coast in Sarasota County; they are Warm Mineral Springs and Little Salt Spring (Figure 44).

Of any Florida spring, Little Salt Spring has been the most intensively studied and the most prolific repository of fossils and artifacts. Until the late 1950's, Little Salt Spring was thought to be just another shallow pond, when divers discovered it to be a flooded sinkhole of impressive dimensions (Figure 45). In 1974, a non-profit research organization was founded to provide support for the professional exploration and study of the site. Some of the more spectacular discoveries from the spring and nearby bog to date include (Biggs, 1976; Clausen, et al., 1979):

1. The shell of an extinct, giant land tortoise, 12 feet in diameter, with a sharp-pointed wooden stake embedded in it, which apparently was used to kill it. The tortoise shell and wooden stake provided radioactive dates of 13,450 and 12,030 years before present (BP), respectively. The 1,000 years difference between the dates can be accounted for by the possible age of the tortoise. The life span for such a giant species could have been several centuries, before it was killed by a paleo-Indian. This fossil and the weapon are evidence for the earliest known human activity in Florida.

2. An Archaic Period cemetery with an estimated 1,000 burials in an adjoining slough. Radiocarbon dates of three bone samples gave dates from 6,180 to 5,220 years BP.

3. Parts of more than 30 human skeletons have been removed from the spring.

4. Fossils of bison, camels, horses, a mastodon, and giant sloth, along with bones of smaller animals.

5. Boomerangs, throwing sticks, atl-atl (a spear-throwing device), and stone projectile points. One of the non-returning boomerangs may be the oldest specimen of this kind of weapon in the world and is the first found in the Western Hemisphere.

6. Portions of a well-preserved brain were found in the skull of one skeleton from the cemetery. Another human brain preserved in a skull was recovered from Warm Mineral Springs; its enclosing sedimentary sequence was radioactive carbon dated at 10,630 to 8,500 years BP.

Based on such geological and archeological evidence from the spring, it has been inferred that the climate of south Florida was much drier 12,000 years ago than it is today. World temperatures were cooler and
Figure 44. Location map of Little Salt and Warm Mineral springs. Warm Mineral Springs is a resort development that is accessible from Route 41. Little Salt Spring is not accessible to the public.
Figure 45. Cross section of Little Salt Spring. The circular upper pool has a diameter of approximately 250 feet, sloping gently down to the circular, 80-feet wide orifice at 40-feet depth. The stepped-back overhanging ledges at 40 and 70 feet have stalactites that formed when water levels were lower than their respective depths below ground. Illustration from Science, February 16, 1979, cover, copyright 1979 by AAAS. Used with permission.
sea level was much lower (Clausen, et al., 1979). Under these conditions most of Florida's sinkholes were probably cenotes, which are large, cavernous sinkholes with water at depth. At that time the water level in Little Salt Spring cenote was near the 90-foot ledge (Figure 45), where the giant tortoise had apparently been killed, overturned, and cooked in its shell by paleo-Indians. The Little Salt Spring archeological site is off-limits to the public.

Hornsby and Darby Springs

The findings at Little Salt and Warm Mineral springs corroborate earlier archeological finds in north Florida at Hornsby and Darby springs, Alachua County (Figure 46). Investigations at Hornsby and Darby springs were sponsored by the Florida Geological Survey in 1951 and 1952. One sedimentary sequence that contained several paleo-Indian chert tools associated with mastodon bones was carbon-dated as being 9,880 (+270) years BP (Dolan and Allen, 1961), which gives a minimum date for human habitation at this north Florida site, and which closely agrees with dated artifacts from Little Salt and Warm Mineral springs. The limestone near the springs contain chert seams that provided the Indians
with the raw materials for stone tools. Judging from the numbers and associations of the stone tools, projectile points, and pottery, they conducted an extensive lithic industry at the springs, from about 10,000 to 3,000 years BP (Dolan and Allen, 1961). Hornsby Spring is inside the grounds of a private camp and is not open to the public.

Recreational Use

Some 49 of Florida's 300 known springs (about 15 percent) are presently developed for recreational use. Several springs form the nucleus of state and private parks or campgrounds, which have pools, bath houses, concessions, and other facilities, where visitors can picnic, swim, boat, and snorkel or scuba dive.

The water temperature of most springs varies only slightly throughout the year, because their sources are underground waters which experience little, if any seasonal temperature variations. The range of temperatures is between 70 to 79 °F (21 to 25.5 °C), with the majority averaging closer to 75 °F (24 °C); these temperatures provide a cool, refreshing swim.

The mention of "hot springs" brings to mind visions of steaming springs where nobility and wealthy gentry congregate to "take the waters" in splendid surroundings. The lore and lure of some hot springs of the world has reached near-legendary proportions. "Spa" is the name of a famous mineral-springs resort in Belgium, whose name has become synonymous with any commercially developed spring which has water that is hot or highly mineralized; odorous, sulfurous water seems to be especially beneficial to both owners and patrons.

Florida has two known hot springs, Little Salt Spring and Warm Mineral Springs. "Hot" is used here to signify that they have discharges of 80 °F (26.5 °C) or hotter. Both springs are in Sarasota County (Figure 44). The archeological significance of Little Salt Spring has been discussed in a preceding section.

Warm Mineral Springs is about 13 miles southeast of Venice on U.S. Highway 41, one mile north of the road. The spring is privately owned and is developed into a public swimming and recreation area. The spring's physical shape is the same as Little Salt Spring, as shown on Figure 45. A comparison of dimensions shows Warm Mineral Springs to be larger: its main orifice, at a depth of 43 feet below water level, is approximately 170 feet in diameter (Little Salt Spring's is 80 to 100 feet); depth to the floor of the main chamber is about 240 feet (versus 200 feet). Comparative water quality data are given in Table 4.

These two springs may be closely related in age, genesis, and sources of water. The source of their warm, saline, sulfurous water may be from the 2,000 to 3,000-feet deep Boulder Zone (Rosenau, et al., 1977). The route of the water from the Boulder Zone is not known, but Sproul, et al. (1972) presented evidence of faulting near Ft. Meyers, 40 miles to the southeast, which could provide avenues of upward migration. They stud-
Table 4. Water quality data for Little Salt Spring and Warm Mineral Springs. Units are in milligrams per liter unless otherwise indicated (Rosenau, et al., 1977).

<table>
<thead>
<tr>
<th></th>
<th>LITTLE SALT SPRING (sampled 10/30/72)</th>
<th>WARM MINERAL SPRINGS (sampled 4/24/72)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calcium</td>
<td>180</td>
<td>500</td>
</tr>
<tr>
<td>Magnesium</td>
<td>130</td>
<td>580</td>
</tr>
<tr>
<td>Sodium</td>
<td>750</td>
<td>5,200</td>
</tr>
<tr>
<td>Chloride</td>
<td>1,300</td>
<td>9,500</td>
</tr>
<tr>
<td>Carbonate</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Sulfate</td>
<td>510</td>
<td>1,700</td>
</tr>
<tr>
<td>Fluoride</td>
<td>1.8</td>
<td>1.9</td>
</tr>
<tr>
<td>Nitrate</td>
<td>.53</td>
<td>—</td>
</tr>
<tr>
<td>Strontium</td>
<td>28</td>
<td>31</td>
</tr>
<tr>
<td>Dissolved solids (calculated)</td>
<td>3,000</td>
<td>18,000</td>
</tr>
<tr>
<td>pH (units)</td>
<td>8.0</td>
<td>7.3</td>
</tr>
<tr>
<td>Temperature (°F/°C)</td>
<td>81/27</td>
<td>85/29.5</td>
</tr>
<tr>
<td></td>
<td>81 to 88 °F</td>
<td>73 to 99 °F</td>
</tr>
</tbody>
</table>

ied old, abandoned irrigation wells in the area, 1,000 to 1,500-feet deep, that were flowing saline, sulfurous water. Regarding chloride concentrations, it was determined that they could range from 15,000 to 20,000 mg/L in aquifers below 1,400 feet in Lee County. Although they could not pin-point the exact source of the mineralized water that was contaminating the shallow aquifers, their evidence led them to conclude that upward leakage may be occurring along the faults that connect the deep strata with shallow strata. A well in Charlotte County, 23 miles southeast of Little Salt Spring, produced 96 °F (35 °C) water from about 1,600 feet (Sproul, et al., 1972). These findings tend to corroborate Kohout's (1965) theory as to the source of some of the springs' water.

It may be, therefore, that Little Salt and Warm Mineral springs occur as hot springs as the result of a combination of geological circumstances that allows anomalously hot and mineralized water to migrate upward. The springs' karst drainage systems probably extend deep enough to intercept aquifers whose confining beds have been breached by faults, allowing the invasion of deep, mineralized water. Since the deeper aquifers are under artesian pressure, some of the water is then diverted through the springs. The springwater is not as mineralized because it is diluted by fresher water from shallower zones that also supply the springs.

**DEEP ZONES OF HIGH TRANSMISSIVITY**

The Floridan Plateau is a relatively flat platform that forms the eastern side of the Gulf of Mexico basin (Figure 47). The emergent part of this plateau is peninsular Florida. The plateau's boundaries are placed at water depths of 300 feet. At Ft. Myers, its edge lies some 100 miles
Figure 47. Floridan Plateau with submarine karst features. The Floridan Plateau is encompassed by the 300-feet depth contour line (modified from Uchupi, 1967, Figure 1). Cross section below shows the broad "platform," of which the Florida peninsula is the part presently above sea level.
offshore; at southeast Florida near Miami, it only lies two to three miles offshore. Geologically, this platform is a layer-cake of rock units. Older, deeper rocks are predominantly carbonates, while younger, shallower units are mixtures of clastics (sands, clays, gravels) and carbonates (Figure 48).

Available evidence indicates that the floor, or "basement," upon which these thousands-of-feet of sedimentary strata have been deposited are granites, basalts, or similar types of volcanic or metamorphic rocks (Applin, 1951), some of which have been dated as old as 634 million years old (Milton, 1972). At some time during that ancient era, carbonate rocks began to accumulate on top of the basement rocks that formed the floor of a shallow sea, much like the reef environment of
south Florida today. While these carbonates were being deposited the basement rocks of this proto-Florida were slowly subsiding. Conditions similar to these persisted for millions of years, because all of the carbonate strata originated under relatively shallow marine conditions, indicating that depositional rates approximated subsidence rates (Banks, 1967). These rocks and their included marine fossils also show evidence for many rises and falls of global sea levels, between then and now.

The most recent episodes of major sea level fluctuation occurred during the past million years or so, when the Pleistocene glaciers and continental icecaps removed so much water from the hydrologic cycle that sea level dropped hundreds of feet, exposing broad expanses of the continental shelves. Whenever sea level dropped low enough to expose the rocks on the platform, weathering and solution of the carbonate could begin to form karst. Given long enough periods of low stands of sea level, extensive karst drainage systems could have formed. Then, as now, the karst drainage would have extended outward beneath the parts of the plateau above sea level, which could have been 200-miles wide in places. Successive rises in sea level, combined with the gradual subsidence of the plateau, have covered these older surficial karst features (springs, sinkholes) with sea water or sediments. Though buried, they should not be forgotten, for recent evidence indicates that some parts of this ancient, underground karst system are still active components of Florida's hydrologic system.

Oceanographic surveys have, by chance, found several sinkholes on the submerged plateau. Jordan (1954) reported the discovery of three large sinkholes 14-miles offshore on the Pourtales Terrace, south of Key West, at 900-feet depths (Figure 47). Each was more than one-half-mile wide at the top, from 450 to 540-feet deep, and appeared to be free from sediment-fill. Jordan (1954) thought these karst features formed when the terrace was emergent and later submerged. Malloy and Hurley (1970) recognized karst-like topography on the Miami Terrace (Figure 47), which they interpreted to be solution and collapse features formed, or at least maintained, by water from the Floridan Aquifer discharging subaqueously into the Straits of Florida.

Similar discoveries indicate that this type of ancient karst may not be unique to the Floridan Plateau—indeed, it probably exists in many coastal regions around the world—wherever ancient carbonate rocks crop out beneath the sea. Robb (1982) reported evidence that undersea discharge of groundwater during periods of lower sea level may have eroded cliffs and terraced valley walls on part of the lower continental slope, about 70 miles offshore New Jersey, at depths of over 6,000 feet. Some karst-like features of the submarine topography suggest that solution of the carbonate rocks also took place.
The Boulder Zone

Generally lying at depths of greater than 1,200 feet beneath peninsular Florida is an extensive zone of solution cavities (Vernon, 1970). This zone is distinct from the surficial and shallow karst features that presently concern citizens of the State. This zone of cavernous porosity is called the Boulder Zone. It is an erroneous name given by early oil-exploration well drillers; the Boulder Zone does not contain any boulders. Rather, it is a zone of very hard and dense dolomite (Vernon, 1970). As drills encountered the roofs of cavities, large chunks of rock (boulders) broke off. By getting between the drill bits and walls of the bore hole these fragments created drilling problems, including severe vibration and damage as the rotating drills bounced and rolled over them. Many holes had to be abandoned because the drillers could not make progress once they encountered the Boulder Zone. Figure 49 shows the porous nature of the dolomite. Figure 50, taken with a special down-hole camera, shows vugs (small cavities) and tunnels. Some of these deep oil test wells have encountered caverns, the two largest being 90 and 100 feet from ceiling to floor (Puri and Winston, 1974). This zone extends to depths greater than 5,530 feet in south Florida (Vernon, 1970). The horizontal and vertical distribution of cavities and caverns seems to be random; drillers cannot predict where they will encounter them. Vernon (1970) reported that this “Boulder” zone of cavernous, high transmissivity appears to respond as a part of the Floridan Aquifer; i.e., they are hydraulically connected.

Kohout (1965) postulated geothermally heated convection currents as a driving mechanism to circulate sea water through the deep zones of high transmissivity in south Florida, depicted in Figure 51. Referring to Figure 51: geothermal heat from deep within the Earth’s mantle is transferred through the low-permeability Cedar Keys anhydrite (calcium sulfate) beds, (1, on figure), raising the temperature of the water in the lower Floridan Aquifer system and generating thermal convection circulation. The warmed, less-dense aquifer water rises, pulling in cold, dense sea water that has access to the aquifer through karstic, cavernous dolomite that crops out in the Straits of Florida (2). The rising convection flow of sea water eventually contacts seaward-moving fresh water, which was recharged to the aquifer from the karst region of central Florida (3). After contact and mixing, the diluted sea water moves seaward and may discharge through the upper part of the aquifer either by upward leakage through confining beds into shallow aquifers, or by discharge through submarine springs and seeps on the continental shelf and slope in the Straits of Florida (4). More recent data from deep oil test wells in the Florida Keys and Gulf of Mexico show that the Boulder Zone extends some distance westward from the peninsula (Vernon, 1970). If Kohout’s theory is valid, then it is possible that his convective circulation model shown in Figure 51 may have a mirror-image to the west, with hydraulic connection to the Gulf.
Porous dolomite “boulder” broken off a cavity’s wall by a diamond drill bit. Note the vugs and pores, which are lined with micro-crystals of dolomite. The striated collar was cut in the rock by the rotating drill bit before the “boulder” broke off the cavity’s wall. Florida Geological Survey photo.
Other investigations lend weight to Kohout’s model. It is normal to find increasing temperatures of rocks with depth. A temperature survey run on an oil-test well, Sun Oil Co. Red Cattle No. 32-3, Hendry County, T45S, R29E, section 32, showed a temperature gradient of one degree Fahrenheit increase for each 122 feet of depth, between 900 to 2,100 feet. From 2,100 to 3,300 feet, through the Boulder Zone, the gradient was less steep, being only one degree for each 480 feet of increasing depth, with a bottom-hole temperature of 100 °F (37 °C).

Meyer (1974) reported on a well near Miami that was drilled 2,927-feet deep, into the Boulder Zone. This well was used to inject secondarily treated sewage effluent into the Boulder Zone. This investigation indicated that locally the Boulder Zone water has the chemistry of sea water with a temperature of 60.4 °F (15 °C). The water’s chemistry and temperature, along with the regional geology, suggest that the Boulder Zone
Figure 51. Idealized cross section through Miami showing concept of geothermally induced convection currents. Modified from Kohout, 1965, Figure 10.
crops out in the Straits of Florida and is hydraulically connected to the Straits.

Uses of Deep Zones of High Transmissivity

With explosive population growth and urban development comes increasing demand for potable water and the attendant problem of waste disposal. Deep zones of high transmissivity may prove helpful in solving both problems.

Florida has sufficient fresh water to supply all of its needs. Water supply problems arise because population centers are distant from sources of fresh water. Also, Florida’s rain occurs in seasonal patterns, which do not always coincide with peak demands. The solution to the water supply problem, then, is to get the water to the population centers in sufficient quantity and when it is needed. Relevant to these problems, several research projects have studied possible uses for these deep zones.

The water in the Floridan Aquifer system at these depths is brackish to saline (Klein, 1975). Although the water in deep zones may be non-potable, the zones themselves may prove to be exploitable, beneficial natural resources—their cavernous porosity represents an enormous potential storage reservoir.

FRESH-WATER STORAGE

Five projects in south Florida have tested the possibility of using deep carbonate aquifers that contain non-potable water as storage zones for surplus fresh water (Figure 52) (Merritt, et al., 1983). In theory, during periods of surplus water supplies, freshwater is injected into non-potable aquifers, where it is stored for a period of time, then pumped out for use when local water supplies are deficient. Theoretical studies and results of test projects indicate that efficient recovery of stored potable water improves in the first few inject-store-recover cycles, provided only potable water is recovered in each cycle (Merritt, et al., 1983).

Advantages of this subsurface storage concept are: (1) storage space is cost-free, (2) it can be conveniently located directly under a water-treatment plant or near a water-transport system, (3) no water is lost by evaporation or evapotranspiration.

Some disadvantages are: (1) cost of testing to ascertain if local, favorable hydrogeological conditions exist, (2) construction of deep wells, (3) cost of operating a system of cyclic injection wells.

These five projects have begun what must be a long research program to determine if this concept may be one factor in cost-effective solutions to south Florida’s increasingly complex and stressful water needs. Some of the tests have shown limited, local success. Similar projects need to be done in other areas of south Florida to determine local hydrogeological
Fresh-water injection test well (Merritt et al., 1983).

Salt-water disposal wells into the Boulder Zone (from Florida Bureau of Geology records). Some locations have more than one well.

Figure 52. Map showing Boulder Zone injection wells. Modified from Merritt, et al., 1983. Lines delineate the primary study area of Merritt's report.
conditions. Only when such basic information is available can government officials make strategic plans to alleviate water-supply problems.

**SALT-WATER INJECTION**

Thirteen salt-water injection wells into the Boulder Zone are in use in south Florida (Figure 52). These are used in conjunction with oil production wells.

Popular terminology ascribes the source of oil and natural gas to underground "pools." In reality, liquid petroleum (crude oil or crude) is contained in the pores and voids in certain rocks. In many cases, such as in south Florida, crude oil, gas, and salt water occur in the same rocks (Figure 53). Through time the oil, being immiscible in water, floated upward, forming separate layers. Gas, being lightest, migrated to the top of the reservoir rocks.

In October 1985, there were 84 producing oil wells in south Florida. The production zone is from 11,322 to 11,892 feet below sea level. For each barrel of oil produced (42 U.S. gallons), the reservoirs yield 100 standard cubic feet of gas and about six barrels of salt water (Florida Bureau of Geology records). Oil and gas are valuable commodities, but the salt water is a waste product that must be disposed of. Disposal of the salt water present problems since its chloride content of approximately 160,000 parts per million (ppm) make it some six-times "saltier" than Gulf water, of 20,000 ppm chlorides.

The Boulder Zone, which causes so many problems for oil well drillers, now is used to solve a problem when oil is found. Many exploratory oil wells do not find oil; they are "dry." However, when oil is found, then some of these dry holes are used to inject the waste brines into the Boulder Zone, which, with its cavernous porosity can accept practically limitless quantities.

**ACID RAIN AND ITS EFFECT ON KARST FORMATION**

As explained earlier, the primary causative agent of karst formation is the chemical dissolution of carbonate rocks by acidic water. It was pointed out that most rain is naturally somewhat acidic because it combines with carbon dioxide in the air. But other, man-made, sources of acid in the atmosphere have caused concern in recent years.

Air pollution—in the form of acid rain or the deposition of particulates capable of forming acids—has become a major, world-wide environmental problem. Some natural processes, such as volcanic eruptions, forest fires, and decomposition of plants, contribute considerable amounts of acid-forming pollutants to the atmosphere. Present concern, however, is with the ever-increasing amounts of acid rain resulting from industrial pollution, especially emissions from electric generating plants that burn fossil fuels. Some particulate and gaseous by-products of burning fuels interact with constituents in the atmosphere to become dilute sulfuric
Microscopic view of porous rock illustrating how oil and water, though immiscible, co-exist in the pores. Producing wells bring up a mixture of oil, brine, and dissolved gas, which are separated near the wellhead.

Figure 53. Generalized cross section showing oil production and brine injection in south Florida. Curvature of beds is greatly exaggerated.
and nitric acids, eventually returning to earth as acid rain or acid snow. During periods of intensive air pollution the acidity of rain can increase 10 to 30 times above normal (LaBastille, 1981).

Today, most of the United States, including Florida, has to contend with air pollution. If air pollution is causing rain to be more acidic and, since acidic water dissolves carbonate rocks to create karst, does that imply that Florida might conceivably experience increased rates of sinkhole formation?

Pertinent to this question, a recent report by the Florida Department of Environmental Regulation (FDER, 1984) presented the following points with respect to the state-of-knowledge of acid rain in Florida:

1. Florida is experiencing acid rain, with 1981-82 pH values ranging from 4.3 in the panhandle to 4.7 in south Florida. So-called "pure-rain" has a pH of about 5.6 (de Pena, 1982).
2. There is evidence that the acidity of Florida rain has increased over the past 20 years, but the trend is not clear.
3. The sources of air pollutants contributing to Florida's acid rain are not well-defined. However, it seems likely that much of the pollutants are from in-state utility power plants.
4. There is little evidence of damage to crops in Florida from acid rain.

Because there are so many unknowns about acid deposition and its effects in Florida, the Florida Congressional Delegation initiated the Florida Acid Deposition Study in 1981 to attempt to address unresolved issues. Scheduled for completion in 1985, the study is focusing on (FDER, 1984):

1. the collection of high quality precipitation chemistry data through a statewide monitoring system;
2. source attribution analysis through a variety of modeling approaches, including mass balances and back trajectory analysis, and
3. an analysis of potential ecological effects.

One of the questions that the FDER study believed should be addressed in future research projects was: Does acid deposition affect structural stability of soils for road beds and does it influence sinkhole formation?

When the primary factors involved in karst formation are examined and placed in perspective, there does not seem to be much reason to expect that Florida will experience a measurable increase in the frequency of sinkhole formation due to foreseeable increases in air pollution or acid rain.

Time—geological time—on the order of hundreds-of-thousands or millions of years, is on our side. Consider Florida's karst today and be aware that it has taken hundreds-of-thousands of years to produce the karst features we see. If the acidity of groundwater were increased by 10 times, and this became "normal," then instead of 100,000 or more
years to produce a sinkhole it might take only a few tens-of-thousands of years. Experience from other parts of the United States, Canada, and Europe has shown that, long before we have to worry about increased karst hazards, we will have to contend with sterile lakes, streams, and possibly extensive damage to forests and crops. And these effects will take place in the course of a few tens-of-years; a person’s lifetime. The greatest danger to mankind’s short-term future from acid rain, then, is the potential decrease in food supplies, as well as other associated health hazards—not an increase in karst formation.

DETECTION AND PREDICTION

Karst areas present enigmatic problems relative to certain basic human activities, such as construction, and the provision of water supplies and waste disposal, which are critical to any modern, technological society. Property owners, planners, government officials, and engineers require information or quantitative data that relate to potential problems in order to assess the chances for success for projects or plans. While most karst-forming processes take place underground and out of sight, it is still possible to study them. Techniques that are used can be classified as direct or indirect.

Direct Methods

Until recently it was only possible to use direct methods to study karst. Scientists and adventurers studied karst first-hand—they climbed and crawled into caves and sinkholes. This method of study is limited by the size of openings in the caves and by water which often floods the underground drainage. While this direct, exploratory approach provides important background information which has been useful in formulating theories to explain how and why karst forms, it is a hindsight approach. One can only study what has happened after a sinkhole collapses, for example.

One of the oldest, most straightforward approaches to evaluating a specific site for karst hazards is drilling. In this approach, holes are drilled, just as for water wells, except the object is to locate cavities. This is still the accepted engineering standard for assessing a site’s foundation qualifications. The number, locations, and depths of test holes are specified depending on the expected types and depths of soil and bedrock, size of building, and type of proposed foundation.

If cavities are found, they can sometimes be sealed by pumping them full of cement, or they may be bypassed by setting pilings into solid bedrock to support the structure. Economics and other engineering considerations will dictate the method used to secure the foundation. Occasionally, though, drilling into a cavity produces more immediate problems, such as when the drill rig begins to sink into the subsiding hole (Figure 12).
These approaches have limited predictive capability. One cannot say with any degree of certainty where or when the next karst feature will appear at the surface, or, for that matter, the extent or location of karst drainage channels.

**Indirect Methods—Remote Sensing**

Indirect approaches to study karst have been used with the hope that a technique would be found to evaluate an area with respect to detecting and predicting potential danger from karst. No perfect technique has been found. Some techniques, however, have shown promise, either alone or in combination with other methods. At present, detection and prediction of karst hazards is mostly state-of-the-art, with new technology and techniques promising to increase the success rate.

As the name implies, remote sensing refers to techniques that indirectly obtain information about an object or place some distance from a station that is remotely located. Six remote sensing techniques that are most commonly used today are discussed below. The field of remote sensing is ever-expanding because of rapid advances in technologies of electronics, optics, satellites, and sensors.

**GEOPHYSICAL METHODS**

Some geophysical methods operate on the principle of detecting and monitoring changes in natural properties of the earth, such as gravity. Other geophysical methods rely on monitoring changes in man-induced signals into the soil or bedrock, such as ground penetrating radar, sound waves, and electrical currents. Regardless of the method, the main objective is to try and detect and quantify any anomalies in the subsurface, which may signify and locate underground cavities. Four of the more common geophysical methods that have been used successfully to identify and locate underground karst features are gravity surveys, seismic refraction, ground penetrating radar, and electrical resistivity.

**Gravity**

In this method of geophysical investigation, extremely sensitive instruments, gravity meters, are used to measure the strength of local gravity. The force of earth’s gravity is not the same at every place on its surface. The force of gravity varies because of (1) difference in elevation, which changes the distance from the center of the earth; (2) effects of the earth’s speed of rotation, which changes with latitude; and (3) variations in density of underlying rocks. Usually, the effect of each of these factors is very small in going short distances from point-to-point in local areas, such as investigating a site for a building foundation.

This technique can be limited by the fact that cavities may be so small, relatively speaking, that the instrument cannot detect the tiny, local dif-
terence in density between rock with cavities and rock without cavities. Also, the instruments are very sensitive to vibrations, a factor that cannot be overlooked when working near highways or urban areas.

Seismic Refraction

In this geophysical technique seismic energy waves are transmitted into the subsurface to determine the depth to and thickness of rock strata, depth to the water table, and anomalous features such as cavities (Figure 54). Seismic energy waves travel at different velocities in materials that have different densities and hardness. The waves are refracted, or bent, at the interfaces between strata of differing composition. An array of microphone sensors, called geophones, that are implanted in the topsoil detect the reflected and refracted seismic waves. Electronic processing of these signals produce patterns that indicate subsurface features (Figure 55).

Portable seismic systems can use a sledgehammer to generate low energy seismic waves for very local, shallow investigations. Automated portable seismic sources can be used for deeper or production work. The depths to which seismic techniques are effective are generally limited only by the amount of transmitted energy; the more energy sent, the deeper the strata penetrated. An inherent weakness of this technique is its sensitivity to extraneous vibrations, particularly if used near noisy urban areas.

Ground Penetrating Radar

Ground penetrating radar (GPR) is a reflection technique using high frequency electromagnetic radiation (Figure 56). GPR surveys produce graphic profiles of subsurface conditions that resemble the side walls of trench cuts. The reflections shown on the radar record are produced as a result of contrasts in the complex dielectric constant of individual, subsurface materials. Electronic processing of the reflected energy waves reveals the configuration of strata, the watertable, cavities, buried pipes, and other subsurface features. With ideal conditions GPR can penetrate up to 100 feet or more and produce a very graphic representation of strata (Benson and Glaccum, 1979). Figure 57 shows an old sinkhole that is filled with clean quartz sand with only a subtle depression at the surface. The cone-shaped profile indicates the extent of sinkhole activity and the zone of potential hazard.

Distinct advantages of GPR over most other geophysical techniques are: (1) its continuous nature of operation as the antenna is moved slowly across the ground surface; (2) mobility of equipment can make total site coverage economically feasible, not just spot-checked as with other methods; and (3) on-the-spot analysis of data because of the picture-like radar presentation.

Since it uses electrical energy, GPR can be severely limited by some
Figure 54. Field layout of a 12-channel seismograph showing the path of direct and refracted seismic waves in a two-layer soil/rock system. Hammer blow sends a trigger pulse that starts recording of signals picked up by geophones. Used with permission of Benson and Glaccum, 1979.
Figure 55. Recording from a 12-channel seismograph. All 12 channels were recorded simultaneously from a single hammer impact. Used with permission of Benson and Glaccum, 1979.
local conditions. The radar waves are attenuated by layers of fine-grained materials, such as silts or clays. Groundwater with high concentrations of dissolved minerals, such as salt water, which is a better electrical conductor than potable water, absorbs the radar's energy instead of reflecting it to the sensors. Under these conditions radar penetration can be limited to about three feet. While man-made electronic sources can interfere with the radar signal, this is not usually a serious problem.
Figure 57. Ground penetrating radar traverse across a paleokarst site. Used with permission of Benson and Glaccum, 1979.
Resistivity techniques measure the natural resistivity of soil, rocks, and groundwater, and can be used to assess vertical sections and lateral changes in subsurface materials.

The method uses arrays of electrodes (usually steel stakes) in different configurations, which are set out along traverse lines across the site being investigated (Figure 58). One pair of electrodes, the two C-electrodes in Figure 58, injects an electrical current into the ground, and the generated voltage field is measured between a second pair of electrodes, the two P-electrodes in Figure 58. The injected current's distribution in the earth is determined by the relative high and low resistivities of subsurface materials. Note in Figure 58 that the lines of current are distorted near the anomalous feature, which may be a cavity.

Resistivity is calculated at each station using the measured voltage, the applied current, and the geometry of the electrodes' placement. In this manner a point-by-point subsurface profile is constructed. By combining data from a grid of traverses a contour map can be made of subsurface features. Figure 59 shows what such a map might look like,
Figure 59. A map constructed from data collected by a resistivity survey. Each dot represents a survey station. The contours indicate the relative resistivity changes over the area being investigated, which are indicative of subsurface anomalies. Used with permission of Benson and Glaccum, 1979.

in which the configuration of the contour lines indicate values of subsurface resistivities, which, in turn, can indicate the presence of anomalous features, such as cavities.

A resistivity survey can be time-consuming due to the necessity to set up each station, take readings, then move to the next station and repeat. Inaccurate or inconsistent data can occur due to poor contact of the electrodes with the ground. For example, dry surface materials with very high resistivity will require special techniques to achieve adequate current injection. It may not be possible to get electrode contact in paved areas, such as parking lots or roads. Inherent in the theory and design of various resistivity techniques is that they work best with uniform, homogeneous, layered geological conditions. Inhomogeneities in shallow soil layers can cause unwanted distortions in data. Obviously, extraneous, man-induced, electrical ground currents, or nearby metallic objects will distort the current distribution; for example, power lines, buried pipes, metal fences, and railroad tracks.

With the exception of ground penetrating radar, some of these geophysical techniques have been in use from 40 to 50 years. Recent technological advances have allowed the creation of more compact and portable instrumentation and more sophisticated electronic data processing,
which, in turn, has expanded the potential usefulness of these techniques. The limitation of the techniques that have been given are not inclusive. Some difficulties can be alleviated by experienced operators or by the use of modified techniques.

Two other remote sensing techniques that can be used to investigate karst are aerial photography and satellite imagery. They are especially suited for regional surveys, although aerial photographs can be used to investigate local sites better than satellite imagery.

AERIAL PHOTOGRAPHY

Pictures of terrain taken with special, precision cameras mounted in airplanes are called aerial photographs. The type of aerial photo most often used is conventional black-and-white. Aerial photos can also be taken using films that are sensitive to different portions of the electromagnetic spectrum. Color aerial photos record light across the entire visible spectrum. Fine details and subtle features of the landscape are not as clearly shown as they are on black-and-white photos. Infrared film (heat sensitive) may be useful in karst investigations because bodies of water reflect almost no infrared and appear as very dark areas. This advantage can be offset in vegetated areas or in terrain with high relief. Since very little infrared energy penetrates shadow areas, they show up as very dark tones and obliterate details of the terrain.

Because of aerial photography’s high altitude point-of-view, surface features can be easily observed over a wide area, including topography, vegetation, and geomorphology. To a trained observer surface features often provide clues to subsurface conditions.

Karst usually has a controlling influence on local groundwater, such as flow patterns, and recharge and discharge areas. Therefore, anything that reflects groundwater conditions may be a clue to karst. When karst drainage systems are well developed, certain characteristics are good indicators of groundwater flow or drainage, including linear patterns of vegetation growth, subtle changes in topography, and differing tones or colors of soil.

SATELLITE IMAGERY

Satellite imagery is a recent remote sensing technology that has come of age with the space program. This technology utilizes unmanned, earth-orbiting satellites carrying automatic, television-like sensors. Each satellite normally carries a system of several sensors, referred to as a multiband or multispectral system, because each sensor is sensitive to a separate portion of the electromagnetic spectrum. With each orbit the satellite stores information from its sensors and transmits the data to tracking stations on earth. This electronic information, when reconstructed by computers, produces “images” similar to aerial photos but which are not true photographs.
Satellites can be equipped with sensors that monitor essentially the same portions of the spectrum as aerial photographs. Because of their higher altitudes and speeds, they can cover much more territory and in less time than an aerial photographic survey of the same area. A disadvantage is that they lack the resolution to define objects or ground features of less than about 50 feet by 50 feet in size.

A planned approach to investigating a site for karst features might include the following techniques, in this order: preliminary site assessment using aerial photography or topographic maps, on-site inspections, selected geophysical surveys, and confirmation of suspected karst features by drilling. Depending on time, equipment availability, budget, a project's scope or size, and acceptable risk factors, one or more of these steps might be eliminated or done with less emphasis.

**SUMMARY**

Karst in Florida is expressed in the form of sinkholes, springs, disappearing streams, natural bridges, caves, swale topography, and underground drainage systems. Florida's karst terrain has evolved over eons of geological time. It will continue to evolve, creating new karst features while modifying existing ones. In some cases, the changes will adversely affect man's activities; in some cases the changes will benefit man. By studying karst man can learn to predict more accurately where its underground components are, thereby avoiding them, or utilizing them to advantage, as the case may be.

Sinkholes, some of the most visible karst features, have acquired a reputation of being hazardous. However, only those sinkholes that damage or threaten buildings or other property are really hazardous. The largest number of sinkholes form in areas and circumstances where they do not threaten life or property. Many of Florida's lakes are the result of solution activity or sinkhole formation. They are justifiably touted as valuable natural resources, since they provide water recreation, visual pleasure, accessible supplies of fresh water, and aquatic environments for wild life.

Many domestic and public water supplies are obtained from aquifers in carbonate rocks, such as limestone or dolomite, which lie at relatively shallow depths in parts of Florida. Most of these shallower carbonate aquifers have karst drainage systems associated with them. A better understanding of karst can help to avert groundwater pollution problems, or to ameliorate or solve such problems if they occur.

Acid rain, an environmental problem that has caused international concern in recent years, also occurs in Florida. Available data for Florida do not indicate significant damage to the environment or to crops. While not enough data exist to say with certainty that acid rain will not increase the rate of karst formation, a reasonable projection is that it will not.

There occur throughout much of the peninsula deeper zones of cavernous porosity in carbonate rocks, which were created by solution activity.
Hydrologically separated from the shallower, freshwater aquifers by confining beds, they generally contain non-potable water and are of little value to Florida in their natural state. However, research has shown that it may be possible to develop techniques to utilize them to store freshwater during time of surplus, then recover the water when needed. If these techniques are successful, these karst systems can acquire inestimable value to some parts of Florida.

More research is required to understand karst, where and why it occurs, where it may occur in the future, and how to avoid harmful effects. New technologies, sometimes in conjunction with older, traditional techniques, promise to increase the success rate in detecting existing underground karst features and in predicting potential occurrences.
REFERENCES


Banks, J.E., 1964, South Florida carbonate sediments, a guidebook for field trip No. 1: GSA Convention, Nov. 1964, pp. 2-4.


Florida Sinkhole Research Institute, 1983, Update, 1/1, Univ. of Central Florida, Orlando, 4 pp.


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